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An optimization-based planning of investment strategies for a renewable energy supply system from biomass utilization

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Abstract−A strategic investment plan to establish renewable energy source (RES) systems plays an important role in various decision-making processes, from a stakeholder in business purposes to a policy maker for public benefits. In this study, we have developed a new optimization model to establish efficient investment strategies to design and operate a biomass to hydrogen (B2H2) system, which includes the features of RES (*e.g.*, intermittent availability) and RES technologies (*e.g.*, low conversion efficiency) along with various external factors on energy economy (energy price fluctuation and demand uncertainty). As a result, we identified the optimal long-term plan of investment strategy including timing, utilized amount, and capacity of facilities. In addition, we performed an economic sensitivity analysis for major parameters and evaluated a sustainability of the B2H2 system using additional metrics such as energy security and environmental protection.

Keywords: Biomass, Investment Strategy, Optimization, Hydrogen, Korea

INTRODUCTION

As the importance of renewable energy source (RES) increases, a wide range of studies for design and analysis of RES-based energy systems have been attempted: design and operation of RES-integrated energy system for power generation [1-3], supply chain optimization [4-6], and multi-objective optimization [7-9]. Economic studies to support a decision-making process for the investment planning of RES-based energy system have been also conducted: Ding et al. proposed a new investment plan for a wind-based power system [10]. Kumbaroğlu et al. integrated renewable technologies into the existing system using learning curves [11]. Dal-Mas et al. provided a framework for planning of ethanol supply chain [12], and Ahn et al. developed an investment model for microalgae-based biodiesel supply system [13].

While a number of alternatives against the current energy system are available, a hydrogen economy can be considered as one of the promising systems due to unlimited potentials of hydrogen production as well as and the huge opportunities for its usage and applications [6]. To demonstrate such a hydrogen economy, many studies have been made: modeling and projection of future hydrogen demand scenarios [14,15], comparative analysis of the effect for different hydrogen production technologies [16-18], and systematic study for design of hydrogen infrastructure [19-21].

Among various renewable sources for hydrogen production, biomass has been considered as an important source, since a positive synergy is expected from combining the merits of biomass as a source (e.g., widely abundance and carbon credit) and hydrogen as an energy carrier (high energy density per unit mass and wide applications) [22]. In the literature, a number of studies are found: Martín et al. analyzed various hydrogen production technologies using biomass as a resource [23]. Lv et al. performed an economic feasibility analysis for a biomass-based hydrogen system [24]. Parker et al. optimized the hydrogen production system from waste biomass using a geographic information system (GIS) [25,26].

While a large number of studies about the biomass to hydrogen (B2H2) system have been conducted, there are still few studies on long-term planning to demonstrate such a system (*e.g.*, investment size and timing, and the installation and change-over of selected technologies in the B2H2 system). Furthermore, this plan needs to be strategically established based on the full understanding of RES characteristics (*e.g.*, intermittent availability of resources and low conversion efficiency of hydrogen production technologies), along with characteristics of an economic system (*e.g.*, changes of amount and prices of supply, and uncertainty of demand).

In this study, we aim to propose a new optimization-based approach to establish the optimal investment strategy for design of a renewable hydrogen system from biomass utilization. In achieving this goal, we first set up the B2H2 system by defining main components and system boundary (Section 2). Second, we develop a new mathematical formulation for modeling various practical issues on biomass cultivation, transport and usage as well as decisions on investment and operation planning of the B2H2 system (Sections 3 and 4). We then apply the optimization model to design problem of hydrogen economy of Korea in the future. Based on the results of the B2H2 system, we analyze the economic performances and the other evaluation criteria (*i.e.*, energy security and environmental protection) (Section 5). Finally, we summarize the major contribution and findings and provide suggestions for future works (Section 6). The overall steps are shown in Fig. 1.

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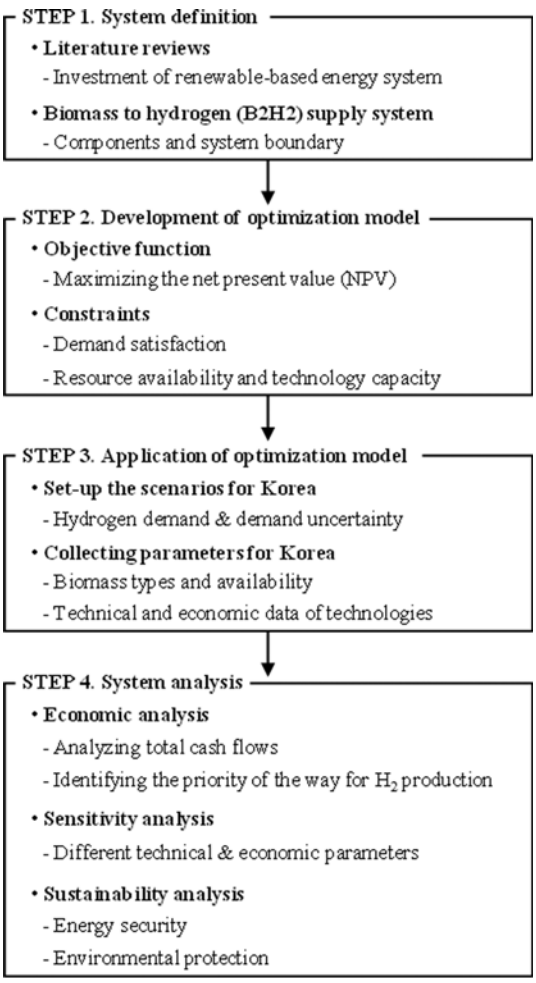

Fig. 1. Major steps of this study for the investment planning of the B2H2 system.

BIOMASS TO HYDROGEN (B2H2) SYSTEM DESCRIPTION

Our objective is to establish the optimal investment strategy to resolve the design problem of the B2H2 system as depicted in Fig. 2. The proposed B2H2 system mainly consists of five subsystems (or nodes): biomass supply, biomass storage, hydrogen conversion, hydrogen storage, and hydrogen demand systems. To satisfy the hydrogen demand from biomass utilization, two different supply ways are assumed in the B2H2 system: *internal way* and *external way*. Internal way represents the hydrogen supply way to utilize domestic resources (existing biomass and newly cultivated biomass for energy generation), while external way means the supply methods from out of the B2H2 system boundary (international import of biomass or hydrogen).

Here we include two types of biomass as resources for hydrogen production: *residue* and *dedicated energy crop*. Residue is assumed as an existing biomass which can be used as an energy source resulting from other activities. On the other hand, the dedicated energy crop is a newly produced biomass only as an energy resource. We assume that while the residue needs only the collecting process, the dedicated energy crop requires three processes (land purchase, cultivating, and collecting) to utilize it as an energy resource as shown in Fig. 2.

Fig. 2 also shows major technical facilities in the B2H2 system including biomass and hydrogen storage, and biomass-to-hydrogen conversion facilities. The collected biomass in supply site is delivered to the hydrogen conversion facility after quality-managing process (e.g., moister level and chip size) in biomass storage facility. Note that even though there is a variety of technologies to produce hydrogen (e.g., pyrolysis, fermentation, combustion, and liquefaction), we consider one type of a technology, indirect gasification process, which includes a fluidized bed for biomass combustion, gas treating and reforming processes such as water gas shift (WGS) and pressure swing adsorption (PSA). This is because the gasification process is easier to operate, has higher economics, and is one of the sustainable processes for hydrogen production than other biomass utilization technologies [27,28]. The produced and imported hydrogen has to be stored at hydrogen storage facility as a liquefied hydrogen, which is a cryogenic spherical tank, due to its high economics and easy operation compared to other types of storage technology [29].

OPTIMIZATION MODEL DEVELOPMENT

1. Constraints

1-1. Demand Satisfaction

The total amount of hydrogen stored in the hydrogen storage

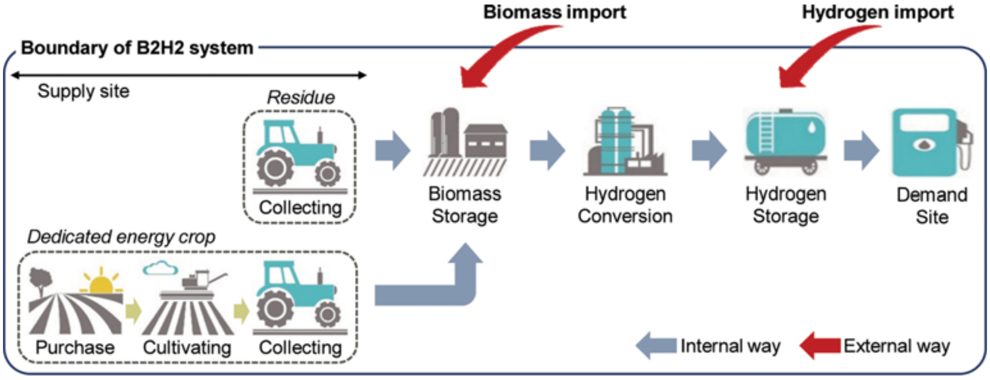

Fig. 2. The schematic structure of main activities and flows.

facility $j \in J^H$ (H_{jt}^{sto}) in the time period $t \in T$ is given by:

$$\sum_{j \in J^H} H_{jt}^{sto} = H_t^{loc} + H_t^{exc} \quad \forall t \in T \tag{1}$$

where H_t^{loc} is the local hydrogen demand and H_t^{exc} is the excess amount of hydrogen. The local hydrogen demand, which could be satisfied by using only biomass, is calculated by:

$$H_t^{loc} = \rho \Lambda_t \quad \forall t \in T \tag{2}$$

where Λ_t is the total hydrogen demand and ρ represents a percentage of the demand that can be satisfied by the biomass to the total hydrogen demand.

1-2. Biomass Production Constraints

The total amount of collected residue $i \in I^R$ (R_{it}) in the time period $t \in T$ should not be greater than an available amount:

$$R_{it} \le \xi_i \ni_{it} \quad \forall i \in I^R, t \in T \tag{3}$$

where ξ_i is the total available amount of residue and $\ni_{it}$ is the fluctuation factor. The amount of newly harvested dedicated energy crop $i \in I^E$ (E_{it}) in the time period $t \in T$ is calculated by:

$$E_{it} = \omega_i A_{it} \ni_{it} \quad \forall i \in I^E, t \in T \tag{4}$$

where A_{it} is the actual used area and ω_i is the cultivation yield [dry ton/km^2]. The actual area used for cultivation of dedicated energy crops should not be larger than the available area:

$$\sum_{i \in I^E} \sum_{t \in T} A_{it} \le \upsilon \tag{5}$$

where υ is the available harvesting area. Therefore, the total amount of produced biomass $i \in I^B$ (B_{it}^{pro}) for hydrogen production in the time period $t \in T$ is calculated by:

$$B_{it}^{pro} = (E_{it} + R_{it})(1 - f_i) \quad \forall i \in I^B, t \in T \tag{6}$$

where f_i is the conservation factor.

1-3. Facility Capacity and Lifespan Constraints

The amount of biomass stored in biomass storage $j \in J^B$ (B_{jt}^{sto}) in the time period $t \in T$ is calculated by:

$$B_{jt}^{sto} = \sum_{i \in I^B} \eta_j (1 - \tau_j) B_{it}^{pro} + B_t^{imp} \quad \forall j \in J^B, t \in T \tag{7}$$

where B_t^{imp} is the amount of imported biomass, η_j is the processing efficiency, and τ_j is the loss factor occurred as processing biomass. On the other hand, the total required number of biomass storage facility $j \in J^B$ (N_{jt}^T) is dependent on its capacity and the stored amount:

$$N_{jt}^T \vartheta_j \le B_{jt}^{sto} \le N_{jt}^T \theta_j \quad \forall j \in J^B, t \in T \tag{8}$$

where ϑ_j and θ_j is the minimum and maximum capacity. The amount of hydrogen produced in hydrogen conversion facility $j \in J^C$ (H_{jt}^{pro}) in the time period $t \in T$ is given by:

$$H_{jt}^{pro} = \sum_{i \in I^B} \sum_{j' \in J^B} \left\{ \nu_i - \chi_i \frac{\pi_i - \pi_i^*}{1 - \pi_i^*} \right\} \eta_j (1 - \tau_j) B_{j't}^{sto} \quad \forall j \in J^C, t \in T \tag{9}$$

where ν_i is the heating value of biomass i, χ_i is the process energy consumed to manage the moisture level of biomass i, π_i and π_i^* are the water content and the targeted water content of biomass i, respectively. The total required number of hydrogen conversion facility also depends on the capacity:

$$N_{jt}^T \vartheta_j \le H_{jt}^{pro} \le N_{jt}^T \theta_j \quad \forall j \in J^C, t \in T \tag{10}$$

The amount of hydrogen stored in hydrogen storage $j \in J^H$ (H_{jt}^{sto}) in the time period $t \in T$ is given by:

$$H_{jt}^{sto} = \sum_{j' \in J^C} \eta_j (1 - \tau_j) H_{j't}^{pro} + H_t^{imp} \quad \forall j \in J^H, t \in T \tag{11}$$

where H_t^{imp} is the amount of imported hydrogen. The total required number of hydrogen storage facility is as follows:

$$N_{jt}^T \vartheta_j \le H_{jt}^{sto} \le N_{jt}^T \theta_j \quad \forall j \in J^H, t \in T \tag{12}$$

The total number of facilities (N_{jt}^T) in the initial time (T_0) is equal to the number of newly installed facilities in T_0:

$$N_{jt}^T = N_{jt}^{new} \quad \forall j \in J, t = T_0 \tag{13}$$

On the other hand, the total number of facilities after the initial time $t \ge T_0$ is calculated by:

$$N_{jt}^T = N_{jt-1}^T + N_{jt}^{new} - N_{jt}^{red} \quad \forall j \in J, t \ge T_0 \tag{14}$$

where N_{jt-1}^T is the total number of facilities in previous time $t-1$, N_{jt}^{new} is the number of newly installed facilities in present time t, and N_{jt}^{red} is the number of removed facilities in time t. All facilities have a maximum lifespan (ζ_j), and this means the facility installed in time $t-\zeta_j$ cannot be operated after the time t due to the expiration of lifespan. Therefore, the number of removed facilities (N_{jt}^{red}) in the time t is equal to the number of newly installed facilities ($N_{j(t-\zeta_j)}^{new}$) in the time $t-\zeta_j$ after the initial time:

$$N_{jt}^{red} = N_{j(t-\zeta_j)}^{new} \quad \forall j \in J, t \ge T_0 + \zeta_j \tag{15}$$

Meanwhile, the hydrogen import and export are limited by the minimum (β_t^{min}) and maximum (β_t^{max}) flows in the time period $t \in T$:

$$\beta_t^{min} Y_t \le H_t^{imp} \le \beta_t^{max} Y_t \quad \forall t \in T \tag{16}$$

$$\beta_t^{min} Z_t \le H_t^{imp} \le \beta_t^{max} Z_t \quad \forall t \in T \tag{17}$$

where Y_t and Z_t are the binary variables. The hydrogen import and export are expected to occur only in one direction at the same time $t \in T$:

$$Y_t + Z_t \le 1 \quad \forall t \in T \tag{18}$$

2. Objective Function

The optimization model aims to ensure the maximum profits from the proposed B2H2 system, which results in setting the objective function as to maximize the net present value (NPV) which is calculated by the total cash flow (TCF_t) in the time period $t \in T$:

$$NPV = \sum_{t \in T} \frac{TCF_t}{(1+d)^t} \tag{19}$$

where d is the discount factor. The total cash flow (TCF_t) is calculated by:

$$TCF_t = (TIN_t - TOU_t)(1 - \partial) + \psi \quad \forall t \in T \tag{20}$$

where TIN_t and TOU_t are the total incoming/outgoing cash flows, ∂ and ψ are tax rate and depreciation, respectively. The total incoming cash flow (TIN_t) consists of hydrogen selling cost (HSC_t) and facility salvage cost (FSC_t):

$$TIN_t = HSC_t + FSC_t \quad \forall t \in T \tag{21}$$

The hydrogen selling cost (HSC_t) means a profit made by selling the produced hydrogen, and it calculated by:

$$HSC_t = \sum_{t \in I^H} \alpha_i \kappa_{it} (H_t^{loc} + H_t^{exc}) \quad \forall t \in T \tag{22}$$

where α_i is the market price of hydrogen and κ_{it} is the fluctuation factor of the market price. The facility salvage cost (FSC_t) is the estimated cost that is expected to be received at the end of the lifespan of the facilities [30]. It is calculated as follows:

$$FSC_t = \sum_{j \in J} \phi \varphi_j N_{jt}^{red} \quad \forall t \in T \tag{23}$$

where ϕ is the percentage of salvage cost to total capital cost and φ_j is the capital cost of facilities. On the other hand, the total outgoing cash flow (TOU_t) consists of biomass supply cost (BSC_t), hydrogen import cost (HIC_t), facility investment cost (FIC_t), and facility operating cost (FOC_t):

$$TOU_t = BSC_t + HIC_t + FIC_t + FOC_t \quad \forall t \in T \tag{24}$$

The biomass supply cost (BSC_t) consists of three cost terms as stated in Eq. (25). The first term is the land purchase cost as a function of actual used area [km^2], the unit land cost (φ) [$\$/km^2$], and the capital charge factor (σ). The second term is the biomass processing cost required for utilizing biomass as resources and the last term is the biomass import cost:

$$BSC_t = \sum_{i \in I^E} \sigma \varphi A_{it} + \sum_{i \in I^B} \delta_i \kappa_{it} B_{it}^{pro} + \sum_{i \in I^B} \gamma_i \kappa_{it} B_t^{imp} \quad \forall t \in T \tag{25}$$

where δ_i is the unit processing cost of biomass and γ_i is the unit biomass import cost. The hydrogen import cost (HIC_t) is given by:

$$HIC_t = \sum_{i \in I^H} \gamma_i \kappa_{it} H_t^{imp} \quad \forall t \in T \tag{26}$$

The facility investment cost (FIC_t) is calculated by:

$$FIC_t = \sum_{j \in J} \sigma_j \varphi_j \lambda_{jt} N_{jt}^{new} \quad \forall t \in T \tag{27}$$

where σ_j and φ_j are the capital charge factor and unit capital cost of facilities. Note that the facilities installed in the late of time period cannot be used for their whole time because the remaining time period is shorter than their lifespans. Thus, we consider the correction factor (λ_{jt}) to revise the losses occurred by the difference between the time period of the study and the lifespan of each facility. The facility operating cost (FOC_t) is as follows:

$$FOC_t = \sum_{j \in J^B} \delta_j B_{jt}^{sto} + \sum_{j \in J^C} \delta_j H_{jt}^{pro} + \sum_{j \in J^H} \delta_j H_{jt}^{sto} \quad \forall t \in T \tag{28}$$

where δ_j is the unit operating cost of facilities.

APPLICATIONS IN THE FUTURE IN KOREA

As a case study, we apply the optimization model to the design problem for transportation sector of Korea in the future. With the case study, we will be able to identify the optimal investment strategy and analyze various national-level metrics to indicate the economic performance of the B2H2 system including net present value (NPV), international trade, and domestic biomass policies of future Korea. In addition, we assess the effect of the B2H2 system on Korean energy target using two extended evaluation criteria: energy security and environmental protection.

1. Hydrogen Demand

The literature indicates that the hydrogen demand for transportation sector of Korea in the future is very sensitive to the externalities such as conventional energy market (*e.g.*, crude oil and natural gas trade prices) and government policy (*e.g.*, energy tax for fossil fuels consumption, subsidy for renewable energy utilization) [7,19]. Based on our previous work [31], we project the hydrogen demand of Korea in the future. To acquire high reliability of the results by avoiding uncertainty of estimation, we generate two other scenar-

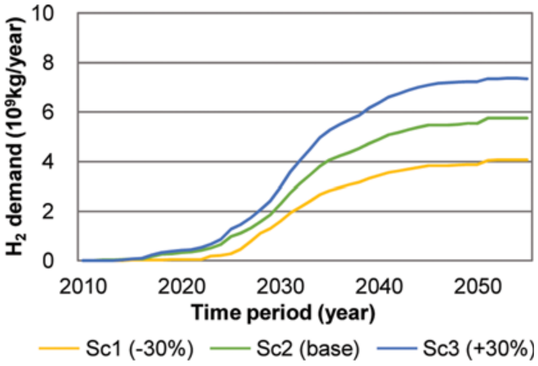

Fig. 3. The projected total hydrogen demand in Korea.

Table 1. Technical, economic, and environmental parameters of residues

	A1	A2	A3	A4	F1	F2	F3	I1	Refs.
Available amount (10^6 dry ton/year)	1.0	0.4	0.1	0.2	6.7	6.6	6.0	2.3	[34,35]
High heating value (kWh/kg)	5.3	4.4	5.3	5.3	5.9	5.8	5.8	5.7	[36,37]
Moisture level (%)	0.2	0.2	0.2	0.2	0.4	0.4	0.4	0.4	[36,37]
Conservation factor	0.7	0.7	0.7	0.7	0.4	0.4	0.4	0.1	[38]
Collecting price (\$/ton)	30	30	30	30	30	30	30	30	-
Importing price (\$/ton)	36	36	36	36	36	36	36	36	-
CO_2 emission value[a]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	[39]

A1: rice straw, A2: rice husk, A3: barley straw, A4: stems and others, F1: soft wood residue, F2: hard wood residue, F3: mixed wood residue, I1: industrial waste

[a] kg CO_2-equivelent/ton of residue

ios: Sc#1 and Sc#3 as well as the base line scenario (Sc#2). The estimated demand scenario is Sc#2 and Sc#1 ran at −30% but Sc#3 ran at +30% from the base demand value of Sc#2, respectively (Fig. 3). We assume the penetration rate of biomass-based hydrogen demand in total hydrogen demand is 20%, and the total time period is 45 years and the time interval is 3 years.

2. Assumptions and Parameters

In this paper, residues are composed of agricultural, forestry, and industrial waste. We assumed that the collecting price of residues is \$30/ton and the import price is 1.2-times higher than the colleting price. We consider three types of dedicated energy crops which are not currently utilized for energy production in Korea. It is assumed that the import price of dedicated energy crops is 1.2-times higher than the required cost for utilizing them (*i.e.* supply cost). Land purchase cost and available land size for dedicated energy crops are also assumed 54 billion \$/km^2 and 2,522 km^2, respectively [19,32]. The technical, economic, and environmental data about residues and dedicated energy crops are shown in Tables 1 and 2, respectively. It is assumed that the surplus can be sold to the outside, and the selling price of hydrogen is \$2.2/kg of hydrogen [33] and the hydrogen import price is 1.2-times higher than the selling price.

The overall economics of the Korean B2H2 system highly depends on the number and type of the selected facilities. For instance, the unit production cost of biomass gasification technologies shows a wide range (1.8-5.4 \$/kg) according to gasifier types and attached treatment processes [49]. Thus, we tried to adopt most related parameters and data considering the scale of the case study. The minimum and maximum capacity of all facilities can be found in Table 3. Some relevant data such as process efficiency, capital and operating cost, and lifespan also can be found. We assume the target water content is 15%, the systematic loss factor is 0.02 across all

Table 2. Technical, economic, and environmental parameters of dedicated energy crops

	E1	E2	E3	Refs.
Cultivation yield (10^3 dry ton/km^2)	1.3	1.2	1.1	[40,41]
High heating value (kWh/kg)	5.3	5.4	5.5	[42,43]
Moisture level (%)	0.2	0.2	0.2	[42,43]
Conservation factor	0.1	0.1	0.1	-
Supply price (\$/ton)	58	41	131	[40,44,45]
Importing price (\$/ton)	70	50	156	-
CO$_2$ emission value[a]	23	20	77	[46-48]

E1: switchgrass, E2: *Miscanthus*, E3: popular

[a] kg CO$_2$-equivelent/ton of dedicated energy crop

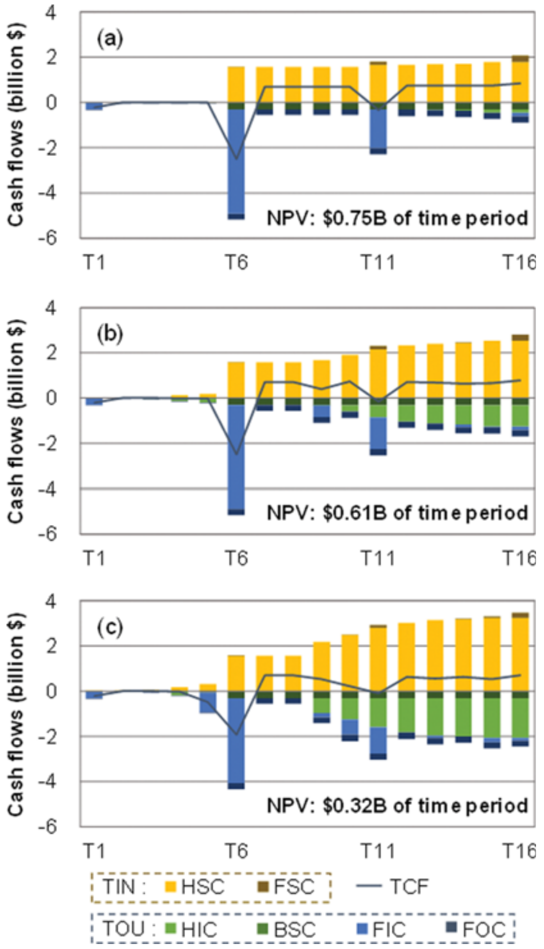

Fig. 4. The total cash flows (TCF) under the different scenarios: (a) Sc#1 (b) Sc#2 (c) Sc#3.

Table 3. Technical, economic, and environmental parameters of the all facilities

	B1	B2	B3	C1	C2	C3	H1	H2	H3	Refs.
Capacity (10^3 dry ton/year)	350	525	700	74	98	147	189[a]	284[a]	378[a]	[50,51]
Process efficiency (%)	97	97	97	46[b]	46[b]	46[b]	99	99	99	[50,51]
Capital cost (\$M)	28	35	42	90	107	136	56	71	84	[50,51]
Operating cost (\$/ton)	15	15	15	140	140	140	15	15	15	[50,51]
Lifespan (year)	15	15	15	30	30	30	15	15	15	[50,51]
CO$_2$ emission value	15[c]	15[c]	15[c]	3.1[d]	3.1[d]	3.1[d]	5.2[d]	5.2[d]	5.2[d]	[52,53]

B1, B2, B3: biomass storage types (small, medium, large), C1, C2, C3: hydrogen conversion types (small, medium, large), H1, H2, H3: hydrogen storage types (small, medium, large)

[a] 10^3 ton/year

[b] Include the gasifier efficiency

[c] kg CO$_2$-equivelent/ton of biomass

[d] 10^3 kg CO$_2$-equivelent/ton of hydrogen

facilities, and the salvage cost of facilities is 20% of capital cost.

RESULTS AND DISCUSSION

1. Economic Analysis

Fig. 4 depicts the cash flows over the projected time periods. While the TIN and TOU increase according the increase of hydrogen demand, the NPV decreases (Fig. 4). The main contributor to the TIN is the HSC (averagely 98% of TIN in the time period), while the FSC is estimated to be negligible (averagely 2% of TIN in the time period). In Sc#1 and #2, the main cost driver on the TOU is the FIC (averagely 49% and 37% of TOU in the time period of the Sc#1 and #2, respectively). However, the main cost driver is changed to the HIC in Sc#3 (45% of TOU in the time period). At time intervals T6 and T11, the positive effect of the HSC is not enough to offset the negative effect of the FIC, thereby resulting in the most negative cash flow at T6.

Between time intervals T1 and T5 in all scenarios, hydrogen tends to be imported to satisfy the demand, as shown in Fig. 5. In low hydrogen demand intervals, it is identified that satisfying the demand by the imported hydrogen is more economically beneficial than the way to meet the demand by producing hydrogen using domestic biomass. In the interval where the hydrogen demand is increasing (*e.g.*, between T6 and T8), the demand is satisfied by domestically produced hydrogen. In this interval, hydrogen is overproduced (maximum eight times than the corresponding demand in Sc#1) and the excess hydrogen is sold to the outside. After time intervals T9 in Sc#2 and #3, the demand is fulfilled not only by the domestically produced hydrogen but also by the imported hydrogen due to lack of available residue-type biomass for hydrogen production. From this result, it is obvious that the strategy to satisfy the hydrogen demand is affected by the quantity of demand and is easily switchable to the change of hydrogen demand.

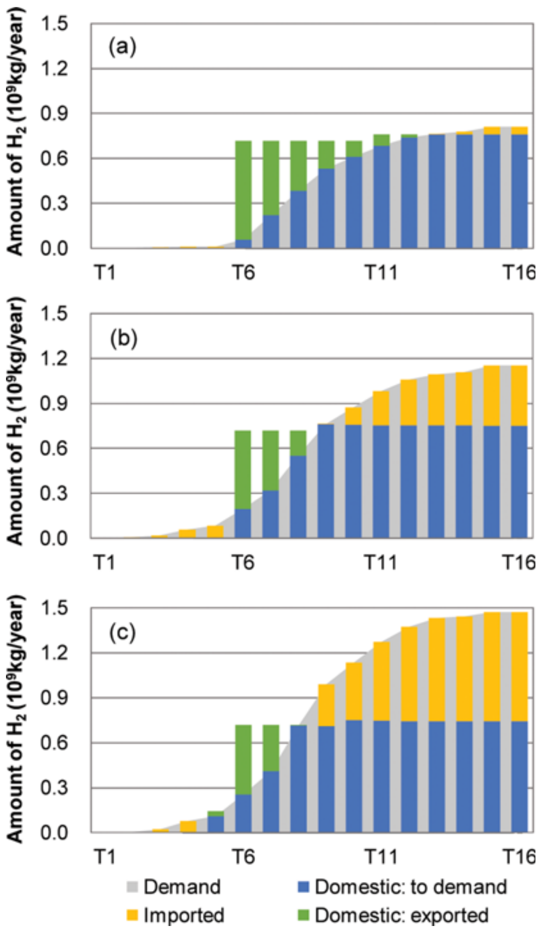

Fig. 5. The total hydrogen flows under the different scenarios: (a) Sc#1 (b) Sc#2 (c) Sc#3.

As mentioned in Section 2, two different strategies to meet the hydrogen demand can be established: internal and external ways. Fig. 6 separately depicts the flows of biomass and hydrogen in different ways. In Fig. 6(a), the amount of utilized residues is almost

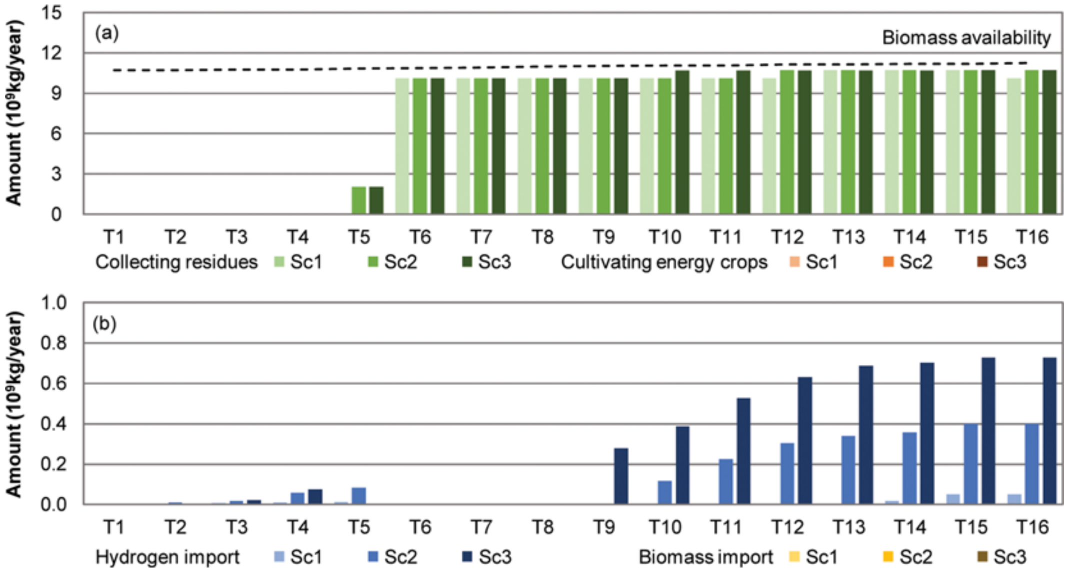

Fig. 6. Details of the flows biomass and hydrogen in the (a) internal and (b) external ways.

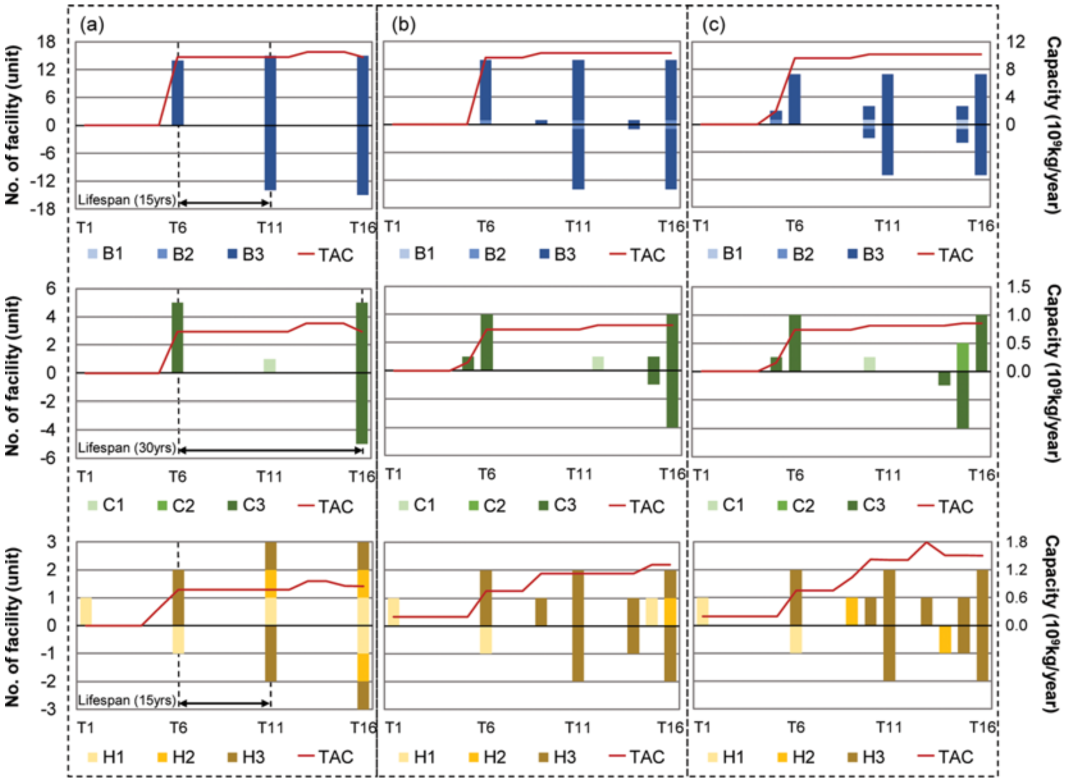

Fig. 7. The accumulated capacity and the changed number of installed facilities in (a) Sc#1 (b) Sc#2 and (c) Sc#3.

maximum (*i.e.*, 10.2 billion ton/year) after T6 in all scenarios, whereas dedicated energy crops are not utilized in any scenarios at all. Thus, it is obvious that utilizing residues up to the maximum availability is a more preferred way than to newly cultivate and utilize dedicated energy crops.

In Fig. 6(b), the amount of imported hydrogen in all scenarios is changed according to the variation of demand, while biomass is not imported in any scenarios. This means that utilizing existing residues is an economically top priority, followed by the way to import hydrogen, and to newly utilize dedicated energy crops. The main reason behind this strategic priority of the investment is that the expense for newly utilizing dedicated energy crops requires huge investments compared to installing new facilities to meet the hydrogen demand.

In this study, utilizing residues requires only one process (*i.e.*, collecting), so it can be cheaply and easily obtained. However, to utilize dedicated energy crops, several steps of facilities (biomass storage, hydrogen production, and hydrogen storage) should be installed to handle the biomass, to convert biomass into hydrogen, and to store the produced hydrogen. Moreover, several expensive processes, such as land purchase and cultivating, should be required as well as collecting or facility installation. This difference is also the other reason of the descending order of the investment strategy between utilizing residues and dedicated energy crops.

In case of the external way (Fig. 6(b)), although the import price of hydrogen is assumed to be very expensive (*e.g.*, biomass: averagely 0.09$/kg; hydrogen: 2.4$/kg, approximately 28 times than the import price of biomass), importing hydrogen is preferred against the strategy of newly harvesting dedicated energy crops. Similarly, although the import price of biomass is much cheaper than that of hydrogen, biomass is little imported due to the low economic performance caused by new installations of downstream facilities (*e.g.*, hydrogen conversion and storage).

Fig. 7 shows the total number of all facilities selected in the time period. The positive values in Fig. 7 mean the installed number of facilities at a certain time, whereas the negative one denotes the number of the removed facilities. The accumulated production capacity of all the selected facilities is also found in Fig. 7. In all scenarios, the installed number of biomass storage facilities (B1 to B3) is the largest of any other facilities. As previously discussed, the hydrogen demand is first satisfied by the strategy of utilizing existing residues and then the unmet demand is covered by imported hydrogen. The installed number of the facilities for the biomass utilization (*i.e.*, biomass storage and hydrogen conversion) remains constant after T6, since the system is already utilizing the maximum quantity of available residues. On the other hand, since the hydrogen storage facilities are essential to utilize either domestically produced hydrogen or imported hydrogen, the number of the facilities is proportionally increased according to the demand increase. From the viewpoint of economy of scale, the system economics tends to increase in larger demand condition. In this study, it is also observed that large size facilities (*e.g.*, B3, C3 and H3) are selectively installed to maximizing the effect of economy of scale.

The other result which we can find in Fig. 7 is the presences of the expired facilities. In this study, we considered the practical issue on the lifespan of facilities; thus the end-of-life facilities are replaced

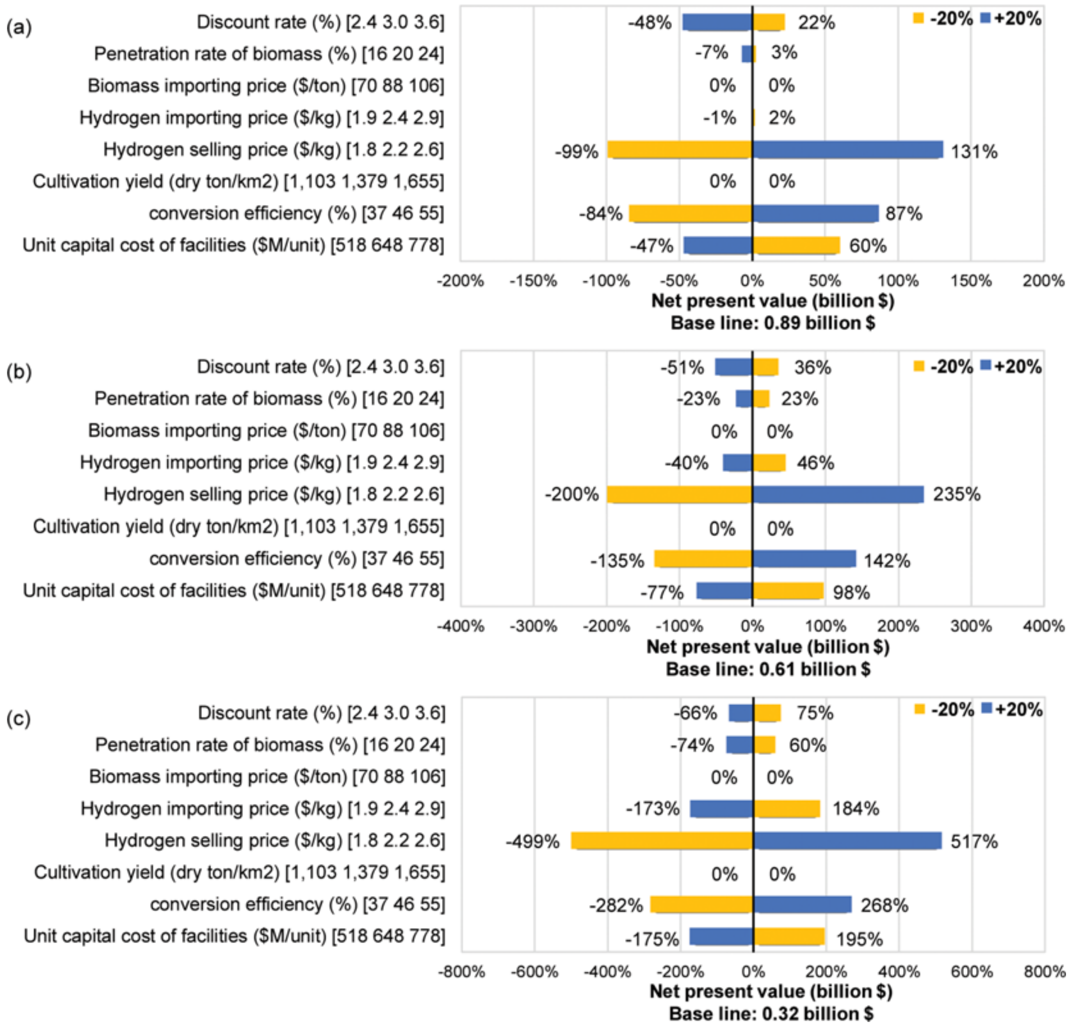

Fig. 8. Sensitivity analysis (±20%) of technical and economic parameters on NPV: (a) Sc#1 (b) Sc#2 (c) Sc#3.

by make-ups of new facilities as leaving salvage values. When the existing facilities are dismantled due to the end of lifespans, the new facilities are spontaneously installed to alleviate the impact by rapid changes of the conversion and storage facilities.

2. Sensitivity Analysis

To investigate the relationship between technical and economic parameters and the objective function, we analyzed the sensitivity of major parameters on the NPV by considering a ±20% change of the base value in all parameters. The selected parameters along with graphical results are depicted in Fig. 8.

The NPV is highly sensitive to the change of the hydrogen selling price, followed by the conversion efficiency, and the capital costs of facilities. It means that these parameters are main cost drivers to determine the overall system economics; c.f., the sensitivity of the penetration rate and the hydrogen importing price on the NPV. In this study, the effect of the same parameter to the NPV varies according to the demand scenarios. For example, the hydrogen selling price, which is the most sensitive factor in Sc#1, becomes more sensitive in Sc#3. On the other hand, the effect of hydrogen importing price, which is negligible in Sc#1, is slightly increased in high demand scenarios. Consequently, the scale of the impact of all parameters related to hydrogen production depends mainly on the required amount of demand. Both the biomass import price and the cultivation yield have little effect on the NPV in any demand scenarios. As previously discussed, the strategies to import biomass, and to newly utilize dedicated energy crops, cannot lead to any economic benefits.

SUSTAINABILITY ANALYSIS

To establish and implement renewable-based energy systems, other factors should be considered as well as economics. For example, it is important to analyze how the designed systems are eco-friendly and how they can contribute to sustainable development. We thus suggest three evaluation criteria which can quantitatively assess the merits of the B2H2 system: economic benefits index (EBI), energy security index (ESI), and environmental protection index (EPI). Each index is calculated as follows:

$$\mathrm{EBI}=\{(\mathrm{UIC}-\mathrm{UOC})/\mathrm{UOC}\}\times 100(\%) \tag{29}$$

$$\mathrm{UIC}=\sum_{t\in T}\mathrm{TIC}_t/\sum_{t\in T}\mathrm{H}_t^{loc} \tag{30}$$

$$\mathrm{UOC}=\sum_{t\in T}\mathrm{TOC}_t/\sum_{t\in T}\mathrm{H}_t^{loc} \tag{31}$$

where the UIC is the unit incoming cash flow per hydrogen (\$/kg of H_2) and the UOC is the unit outgoing cash flow per hydrogen (\$/kg of H_2).

$$\mathrm{ESI}=(\mathrm{LHF}/\mathrm{THF})\times 100(\%) \tag{32}$$

$$\mathrm{LHF}=\sum_{j\in J^C}\sum_{t\in T}\mathrm{Q}_{jt}^{LH} \tag{33}$$

$$\mathrm{THF}=\sum_{t\in T}\mathrm{Q}_t^{BH}+\sum_{j\in J^C}\sum_{t\in T}\mathrm{Q}_{jt}^{LH}+\sum_{t\in T}\mathrm{Q}_t^{IH} \tag{34}$$

where the LHF is the local hydrogen flow, which is identical to the amount of the produced hydrogen using only the domestic biomass (Q_{jt}^{LH}) and the THF is the total hydrogen flow. Q_t^{BH} is the amount of produced hydrogen using the imported biomass, and Q_t^{IH} is the amount of the imported hydrogen. Here, the sum of Q_t^{BH} and Q_{jt}^{LH} is equal to H_{jt}^{pro}, as shown in Eq. (9).

$$\mathrm{EPI}=\{(\mathrm{UCE}^0-\mathrm{UCE}^*)/\mathrm{UCE}^0\}\times 100(\%) \tag{35}$$

where the UCE^* is the unit CO_2 emission per hydrogen (kg CO_2-eq./kg of H_2) and the UCE^0 is unit CO_2 emission per hydrogen (kg CO_2-eq./kg of H_2) in the base case. Note that the base case is the case that the resource mix for hydrogen production is same with the base year (2010, natural gas: 48%; oil: 30%; coal: 18%; water electrolysis: 4%).

$$\begin{aligned}\mathrm{UCE}^*=\Big(&\sum_{i\in I^B}\sum_{t\in T}\Upsilon_i^B\mathrm{B}_{it}^{pro}+\sum_{j\in J^B}\sum_{t\in T}\Upsilon_j^F\mathrm{B}_{jt}^{sto}+\sum_{j\in J^C}\sum_{t\in T}\Upsilon_j^F\mathrm{H}_{jt}^{pro}\\&+\sum_{j\in J^H}\sum_{t\in T}\Upsilon_j^F\mathrm{H}_{jt}^{sto}\Big)/\sum_{t\in T}\mathrm{H}_t^{loc}\end{aligned} \tag{36}$$

where Υ_i^B is the CO_2 emission factor of the biomass utilization activity and Υ_j^F is the CO_2 emission factor of the facilities.

The evaluation results are summarized in Table 4. The UOC is little sensitive to the change of demand, while the UIC and the EBI decrease as the demand increases. This means that the unit required cost for establishing the B2H2 system increases according to the increase of demand. It is mostly common to think that the overall cost would decrease as the demand increases due to *economy of scale*. However, such a general effect is not applied in this case study. A main reason behind this result is that unlike other renewable sources (*e.g.*, wind and solar), an unlimited quantity of biomass cannot be utilized due to the limited biomass availability. Accordingly, additional hydrogen supply ways of high costs compared to residues utilizing (*e.g.*, dedicated energy crop cultivation or biomass/hydrogen import) should be adopted, thereby leading to worse economics.

Similarly, the THF increases according to the increase of the hydrogen demand, whereas the LHF remains almost constant due to the limitation of biomass availability. Because the hydrogen amount which can be domestically produced is limited, the unmet hydrogen demand should be covered by different ways; the most preferred alternative way is to import hydrogen (See Section 5.1). Accordingly, the amount of imported hydrogen increases according to the increase of the hydrogen demand, which leads to the aggravation of the energy security.

Finally, the EPI increases according to the increase of hydrogen demand. It means that a larger effect for the reduction of CO_2 emission is expected, more hydrogen demand assumed in the B2H2 system. This is because although CO_2 emission in the downstream is little, a certain amount of CO_2 is emitted in the upstream activities, especially the biomass gasification facility along with biomass cultivation. However, if carbon aggregate credit of biomass is taken into account, the EPI would be improved by offsetting the CO_2 emission by such activities.

CONCLUSIONS

We developed a new approach to support the decision-making process for establishment of the investment and operation planning of the B2H2 system. To achieve this goal, we have proposed a new optimization model to maximize the NPV which is subjected to various practical constraints. We analyzed the optimal plan of the investment strategy including cash flows, utilized amount, and capacity of facilities. We then evaluated the sustainability of the B2H2 system using extended analysis study, such as energy security and environmental protection.

The following are the major contributions and findings of this study:

- The main factor to determine the total incoming cash flow (TIN) is the hydrogen selling cost (HSC), whereas the main contributors to the total outgoing cash flow (TOU) are the facility investment cost (FIC) in Sc#1 and Sc#2, and the hydrogen importing

Table 4. Energy independency and CO_2 reduction of the B2H2 system in the different demand scenarios

	Sc#1	Sc#2	Sc#3
Economic benefit index (EBI, %)	**38.5**	**23.3**	**14.2**
Unit incoming cash flow (UIC, \$/kg of H_2)	2.9	2.5	2.4
Unit outgoing cash flow (UOC, \$/kg of H_2)	2.1	2.1	2.1
Energy security index (ESI, %)	**97.5**	**77.7**	**63.3**
Local hydrogen flow (LHF, 10^9 kg of H_2)	7.8	8.2	8.2
Total hydrogen flow (THF, 10^9 kg of H_2)	8.2	10.5	12.9
Environmental protection index (EPI, %)	**13.1**	**29.9**	**37.5**
Unit CO_2 emission (UCE^*, kg CO_2-eq./kg of H_2)	10.9	8.8	7.8
Unit CO_2 emission of base case (UCE^0, kg CO_2-eq./kg of H_2)	12.5	12.5	12.5

cost (HIC) in Sc#3.

- In the low hydrogen demand intervals, importing hydrogen to meet demand is preferred against domestically producing hydrogen. However, in the high hydrogen demand intervals, the demand is fulfilled by not only the produced hydrogen but also imported hydrogen due to the limited biomass availability.
- Among four different strategies (*i.e.* utilizing existing residues or cultivating new dedicated energy crops, importing hydrogen and biomass), the way to utilize residues shows the highest economics, followed by importing hydrogen, importing biomass and utilizing new dedicated energy crops.

Again, we have proposed a basic approach for the long-term planning of the investment and operation of the B2H2 system. This basic approach including the optimization model can be further extended to address different issues on the B2H2 system such as transportation, regional imbalances of resources and demand, integration with existing facilities, and energy market volatility. Systematic approach and high level analysis will be able to be attempted upon this study to determine international energy trades by extending the boundary the B2H2 system, and to analyze different energy systems such as alternative energy pathways and final products.

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NOMENCLATURE

Set

I : compounds
J : facilities
T : time periods

Subset

I^B : biomass
I^H : hydrogen
I^R : residues
I^E : dedicated energy crops
J^B : biomass storage facility
J^C : hydrogen conversion facility
J^H : hydrogen storage facility

Parameters

Λ_t : the total hydrogen demand in the time period $t\in T$
ρ : the penetration rate of biomass-based hydrogen demand in total hydrogen demand
ξ_i : the available amount of residues $i\in I^R$
$\backepsilon_t$: the fluctuation factor of biomass $i\in I^B$ in the time period $t\in T$
ω_i : the cultivation yield of dedicated energy crops $i\in I^E$
υ : the available harvesting area
f_i : the conservation factor of biomass $i\in I^B$
η_j : the processing efficiency of facilities $j\in J$
τ_j : the systematic loss factor of facilities $j\in J$
ν_i : the calorific value of biomass $i\in I^B$
χ_i : the energy needed for handling of biomass $i\in I^B$
π_i : the water content of biomass $i\in I^B$
π_i^* : the targeted water content of biomass $i\in I^B$
ϑ_j : the minimum capacity of facilities $j\in J$
θ_j : the maximum capacity of facilities $j\in J$
ζ_j : the maximum lifespan of facilities $j\in J$
β_t^{min} : the minimum flow rate of hydrogen in the time period $t\in T$
β_t^{max} : the maximum flow rate of hydrogen in the time period $t\in T$
d : the discount rate of cash flow
ψ : the depreciation
∂ : the tax rate
α_i : the unit selling price of compounds $i\in I$
γ_i : the unit import price of compounds $i\in I$
κ_{it} : the price fluctuation of compounds $i\in I$ in the time period $t\in T$
ϕ : the percentage of salvage cost to total capital cost
σ : the capital charge factor
σ_j : the capital charge factor of facilities $j\in J$
φ : the unit land purchase cost
φ_j : the unit capital cost of facilities $j\in J$
δ_i : the unit processing cost of biomass $i\in I^B$
δ_j : the unit operating cost of facilities $j\in J$
λ_{jt} : the correction factor of facilities $j\in J$ to revise the loss of capital cost in the time period $t\in T$
Υ_i^B : the CO_2 emission coefficient for biomass utilization activities $i\in I^B$
Υ_j^F : the CO_2 emission coefficient for hydrogen conversion activities $j\in J$

Continuous variables

A_{it} : the actual use area for dedicated energy crops $i\in I^E$ in the time period $t\in T$
B_{it}^{pro} : the total amount of produced biomass $i\in I^B$ in the time period $t\in T$
B_{it}^{sto} : the amount of biomass stored in biomass storage $j\in J^B$ in the time period $t\in T$
B_t^{imp} : the amount of imported biomass in the time period $t\in T$
E_{it} : the amount of harvested dedicated energy crops $i\in I^E$ in the time period $t\in T$
H_{jt}^{pro} : the amount of hydrogen produced in hydrogen production $j\in J^P$ in the time period $t\in T$
H_t^{loc} : the amount of produced hydrogen for satisfying local demand in the time period $t\in T$
H_{jt}^{sto} : the amount of hydrogen stored in hydrogen storage $j\in J^H$ in the time period $t\in T$
H_t^{imp} : the amount of imported hydrogen in the time period $t\in T$
H_t^{exc} : the excess amount of hydrogen in the time period $t\in T$
R_{it} : the amount of collected residues $i\in I^R$ in the time period $t\in T$
BSC_t : the biomass supply cost in the time period $t\in T$
FIC_t : the facility investment cost in the time period $t\in T$
FOC_t : the facility operating cost in the time period $t\in T$
FSC_t : the facility salvage cost in the time period $t\in T$
HIC_t : the hydrogen import cost in the time period $t\in T$
HSC_t : the hydrogen selling cost in the time period $t\in T$
NPV : the net present value
TCF_t : the total cash flow in the time period $t\in T$

TIN_t : the total incoming cash flow in the time period $t \in T$
TOU_t : the total outgoing cash flow in the time period $t \in T$
EBI : the economic benefit index
EPI : the environmental protection index
ESI : the energy security index
LHF : the local hydrogen flow
THF : the total hydrogen flow
UCE^0 : the unit amount of emitted CO_2 in base case
UCE^* : the unit amount of emitted CO_2
UIC : the unit incoming cash flow of hydrogen
UOC : the unit outgoing cash flow of hydrogen

Integer variables

N_{jt}^{new} : the number of newly installed facilities $j \in J$ in the time period $t \in T$
N_{jt}^{red} : the number of removed facilities $j \in J$ in the time period $t \in T$
N_{jt}^{T} : the total required number of facilities $j \in J$ in the time period $t \in T$

Binary variables

Y_t : 1 if the biomass or hydrogen are to be imported in the time period $t \in T$, 0 otherwise
Z_t : 1 if the biomass or hydrogen are to be exported in the time period $t \in T$, 0 otherwise

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