

# Optimization of the wood pellet supply during the continued increase of the renewable energy's proportion in the energy portfolio

Namjin Jang\*, Ian Cho<sup>\*\*,‡</sup>, Hyelynn Jeon<sup>\*\*,‡</sup>, and Jamin Koo<sup>\*\*,†</sup>

\*Hanwha Solutions, Deajeon 34128, Korea

\*\*Department of Chemical Engineering, Hongik University, Seoul 04066, Korea

(Received 3 February 2022 • Revised 12 March 2022 • Accepted 15 March 2022)

**Abstract**—The share of renewable energy (RE) in the energy portfolio has been increasing steadily during the past decades. While the trend contributes in lowering the emission of greenhouse gases, it presents new challenges in terms of costs and intermittency. This study evaluates enhanced utilization of biomass energy as a viable solution and presents the mathematical framework for evaluating the costs associated with supplying the required amount of wood pellets. The framework addresses the uncertainty in the future price of pellets, as well as variability in the shipping and storage cost with respect to the supplier and type of facility. A case study based on the latest RE plan of the Korean government shows how the costs and net CO<sub>2</sub> emission can change when the biomass energy is used to provide energy during the intermittency caused by the RE technologies. The results of the study suggest that a substantial difference in costs can occur depending on the supply strategy and that the biomass energy has the potential to resolve the intermittency issue while realizing the South Korean RE plan.

Keywords: Bioenergy, Renewable Energy, Supply Chain, Uncertainty, Optimization

## INTRODUCTION

Renewable energy technology generates energy, mostly in the form of electricity using renewable resources like sunlight, wind, and biomass. The technologies first received attention due to concerns on the rising prices of fossil fuels and their limited availability [1,2]; the attention heightened as researchers recognized their potential in reducing the CO<sub>2</sub> emission from power supply, which accounts for roughly 22% of the total emission for the year 2020 [3]. The recognition resulted in the continued increase of the RE's proportion in the energy portfolio around the world [3-5]. The share of wind power in the national energy portfolio, for example, rose from 0.2% to 0.4% in South Korea between 2012 and 2018 [6].

The increased utilization of the RE technologies in the energy portfolio brought forth new opportunities as well as challenges. For instance, the solar photovoltaic (PV) market expanded by more than ten-fold during the past decade [7]; the external cost of managing PV wastes also rose sharply at a compounded annual growth rate of 4.3% during the same period [8]. The specific cost of supplying energy (USD per kilowatt-hour) also increased as most of the RE technologies are still more expensive than the traditional, fossil fuel based technologies. Numerous governments adopted carbon tax and/or other incentives to make the RE technologies more economically rewarding. South Korea has also been providing financial compensation as high as USD 0.08 per kilowatt-hour to energy

suppliers in order to promote the RE technology [9]. Such measures enabled increasing the share of RE from 0.3 to 4.7% as announced in the national plan [5].

The intermittency in power supply is another challenge that exacerbates as the share of RE technology rises. Solar PV and wind power are the two major RE technologies suffering from the intermittency. While the operational availability of solar PV is more regular and predictable than that of wind power, the intermittency cost imposed by the former is comparable to that of the latter, incurring nearly 10% of the total costs [10,11]. Power plants running on coal or petroleum have been commonly used to provide power during intermittency; however, such measures result in greater CO<sub>2</sub> emission and continued reliance on the fossil fuels.

In this study, we evaluated the use of biomass energy as an alternative to the fossil fuel based power plants during the intermittency caused by the use of RE technologies. The mathematical framework for estimating the total costs and net CO<sub>2</sub> emission is first presented. We then apply the framework to the case study where the proposed solution is adopted while expanding the share of the RE technologies according to the South Korean government's latest plan [5]. The case study compares the cost of supplying the wood pellet required when the biomass energy or fossil fuel based power plants are utilized to provide energy during the intermittency. An optimal solution that minimizes the total cost of the former is sought to provide insights on the necessary resources needed to implement the solution.

## MATHEMATICAL FRAMEWORK

### 1. Cost of Supplying Wood Pellet

In previous work, we developed mathematical models for esti-

<sup>†</sup>To whom correspondence should be addressed.

E-mail: jaminkoo@hongik.ac.kr

<sup>‡</sup>These authors contributed equally to the work described in this paper.

Copyright by The Korean Institute of Chemical Engineers.

mating the total cost of utilizing RE technologies for supplying energy [11,12]. The models included all types of the costs—internal, external, fixed and variable—associated with installation and operation of the RE systems, as well as the disintegration and intermittency costs. The models, however, made several simplifying assumptions when calculating the cost of supplying fuels since the emphasis was on developing the generalizable equations for all types of the RE systems.

This study focused on providing a mathematical framework capable of analyzing the variable cost, especially the cost of supplying wood pellets for biomass energy, with greater precision. The previous model calculated the cost as the product of the fuel's unit price and capacity used during a given period. Here, we propose that the total cost (TC) of supplying wood pellets for operating biomass energy power plant be calculated as follows:

$$TC = \sum_{i=1}^n (FC^t + DC^t + SC^t) \quad (1)$$

where  $FC^t$ ,  $DC^t$ , and  $SC^t$  represent fuel, transportation, and storage cost, respectively for the time  $t$ . Each type of the costs is estimated using the equations in below:

$$FC^t = \frac{1}{(1+d)^{t-1}} \sum_{i=1}^N [M_i^t PF_i^t] \quad (2.1)$$

$$DC^t = \frac{1}{(1+d)^{t-1}} \sum_{i=1}^N [M_i^t (D_{i, truck} C_{truck} + D_{i, ship} C_{ship})] \quad (2.2)$$

$$SC^t = \frac{1}{(1+d)^{t-1}} (OC \sum_{i=1}^N S_i^t + IC^t CC) \quad (2.3)$$

The fuel cost for time  $t$ ,  $FC^t$ , is the aggregate product of the mass of wood pellets bought from the vendor  $i$  ( $M_i$ ) and the unit price ( $PF_{i,t}$ ). Many regions, including S. Korea, import wood pellets from multiple vendors who sell under different prices [13,14]. The transportation cost for time  $t$ ,  $DC^t$ , is the aggregate product of the mass of wood pellets bought from a vendor, transportation distance ( $D_i$ ), and the unit shipping cost of transportation ( $C_{truck}$  or  $C_{ship}$ ). The unit cost changes depending on the vehicle used, which is mostly a truck or a ship [13]. The proposed model assumes that there are no intermediate processing centers and that negligible costs occur when surplus wood pellets are transported to nearby storage facilities. Such assumptions will not be applicable when planning supply for vast geographic areas; the allocation problem also becomes important and can affect the total cost significantly in such cases [15]. The storage cost for time  $t$ ,  $SC^t$ , is the sum of the operating cost and capital cost: The former is the product of the amount of wood pellets being stored ( $S^t$ ) and the unit operating cost (OC) while the latter is the product of the newly installed facility size (IC) and the unit capital cost (CC). The proposed model assumes that the land and employment costs are relatively smaller than the and capital cost, which is generally the case as most biomass energy power plants are installed in rural areas [13-15].

## 2. CO<sub>2</sub> Emission

We have previously developed a mathematical framework for estimating the amount of CO<sub>2</sub> emitted by operating biomass energy or fossil fuel based power plants [11,16]. The framework utilizes the emission rates calculated by analyzing the amount emitted over the lifetime of each type of plant, as shown in below:

$$V^t = \sum_{j=1}^N [R_j CI_j^t \tau_j^t] = R_b CI_b^t \tau_b^t + R_f CI_f^t \tau_f^t \quad (3)$$

where  $R_j$ ,  $CI_j^t$ , and  $\tau_j^t$  stand for the emission rate (ton-CO<sub>2</sub>/MW-hr), installed capacity (MW) and capacity factor (hrs) of power plant type  $j$ , respectively; the subscripts  $b$  and  $f$  indicate the type of power plant—biomass energy or fossil-fuel. Only the two types are considered here since this study aims to evaluate the changes in CO<sub>2</sub> emission when the biomass energy versus fossil fuel based powerplant is used to supply energy during the intermittency caused by one or more RE technologies.

## 3. Constraints

The following set of constraints must be met when determining the optimal supply of wood pellets for a period of  $t$  months:

$$\sum_{i=1}^N [(M_i^t - S_i^t + S_i^{t-1}) EC_i^t] = CI_b^t \tau_b^t \quad (4.1)$$

$$\sum_{i=1}^N M_i^t EC^t \leq \kappa CI_b^t \tau_b^t \quad (4.2)$$

$$\sum_{i=1}^N S_i^t \leq IC^0 + \sum_{i=1}^N IC^t \quad (4.3)$$

$$S_i^t - S_i^{t-1} \leq M_i^t \quad (4.4)$$

where  $EC_b$ ,  $\varepsilon$ ,  $\kappa$ , and  $IC^0$  represent the energy content of wood pellets sold by the vendor  $i$ , minimum, or maximum amount of wood pellets bought, and the initial capacity of the storage facilities. The first constraint dictates that the total energy content of all wood pellets used be equal to the amount of energy generated by the biomass energy power plant during time  $t$ . Here, we recognize that the energy content of wood pellets can vary from vendor to vendor and/or year to year [13]. The second constraint dictates that the amount of wood pellets purchased for time  $t$  be at most the maximum multiple ( $\kappa$ ) of the amount needed to supply the required energy without storing; such a level is mostly imposed by the available budget that does not vary much from time to time. The third constraint requires the total amount of wood pellets stored be at most equal to the total capacity of the storage facilities for time  $t$ . The last constraint makes it impossible to store wood pellet more than the total mass bought during the time  $t$ .

## CASE STUDY

### 1. The Renewable Energy Plan of S. Korea

The total capacity of biomass energy power plants in S. Korea is expected to rise from 2.6 to 3.3 GW between 2021 and 2030 [11]. Assuming that the capacity factor is maintained at 74% [17] throughout the decade, the total amount of energy supplied will increase from 16,650 to 21,350 GW-hrs by the year 2030 (Fig. 1, solid line). These amounts do not include using biomass energy power plants to supply energy during the intermittency of RE technologies—mainly solar PVs and/or wind power; therefore, they represent the baseline levels, which we attribute to the scenario A. The other scenario, namely B, does include using the biomass energy power plants during the intermittency; the capacity factor and the amount of energy supplied increase to 95% and 27,400 GW-hrs, respectively (Fig. 1, dotted line). The difference in the amount of energy supplied by the BEP between the two scenarios will be roughly 6,060 GW-hrs by the year 2030. Previous work suggested that intermittency can cause up to 15 and 20% reduction in the capacity factor

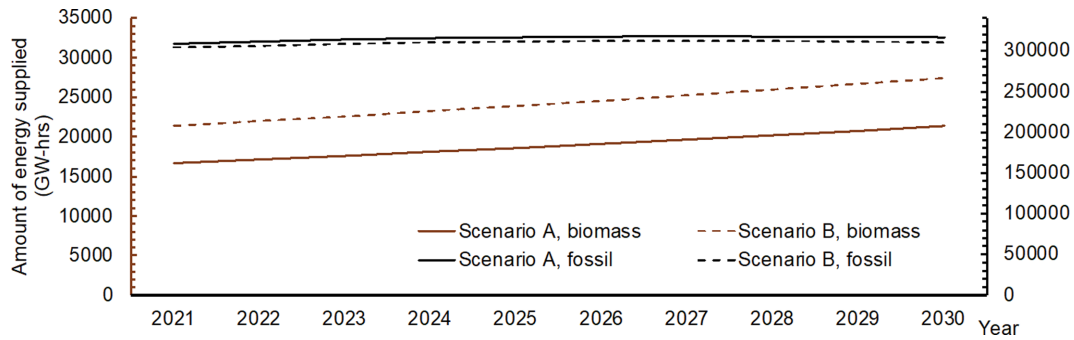


Fig. 1. The amount of energy supplied by the biomass energy and fossil fuel based power plants between 2021 and 2030 under the latest renewable energy plan of S. Korea.

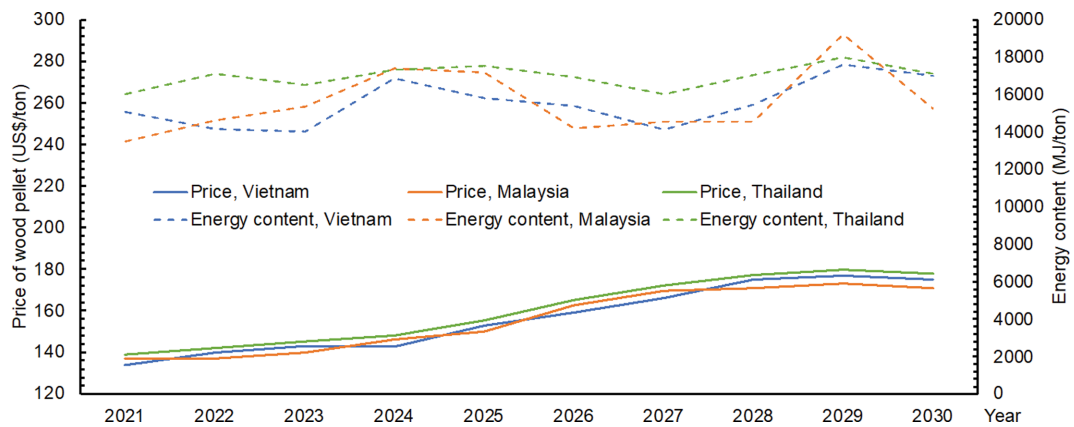


Fig. 2. The projected prices and energy content of wood pellet imported from Vietnam, Malaysia and Thailand over the next decade.

Table 1. Numerical values of the time-independent parameters used in the case study

Parameter	Value	Reference	Parameter	Value	Reference
$D_{Vietnam, ship}$	4,667 km	14	OC	\$1.51/ton/yr	21
$D_{Malaysia, ship}$	6,300 km	14	CC	\$151.00/ton	21
$D_{Thailand, ship}$	6,275 km	14	$R_{biomass}$	49 ton/GW-hr	22
$C_{ship}$	\$0.01/km/ton	13	$R_{fossil}$	847 ton/GW-hr	23
$\kappa$	1.5	n/a	$IC^0$	19,000 tons	24

for the solar PV and wind power, respectively [6,10]. The additional 6,060 GW-hrs provided by the BEP in the second scenario will be able to back up about 40% of the energy loss due to the maximum level of intermittency. During the same period of time, the proportion of energy to be supplied by the fossil fuel based power plants is planned to decrease from 60 to 51% [18]. The fossil fuel based power plants are used as the back-up during the intermittency in the scenario A, which enables the comparative analysis described as one of the primary aims of this study (see the *Introduction*). Such a measure results in the capacity factor of fossil fuel based power plants to decrease from 91 to 89% in scenario B.

## 2. Empirical Parameters

South Korea was importing more than 90% of the wood pellets used in biomass energy power plants between 2011 and 2020 [14]. The major three countries that exported the most to S. Korea were Vietnam, Malaysia and Thailand; the sum of wood pellets

supplied by these countries exceeded 85% of the total mass imported. The unit prices and energy content of the wood pellets supplied by these countries differed throughout the past decade (Fig. 2). In this case study, we generated the future prices for each country based on the forecasts and median prices of the past decade [19]. We will assume that the time series of variability in the energy content over the next decade is also the same as the series observed during the past decade.

The numerical values for the rest of the parameters are listed in Table 1. The authors believe that the following two need to be mentioned to better understand the scope and limitations of the proposed case study. First, we assumed the unit shipping cost to be constant throughout the scenarios; however, the level has changed significantly in an unpredictable way during the past two years. Some researchers believe that the ongoing COVID pandemic may be responsible for this phenomenon [20], which is out of scope of this

study. The unit cost of delivery by truck ( $C_{truck}$ ) is roughly \$0.02/km/ton [13]; however, we do not list this in Table 1 given its invariant, relatively small contribution to the total costs. Second, we do not include the CO<sub>2</sub> emission due to the shipping of wood pellet as it depends on the multitude of factors ranging from the type of vehicle used to the navigation conditions. We did, however, confirm that the amount of emission due to shipping will be less than 2.0% of the total emission for both scenarios, meaning that the effects on the proposed implications are negligible.

### 3. Results of the Mathematical Programming

When wood pellets are purchased in the business-as-usual (BAU) manner, i.e., no storage and buying only the mass required to meet the renewable plan without adjusting the proportions among the three vendors, the total costs over the next decade (2021 to 2030) will be USD 7.9 and 9.9 billion for the scenario A and B, respectively. The optimization using the parameters specified in Table A can reduce these total costs by 6%. The extent of cost savings made possible by applying the proposed optimization algorithm depends mainly on the price volatility of wood pellets and  $\kappa$ , or equivalently how much more one can spend to buy extra mass of wood pellets and store in silo(s). Expectedly, the extent of cost savings increases with  $\kappa$  and can become as large as 9% of the total costs under the BAU for  $\kappa=3.0$ . The higher volatility of the wood pellet price can also contribute to increase the cost savings made possible by the proposed optimization.

The optimized total cost of supplying wood pellets under the scenario A is about USD 7.4 billion (Fig. 3(a)). This total cost increases by 1.26-fold under the scenario B where the biomass energy power plant is used to provide additional energy during the inter-

mittency. The capacity factor of the biomass energy power plant in the scenario B is 95%, which is 1.28-fold of the level in the scenario A. Expectedly, the increases are similar as the rest of the parameters used in the mathematical programming are identical between the two scenarios. The total amount of CO<sub>2</sub> emitted by the biomass energy and fossil fuel based power plant used to back up during the intermittency differed drastically under the two scenarios (Fig. 3(b)). The total emission over the next decade is 44 million tons lower when wood pellets are used instead of fossil fuels to provide the back up; the emission rate of the former being more than ten-fold lower than that of the latter (Table 1) enabled this reduction. The annual decrease in CO<sub>2</sub> emission under the scenario B compared to A is roughly 0.7% of the total CO<sub>2</sub> emitted in S. Korea during 2020 [25]. When divided by the increase in the total cost of supplying wood pellet, the cost of reducing CO<sub>2</sub> emission is about USD 37 per ton, which is comparable to the price estimated by the world bank [26].

The results show that the transportation cost is responsible for roughly 20% of the total cost for supplying wood pellets. No storage costs were incurred except the years 2023 and 2029 during which extra masses equal to the initial capacity of the storage facilities (19,000 tons) were bought and stored. These amounts were immediately exhausted the following years as they are cheaper with no additional shipping cost. The optimal supply under both scenarios was different throughout the decade (Fig. 3(c) and (d)). While most of the masses were bought from Thailand in the scenario A, the masses were more evenly bought from the three exporters in the scenario B. In the latter, the energy content of the wood pellet matters more, a consequence of the higher capacity factor

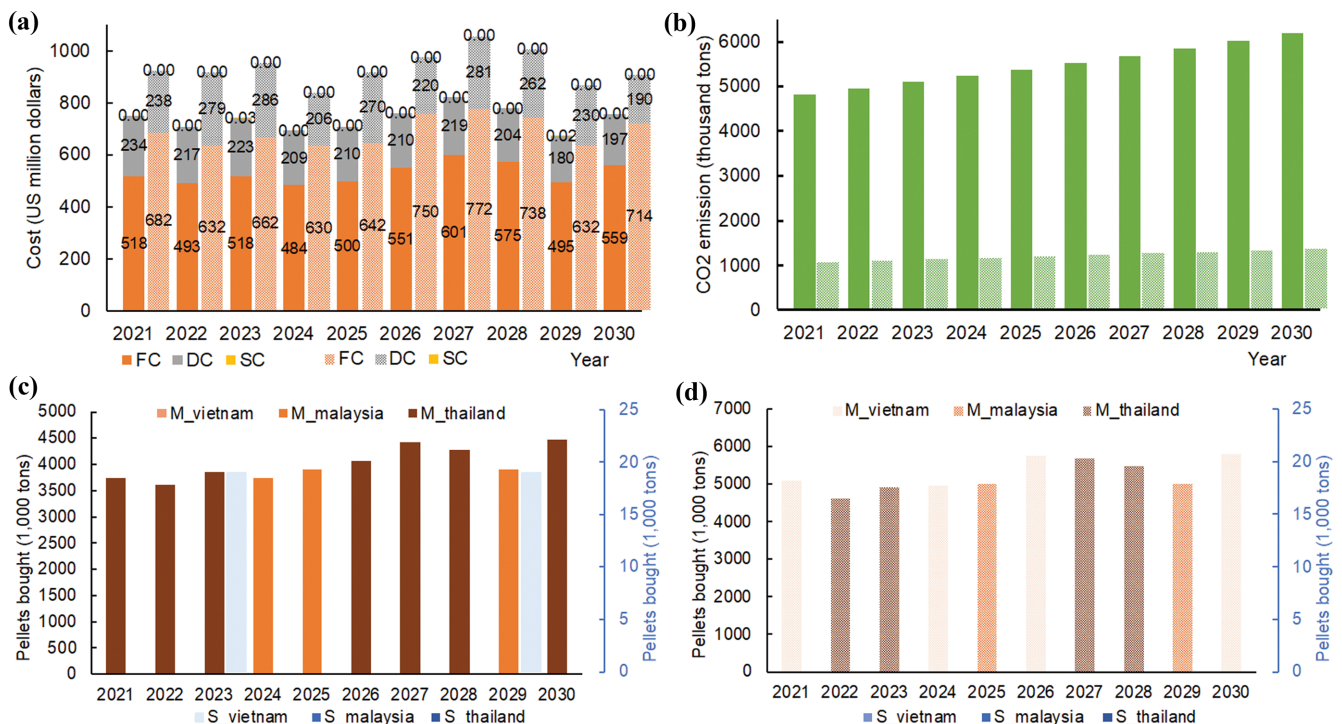


Fig. 3. (a) The fuel, transportation, and storage costs of supplying wood pellet, (b) the amount of CO<sub>2</sub> emission by the BEP and FFP between 2021 and 2030 under the scenario A (solid) and B (shaded). The masses of wood pellet bought vs stored under the optimal supply between 2021 and 2030 under the (c) scenario A and (d) scenario B.

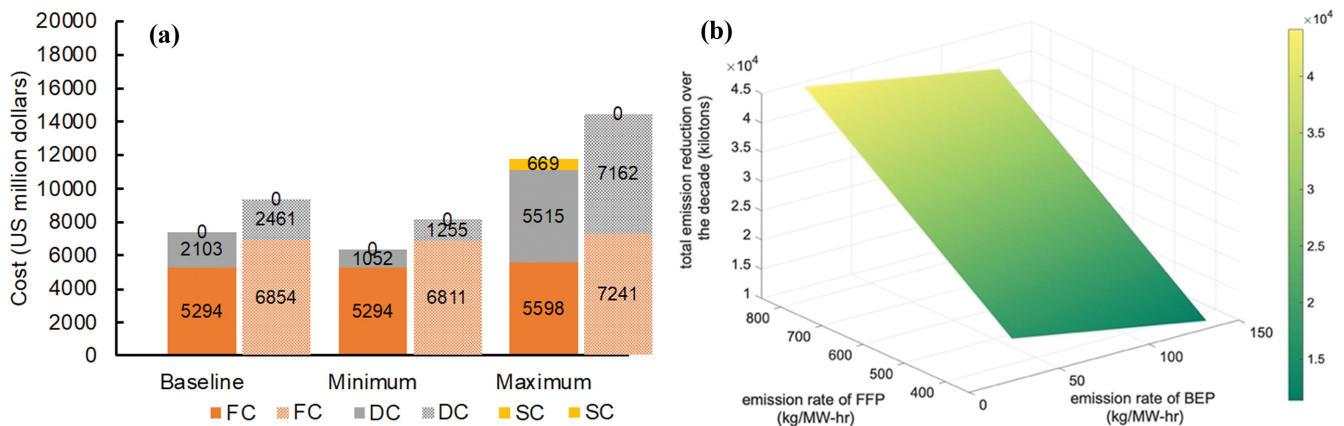


Fig. 4. (a) The changes in the costs of supplying wood pellets with respect to the changes in the unit shipping cost, and (b) the changes in the CO<sub>2</sub> emission reduction with respect to the changes in the emission rates under the scenario A (solid) and B (shade).

required due to the biomass energy power plant being used during the intermittency of the RE technologies. No wood pellets are being stored in the scenario B throughout the decade, hinting that the storage cost is not low enough to offer savings even when the price of wood pellet becomes the highest. Another interpretation would be that the variability in the price of wood pellets is not high enough in this case study to enforce storage.

A sensitivity analysis was first conducted to understand the influence of shipping cost on the optimal supply. During the past decade, the cost of transporting via ships varied between USD 0.005 and 0.032 per kilometer per ton [13]. The total cost of supplying wood pellets in the two scenarios becomes as low as 0.86-fold and as high as 1.59-fold of the base level (Fig. 4(a)) when the unit shipping cost varies between the historical minimum and maximum of the past decade. The storage cost over the projected years becomes zero when the unit shipping cost is assumed to be the minimum; a significant storage cost worth 6% of the total cost is incurred when the unit shipping cost becomes the maximum. This is expected since higher shipping cost makes storing cheaper when the price of the shipped good, i.e., wood pellets, increases. Furthermore, most of the wood pellets are bought from Vietnam since the shipping distance is at least 1,500 km shorter when compared to the other sources.

The emission rates of the biomass and fossil fuel-based power plants are another parameter that may vary significantly depending on the assumptions made in the life cycle analysis (LCA). The emission rate of the former has been reported to lie between 24 to 132 ton/GW-hr [22], while a much broader range of 344 to 847 ton/GW-hr has been reported for the latter, owing to the heterogeneity in the type of the fuel and configuration of the power plant [27]. When the full ranges of the two emission rates are applied, the reduction in CO<sub>2</sub> emission in the scenario B can be as small as 11,300 kilotons and as large as 44,200 kilotons over the decade (Fig. 4(b)). In terms of the annual reduction, these amounts are 0.2 and 0.7% of the total CO<sub>2</sub> emitted in S. Korea during 2020.

## CONCLUSION

We have proposed the mathematical framework for calculating

the total cost of supplying wood pellets to and CO<sub>2</sub> emission by biomass energy power plant. We applied the framework to a case study where the capacity of the RE technologies, including the biomass energy power plants, increases steadily over the next decade according to the latest RE plan of S. Korea. The results demonstrated the total costs required to implement the plan, as well as the opportunity to further decrease CO<sub>2</sub> emission by using the BEP during intermittency of the RE technologies. We also used the framework to find the optimal masses of wood pellets to be bought from multiple vendors, as well as the masses to be stored over the decade that minimize the total costs. We believe that the proposed framework provides grounds for developing more refined optimization schemes that can contribute to implementing the RE plan and mitigating global warming in an economical way.

## ACKNOWLEDGEMENTS

This work was supported by the 2021 Hongik University Research Fund and the National Research Foundation of Korea (NRF-2019 R1C1C1002642). This manuscript is submitted in commemoration of Prof. Jaewook Ko (Dept. of Chemical Engineering, Kwangwoon University), who we deeply thank for his devotion and commitment to the Korean Institute of Chemical Engineers.

## ABBREVIATIONS

BEP : biomass energy power plant  
 FFP : fossil fuel based power plant  
 COVID : coronavirus disease  
 LCA : life cycle analysis  
 PV : photovoltaics  
 RE : renewable energy

## Nomenclature

$C_{ship}$  : unit cost of transportation with ship as the vehicle [USD/ton/kilometer]  
 $C_{truck}$  : unit cost of transportation with truck as the vehicle [USD/ton/kilometer]  
 CC : unit capital of biomass storage facility [USD/ton]

$CI_j^t$  : installed capacity of the power plant type  $j$  for time  $t$  [GW]  
 $D_i$  : shipping distance from the exporter to the importer [km]  
 $d$  : discount rate [%]  
 $DC^t$  : transportation cost for time  $t$  [USD]  
 $EC_i^t$  : energy content of the wood pellet sold by vendor  $i$  for time  $t$  [MJ/ton]  
 $FC^t$  : fuel cost for time  $t$  [USD]  
 $IC^t$  : size of the wood pellet storage facility to be newly installed for time  $t$  [ton]  
 $M_i$  : mass of wood pellet bought from the vendor  $i$  [ton]  
 $OC$  : unit operating cost of the wood pellet storage facility [USD/ton/year]  
 $PF_i^t$  : unit price of wood pellet for time  $t$  purchased from the vendor  $i$  [USD/ton]  
 $R_j$  : emission rate of the power plant type  $j$  [ton-CO<sub>2</sub>/MW-hr]  
 $S_i^t$  : mass of the wood pellet bought from vendor  $i$  to be stored in silo for time  $t$  [ton]  
 $SC^t$  : storage cost for time  $t$  [USD]  
 $TC$  : total cost of supplying wood pellet for operating biomass power plant [USD]  
 $\kappa$  : maximum multiple of the wood pellet purchase volume compared to the standard amount  
 $\tau_j^t$  : capacity factor of the power plant type  $j$  for time  $t$

## REFERENCES

1. R. E. H. Simsa, H.-H. Rognerb and K. Gregory, *Energy Policy*, **31**, 1315 (2003).
2. P. Moriarty and D. Honnery, *Renew. Sustain. Energy Rev.*, **16**, 244 (2012).
3. International Energy Agency, *Global Energy Review 2021*, IEA, Paris (2021).
4. O. Ellabban, H. Abu-Rub and F. Blaabjerg, *Renew. Sustain. Energy Rev.*, **39**, 748 (2014).
5. D. Son, J. Kim and B. Jeong, *Energies*, **12**, 1667 (2019).
6. Korean National Renewable Energy Center, *The status of wind power*, South Korean Government Public Data, Ulsan (2022). Available at: [https://www.knrec.or.kr/business/windpowerTF\\_internal.aspx](https://www.knrec.or.kr/business/windpowerTF_internal.aspx).
7. A. Cherp, V. Vinichenko, J. Tosun, J. A. Gordon and J. Jewell, *Nat. Energy*, **6**, 742 (2021).
8. B. Kim, J. Kang, S. Park, J. Jang and J. H. Hong, *New Renew. Energy*, **15**, 36 (2019).
9. S. Kim, H. Lee, H. Kim, D.-H. Jang, H.-J. Kim, J. Hur, Y.-S. Cho and K. Hur, *Renew. Sustain. Energy Rev.*, **98**, 150 (2018).
10. G. Notton, M. Nivet, C. Voyant, C. Paoli, C. Darras, F. Motte and A. Fouilloy, *Renew. Sustain. Energy Rev.*, **87**, 96 (2018).
11. N. Jang, W. Kim, D. Lee, G. Yoon, J. Yang, I. Cho, H. Jeon and J. Koo, *Korean J. Chem. Eng.*, **38**, 2397 (2021).
12. J. Koo, K. Han and E. S. Yoon, *Renew. Sustain. Energy Rev.*, **15**, 665 (2011).
13. L. Visser, R. Hoefnagels and M. Junginger, *Renew. Sustain. Energy Rev.*, **118**, 109506 (2020).
14. J. R. Park, *Statistics on the wood pellet*, Korean Forest Service, Daejeon (2018).
15. I. M. Bowling, J. M. Ponce-Ortega and M. M. El-Halwagi, *Ind. Eng. Chem. Res.*, **50**, 6276 (2011).
16. J. Koo, K. Park, D. Shin and E. S. Yoon, *Appl. Energy*, **88**, 2254 (2011).
17. H. K. Kang, K. C. Park and L. H. Kim, *Korean Soc. Energy*, **23**, 7 (2014).
18. C. Kim, *Renew. Sustain. Energy Rev.*, **144**, 110870 (2021).
19. H. Seok and S. Kim, *Trends in the global wood pellet market*, Korean Forest Service, Daejeon (2021).
20. S. Singh, R. Kumar, R. Panchal and M. K. Tiwari, *Int. J. Production Res.*, **59**, 1993 (2021).
21. G. Thek and I. Obernberger, *Biomass Bioenergy*, **27**, 61 (2004).
22. A. Evans, V. Strezov and T. J. Evans, *Renew. Sustain. Energy Rev.*, **14**, 1419 (2010).
23. R. S. Middleton and J. K. Eccles, *Appl. Energy*, **108**, 66 (2013).
24. Dongyang. *Construction-Site Information*, WordPress, Seoul (2020). Available at: <http://tyboard.dechive.net/info/>.
25. Knoema, Republic of Korea - CO<sub>2</sub> emissions, Knoema, New York (2022). Available at: <https://knoema.com/atlas/Republic-of-Korea/CO2-emissions>.
26. K. Rose and E. Mann, *International carbon pricing*, World Bank, Washington D.C. (2022). Available at: <https://carbonpricingdash-board.worldbank.org/what-carbon-pricing>.
27. E. S. Rubin, C. Chen and A. B. Rao, *Energy Policy*, **35**, 4444 (2007).