Korean J. Chem. Eng., 38(12), 2397-2405 (2021)
DOI: 10.1007/s11814-021-0883-4

pISSN: 0256-1115
eISSN: 1975-7220

Cost and robustness analysis of the Korean government's renewable energy plan under varying scenarios

Namjin Jang*, Wonjun Kim,‡, Dongchan Lee**,‡, Geol Yoon**,‡, Jiho Yang**,‡, Ian Cho**,‡, Hyelynn Jeon**,‡, and Jamin Koo**,†**

*Hanwha Solutions, Daejeon 34128, Korea
**Department of Chemical Engineering, Hongik University, Seoul 04066, Korea
(*Received 19 April 2021 • Revised 3 June 2021 • Accepted 27 June 2021*)

Abstract−In the ongoing global warming era, increasing the share of renewable energy systems (RES) in the energy portfolio has been a goal for many governments around the world. South Korea is not an exception and has employed numerous policy measures to promote adoption of RES. The latest renewable energy plan is one of those measures in which the target shares of RES are set for the coming decade. This study proposes a revised, more comprehensive mathematical model for assessing the total costs associated with installment, operation, and disintegration of RES. The proposed model is applied to examine the Korean government's latest plan in terms of the four major RES: solar PV, wind power, biomass energy, and fuel cell power. Sensitivity analysis was conducted to evaluate robustness of the plan with respect to changes in the price of fuels and CO_2 emission. The results illustrate the contribution of various types of costs for implementing the plan and provide insight on numerous issues, including key areas of research for minimizing the costs.

Keywords: Wind Power, Solar Photovoltaics, Bioenergy, Fuel Cells, Renewable Energy

INTRODUCTION

Since the establishment of the first national renewable energy plan in 2008, the South Korean government has been promoting adoption of various renewable energy technologies. The proportion of the national energy supplied by the four major renewable types—wind power, solar photovoltaics (PV), bioenergy, and fuel cells—increased from 0.2% in 2008 to 4.4% in 2018 [1]. The increased utilization of RES contributed to reduced emission of greenhouse gases in Korea, as well as growth of the pertinent private sectors. The market size of the domestic photovoltaics industry, for example, grew from USD 33M to 406M between 2008 and 2018 [2].

The increased utilization of the renewable energy technologies has been achieved by providing subsidies and tax benefits [1,2]. The levelized cost of energy (LCOE) of the four major renewable types in Korea, for example, has been up to nine-fold higher than the cost of traditional energy technologies, mainly fossil fuel based and nuclear power plants [3,4]. The proportion of the renewable energy technologies was still raised by the Korean government in order to meet the internationally agreed targets of greenhouse gas emission. The fossil fuel based power plants emit up to 20-fold more CO_2 per kilowatt hour (kWh) than the average amount the four renewable energy technologies does [5]; therefore, replacing the former with the latter results in reduced emission.

The continued increase in use of the renewable energy technologies also resulted in lower LCOEs, primarily due to learning effects and technological advancement. The LCOE of photovoltaics, for example, was reduced from 0.43 to 0.14 $/kWh between 2008 to 2018 [6,7], corresponding to an average learning rate of 32%. The total capacity of solar PVs installed in South Korea increased from 0.4 GW to 5.7 GW during the same period [1,8]. The efficiency of solar energy conversion using Si crystalline cell reported in literature rose from 20.4% to 26.7% [9,10]. The LCOEs of the other renewable energy technologies decreased as well, owing to some or all of the aforementioned effects and advancements.

We previously assessed the total cost associated with implementing the renewable energy plan in 2011 [8]. The work provided the means to estimate and plan the budget necessary for increasing the proportion of RES by a certain amount, which is especially useful for regions where the energy supply is determined by government as in South Korea. The intermittency of RES as well as variability in the price of fuels such as biomass and natural gas was not addressed in the previous models; however, the recent work showed that these two factors can have significant impact on the total cost of RES [11-14]. Notton and colleagues, for example, suggested that intermittency adds profile, balancing, and grid-related costs which can be as high as USD 14 per MWh [15]. Batalla-Bejerano and Trujillo-Baute also argued that adjustment costs will increase proportionately as the share of solar PV and wind power increases within the electricity grid [16]. In terms of the variable prices of renewable fuels, Golecha and Gan showed that the price of corn stover has changed up to 30% annually and that this variability added extra feedstock cost for using corn stover as bioenergy [17]. Wil-

†To whom correspondence should be addressed.
E-mail: jaminkoo@hongik.ac.kr
‡These authors contributed equally to the work described in this paper.

liams et al. reported that the characteristics of biomass such as moisture and lignin content vary with respect to sources and that such variability can result in inconsistent amount of energy produced per mass of biomass [18]. To our best knowledge, no work has been reported that integrates all those aspects when evaluating the total costs of implementing the RES.

In this study, we propose a revised method for assessing the total cost of renewable energy systems that takes into account intermittency and variable prices of renewable fuels, as well as learning effects and uncertain prices of fossil fuels and carbon. The proposed method is applied in analyzing the total cost associated with implementing the latest renewable energy plan of South Korea. In the process, we hypothesize three scenarios that represent the business as usual (BAU), most unfavorable, and favorable environment towards utilization of renewable energy sources. Only solar PV, wind power, biomass energy, and fuel cells are included as RES in the analysis due to availability of data and relevance to the Korean government's plan.

MATHEMATICAL MODELING

1. Total Costs

In previous work, we proposed that the total cost of utilizing a renewable energy technology for supplying energy can be calculated as the sum of capital, fixed, variable, and external costs [8]. The model included all types of the costs associated with installation and operation of the RES, as well as damages incurred with respect to health and environment; however, the costs associated with stripping the facilities after use were excluded. Recent studies show that the stripping cost can be substantial for the four RES covered in this study [19-22]. We thus developed and applied the following updated equation for calculating the total cost (TC_i) of utilizing a renewable energy system i:

$$TC_i=CC_i+FC_i+VC_i+EC_i+SC_i+IC_i \tag{1}$$

where CC, FC, VC, EC, SC, and IC represent capital, fixed, variable, external, stripping, and intermittence cost, respectively.

The first five costs in the above equation can be calculated as follows:

$$CC_i=\Sigma_{t=1}^{N}\left[\frac{1}{(1+d)^{t-1}}\left\{\left(\frac{C_{i,\,t-1}}{C_{i,\,0}}\right)^{\alpha_i}KC_{i,\,t=0}\right\}I_{i,\,t}\right] \tag{2.1}$$

$$FC_i=\Sigma_{t=1}^{N}\left[\frac{1}{(1+d)^{t-1}}\left\{\left(\frac{C_{i,\,t-1}}{C_{i,\,0}}\right)^{\alpha_i}KF_{i,\,t=0}\right\}C_{i,\,t}\right] \tag{2.2}$$

$$VC_i=\Sigma_{t=1}^{N}\left\{\frac{1}{(1+d)^{t-1}}(PF_{i,\,t})(\tau_{i,\,t},\,C_{i,\,t})\right\} \tag{2.3}$$

$$EC_i=\Sigma_{t=1}^{N}\left\{\frac{1}{(1+d)^{t-1}}(PC_t+PP_i)(\tau_{i,\,t},\,C_{i,\,t})\right\} \tag{2.4}$$

$$SC_i=\Sigma_{t=1}^{N}\left[\frac{1}{(1+d)^{t+lt_i}}\left\{\left(\frac{C_{i,\,t-1}}{C_{i,\,0}}\right)^{\alpha_i}PR_{i,\,t=0}\right\}I_{i,\,t}\right] \tag{2.5}$$

The capital cost (CC) of an RES i is the product of its unit capital cost (KC_i) multiplied by the size to be newly installed in that year ($I_{i,t}$). In order to apply the learning effect, the unit capital cost is adjusted by using α_i [8], which is related to the learning rate (LR) of the RES i. The fixed cost (FC), mainly due to operation and maintenance, is calculated in a similar manner using KF_i and $C_{i,t}$ that represent the unit fixed cost and the total capacity of the RES i in use during the year t. As in the previous work, the learning effects are applied to these two types of costs. Variable cost (VC) represents the cost of (renewable) fuels and is the product of unit price of fuel PF, capacity, and capacity factor τ. Expectedly, variable costs are non-zero for only bioenergy and fuel cell power. Capacity factor is to adjust for the proportion of the total capacity used in generating energy during the year t. Capacity factor, τ, of RES is usually much lower than that of the fossil fuel based energy production technologies (Table 1), and varies from time to time, place to place.

Table 1. Average capacity factors of the four RES in S. Korea

RES	τ (%)	Reference
Solar PV	17	20
Wind power	23	23
Biomass energy	74	24
Fuel cell power	97	25

External cost (EC) stands for the cost associated with environmental impact. In previous work, we only included the cost of CO_2 emission using PC_t, which is the average price of carbon in year t [8]; however, we also recognize the growing contribution of non-carbon costs such as pollution due to heavy metal (ion) leakage for solar PVs [26] and other RES. We thus added another term within Eq. (2.4) to account for these contributions, with PP_i being the sum of environmental costs over the life cycle for renewable energy system i divided by its lifetime (lt). Lastly, SC represents the stripping cost, or the cost of disintegrating the system after the lifetime [19]. PR_i is the per MW cost of uninstalling a facility of the renewable energy system i.

2. Intermittency of RES

Not all RES are subject to the intermittency problem. Among the four major types studied in this paper, biomass energy and fuel cells are free of the issue as they can produce energy at any time as long as fuels are provided. In contrast, solar PV and wind power suffer from intermittency (Fig. 1). The amount of power delivered by the solar PV throughout a day usually follows the gaussian curve with the center being near 1:00 PM; the curve for a monthly basis takes the form of an inverted parabola with the maximum between April and July [27]. The curves for wind power are less consistent across hours (Fig. 1(b)) and days; however, they tend to follow the parabola with the minimum occurring around June throughout a year [28].

Additional costs arise when integrating solar PV and wind power due to this stochastic intermittency. The costs are due to profiling, balancing, and managing the grid, which includes preparing and operating reserve power plants as well as storage devices. Notton et al. thoroughly investigated the magnitude of the intermittence cost for solar PV and wind power [15]. Based on their and other

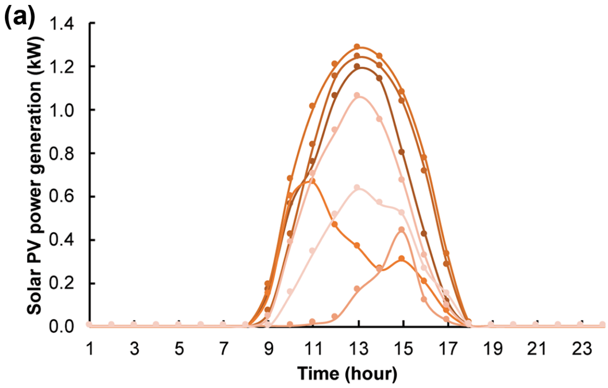

Fig. 1. Electricity generation by (a) solar PV or (b) wind power across hours in S. Korea. Each colored line represents a different day within a week of July or January, 2018, for the solar PV and wind power, respectively.

previous work, the intermittence cost is calculated as follows:

$$IC_i = \Sigma_{t=1}^{N}\left[\frac{1}{(1+d)^t}\left\{\left(\frac{C_{i,\,t-1}}{C_{i,\,0}}\right)^{\beta_i} CI_{i,\,t=0}\right\}C_{i,\,t} \quad \tau_{i,\,t}\right] \qquad (2.6)$$

where CI_i and β_i are the cost of intermittency and its learning effect for the RES i. The learning rate is applied based on the previous reports showing that improvements in the profiling, balancing, and/or grid managing can lower the intermittence cost. For example, reduction in the mean average errors of forecasting wind power by 3.5% enabled saving US$2.5 million [15]. Breakthrough enhancement in battery performance and capacity will also contribute to lowering the intermittence cost.

EMPIRICAL DATA AND SCENARIOS

1. Capital Cost, Fixed Cost, and Learning Rates

Numerous institutions, including the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA), publish annual reports on parameters related to consumption, production, and costs for both traditional and renewable energy systems. In this study, we investigated both these international literature and domestic reports made by Korean organizations to find numerical values for the parameters used in the proposed model (Table 2). It is important to note that the cost parameters are based on the standard sizes of the four RES that are the most commonly used in S. Korea. Our goal is to assess the total costs

Table 2. Capital cost, fixed cost, lifetime, and learning rates of the four RES

RES technology	KC ($/MW)	KF ($/MW)	lt (yrs)	LR (%)	Reference
Solar PV	1,490,000[a]	17,800	25	24.5	4,29,30
Wind power	890,000[a]	22,250	20	6.5	31-33
Biomass energy	2,460,000[a]	114,390	25	6.0	24,34
Fuel cell	3,750,000[a]	297,620	5	17.4	35,36

[a]Accordingly, these parameters are based on the following standard sizes of the four RES technologies: 0.2 kW per panel (solar PV), 2.5 MW (wind power), 10 MW (biomass energy), and 2.5 MW (fuel cell).

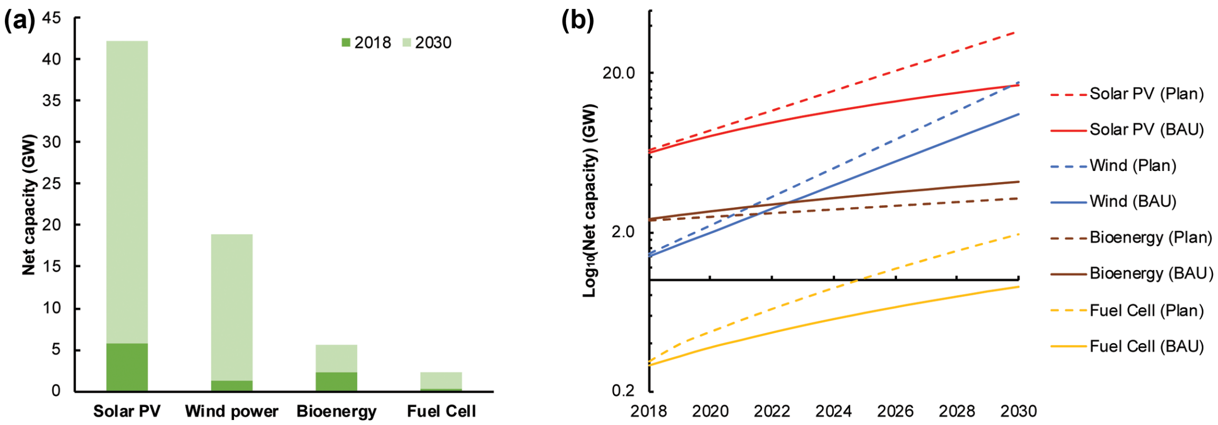

Fig. 2. (a) Prospect on the overall, and (b) annual changes in the net capacity of the four RES in S. Korea.

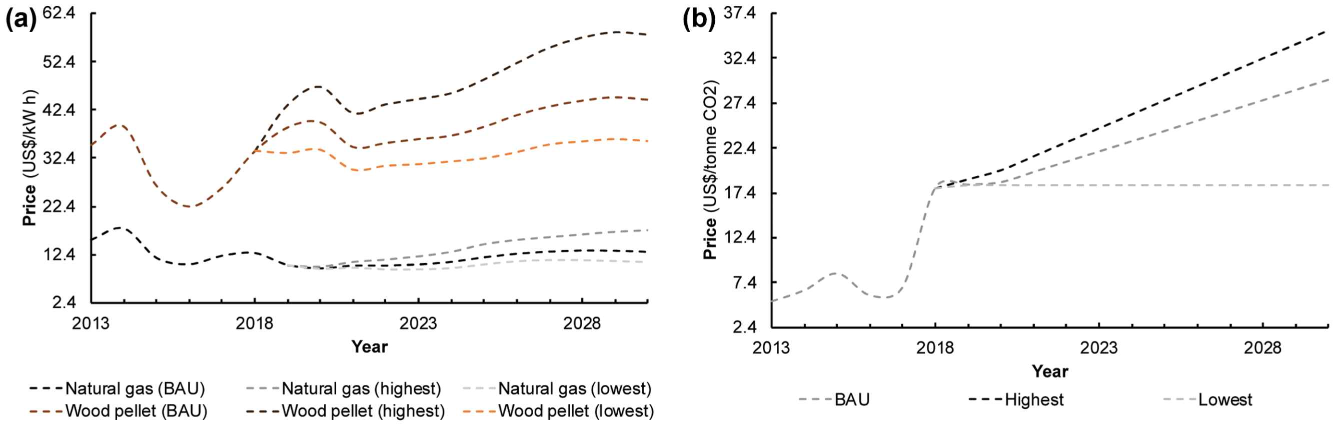

Fig. 3. (a) Prospects on the price of wood pellet and natural gas, and (b) CO_2 emission allowance until 2030.

and robustness of the S. Korean government's newest renewable energy plan; therefore, we adopted the values reported by the domestic agencies when available.

2. Capacity of New Installments

According to the South Korean government's latest plan, the capacity of the four RES will increase from the current levels as shown in Fig. 2(a). The solar PV will be responsible for 63% of the net increase, followed by the wind power covering 34%, which equals to 16.5 GW to be newly installed between 2018 and 2030. The percent increase in capacity will be the lowest for the bioenergy (43%). In contrast, the net capacity of fuel cell power plants will increase about 6.3-fold, which is second to the 14.8-fold for the wind power.

We analyzed the growth rate of the net capacity of the four RES in S. Korea between 2008 and 2017 and used it in drawing the business as usual (BAU) curves (Fig. 2(b)). In terms of the government's plan, we also assumed a constant growth rate so that the targeted sizes can be reached by the year 2030. The total cost may be minimized by planning annual installments differently [19] but it is out of scope for this study. The comparison with the aforementioned plan shows that all RES except bioenergy will increase more under the government's plan than it would in the BAU scenario. Among the three, the difference between the BAU and the government plan is the largest for the fuel cell; the difference is little more than two-fold of the net capacity under the BAU. In contrast, the net capacity by the year 2030 under the S. Korean government's latest plan will be lower than the BAU by 20% for bioenergy.

3. Prices of Fuels and Carbon

Among the four RES, biomass and fuel cell power require fuels to generate energy in the form of electricity and heat. Wood pellets and H_2 are the primary fuels for the two RES in S. Korea. While more than 70% of the former is imported, the latter is produced locally using natural gas via the reforming process [36,37]. Fig. 3(a) shows the prices of the two for the past five years, as well as prospects until 2030 [37,38]. Evidently, the prices are volatile for both, with the wood pellet featuring a greater variance in the past. For prices in the future, three representative scenarios—BAU, the cheapest, and the most expensive—have been adopted. Statistical analysis suggests that the prices of wood pellet and natural gas are highly correlated, at least for the past 10 years.

The price of CO_2 emission allowance is another that may be significantly different under each scenario. South Korea is currently not assigning tax on CO_2 emission. Instead, the government supports the employment of RES by providing subsidies. In this study, we used the allowance price for calculating the external cost. Previous work suggests that the price may increase up to $35 per tonne of CO_2 by 2030 (Fig. 3(b)) [39]. Statistical analysis suggests that the allowance price is weakly correlated to the price of aforementioned renewable fuels; therefore, we did not couple the allowance price to the price of wood pellet and natural gas in the analysis.

4. Environmental, Disintegration, and Intermittence Cost

The component-wise analyses of the environmental impacts for

Table 3. CO_2 emission rate, environmental (PP), disintegration (PR), intermittence cost (CI), and learning rate for adjusting the intermittence cost

RES technology	Emission (CO_2 ton/MWh)	PP ($/MWh)[a]	PR ($/MW)	CI ($/MWh)	LR (%)	Reference
Solar PV	0.097	1.24	159,000	9.5	1.3	15,20
Wind power	0.016	0.33	145,000	5.0	6.6	15,40
Biomass energy	0.090	3.38	53,000	0.0	-	40,41
Fuel cell	0.080	8.86	860,000	0.0	-	36,42

[a]The value for each RES was obtained by dividing the sum of costs for all environmental impact (except one due to CO_2 emission) by the lifetime.

the four RES over the life cycle have been adopted in assigning numerical values to the parameters (Table 3). As explained, these numbers (PP) exclude the environmental cost of emitting CO_2 since it is evaluated separately as PC in the model (Eq. (2.4)). These non-carbon environmental costs are larger than the external cost due to CO_2 emission for biomass energy and fuel cells; they are up to 2.4-fold lower than the CO_2 emission cost for solar PV and wind power.

Disintegration will take place at least 20 years after installing any of the three RES except fuel cell power. Previous work revealed that the magnitude of this cost is invariably lower than the other types of costs (Table 2). The stripping cost per MW is the highest for the fuel cell, which is more than five times the cost for the other three RES; however, it will likely fall the fastest over the coming years considering its relatively short history of commercialization and potential for improvement. In contrast, IC is zero for both the fuel cell and biomass energy. Solar PV features the highest intermittence cost that is seven-fold larger than the environmental cost (PP). CI is lower for wind power, and the difference with respect to the intermittence cost of solar PV will increase due to the higher learning rate.

COSTS AND ROBUSTNESS OF SOUTH KOREA'S RENEWABLE ENERGY PLAN

1. Total Cost and Proportion of Each Cost

At a discount rate of 4%, executing the South Korean government's latest renewable energy plan until 2030 will cost about USD 63 billion (Fig. 4(a)). This is roughly 20% larger than the budget required if the capacity of the four RES grows in the BAU scenario and reflects the government's dedication to promoting (domestic) adoption of RE technologies. According to the plan, solar PV will be responsible for 48% of the total cost, which is expected since its capacity is to increase by the largest magnitude. Biomass energy will cost roughly the same amount of budget as wind power (USD 13 billion); however, the annual total cost of wind power will increase by five-fold, while the TC of biomass energy will remain the same. The proportion of fuel cell power in the total cost will be the lowest (13%) but is disproportionately large considering its share of the total capacity (3%).

Fig. 4(a) also shows that the total costs of solar PV and biomass energy are the most affected by the South Korean government's latest plan. If the capacity of the four RES increased as it did in the past ten years (BAU, Fig. 2(b)), the annual $TC_{bioenergy}$ will be the largest in 2030; however, it would be the second smallest under the plan. Similarly, the annual total cost of solar PV will be smaller than the amount for the wind power by the year 2030 if there was no plan. The total cost of fuel cell until 2030 is 1.5-fold larger under the plan than in the BAU scenario. In this manner, the comparative analysis illustrates that the South Korean plan promotes greater adoption of solar PV and fuel cell while curbing the growth of biomass energy.

Fig. 4(b) demonstrates how the composition of the total cost changes by 2030 under the plan. To begin with, one can see that the proportion of the capital cost for solar PV decreases, owing to the high learning rate and substantial increase in the cumulative capacity over the years. The changes in the proportions are negligible for wind power due to the low learning rate in spite of the similarly large increase in capacity. Biomass energy is also expected to experience insignificant changes in the proportion of each cost under the plan if the price of wood pellet follows the BAU scenario (Fig. 3(a)); however, the proportion will change significantly if the price of biomass unfolds differently (details in Section 4.2). Fuel cell power will face the largest changes, with the share of CC reduced by one-third while that of VC and EC increasing by more than double. As such, more emphasis should be given towards managing and minimizing these costs in the future.

2. Sensitivity Analysis and Robustness

The (annual) total cost and proportions of each cost are markedly different under the three scenarios with respect to the price of fuels and CO_2 emission. As mentioned, the results in Section 4.1 are based on the scenario where the two prices follow the BAU

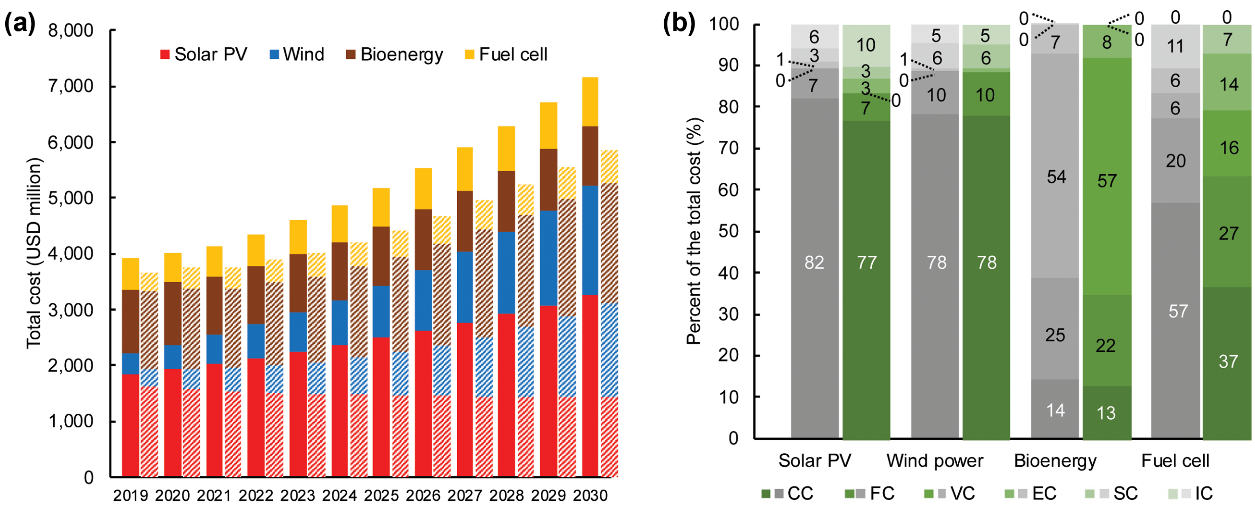

Fig. 4. (a) Total cost of the four RES until the year 2030 when the capacity increases as in the plan (left bars) vs the BAU scenario (right bars); (b) the proportions of each cost in the year 2019 (left) vs 2030 (right).

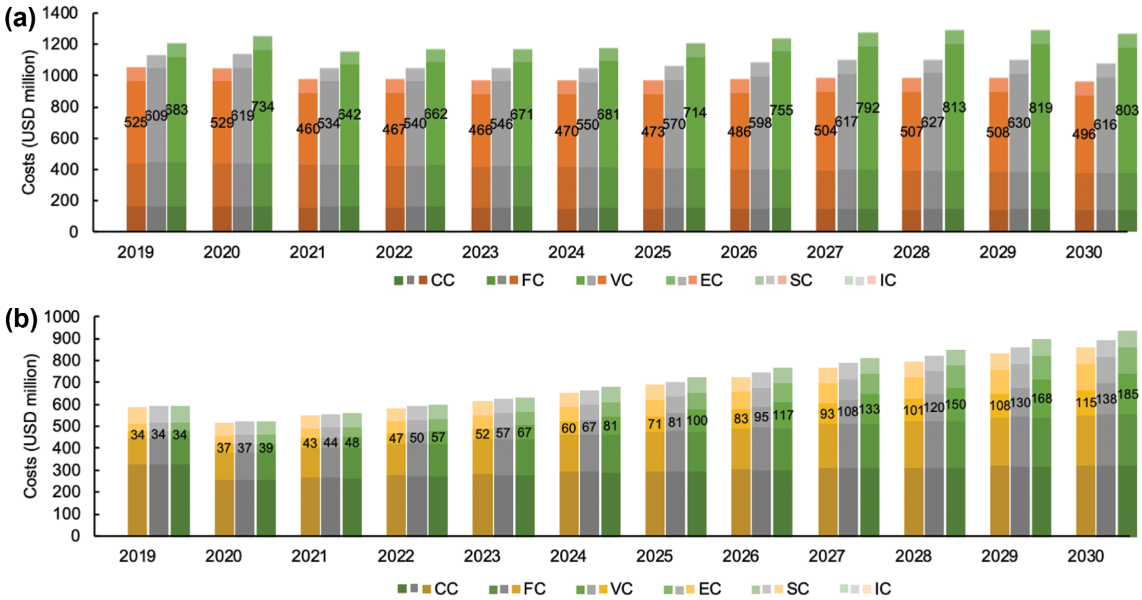

Fig. 5. Total costs of the (a) biomass energy and (b) fuel cell power until the year 2030 when the prices of fuels unfold as in the lowest (left), BAU (middle), and highest (right) scenarios.

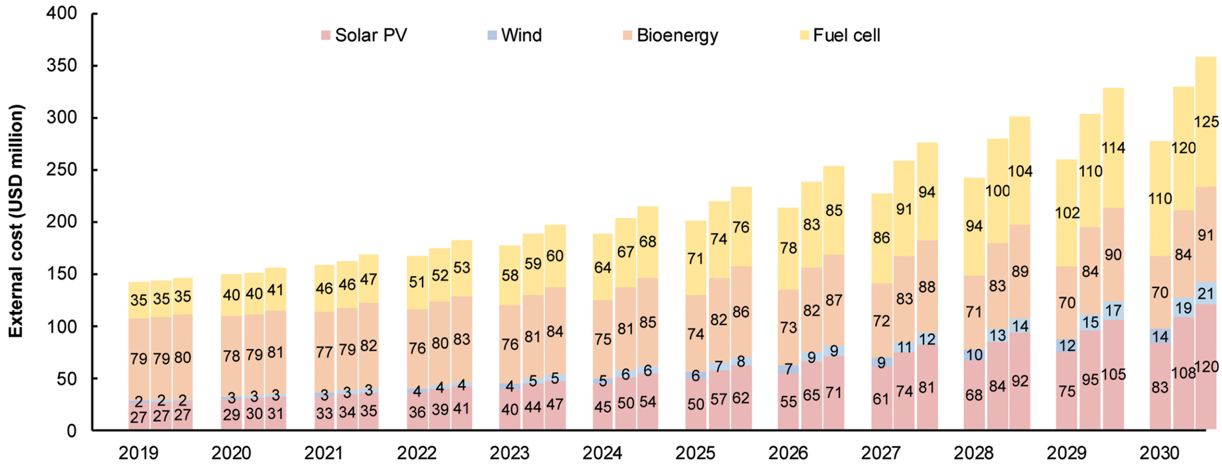

Fig. 6. External cost of the four RES until the year 2030 when the price of CO_2 emission unfolds as in the lowest (left), BAU (middle), and highest (right) scenarios.

scenario. If the price of wood pellet increases by the highest margin (Fig. 3(a)), the total cost of biomass energy over the same period will increase 13% (Fig. 5(a)); the proportion of the VC, i.e., cost of purchasing fuel, will become 63% vs 57% in the BAU scenario. Under the lowest price scenario, the total cost and proportion of the VC will become 91% of the TC and 52% under the BAU scenario, respectively. Similarly, the total cost of fuel cell power will be 1.03- and 0.98-fold of the amount under the BAU scenario (Fig. 5(b)) when the fuel price increases or decreases the most, respectively. Compared to the biomass energy, the differences among the three scenarios are significantly smaller, because, in part, the differences in the price of natural gas in these scenarios are much smaller than those of wood pellet. Furthermore, the proportion of the fuel cost, i.e., VC, is relatively smaller for the fuel cell power—16 vs 57% for biomass energy. Fig. 5(b) also shows that the proportion of the VC changes to a lesser extent for fuel cell power: 14 to 20% of the TC.

The external cost of the four RES also varies significantly with respect to the price of CO_2 emission (Fig. 6). To begin with, $EC_{wind\,power}$ is the most sensitive to the price and becomes 0.83- and 1.08-fold of the BAU amount under the lowest and highest price scenarios, respectively. The situation is similar for solar PV: 0.85- and 1.08-fold under the two extreme scenarios. These results are expected given the high ratio of the emission rate to the other environmental costs for the two RES (Table 2). The external cost of fuel cell power is the least sensitive to the price of CO_2 emission; the sum of EC over the same period ranges from 0.95- to 1.03-fold of the BAU amount. Expectedly, the ratio of emission rate to the other environmental costs is the lowest for fuel cell. Biomass energy shows an intermediate level of sensitivity; however, the absolute magni-

Table 4. All-time high and low prices of fuels and CO_2

Item	Highest price in history	Lowest price in history	Reference
Wood pellet	USD 112/tonne	USD 210/tonne	[37,43]
Natural gas	USD 20/MMBtu	USD 1.8/MMBtu	[38]
CO_2 emission	0 euros/tonne	32 euros/tonne	[44]

tude of change across the scenarios is the second largest (USD 21 million) due to its relatively large emission rate and cumulative capacity.

The prices of fuels and CO_2 emission increase monotonically until 2030 in the three scenarios that we adopted from the previous work [37-39]. In order to better understand the robustness of the plan under extreme conditions, we analyzed the total cost of implementing the plan under two additional scenarios where the prices reach historically high or low levels (Table 4). When the price of natural gas reaches the all-time high level, the annual TC in 2030 becomes 1.8-fold of the BAU value for the fuel cell power. If the prices become historically low levels by 2030, the annual TCs will be 0.73- and 0.89-fold of the BAU for the biomass energy and fuel cell power. These results reflect the fact that the range of price covered in the three scenarios is around the historically high level for wood pellet versus all-time low level for natural gas. As for the price of carbon, the historically low level (zero) by the year 2030 will cause the TC of the four RES to decrease by only 2%. This minor reduction in the TC was expected given the low CO_2 emission rate of the solar PV and wind power (Table 3) that are projected to constitute more than 90% of the total capacity under the governmental plan by 2030.

3. Implications for the Stakeholders

The results presented in the previous two subsections offer valuable insights for policy makers, industrial organizations, and other related parties. To begin with, one can discern that the capital costs of solar PV and wind power will be responsible for the largest proportion (50%) of the total costs over the coming decade. Technologies that reduce the cost of manufacturing PV panels or wind turbines will thus contribute the most in lowering the total cost of implementing the Korean government's latest plan. Examples of the latest research and development (R&D) efforts in this venue include lowering specific ratings for wind turbines [45] and synthesizing novel materials for use as PV cell [46].

An important insight can be obtained from the results of sensitivity analysis. Across all scenarios, the greatest change in cost takes place with respect to the fuel cost of biomass energy. The difference in this single cost can be as large as USD 3 billion, which is roughly 5% of the total cost for implementing the plan. Therefore, efforts towards optimizing supply chain of wood pellet [47] and investing in technologies that lower the cost of producing and/or storing biomass [48], for example, can also result in significant savings. Another insight that the sensitivity analysis offers is related to the robustness with respect to the changes in the price of CO_2 emission. The results suggest that the carbon price is responsible for a low proportion of the external cost for these four RES. On average, the other environmental costs making up the EC are responsible for 30 to 79%. This is the most pronounced for fuel cell power, resulting in only 21% increase in EC when the price of CO_2 emission increases by 2-fold. In this regard, more incentives and attention should be devoted towards mitigating these non-carbon waste materials coming out of (used) fuel cells. One of the latest work in this field assessed the environmental impact of various processes treating platinum in disposed fuel cells, suggesting the need to recover and reuse the material [49].

CONCLUSION

We have proposed a revised model for evaluating the economics of RES under varying scenarios. The updated model includes disintegration and intermittence costs, as well as comprehensive environmental costs for estimating the total cost of supplying energy using renewable energy sources. We applied the model in analyzing the total cost required for implementing the latest renewable energy plan of South Korea. The results were obtained with respect to the four major RES that are expected to have cumulative capacities increase by the largest margins. Comparative analysis against the BAU scenario where the capacities of the four RES increase as they did over the past decade was provided to illustrate how the plan promotes greater adoption of the RES. Sensitivity analysis was also conducted to show the influence of key uncertain parameters, i.e., price of fuels and CO_2 emission, on the total costs.

Several simplistic assumptions, such as constant discount and learning rates, were taken in the case study. Emerging novel technologies for the four RES, like hybridization with other energy sources, were also not considered. Still, the results can provide a valuable insight to the stakeholders across all areas—from government agencies to private firms. The outlook on costs and their sensitivity to changes in the key variables like prices of carbon and fuels hint on where to focus R&D efforts for effective reduction in costs. They also reveal business opportunities in the energy sector and the amount of investment needed to be cost-competitive in the market. In this manner, we believe that the findings in this study will benefit diverse decision makers in the renewable energy field not limited to South Korea.

ACKNOWLEDGEMENTS

This work was supported by 2020 Hongik University Research Fund, and the National Research Foundation of Korea (NRF-2019 R1C1C1002642).

ABBREVIATIONS

BAU : business as usual
EIA : energy information administration

GW : gigawatt
IEA : international energy agency
kWh : kilowatt hour(s)
LCEO : levelized cost of energy
LR : learning rate
MW : megawatt
PV : photovoltaics
RES : renewable energy system

Nomenclature

α_i : learning effect for the capital, fixed, and stripping cost of renewable energy system i
β_i : learning effect for the intermittence cost of renewable energy system i
$C_{i,t}$: cumulative capacity of renewable energy system i in year t
CC_i : capital cost of renewable energy system i
CI_i : unit intermittence cost of renewable energy system i
d : discount rate
EC_i : external cost of renewable energy system i
FC_i : fixed cost of renewable energy system i
$I_{i,t}$ capacity of renewable energy system i installed in year t
IC_i : intermittence cost of renewable energy system i
KC_i : unit capital cost of renewable energy system i
KF_i : unit fixed cost of renewable energy system i
lt_i : lifetime of renewable energy system i
PC_t : price of CO_2 emission allowance during year t
$PF_{i,t}$: price of fuel for renewable energy system i in year t
PP_i : unit environmental cost excluding that due to CO_2 emission for renewable energy system i
PR_i : unit disintegration cost for renewable energy system i
SC_i : Stripping cost of renewable energy system i
t : time [year]
$\tau_{i,t}$: capacity factor of renewable energy system i during year t
TC_i : total cost of renewable energy system i
VC_i : variable cost of renewable energy system i

REFERENCES

1. D. Son, J. Kim and B. Jeong, *Energies*, **12**, 1667 (2019).
2. Y. Ha, J. Byrne, H.-S. Lee, Y.-J. Lee and D.-H. Kim, *WIREs Energy Environ.*, **9**, 1 (2020).
3. C. Lee and S. Huh, *Renew. Sustain. Energy Rev.*, **69**, 207 (2017).
4. S. Huh and C. Lee, *Energy Policy*, **69**, 248 (2014).
5. R. Turconi, C. O. Dwyer, D. Flynn and T. Astrup, *Appl. Energy*, **131**, 1 (2014).
6. A. Allouhi, R. Saadani, M. S. Buker, T. Kousksou, A. Jamil and M. Rahmoune, *Sol. Energy*, **178**, 25 (2019).
7. C. Breyer, A. Gerlach, J. Mueller, H. Behacker and A. Milner, *2009 34th IEEE Photovoltaic Specialists Conference (PVSC)* (2009).
8. J. Koo, K. Park, D. Shin and E. S. Yoon, *Appl. Energy*, **88**, 2254 (2011).
9. M. A. Green, N. Kopidakis, E. D. Dunlop and A. W. Y. H. Baillie, *Prog. Photovoltaics*, **2**, 3 (2020).
10. M. A. Green, *Prog. Photovoltaics*, **17**, 183 (2009).
11. Y. Liang, B. Yu and L. Wang, *Renew. Energy*, **131**, 700 (2019).
12. A. N. Arnette, *Renew. Sustain. Energy Rev.*, **70**, 254 (2017).
13. C. D. Yue, C. S. Chen and Y. C. Lee, *Renew. Energy*, **86**, 930 (2016).
14. W. Deason, *Renew. Sustain. Energy Rev.*, **82**, 3168 (2018).
15. G. Notton, M. Nivet, C. Voyant, C. Paoli, C. Darras, F. Motte and A. Fouilloy, *Renew. Sustain. Energy Rev.*, **87**, 96 (2018).
16. J. Batalla-bejerano and E. Trujillo-baute, *Energy Policy*, **94**, 411 (2016).
17. R. Golecha and J. Gan, *Renew. Sustain. Energy Rev.*, **57**, 34 (2016).
18. C. L. Williams, T. L. Westover, R. M. Emerson, J. S. Tumuluru and C. Li, *Bioenergy Res.*, **9**, 1 (2016).
19. J. Koo, K. Han and E. S. Yoon, *Renew. Sustain. Energy Rev.*, **15**, 665 (2011).
20. B. Kim, J. Kang, S. Park, J. Jang and J. H. Hong, *New Renew. Energy*, **15**, 36 (2019).
21. X. Ouyang and B. Lin, *Energy Policy*, **70**, 64 (2014).
22. M. J. Kaiser and B. Snyder, *Mar. Policy*, **36**, 153 (2012).
23. H. Kim, Y. Kang and C. K. Kim, *J. Wind Power*, **8**, 21 (2017).
24. H. K. Kang, K. C. Park and L. H. Kim, *Korean Soc. Energy*, **23**, 7 (2014).
25. J. Kim and T. J. Lee, *2019 Annual Meeting of Korea Society of Energy & Climate Change*, 33 (Korea Society of Energy&Climate Change, 2019).
26. P. Sinha, M. de Wild-Scholten, A. Wade and C. Breyer, *28th European Photovoltaic Solar Energy Conference and Exhibition*, 4583 (2013).
27. Hourly power generation by the solar PV unit 1. *South Korean Government Public Data* (2020). Available at: https://www.data.go.kr/data/15050345/fileData.do.
28. Hourly power generation by the wind power unit 1. *South Korean Government Public Data* (2020). Available at: https://www.data.go.kr/data/15043275/fileData.do.
29. C. Parrado, A. Girard, F. Simon and E. Fuentealba, *Energy*, **94**, 422 (2016).
30. L. Meng, J. You and Y. Yang, *Nat. Commun.*, **9**, 5265 (2018).
31. E. Williams, E. Hittinger, R. Carvalho and R. Williams, *Energy Policy*, **106**, 427 (2017).
32. G. D. Lee, M. D. Park, Y. J. Cheong, H. C. Shin and J. H. Yang, *A study on the calculation of LCOEs for various energy technologies*, Korean Power Exchange, Seoul (2018).
33. L. Ziegler, E. Gonzalez, T. Rubert, U. Smolka and J. J. Melero, *Renew. Sustain. Energy Rev.*, **82**, 1261 (2018).
34. International Energy Agency, *International Energy Outlook 2019* (2019).
35. M. Wei, S. J. Smith and M. D. Sohn, *Appl. Energy*, **191**, 346 (2017).
36. J. H. Kim, An Empirical Analysis of Fuel Cell Generation Operation, Soongsil University (2019).
37. J. R. Park, *Statistics on the wood pellet*, Korean Forest Service, Daejeon (2018).
38. Import prices of natural gas. *Korea Energy Statistical Information System* (2020). Available at: http://www.kesis.net/main/main.jsp.
39. S. Schjolset, *The MSR: Impact on market balance and prices*, Thomson Reuters, Toronto (2014).
40. Braun, M. Environmental External Costs from Power Generation by Renewable Energies, Universität Stuttgart (2004).
41. V. Nian, Q. Sun and H. Li, *Energy Procedia*, **104**, 556 (2016).
42. I. Staffell, A. Ingram and K. Kendall, *Int. J. Hydrogen Energy*, **37**, 2509 (2011).

43. D. Thrän, K. Schaubach, D. Peetz, M. Junginger, T. Mai-Maulin, F. Schipfer, O. Olsson and P. Lamers, *Biofuels, Bioprod. Biorefining*, **13**, 267 (2019).
44. Y. Huang, X. Dai, Q. Wang and D. Zhou, *Appl. Energy*, **285**, 116485 (2021).
45. M. Odenberger, L. Reichenberg, V. Johansson, L. Thorson, J. Goop, L. Goransson, M. Taljegard and F. Johnsson, *Energy*, **126**, 352 (2017).
46. A. K. Pandey, M. S. Hossain, V. V. Tyagi, N. A. Rahim, J. A. L. Selvaraj and S. Ahmet, *Renew. Sustain. Energy Rev.*, **82**, 281 (2018).
47. T. Boukherroub, L. Lebel and S. Lemieux, *Appl. Energy*, **198**, 385 (2017).
48. L. Kumar, A. A. Koukoulas, S. Mani and J. Satyavolu, *Energy Fuels*, **31**, 37 (2017).
49. L. Duclos, M. Lupsea, G. Mandil, L. Svecova, P.-X. Thivel and V. Laforest, *J. Clean. Prod.*, **142**, 2618 (2017).