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Feasibility study and benefit analysis of biomass-derived energy production strategies with a MILP (mixed-integer linear programming) model: Application to Jeju Island, Korea

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Abstract−We developed a new approach to analyze the feasibility and benefits of biomass utilization strategies for energy production. To achieve this goal, we first generated a biomass-to-energy network which consists of different conversion technologies and corresponding compounds. We then developed new optimization models using a mixed integer linear programming technique to identify the optimal and alternative strategies and point out their major cost drivers. We applied these models to the biomass-derived energy supply problem on Jeju Island, Korea, to answer a wide range questions related to biomass utilization. What is the cheapest way to produce liquid fuels from available biomass on Jeju Island? How much demand can be satisfied by biomass-derived liquid fuels? What combination of technologies and biomass resources gives the best economic benefits or productivity? Based on the case study of Jeju Island, we could provide useful guidelines to policy-makers and stakeholders in the energy business.

Keywords: Biomass, Energy Production, Optimization, MILP, Korea

INTRODUCTION

The production of fuels and chemicals depends heavily on fossil fuels. The demand for fuels in the transportation sector accounts for nearly 25% of the total net primary energy and 70% of the energy provided by petroleum. The depletion of fossil fuels, and rising energy demand, as well as increasing environmental issues, have directly influenced regional economic stability and energy security [1]. Therefore, in 2012, the Korean government announced the "*Carbon Free Jeju Island by 2030*" plan, which aims to meet the energy demand of Jeju Islands with 100% renewable energy sources [2].

Biomass is one of the most promising alternative energy sources for achieving this goal. It is widely abundant and can be used to produce a broad range of marketable products (fuels [3-5], chemicals [6,7], and energy [8,9]) due to its carbon aggregate credit [10]. Furthermore, several studies on biomass-to-energy conversion technologies have been conducted for achieving high conversion and high energy efficiency. These include chemical [11,12], biochemical [13-18], and thermochemical [19-24] technologies utilizing various kind of biomass, such as agricultural and forestry residues [21-24] and, dedicated energy crops [25]; economic assessments are also analyzed.

Jeju Island in Korea has a relatively high biomass potential compared to other regions in the country, and this can be conventionally used to generate energy (e.g., heat and electricity) and produce chemical products. While various types of biomass, including agricultural, forestry residue and livestock waste are utilized as biomass resources, the latter are limited in quantity. Therefore, utilizing biomass resource in a profitable and efficient manner is crucial. Accordingly, several researchers have sought to find a suitable biomass utilization strategy on Jeju Island. There are studies on the pyrolysis of particular agricultural residues, with the aim of producing biofuel or chemicals [26-28]. Woo et al. [29] dealt with the biomass-based hydrogen supply chains on Jeju Island and considered biomass types, production facilities, storage facilities, and occupied areas.

Another important issue on the utilization of biomass as an energy source is to do a systematic analysis to identify the best options from a number of alternatives [30]. Santibañez-Aguila et al. [31] proposed an optimization model to evaluate biomass conversion processes for transportation fuels from the economic and environmental aspects. Garcia et al. [32] developed an optimization-based approach to analyze the optimal pathway for fuels production in a biomass utilization network. Kim et al. [33] and Maronese et al. [34] also used an optimization model to assess different strategies for the biomass utilization. Although many high-level analysis studies are found in the literature, there is still a lack of study to provide comprehensive solutions and guidelines for the biomass utilization. For example, studies above focused on i) the best (or optimal) solution without discussion about the alternative strategies that allows to identify major cost-drivers and extend the choice to suboptimal ones, and ii) theoretical analysis of the modeled system without dealing with real data (e.g., biomass availability and fuel demand), thereby providing practical solutions and demonstrations.

Accordingly, we developed a new approach to model a biomass utilization network that demonstrates the interconnectivity between various types of technologies and corresponding compounds, ii) identified economically viable strategies along with major cost-driv-

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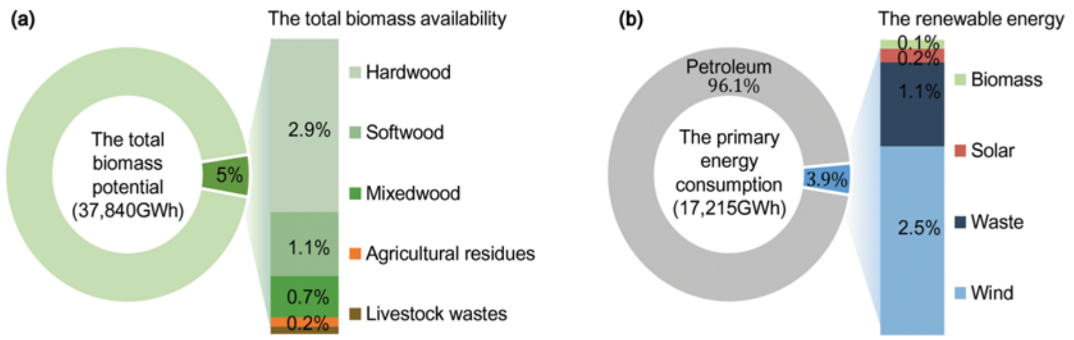

Fig. 1. (a) The total biomass potential and (b) the primary energy consumption by energy source on Jeju Island in 2011.

ers, and iii) resolved the practical problems on the utilization of biomass as a resource of energy. In achieving the goals, we first generated a biomass-to-energy network. We then developed new network optimization models to identify the most profitable and efficient biomass utilization strategies (Section 3). To illustrate the capability of the proposed models, we finally dealt with a real case study, biomass-derived liquid fuels production for the transportation sector on Jeju Island, Korea.

PROBLEM DESCRIPTION

1. Biomass on Jeju Island

Fig. 1 shows the biomass potential and availability, and the primary energy consumption on Jeju Island in 2011 [35,36]. Here the biomass potential is defined as the total amount of the biomass resources that can be generated annually, whereas biomass availability is what can actually be used for the purposes of energy production. The biomass potential can be utilized for different purposes (e.g., food and livestock feed); however, some should remain for ecosystem conservation (e.g., soil protection). Therefore, there should be an upper limit on the use of biomass for energy production. We represent the quantities of the biomass potential and availability as an *energy content* of biomass, which is the energy level released per unit mass of biomass when the latter is combusted completely. The unit of energy is standardized to GWh per year to quantitatively compare biomass and other energy resources conveniently. A detailed discussion, with numerical results, is presented in Section 2.2.1.

The total biomass potential (37 TWh) is calculated mainly by agricultural and forest residues, and livestock waste of Jeju Island [36]. While Jeju Island has high biomass potential, including forest and agricultural residues and livestock wastes, only 5%, 24.5% and 5% of the total potentials, respectively, can be used for energy production due to the conservation of the ecosystem [37]. The largest constituent of the total biomass availability is forest residues, such as hardwood, softwood and mixed (unclassified) wood, followed by agricultural residues. Agricultural residues represent the major crops cultivated on Jeju Island, such as beanstalk, rapestraw and other unclassified perennial crops; beanstalk is the largest contributor (95.6%). The smallest of the total biomass availability is livestock wastes gained from cows, pigs, and chickens.

Fig. 1(b) shows the energy consumption of Jeju Island in 2011. Most energy consumed on Jeju is generated from fossil fuel, whereas the renewable energy contributes 3.9% (671 GWh) of the total energy consumption. Note that wind power is the main contributor of the renewable energy due to the good wind speed and wind rose[1] of Jeju Island [38]. The next main source is waste, which includes municipal solid wastes and refinery fuel oil; the waste is subjected to incineration, supplying heat and flue gas [39]. Solar source and biomass is poorly used in comparison to other renewable energy sources.

In this study we selected four types of biomass as a resource for energy production: two woody types (hardwood and softwood) and two herbaceous (beanstalk and rape straw). The annual biomass availability of beanstalk, rape straw, hardwood, and softwood is estimated to be 11,925, 477, 190,282, and 75,358 dry tons, respectively [40]. Accordingly, the total quantity of biomass availability on Jeju Island can be calculated by the sum of the selected biomass resources (278,042 dry tons/year).

2. Biomass-to-energy Network (BEN)

Based on an extensive search of the literature, we generated the *biomass-to-energy network* (BEN), which includes all the possible strategies for biomass utilization. Within the context of this study, the BEN can be explained as a superstructure that consists of all major conversion technologies and the corresponding compounds (feedstocks, intermediates, and final products); this leads to a wide range of strategies for the utilization of the selected feedstocks (i.e., beanstalk, rapestraw, hardwood, and softwood). The BEN is developed as a macroscopic structure to provide a holistic view for evaluating possible strategies. At this macro-level, the purpose of this study was not to analyze a detailed integrated process, but to evaluate and simply compare various and different processes with multiple types of feedstock. Furthermore, we ranked the optimal and alternative strategies for the utilization of each feedstock using integer-cuts constraints. Fig. 3 schematically presents the BEN. A detailed explanation of the conversion technologies and corresponding compounds follows in the subsections.

2-1. Compounds

We classify compounds in the BEN into four groups: feedstocks,

[1]Wind rose is a graphical diagram that depicts the distributions of wind speeds, and the frequency of the varying wind directions. The wind rose is an essential concept and basis for placing, sizing, and designing the layout of the wind turbines correctly.

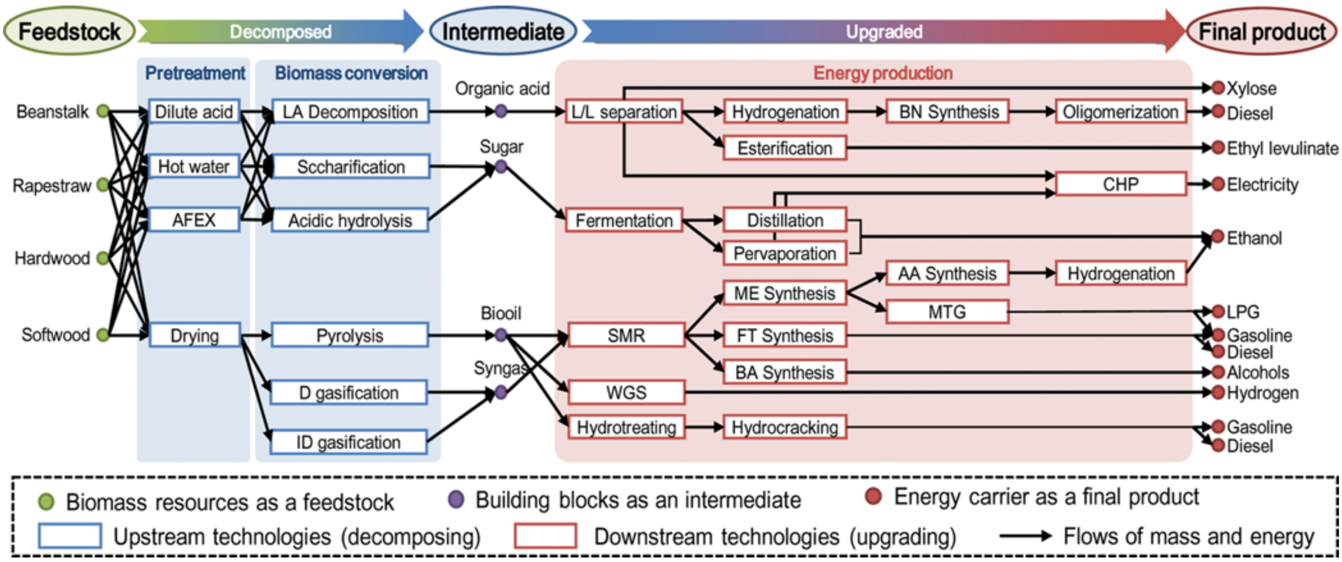

Fig. 2. Biomass-to-energy network. Abbreviation: *Technologies*. AFEX: ammonia fiber expansion based pretreatment, CHP: combined heat and power generation, D: direct, MTG: methanol to gasoline technology, ID: indirect, SMR: steam methane reforming, WGS: water-gas-shift. *Compounds*. AA: acetic acid, BA: blended alcohols, BN: butane, FT: Fischer-Tropsch, LA: levulinic acid, ME: methanol, OA: organic acids.

Table 1. The market prices and energy contents of feedstocks and final products

	Market price ($/kg)	Energy content (kWh/kg)
Feedstock		
Beanstalk	0.174	4.7
Rape straw	0.184	4.7
Hardwood	0.108	5.5
Softwood	0.129	5.8
Product		
Diesel	0.71	11.9
Ethanol	0.65	7.5
Ethyl levulinate	3.20	7.2
Gasoline	0.73	12.0
Hydrogen	2.09	39.0
Alcohols	0.53	8.0
LPG	0.90	13.9
Byproduct		
Formic acid	0.63	1.7
Xylose	0.075	4.5
Electricity	0.075*	-

*The unit of electricity is $ per kWh

intermediates, products, and byproducts. As discussed in subsection 2.1, we consider four types of feedstock: beanstalk, rape straw, hardwood, and softwood. The types of intermediates and final products (i.e., products and byproducts) vary with the technologies that produce them. The market price and energy content of feedstocks and final products are in Table 1. The market prices [41-47] and energy content [48-51] of final products were from the literature. The market prices of feedstocks were from Wood Resources International LLC (WRI) [52], the United States Department of Agriculture (USDA) [53], and Rural Development Administration (RDA) [54].

The *energy content (EC)* of the feedstock listed in Table 1 was estimated from the chemical composition of each feedstock in weight percentage (dry basis) of carbon B^C, hydrogen B^H, sulfur B^S, nitrogen B^N, oxygen B^O, and ash content B^{ash} [55].

$$EC=0.097B^C+0.328B^H+0.028B^S-0.006B^N-0.028B^O-0.006B^{ash} \quad (1)$$

The chemical composition of the feedstock selected in this study is listed in Table 2.

2-2. Technologies

The technologies used in BEN are largely classified as *upstream* and *downstream technology.* Upstream technology aims to decompose feedstocks and extract the main intermediates that involve

Table 2. The composition of feedstock [56]*

	Moisture (%)	Chemical composition (dry weight fraction)					
		Carbon (%)	Hydrogen (%)	Sulfur (%)	Nitrogen (%)	Oxygen (%)	Ash (%)
Beanstalk	20	42.97	5.59	0.01	0.83	44.93	5.54
Rapestraw	20	43.20	5.00	0.11	0.61	39.40	11.40
Hardwood	25	49.25	5.99	0.03	0.06	44.36	0.30
Softwood	25	50.64	5.98	0.01	0.36	39.69	0.56

organic acids, sugar, bio-oil and syngas. Upstream technology contains pretreatment and biomass conversion technologies. Pretreatment technologies are used to physically and chemically break the structural framework of the feedstocks to achieve a high efficiency in converting the feedstocks to the main intermediates. We consider that the size reduction process, such as handling and chopping, is basically contained in all pretreatment technologies. Biomass conversion technologies deal with the preprocessed feedstocks using high temperature or chemical and enzymatic method to produce the main intermediates. In contrast, downstream technology consists of energy production technologies that refer to producing the final products using the main intermediates.

The data required for the technologies, such as input and output materials, conversion yield, and unit production cost are presented in Table 3. The technical and economic data of the technologies are from [4,5,11-14,17,19-25,57-70]. Note that *conversion yield* in Table 3 denotes the mass ratio of output material to input material of a technology. The *unit production cost* (*UPC*) is the

Table 3. Summary of the technical and economic parameters of technologies

Technology name	Input materials	Output materials	Conversion yield* (kg/kg)	UPC** ($/kg)
Pretreatment				
Dilute acid	Feedstock	Hydrolyzate	3.59-3.75	0.008-0.010
Hot water	Feedstock	Hydrolyzate	4.72-4.91	0.001-0.002
AFEX	Feedstock	Hydrolyzate	3.92-3.93	0.002
Drying	Feedstock	Dried feedstock	0.53-0.81	0.008-0.009
Biomass conversion				
OA Decomposition	Hydrolyzate	Organic acids	0.13-0.14	<0.001
Saccharification	Hydrolyzate	Sugar	0.94-1.07	0.011-0.015
Acidic hydrolysis	Hydrolyzate	Sugar	0.98-1.02	0.001
Pyrolysis	Dried feedstock	Biooil	0.75-0.77	0.022-0.023
D gasification	Dried feedstock	Syngas	1.16-1.19	0.029
ID gasification	Dried feedstock	Syngas	0.84-0.86	0.019-0.020
Energy production				
L/L separation	Organic acids	Levulinic acid	0.48-0.57	0.016-0.025
		Xylose	0.33	
		Residue	0.50-0.56	
Esterification	Levulinic acid	Ethyl levulinate	0.79	0.071
LA Hydrogenation	Levulinic acid	γ-Valerolactone	0.34	0.097
BN Synthesis	γ-Valerolactone	Butene	0.96	0.071
Oligomerization	Butene	Alkene	0.57	0.009
Fermentation	Sugar	Broth	0.98-0.99	0.001
Distillation	Broth	Ethanol	0.02-0.03	0.099-0.267
		Residue	0.08-0.26	
Pervaporation	Broth	Ethanol	0.01-0.05	0.202-0.463
		Residue	0.10-0.26	
SMR	Syngas	Refined syngas	0.54-0.6.	0.047-0.069
ME Synthesis	Refined syngas	Methanol	0.86	0.036
FT Synthesis	Refined syngas	Gasoline	0.13	0.457
		Diesel	0.11	
BA Synthesis	Refined syngas	Blended alcohols	0.55	0.812
AA Synthesis	Methanol	Acetic acid	1.81	0.189
AA Hydrogenation	Acetic acid	Ethanol	0.76	0.255
MTG	Methanol	Gasoline	0.32	0.246
		LPG	0.18	
WGS	Biooil	Hydrogen	0.06	0.537
Hydrotreating	Biooil	Refined biooil	0.46	0.066
Hydrocracking	Refined biooil	Gasoline	0.41	0.160
		Diesel	0.55	
CHP	Residue	Electricity	0.25-1.93	0.024-0.052

*The conversion yield of some technologies is higher than 1 due to the additional material input (e.g., makeup water, solvents, catalysts and enzymes) total required cost including capital and operating costs, divided by the amount of the output material produced in a technology.

$$\mathrm{UPC}=\frac{\mathrm{ACC}+\mathrm{OC}}{\mathrm{APR}} \tag{2}$$

where OC is the operating cost, APR is the annual production rate, and ACC is the amortized capital cost, which is calculated by

$$\mathrm{ACC}=\mathrm{CCF}\cdot\mathrm{CC} \tag{3}$$

where CCF is the capital charge factor and CC is the capital cost.

$$\mathrm{CCF}=\frac{\mathrm{r}(1+\mathrm{r})^{n}}{(1+\mathrm{r})^{n}-1} \tag{4}$$

where r is the interest rate in percent and n is the lifetime of technologies. We assume the interest rate of 10% and the lifetime of 20 years; thus, the resulting CCF is 0.1175. The baseline capacities of the technologies are assumed to process 2,000 dry tons of biomass

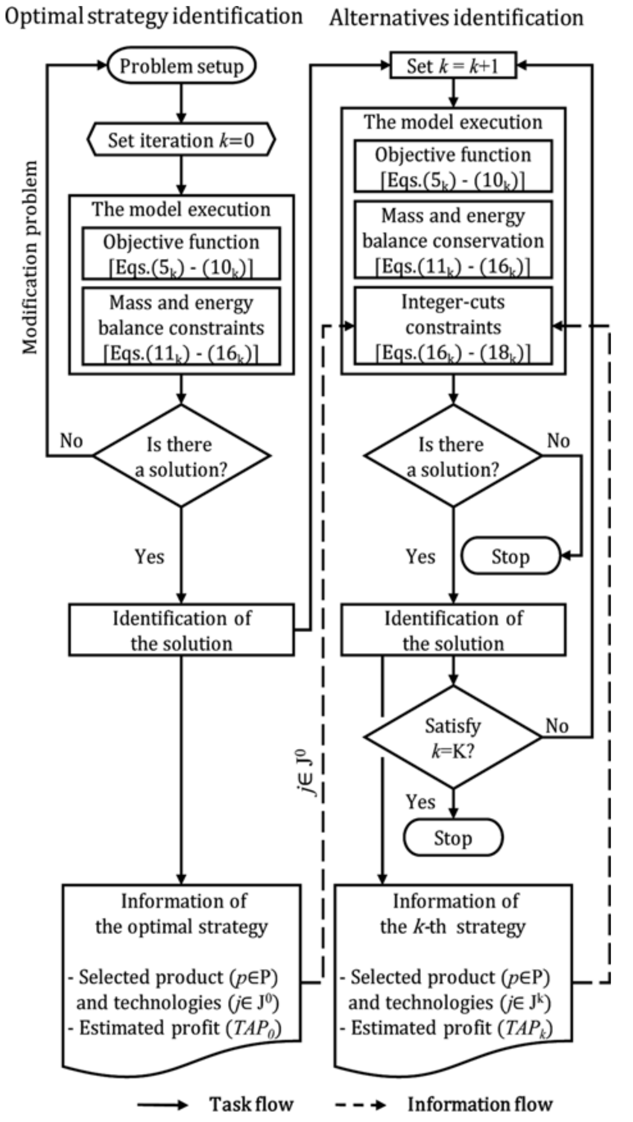

Fig. 3. Algorithm for the identification of the optimize and alternative strategies.

per day [8]. The detailed technical and economic data of the technologies listed in Table 3 are summarized in Table S1 of Appendix A.

THE OPTIMIZATION MODEL

We introduce two new optimization models using a mixed integer linear programming (MILP) formulation: *Base model* (section 3.1) and *Extended model* (section 3.2).

1. Base Model for Strategy Identification

We propose a new (MILP) formulation as the base model to identify the optimal and alternative strategies for biomass utilization. Fig. 3 shows major tasks and information flows in the model. The object function in the model is subjected by different types of constraints including mass and energy balances and integer-cuts constraints. We first execute the model excluding integer-cut constraints to identify the optimal strategy among all the possible strategies in BEN. We then iteratively execute the model including integer-cut constraints to sequentially identify next best alternatives. To avoid duplication of the selection of the strategy in each iteration, the integer-cuts constraints work on the value of integer variables, which indicates the employment of technologies in the strategies identified in the previous iterations of the model.

1-1. The Objective Function

The objective function is to maximize the total annual profit (TAC) by implementing the biomass utilization strategies. The total annual profit TAO_k [\$/yr] is defined as the difference between the total revenue TR_k [\$/yr] and the total production cost TOC_k [\$/yr]. $\mathrm{k}\in\mathrm{K}$ denotes the number of iterations in the model; if k=0, the model excluding integer-cuts constraints identifies the optimal strategy, while if k>0, the model is executed with the integer-cuts constraints to search alternative strategies. The function that leads to the maximum TAP_k is given as follows:

$$\max\mathrm{TAP}_k=\mathrm{TR}_k-\mathrm{TPC}_k\ \forall\mathrm{k}\in\mathrm{K} \tag{5}$$

TR_k is obtained by selling product $\mathrm{p}\in\mathrm{P}$ and byproduct $\mathrm{b}\in\mathrm{B}$ as stated in Eq. (6).

$$\mathrm{TR}_k=\sum_p\vartheta_p\mathrm{X}_{kp}+\sum_b\vartheta_b\mathrm{X}_{kb}\ \forall\mathrm{k}\in\mathrm{K} \tag{6}$$

where the market price for product ϑ_p [\$/kg] and byproduct ϑ_b [\$/kg] are in Table 2. X_{kp} [kg/yr] and X_{kb} [kg/yr] are the amounts of the produced compound $\mathrm{p}\in\mathrm{P}$ and $\mathrm{b}\in\mathrm{B}$, respectively.

TPC_k consists of two main components: the total facility establishment cost TTC_k [\$/yr] and the feedstock purchase cost FC_k [\$/yr], as shown in Eq. (7):

$$\mathrm{TPC}_k=\mathrm{TTC}_k+\mathrm{FC}_k\ \forall\mathrm{k}\in\mathrm{K} \tag{7}$$

TTC_k is then calculated using Eqs. (8) and (9) as follows.

$$\mathrm{TTC}_k=\sum_j\mathrm{TC}_{kj}\ \forall\ \ \in \tag{8}$$

$$\mathrm{TC}_{kj}=\mu_j\mathrm{X}_{kj}\ \forall\mathrm{k}\in\mathrm{K} \tag{9}$$

where TC_{kj} is the facility establishment cost of each technology $\mathrm{j}\in\mathrm{J}$ [\$/kg] is UPC of technology $\mathrm{j}\in\mathrm{J}$ and X_{kj} [kg/yr] is the amount of compounds processed in technology $\mathrm{j}\in\mathrm{J}$. μ_j is discussed in the previous section, and the resulting μ_j values are listed in Table 3.

$$FC_k=\sum_f \vartheta_f X_{kf}\ \forall k\in K \quad (10)$$

where X_{kf} [kg/yr] is the amount of feedstock f∈F, and the market price of feedstock ϑ_f [$/kg] is listed in Table 1.

1-2. Constraints

1-2-1. Mass and Energy Balance

The following equations are used to balance mass and energy on a strategy from feedstock through intermediates to final products. First, the amount of feedstock X_{kf} must be balanced against the amount of the feedstock that is processed in technologies X_{kj}.

$$X_{kf}=\sum_j X_{kj}\eta_{fj}^{-}\ \forall f\in F,\ k\in K \quad (11)$$

where $\eta_{fj}^{-}\in\{0, 1\}$ is the conversion yield of technology, which represents whether feedstock f∈F can be consumed in the technology j∈J (where 1 means active, and 0 inactive).

Eqs. (12) and (13) enforce the same input to output balance for intermediate i∈I and represent the production/consumption of intermediate i∈I in technology j∈J, respectively. η_{ij}^{+} and η_{ij}^{-} are the conversion yields of technology j∈J, which produces/consumes intermediate i∈I. Likewise η_{fj}^{-}, $\eta_{ij}^{-}\in\{0, 1\}$ represents whether or not intermediate i∈I can be consumed in technology j∈J, while η_{ij}^{+} is the mass ratio of intermediate i∈I over input-materials in technology j∈J. This is reported in Table 3.

$$X_{ki}=\sum_j X_{kj}\eta_{ij}^{+}\ \forall i\in I,\ k\in K \quad (12)$$

$$X_{ki}=\sum_j X_{kj}\eta_{ij}^{-}\ \forall i\in I,\ k\in K \quad (13)$$

Eqs. (14) and (15) represent the amount of product p∈P and byproduct b∈B produced by technology j∈J. η_{pj}^{+} and η_{bj}^{+}, likewise η_{ij}^{+}, are the conversion yields in technology j∈J for producing p∈P and byproduct b∈B, respectively; the conversion yields (conversion yield of input to output) are reported in Table 3.

$$X_{kp}=\sum_j X_{kj}\eta_{jp}^{+}\ \forall k\in K,\ p\in P \quad (14)$$

$$X_{kb}=\sum_j X_{kj}\eta_{bj}^{+}\ \forall b\in B,\ k\in K \quad (15)$$

1-2-2. Non-negative Constraints

The variables associated with the amount of compounds are required to be non-negative:

$$X_{kf}, X_{ki}, X_{kp}, X_{kj}\geq 0 \quad (16)$$

1-2-3. Integer-cuts Constraints

It is important to identify not only the optimal strategy but also the alternative strategies, because in practice, the optimal strategy cannot be occasionally implemented by external factors. For example, the shortage of the biomass is selected in the optimal strategy.

Alternative strategies can be identified by integer-cuts constraints, which are defined as new formulations with sequentially added constraints, including an integer variable related to the use of technologies. Eq. (17) activates the integer variable $Y_{kj}\in\{0, 1\}$, when technology j∈J is selected in the k^{th} iteration as the k^{th} alternative strategy; selected=1, otherwise=0.

$$X_{kj}\leq Y_{kj}U\ \forall j\in J,\ k\in K \quad (17)$$

where U is a large number.

The integer variable is then utilized in Eq. (18) to prohibit duplicate selection of a technology during iterations. Thus Eq. (18) identifies k^{th} alternative strategy by cutting off any strategies which are selected in previous iterations (iteration l=0, 1, …, k−1)

$$\sum_{j\in J^l} Y_{kj}\leq \sum_{j\in J^l} Y_{lj}-1\ \ l=0, 1, \ldots\ldots, k-1,\ \forall k\in K \quad (18)$$

where $Y_{lj}\in\{0, 1\}$, likewise Y_{kj}, is the integer variable related with the use of technology j∈J in the optimal strategy (iteration l=0) and previously identified alternatives (iteration l=1, …, k−1). Thus, J^l is the subset of J, and includes the technologies selected in iteration l as an element. For example, J^0 is the set which consists of the technologies selected in the optimal strategy (iteration l=0).

To identify the k^{th} alternative strategy, we first solve the model excluding the integer-cuts constraints to get the information of the selected technologies from the optimal strategy J^0. We then choose K and set k=1, and execute the model including integer-cuts constraints to find the next best strategy (iteration k=1). We define the subset of the technologies employed in the first alternative strategy J^1. If k<K, set k=k+1, the model is relaunched, including the integer-cuts constraints, and J^k is defined until k=K.

2. Extended Model for Strategy Integration

Based on the base model (Section 3.1), we developed a new optimization model capable of efficiently selecting and integrating the strategies to address practical issues of real world problems. For example, we may choose multiple biomass utilization strategies due to imbalance between energy supply and demand resulting from a lack of a specific biomass resource or limited capacity of a specific technology.

2-1. The Objective Function

The objective function is to minimize the total net cost TNC [$/yr], which includes total production cost TPC_s [$/yr] and total byproduct credit TBC_s [$/yr] of strategies s∈S.

$$\text{Min}\,TNC=\sum_s (TPC_s-TBC_s) \quad (20)$$

TPC_s consists of the facility establishment cost and the feedstock purchase cost.

$$TPC_s=\sum_{j\in J^s}\mu_j X_{sj}+\sum_{f\in F}\vartheta_f X_{sf}\ \forall s\in S \quad (21)$$

where X_{sf} [kg/yr] is the amount of feedstock f∈F, and X_{sj} [kg/yr] is the amount of compounds processed in technology $j\in J^s$ which is included in a strategy s∈S.

TBC_s is the additional credits obtained by selling byproducts, as follows:

$$TBC_s=\sum_b \vartheta_b X_{sb}\ \forall s\in S \quad (22)$$

where X_{sf} [kg/yr] is the amount of byproduct b∈B.

2-2. Constraints

2-2-1. The Availability of Biomass

Eq. (23) states that the sum of the amount of feedstock X_{sf} utilized in the strategies cannot exceed the biomass availability of feedstock α_f [kg/yr]; the data of α_f is mentioned above in section 2.1.

$$\sum_s X_{sf} \le \alpha_f \ \forall f \in F \quad (23)$$

2-2-2. Mass and Energy Balance

Eqs. (24)-(27) determine mass and energy balance on a strategy, working with the same mechanism of Eqs. (11)-(15).

$$X_{sf} = \sum_{j \in J^s} X_{sj} \eta_{fj}^- \ \forall f \in F, \ s \in S \quad (24)$$

$$\sum_{j \in J^s} X_{sj} \eta_{ij}^- = \sum_{j \in J^s} X_{sj} \eta_{ij}^+ \ \forall i \in I, \ s \in S \quad (25)$$

$$\sum_{j \in J^s} X_{sj} \eta_{bj}^+ = X_{sb} \forall b \in B, \ s \in S \quad (26)$$

$$\sum_{j \in J^s} X_{sj} \eta_{pj}^+ = X_{sp} \forall p \in P, \ s \in S \quad (27)$$

where X_{sp} is the amount of product $p \in P$ produced in a strategy $s \in S$.

2-2-3. Demand Satisfaction

The total amount of energy obtained from the produced products must be greater or equal to the energy demand.

$$\sum_{s \in S} \sum_{p \in P} \varepsilon_p X_{sp} \ge \delta \quad (28)$$

where ε_p is the energy content of product $p \in P$, and δ is the energy demand.

BIOMASS UTILIZATION STRATEGIES ON JEJU ISLAND

Our goal in this study was to identify a profitable and efficient way to develop the biomass-based energy supply system for feedstocks which are available on Jeju Island. To achieve this goal, we first applied the base model to identify the biomass utilization strategies and evaluate the economic performance of the strategies. Based on the results of the base model, we executed the extended model to establish integrated biomass utilization strategies for energy production on Jeju Island. The results from the extended model will be analyzed in Section 5. Both base and extended models are implemented in the General Algebraic Modeling System (GAMS) and solved using the MILP solver of CPLEX 12.4.0.1 [71].

1. Identification of the Optimal Strategies

First, we solved the Jeju Island problem using the base model to identify the most economical strategy. The resulting MILP problem consists of 39,123 and 174 continuous and discrete variables, and 39,230 constraints. The calculation time to solve the problem was less than three seconds using 4.10 GHz PC of 16 GB RAM. The results are in Fig. 4. The optimal strategy of the examined four cases (i.e., four different feedstock types) is identical: gasoline and diesel production as a final product through hydrocracking technology followed by the hydrotreating, pyrolysis, and drying technologies. The size of feedstocks was reduced by drying technology and then was fed to pyrolysis technology, which synthesized the bio-oil using dried biomass. The bio-oil was then purified in hydrotreating technology, and fed to hydrocracking technology to produce gasoline and diesel. We denoted the optimal strategy of the utilization of beanstalk, rape straw, hardwood and softwood by F1S1, F2S1, F3S1, and F4S1, respectively in Fig. 4.

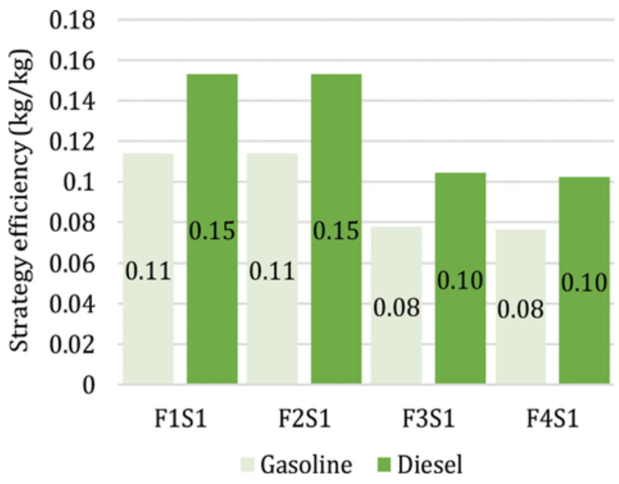

Fig. 5. The strategy efficiency of the optimal strategies.

Fig. 5 displays the *strategy efficiency*, which is one of factors that affect the total revenue and cost. The strategy efficiencies of the optimal strategies for utilization of the herbaceous species (*i.e.*, F1S1 and F2S1) are better than the woody species (*i.e.*, F3S1 and F4S1). The conversion yield of drying technology is the main factor accounting for the differences between the strategy efficiencies of the herbaceous species and woody species. The moisture content of the feedstock decreases the conversion yield of the drying technology. The moisture content before drying is 20% and 25% for the herbaceous and woody species, respectively. The conversion yield of the drying technology of the herbaceous and woody species is about 0.8 and 0.5, respectively.

Fig. 6 displays the revenue contribution of the liquid fuel which is mixed with gasoline (43%) and diesel (57%). The mixture ratio of the liquid fuel is identical within the optimal strategies, because the refined bio-oil from each feedstock is converged to gasoline and diesel by the hydrocracking technology using the same proportion. Thus, the difference between the revenues of the optimal strategies for utilizing herbaceous and woody species is largely affected by strategy efficiency. For that reason, the revenues of the optimal strategies for utilizing herbaceous species are more than woody species.

Fig. 7 shows the total production cost (TPC) per kg of the liq-

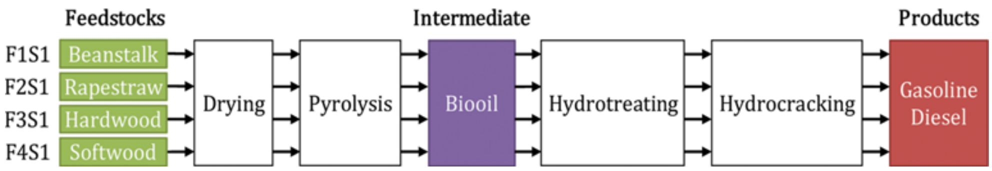

Fig. 4. The optimal strategy of four feedstocks on Jeju Island.

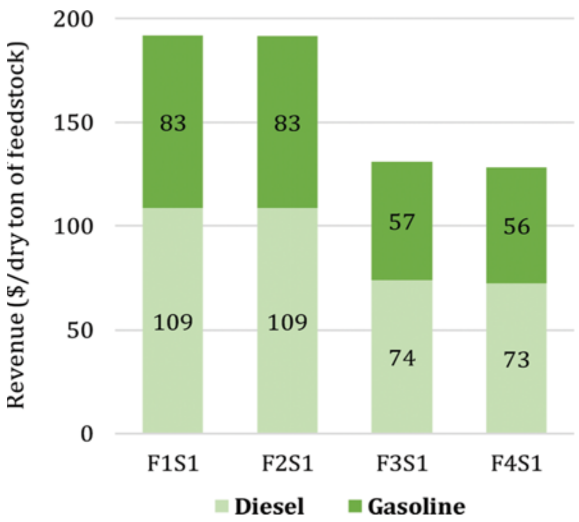

Fig. 6. The revenue contributions of the optimal strategies.

uid fuel of F1S1, F2S1, F3S1 and F4S1. We analyze the structure of TPC to identify the major cost driver in the optimal strategies. The resulting TPC per kg of liquid fuel of F1S1, F2S1, F3S1 and F4S1 are 1.07$/kg, 1.11$/kg, 1.03$/kg, and 1.16$/kg, respectively. The feedstock purchase cost (FC) is a major cost driver. Of all optimal strategies, it accounts for the largest fraction of TPC (57-62%). The market price of hardwood is the cheapest among the feedstocks, thus, the TPC of F3S1 is cheaper than any other optimal strategies. The remaining part of TPC is taken by *the total facility establishment cost (TTC)*, which consists of the costs for installing and operating technologies. The major cost driver among the technologies is the hydrocracking technology due to its operating cost, followed by hydrotreating, pyrolysis and drying technologies. In hydrocracking, a catalyst is needed to exhibit high conversion yield under mild temperature and pressure, and its cost is attributed to the expensive operating cost of the technology [63,65].

The conversion yield affects the facility's establishment cost (TC).

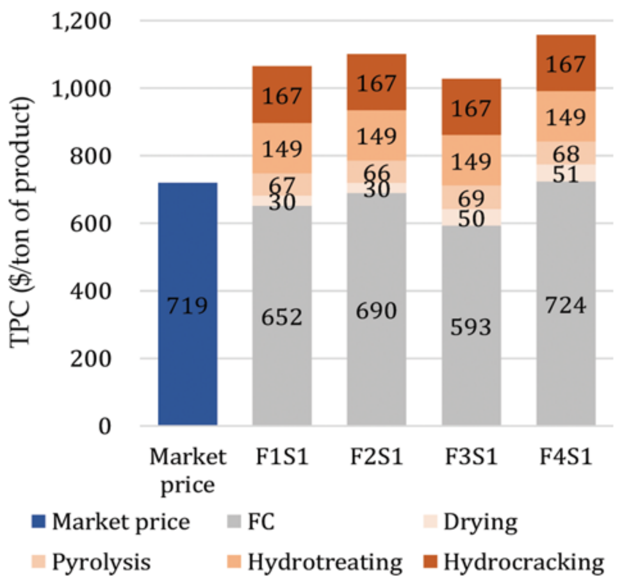

Fig. 7. The cost contribution and minimum selling price of the optimal strategies.

Having better conversion yield, the technology needs less input materials and TC to produce output materials. In the optimal strategies, each technology (except for drying technology) of one feedstock has the same UPC and conversion yield with the identical technology of other feedstock. The UPC of the feedstock's drying technology is almost the same; however, the conversion yields of the drying technology of the herbaceous species differ from that of the woody species. Thus, the difference between TCs of the drying technology of two species is a result of the difference between the conversion yields of drying technology of two species. Furthermore, the conversion yield of the *drying* technology has an impact on the feedstock cost, because the technology with the better conversion yield requires less feedstock to produce 1 kg of liquid-fuel.

The minimum selling price is equal to TPC per 1 kg of the liq-

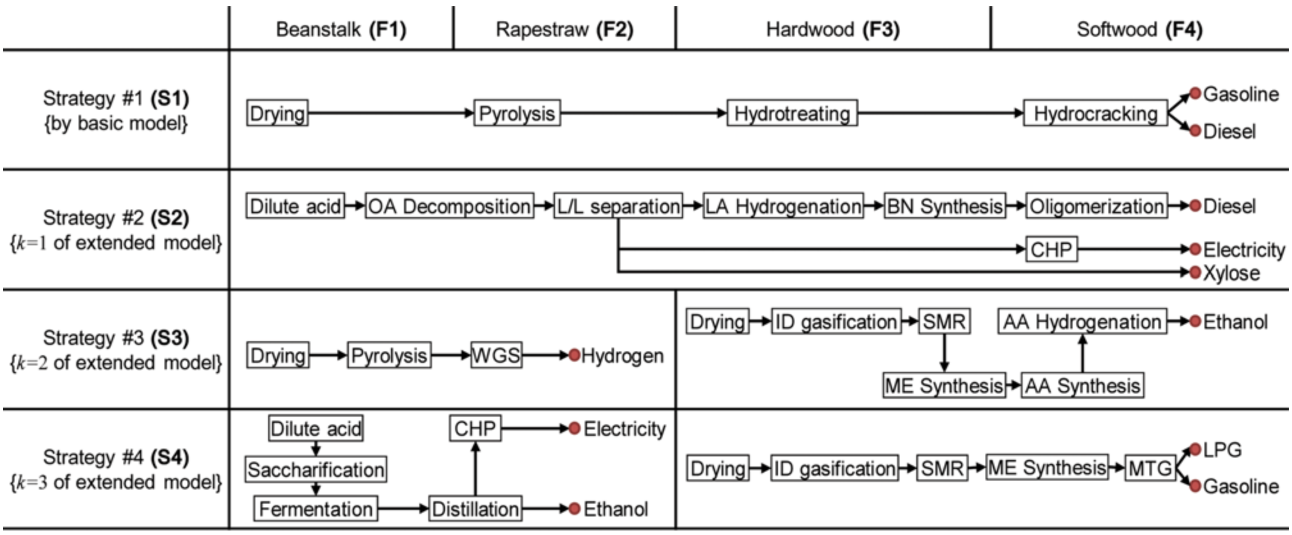

Fig. 8. Identification of the optimal and top-three alternative strategies of four feedstocks on Jeju Island.

uid fuels. Hardwood has the lowest minimum selling price (1.03 $/kg) among four feedstocks; however, the minimum selling price is higher than the market price of liquid fuel (0.72 $/kg), which is produced in conventional ways. To improve the price competitiveness of the optimal strategies, a lower market price of feedstocks is required for reducing the cost. Conversion yield needs to be enhanced by modifying the process system (e.g., cheaper catalyst) to reduce the operating cost.

2. Identification of the Alternative Strategies

2-1. Strategy Identification

We identified the top three alternative strategies of utilization of the four feedstocks using the extended model to analyze how changes in revenue and production cost affect the ranking of optimal and alternative strategies. Fig. 8 summarizes the sixteen solutions that include the processing routes and final products of the optimal and top-three alternative strategies of the four types of feedstock. For instance, we denoted the optimal strategy of beanstalk as F1S1, which signifies the first-place strategy of the first type of feedstock.

We observed that the optimal and second strategies for utilization of the herbaceous species are identical to the woody species. In the same species, like woody type biomass, the chemical compositions of biomass are similar to each other. Thus, the ranking of the strategies for utilization of one feedstock is identical to the other feedstock in the same species. As mentioned, all optimal strategies are the production of gasoline and diesel, and the specific features of the optimal strategies are explained in section 4.1. All second strategies are the production of diesel from organic acid through decomposing hydrolyzates. The organic acid is separated into levulinic acid, xylose, and residue by L-L separation. Levulinic acid is then converted into diesel, and the other intermediate residue is incinerated in CHP to produce electricity.

The third and fourth strategies for utilization of the herbaceous species differ from the woody species. The higher ash content of the feedstocks is the main cause for the lower conversion yield of the gasification technology. The ash content of the herbaceous species is much higher than the woody species. Thus, the gasification technology is not suitable for the herbaceous species [72]. In woody species, the third and fourth strategies are based on the indirect gasification technology followed by methanol synthesis. The third strategy (i.e., F3S3 and F4S3) is the production of ethanol from methanol, and the fourth strategy (i.e., F3S4 and F4S4) are the production of gasoline and LPG from methanol. In herbaceous species, the third strategies (i.e., F1S3 and F2S3) are based on the pyrolysis technology similar to the optimal strategies, and the difference between the third and optimal strategies is that the former are the production of hydrogen from bio-oil through the water-gas-shift technology. The fermentation-based strategy for ethanol production is the fourth strategy (F1S4 and F2S4).

2-2. Profit Contributions

The profit contribution of strategies is shown in Fig. 9, expressed as $/dry ton of feedstock. The profit contributions are categorized by FC, TTC, and revenue obtained from final products sales. In the strategies for utilization of one feedstock (e.g., F1S1, F1S2, F1S3, and F1S4), all strategies have the same FC because it is equal to the market price of feedstock; thus, the ranking of the optimal and alternative strategies is determined by conversion yield, UPC, and market price of final products. In the same species, the chemical compositions of feedstocks are similar to each other. TTC and the revenue of a strategy of one feedstock are similar to those of the one identical to the other feedstock. The profit of the equivalent strate-

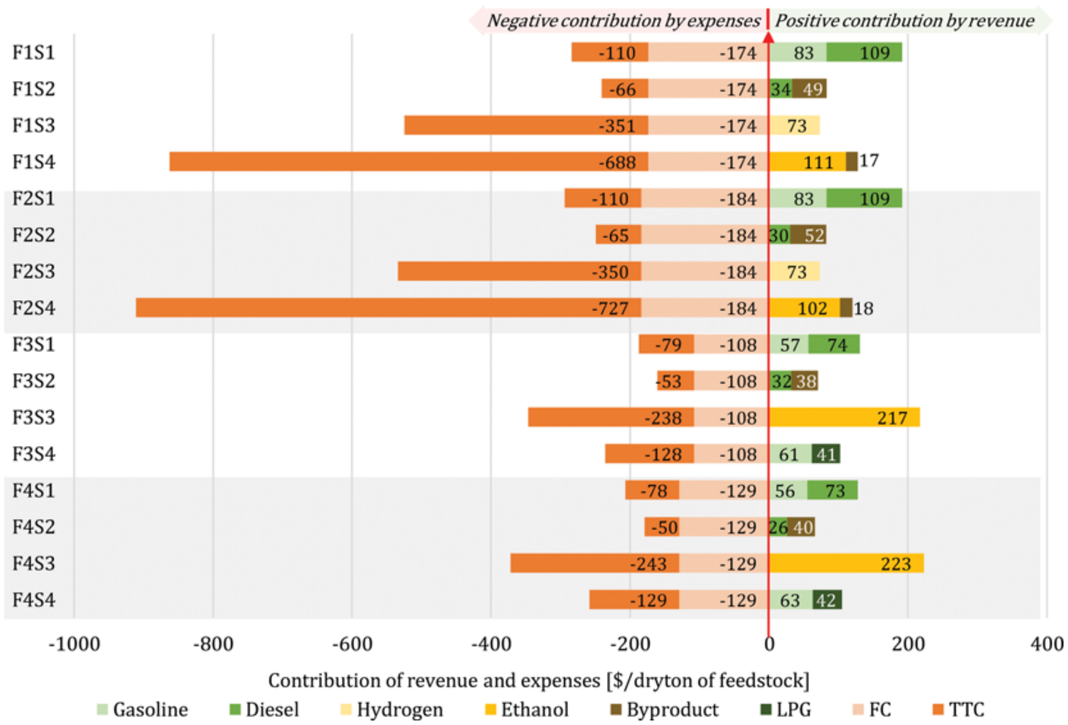

Fig. 9. Profit contributions of the strategies for utilization of the selected feedstocks.

gies (F1S3 and F2S3) is differentiated by the FC of the strategies.

First, we compared the optimal to top three alternative strategies to analyze the effects of changes in revenue and expenses (production cost) to the ranks of the strategies. Although the production cost in the second strategy of each feedstock is lower than the corresponding optimal strategy, profit is lower than the optimal strategy due to much lower revenue. For example, the strategy efficiency for the diesel of the optimal strategy shows 10-15% according to the feedstock type, but the efficiency of the second strategies remains at 5%. Furthermore, the credit from gasoline sales in the optimal strategy is significantly higher than that from electricity and xylose sales in the second strategy.

In the woody species, both TRs of the third and fourth strategies belonging to those that are indirectly gasification-based, are higher than the second strategy. Similarly, the TTCs of the third and fourth strategies are much higher than second strategy because the gasification technology on the third and fourth strategies requires a high capital cost for a pressurized gasifier. Furthermore, the ethanol production strategy based on the gasification strategy (F3S3 and F4S3) requires CO and H_2 for producing acetic acid and ethanol, respectively [73]; this leads to the increase in the operating cost of the third strategy. For that reason, the total production cost of third strategy is higher than any other strategies for the utilization of the woody species. However, the strategy efficiency for ethanol of the third strategy is about 34%, and those for gasoline and LPG of the fourth strategy are about 8% and 5%, respectively. The market price of ethanol is slightly lower than gasoline and LPG. Thus, together, gasoline and LPG production (F3S4 and F4S4) are the fourth strategy.

In the herbaceous species, the hydrogen production strategies (F1S3 and F2S3) have higher capital and operating costs than the second strategies (F1S2 and F2S2) due to water-gas-shift technology for bio-oil upgrading. The main causes of the production cost of the fourth strategies (F1S4 and F2S4) are the saccharification and fermentation technologies. Enzyme is utilized to synthesize ethanol and its cost leads to the higher production costs of the fourth strategies.

STRATEGY INTEGRATION FOR ENERGY SUPPLY

Based on the results of the base model in the previous section, we selectively included different types of final products, which are compatible with the current energy supply system on Jeju Island, such as gasoline, diesel, ethanol, and LPG, before the execution of the extended model. We then calculated the *levelized cost of energy* (LCOE) of the identified strategies by the extended model to analyze what combination of strategies can satisfy the demand of the final products cheaply and efficiently. The LCOE is an economic metric of the net cost to install and operate a facility of a strategy divided by the total produced energy, which can be used in the

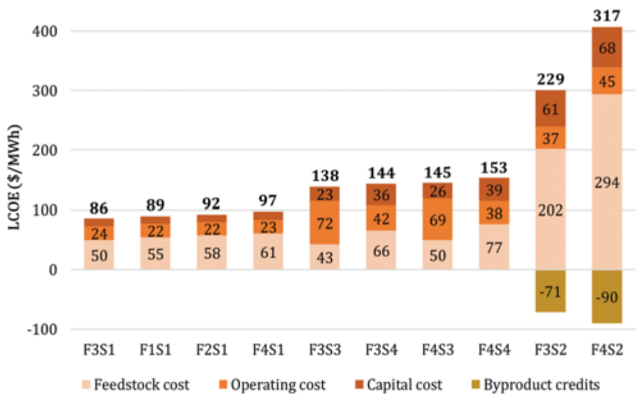

Fig. 10. Levelized cost of energy (LCOE) of the top-ranked strategies.

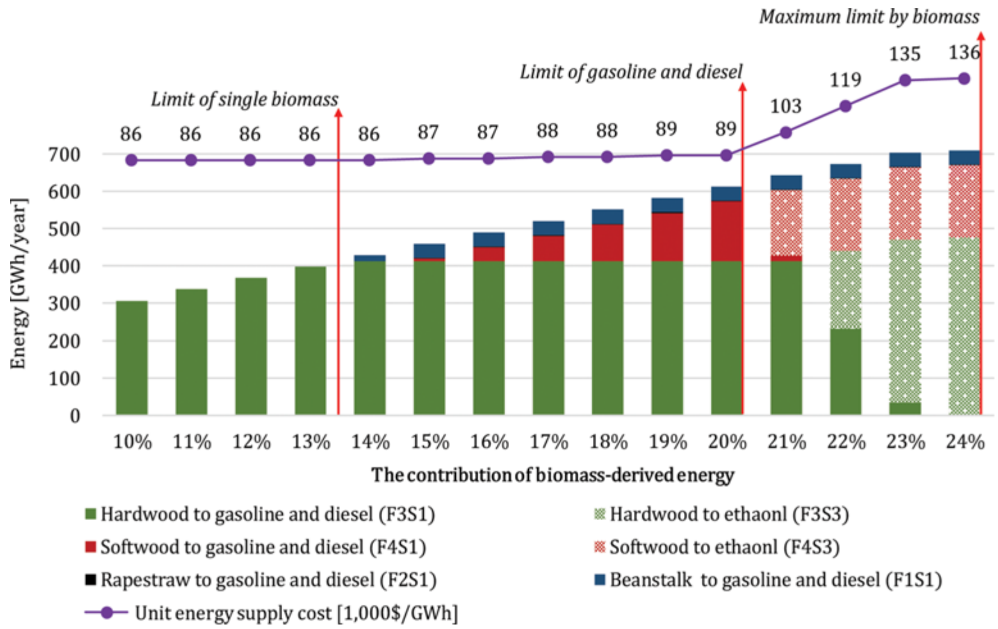

Fig. 11. Feasibility of biomass-derived energy to contribute to the demand of the transportation sector in 2011.

transportation sector. The net cost combines the FC, and capital and operating costs (CC and OC), which is reduced by any credit from byproducts sales. LCOE is calculated as follows:

$$\mathrm{LCOE} = \frac{\text{All exepenses} - \text{byproduct credits}}{\text{The total quantity of energy for transportation sector}} \quad (29)$$

Fig. 10 shows the top ten strategies from the viewpoint of LCOE on Jeju Island. First, all the optimal strategies of the four biomass feedstocks are ranked within the top four strategies in the order of F3, F1, F2, and F4. The optimal and alternative strategies that utilize the woody species, especially hardwood, produce energy more cheaply than the strategies utilizing the herbaceous species. The feedstock cost accounts for more than half of the LCOE, which are the top ten strategies, while the unit purchase cost of the woody species is relatively cheaper than the herbaceous species. This also revealed that the economics of the biomass utilization strategy in the transportation sector could be dramatically improved by the reduction of the feedstock cost.

Fig. 11 shows the selection and integration of strategies for supplying energy to meet the different energy demand of the transportation sector of Jeju Island. When all the biomass availability of Jeju Island is utilized for energy production, the energy from biomass can satisfy up to 24% (710 GWh/year) of the energy demand of the transportation sector. Biomass cannot contribute over 24% of the total demand, not because of the economics, but because of the shortage of the quantity of biomass availability.

The maximum quantity of energy that can be produced from a single biomass type is approximately 413 GWh/year (13.5% of the total energy demand of the transportation sector); the selected strategy (F3S1) utilizes hardwood as a resource and produces gasoline and diesel as products. Since the F3S1 strategy is the most economically viable, this strategy can remain as a main energy supply option still satisfying 20% of the energy demand (i.e., the point of *limit of gasoline and diesel* in Fig. 10). In the range of 14%-20%, the other feedstocks, in the order of rapestraw (F2S1) and softwood (F4S1), should be additionally utilized for higher contribution due to the shortage of hardwood.

To satisfy more than 20% of the energy demand from biomass utilization, the type of final product should be changed from gasoline and diesel to ethanol. The reason behind this is that we can supply more energy quantity when we produce ethanol instead of gasoline and diesel, although the strategy that produces gasoline and diesel has higher economics than the corresponding strategy to produce ethanol (c.f., F3S1 and F3S3). Thus, if we decide to produce the largest energy quantity regardless of the economics, 24% of the total energy demand can be contributed by the energy derived from biomass (i.e., the point of *maximum limit by biomass* in Fig. 11), which is made up of 94.4% ethanol, 3.2% diesel, and 2.4% gasoline.

Fig. 11 also shows that the unit energy supply cost is increased according to the quantity of energy produced. When one type of biomass is selected for energy production (e.g., till the point of *limit of single biomass* in Fig. 11), the energy can be supplied at the lowest cost of 86 $/MWh. To satisfy more than 13.5% (after the *limit of single biomass* point in Fig. 11), the UESC is increased by additionally adapting different strategies that utilize different feedstocks or produce different products. As mentioned, this is because in the economic analysis of the strategies, the first strategy is preferentially utilized and then the next strategies follow in order of the ranking. Afterwards, at the point of the commencement of ethanol production, the UESC is dramatically increased. Finally, when we produce the maximum amount of energy (i.e., 24% satisfaction, the last bar graph in Fig. 11), the unit supply production cost reaches up to 136 $/MWh, which is a 58% increase in the cost compared to the first strategy (F3S1).

CONCLUSIONS

We have proposed a new approach to economically assess the biomass utilization strategies for energy supply. We generated a superstructure which includes a number of compounds and technologies for energy production from biomass. We then developed two optimization models, a base model to identify optimal strategy along with alternatives for biomass utilization and to analyze the main cost drivers and contribution of the selected strategies; and an extended model to evaluate the feasibility of the biomass-driven energy supply system by integrating multiple strategy to meet energy demand. We then applied the developed models to the energy supply problem in the transportation sector of Jeju Island, Korea.

We identified that the optimal strategies of all types of feedstock include liquid fuels (i.e., gasoline and diesel) as the final product through thermochemical conversion technologies due to their highest cost-effectiveness; these are followed by the catalytic conversion strategies for the alkane-ranged liquid fuels production. Also, the strategies utilizing woody-species biomass show better economic decisions than herbaceous-species biomass due to the low ash proportion in woody species. Accordingly, this difference leads to a higher conversion efficiency to the final products of the selected strategies.

The strategy which utilizes hardwood for the gasoline and diesel production (F3S1) was identified as the best way with LCOE of 86 $/MWh, which can be an economically viable alternative to the current fossil fuels based energy system of the transportation sector. Note that, annually, hardwood biomass of the highest availability can account for 13.5% of the total energy demand of the transportation sector. In contrast, the contribution of the energy derived from biomass to the total demand can be increased up to 24% by adopting different strategies that produce large quantities of energy. Finally, we analyzed that different strategies can be established for the biomass utilization for energy production on Jeju Island, which ranges between the cheapest energy production (86 $/MWh; 413 GWh/year) and the largest energy production (136 $/MWh; 710 GWh/year).

This study provides a new methodology along with optimization models as a suite of tools for analyzing the feasibility and economics of biomass utilization strategies, and identifying the benefits from the integration of multiple strategies to meet the demand of the transportation sector on Jeju Island. Building upon this study, future research may focus on developing robust optimization models to deal with realistic problems, such as the inclusion of other evaluation metrics (e.g., life cycle analysis and sustainability), the operation of supply chain of biomass and fuels under governmental regulations and policies, as well as a consideration of energy market changes and the demand uncertainty.

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NOMENCLATURE

Sets

B : byproducts
F : feedstocks
I : intermediates
J : technologies
K : the number of iteration of the basic model
P : products
S : the strategies selected in the biomass-to-energy network

Subsets

J^k : the selected technologies of the k^{th} alternative strategy
J^s : the selected technologies of the strategy $s \in S$

Parameters

U : a large number
α_f : biomass availability of feedstock $f \in F$
δ : energy demand [kWh]
ε_p : energy content of product $p \in P$ [kWh/kg]
η^-_{fj} : coefficient of technology $j \in J$ consuming feedstock $f \in F$
η^+_{ij} : conversion yield of technology $j \in J$ producing intermediate $i \in I$
η^-_{ij} : coefficient of technology $j \in J$ consuming intermediate $i \in I$
η^+_{jp} : conversion yield of technology $j \in J$ producing product $p \in P$
η^+_{bj} : conversion yield of technology $j \in J$ producing byproduct $b \in B$
μ_j : unit production cost of technology $j \in J$ [\$/kg]
ϑ_f : market price of feedstock $f \in F$ [\$/kg]
ϑ_p : market price of product $p \in P$ [\$/kg]
ϑ_b : market price of byproduct $b \in B$ [\$/kg]

Continuous Variables

FC_k : total feedstock purchasing cost at iteration $k \in K$ [\$/yr]
TC_{kj} : facility establishment cost of technology $j \in J$ at iteration $k \in K$ [\$/yr]
TR_k : total revenue at iteration $k \in K$ [\$/yr]
TAP_k : total annual profit at iteration $k \in K$ [\$/yr]
TBC_s : total byproduct credit in strategy $s \in S$ [\$/yr]
TNC : total net cost [\$/yr]
TPC_k : total production cost at iteration $k \in K$ [\$/yr]
TPC_s : total production cost in the strategy $s \in S$ [\$/yr]
TTC_k : total facility establishment cost at iteration $k \in K$ [\$/yr]
X_{kb} : amount of byproduct $b \in B$ at iteration $k \in K$ [kg/hr]
X_{kf} : amount of feedstock $f \in F$ at iteration $k \in K$ [kg/hr]
X_{ki} : amount of intermediate $i \in I$ at iteration $k \in K$ [kg/hr]
X_{kj} : amount of compounds processed in technology $j \in J$ at iteration $k \in K$ [kg/hr]
X_{kp} : amount of product $p \in P$ at iteration $k \in K$ [kg/hr]
X_{sb} : amount of byproduct $b \in B$ in the strategy $s \in S$ [kg/hr]
X_{sf} : utilized amount of feedstock $f \in F$ in the strategy $s \in S$ [kg/hr]
X_{sj} : amount of compounds processed in technology $j \in J$ in the strategy $s \in S$ [kg/hr]
X_{sp} : amount of product $p \in P$ in the strategy $s \in S$ [kg/hr]

Binary Variables

Y_{kj} : 1 if the technology $j \in J$ is selected at iteration $k \in K$, 0 otherwise

REFERENCES

1. N. Sammons, M. Eden, W. Yuan, H. Cullinan and B. Aksoy, *Environ. Prog.*, **26**(4), 349 (2007).
2. I. Shin, G. Park, J. Lee, E. Kim and Y. Kim, *2014 IEEE Conference and Expo*, 1 (2014).
3. M. Han, Y. Kim, W. Cho, G. Choi and B. Chung, *Korean J. Chem. Eng.*, **33**(1), 223 (2016).
4. L. F. Gutiérrez, Ó J. Sánchez and C. A. Cardona, *Bioresour. Technol.*, **100**(3), 1227 (2009).
5. M. Wright and R. C. Brown, *Biofuel. Bioprod. Bior.*, **1**(3), 191 (2007).
6. J. H. Clark, *J. Chem. Technol. Biot.*, **82**(7), 603 (2007).
7. P. Parthasarathy and S. Narayanan, *Korean J. Chem. Eng.*, **32**(11), 2236 (2015).
8. A. Aden, M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton and J. Lucas, *NREL/LP-510-32438* (2002).
9. M. Brennan, D. Specca, B. Schilling, D. Tulloch, S. Paul, K. Sullivan, Z. Helsel, P. Hayes, J. Melillo and B. Simkins, *New Jersey Agr. Exp. Station Publ.*, **1** (2007).
10. H. R. Ghatak, *Renew. Sust. Energ. Rev.*, **15**(8), 4042 (2011).
11. D. J. Braden, C. A. Henao, J. Heltzel, C. C. Maravelias and J. A. Dumesic, *Green Chem.*, **13**(7), 1755 (2011).
12. S. Murat Sen, C. A. Henao, D. J. Braden, J. A. Dumesic and C. T. Maravelias, *Chem. Eng. Sci.*, **67**(1), 57 (2012).
13. S. A. Hosseini and N. Shah, *Interface Focus.*, **1**(2), 255 (2011).
14. C. Piccolo and F. Bezzo, *Biomass Bioenergy*, **33**(3), 478 (2009).
15. F. K. Kazi, J. Fortman, R. Anex, G. Kothandaraman, D. Hsu, A. Aden and A. Dutta, *NREL/TP-6A2-46588* (2010).
16. F. K. Kazi, J. A. Fortman, R. P. Anex, D. D. Hsu, A. Aden, A. Dutta and G. Kothandaraman, *Fuel*, **89, Supplement 1**, S20 (2010).
17. S. A. Hosseini, R. Lambert, S. Kucherenko and N. Shah, *Energy Fuels*, **24**(9), 4673 (2010).
18. S. Ngamprasertsith, S. Sunphorka, P. Kuchonthara, P. Reubroycharoen and R. Sawangkeaw, *Korean J. Chem. Eng.*, **32**(10), 2007 (2015).
19. R. P. Anex, A. Aden, F. K. Kazi, J. Fortman, R. M. Swanson, M. M. Wright, J. A. Satrio, R. C. Brown, D. E. Daugaard, A. Platon, G. Kothandaraman, D. D. Hsu and A. Dutta, *Fuel*, **89, Supplement 1**, S29 (2010).
20. T. R. Brown, M. M. Wright and R. C. Brown, *Biofuel. Bioprod. Bior.*, **5**(1), 54 (2011).

21. E. D. Larson, S. Consonni, R. E. Katofsky, K. Iisa and W. Frederick, *DE-FG26-04NT42260, Princeton Environmental Institute, Princeton University, Princeton, NJ*, **21** (2006).
22. V. Dornburg, A. P. C. Faaij and B. Meuleman, *Resour. Conserv. Recycling*, **49**(1), 68 (2006).
23. S. N. Naik, V. V. Goud, P. K. Rout and A. K. Dalai, *Renew. Sust. Energ. Rev.*, **14**(2), 578 (2010).
24. V. Chambost and P. R. Stuart, *Ind. Biotechnol.*, **3**(2), 112 (2007).
25. L. K. James, S. M. Swinton and K. D. Thelen, *Agron. J.*, **102**(2), 675 (2010).
26. Y. Kim, H. W. Lee, S. Lee, S. Kim, S. H. Park, J. Jeon, S. Kim and Y. Park, *Korean J. Chem. Eng.*, **28**(10), 2012 (2011).
27. J. W. Kim, S. Lee, S. Kim, S. H. Park, J. Jeon and Y. Park, *Korean J. Chem. Eng.*, **28**(9), 1867 (2011).
28. S.-I. Um, J. Jung, S. Choi, J. Won and J. Lee, *J. Energ. Clim. Change*, **5**(1), 155 (2010).
29. Y. Woo, S. Cho, J. Kim and B. S. Kim, *Int. J. Hydrogen Energy*, **41**(12), 5405 (2016).
30. A. C. Kokossis and A. Yang, *Comput. Chem. Eng.*, **34**(9), 1397 (2010).
31. J. E. Santibañez-Aguilar, J. B. González-Campos, J. M. Ponce-Ortega, M. Serna-González and M. M. El-Halwagi, *Ind. Eng. Chem. Res.*, **50**(14), 8558 (2011).
32. D. J. Garcia and F. You, *AIChE J.*, **61**(2), 530 (2015).
33. J. Kim, S. M. Sen and C. T. Maravelias, *Energy Environ. Sci.*, **6**(4), 1093 (2013).
34. S. Maronese, A. V. Ensinas, A. Mian, A. Lazzaretto and F. Maréchal, *Ind. Eng. Chem. Res.*, **54**(28), 7038 (2015).
35. S. Kim, W. Won and J. Kim, *Renew. Energy*, **97**(1), 177 (2016).
36. K. No, Y. Jeon, J. Yang, H. Cheon and S. Jeong, *Korea Livestock Economic Institute (KLEI/K10-06)* (2010).
37. J. Kook, S. Jeon, S. Park, H. You, J. Shin and S. Lee, *Appl. Chem. Eng.*, **26**, 178 (2015).
38. Y. C. Park, D. S. Kim, J. Huh and Y. G. Kim, *World Renewable Energy Congress (ISBN 978-91-7393-070-3)* (2011).
39. Y. Seo, Current MSW Management and Waste-to-Energy Status in the Republic of Korea, Columbia University, New York (2013).
40. J. Kook and S. Lee, *Appl. Chem. Eng.*, **26**(2), 178 (2015).
41. J. Bae, *Korean energy economic review (ISBN 978-89-5504-228-3)* (2009).
42. E.-J. Min and S. Kim, *Korean energy economic review (ISSN 1599-7057)*, **7**(1), 133 (2008).
43. L. Castillo and C. Dorao, *J. Nat. Gas. Sci. Eng.*, **2**(6), 302 (2010).
44. A. D. Patel, J. C. Serrano-Ruiz, J. A. Dumesic and R. P. Anex, *Chem. Eng. J.*, **160**(1), 311 (2010).
45. M. Lim, J. Bang and Y. Yoon, *Trans. Korean Hydrog. New Energy Soc.*, **17**(2), 218 (2006).
46. M. Sloan and R. Meyer, *ICF International, Inc., Propane Education & Research Council*: Washington, DC (2009).
47. M. Rushton, *CanBio Annual Conference* (2012).
48. T. J. Schwartz, A. R. van Heiningen and M. C. Wheeler, *Green Chem.*, **12**(8), 1353 (2010).
49. R. Chetty and K. Scott, *J. New. Mat. Electr. Sys. Journal*, **10**(3), 135 (2007).
50. D. Supple, *MIT Energy Club,* http://web.mit.edu/mit_energy (latest update 04.15.07) (2007).
51. U. Lassi, R. Keiski, K. Kordás and J. Mikkola, *Energy Research at the University of Oulu* (2009).
52. Wood Resources International LLC, North American Wood Fiber Review 06-11 (2011).
53. M. Ash, *United States Department of Agriculture (OCS-15c)* (2015).
54. Y. Lee, K. Kim, Y. Jang and K. Park, *RDA Interrobang*, **99** (2013).
55. B. Boundy, S. W. Diegel, L. Wright and S. C. Davis, *United States Department of Energy (ORNL/TM-2011/446)* (2011).
56. J. Yun, *Korea Institute of Industrial Technology (KITECH 06-14)* (2014).
57. M. Pfeffer, W. Wukovits, G. Beckmann and A. Friedl, *Appl. Therm. Eng.*, **27**(16), 2657 (2007).
58. E. Ahmetovic, M. Martín and I. E. Grossmann, *Ind. Eng. Chem. Res.*, **49**(17), 7972 (2010).
59. V. Dornburg and A. P. Faaij, *Resour. Conserv. Recycling*, **48**(3), 227 (2006).
60. B. O. Palsson, S. Fathi-Afshar, D. F. Rudd and E. N. Lightfoot, *Science*, **213**(4507), 513 (1981).
61. A. Jimenez and O. Chavez, *Chem. Eng. J.*, **37**(1), B1 (1988).
62. A. C. Dimian, *Comput. Aided Chem. Eng.*, **24**, 309 (2007).
63. D. R. Batsy, C. C. Solvason, N. E. Sammons, V. Chambost, D. L. Bilhartz, M. R. E. II, M. M. El-Halwagi and P. R. Stuart, *Integrated Biorefineries: Design, Analysis, and Optimization*, 1 (2012).
64. B. Kamm and M. Kamm, *Biorefineries–multi product processes*, Springer (2007).
65. L. R. Lynd and M. Q. Wang, *J. Ind. Ecol.*, **7**, 17 (2003).
66. S. Fernando, S. Adhikari, C. Chandrapal and N. Murali, *Energy Fuels*, **20**(4), 1727 (2006).
67. H. D. Hotel, V. Herndon, D. Beck, K. Boyack and M. Berman, *Sandia National Laboratories (SAND98-0643)* (1997).
68. R. M. Bright and A. H. Strømman, *J. Ind. Ecol.*, **13**(4), 514 (2009).
69. R. M. Bright, A. H. Strømman and T. R. Hawkins, *J. Ind. Ecol.*, **14**(3), 422 (2010).
70. F. Cherubini, G. Jungmeier, M. Wellisch, T. Willke, I. Skiadas, R. Van Ree and E. de Jong, *Biofuel. Bioprod. Bior.*, **3**(5), 534 (2009).
71. R. E. Rosenthal, *GAMS - A User's Guide*, Gams Development Corp. (2006).
72. R. Gonzalez, J. Daystar, M. Jett, T. Treasure, H. Jameel, R. Venditti and R. Phillips, *Fuel Process Technol.*, **94**(1), 113 (2012).
73. S. B. Jones, Y. Zhu and C. Valkenburg, *Richland, WA: Pacific Northwest National Laboratory (PNNL-18482)* (2009).

APPENDIX A. TECHNICAL AND ECONOMIC DATA OF THE SELECTED TECHNOLOGIES

Abbreviations

- *Technologies.* AFEX: ammonia fiber expansion based pretreatment, CHP: combined heat and power generation, D: direct, MTG: methanol to gasoline technology, ID: indirect, SMR: steam methane reforming, WGS: water-gas-shift, Deo: Decomposition, DA Pre: Dilute acid pretreatment, HW Pre: How water pretreatment, Ac Hy: Acidic hydrolysis, ESTER: Esterification, OLIGO: Oligomerization, BN Sy: Butane synthesis, FERM: Fermentation, DISTI: Distillation, LL Sep: L/L separation, PERV: Pervaporation, Hyd T: Hydrotreating, Hyd C: Hydrocracking
- *Compounds.* AA: acetic acid, BN: butane, FT: Fischer-Tropsch, LA: Levulinic acid, ME: methanol, OA: OrA, Hyd: Hydrolyzate,

OrA: Organic acids, LA: Levulinic acid, EL: Ethyl levulinate
- UPC: unit production cost ($/kg)

Table S1. Detailed data of the technologies

Name	In	Out	UPC	Yield
DA Pre	Beanstalk	Hyd_1	0.010	3.745
	Rapestraw	Hyd_2	0.010	3.743
	Hardwood	Hyd_3	0.008	3.610
	Softwood	Hyd_4	0.008	3.598
HW Pre	Beanstalk	Hyd_5	0.001	4.907
	Rape straw	Hyd_6	0.001	4.907
	Hardwood	Hyd_7	0.002	4.720
	Softwood	Hyd_8	0.002	4.767
AFEX	Beanstalk	Hyd_9	0.002	3.923
	Rapestraw	Hyd_10	0.002	3.923
	Hardwood	Hyd_11	0.002	3.923
	Softwood	Hyd_12	0.002	3.928
Drying	Beanstalk	Dried_1	0.008	0.802
	Rapestraw	Dried _2	0.008	0.802
	Hardwood	Dried _3	0.009	0.535
	Softwood	Dried _4	0.009	0.535
OA Dec	Hyd_1	OrA_1	0.00	0.132
	Hyd_2	OrA_2	0.00	0.132
	Hyd_3	OrA_3	0.00	0.138
	Hyd_4	OrA_4	0.00	0.135
SSF	Hyd_1	Sugar_1	0.014	1.031
	Hyd_2	Sugar_2	0.014	1.031
	Hyd_3	Sugar_3	0.016	0.945
	Hyd_4	Sugar_4	0.016	0.945
	Hyd_5	Sugar_5	0.012	1.028
	Hyd_6	Sugar_6	0.012	1.028
	Hyd_7	Sugar_7	0.012	1.110
	Hyd_8	Sugar_8	0.011	1.068
	Hyd_9	Sugar_9	0.014	1.031
	Hyd_10	Sugar_10	0.014	1.031
	Hyd_11	Sugar_11	0.012	1.042
	Hyd_12	Sugar_12	0.012	1.036
AC Hy	Hyd_1	Sugar_13	0.001	1.019
	Hyd_2	Sugar_14	0.001	1.019
	Hyd_5	Sugar_15	0.001	0.982
	Hyd_6	Sugar_16	0.001	0.982
	Hyd_9	Sugar_17	0.001	0.982
	Hyd_10	Sugar_18	0.001	0.982
Pyrolysis	Dried _1	Biooil	0.022	0.754
	Dried _2	Biooil	0.022	0.753
	Dried _3	Biooil	0.023	0.771
	Dried _4	Biooil	0.023	0.755
D Gas	Dried _3	Syngas1	0.029	1.155 9
	Dried _4	Syngas2	0.029	1.188
ID Gas	Dried _3	Syngas3	0.020	0.843
	Dried _4	Syngas4	0.019	0.864
LL Sep	OrA_1	LA	0.023	0.523

Table S1. Continued

Name	In	Out	UPC	Yield
		Xylose		0.311
		Residue		0.529
	OrA_2	LA	0.025	0.473
		Xylose		0.326
		Residue		0.559
	OrA_3	LA	0.016	0.570
		Xylose		0.217
		Residue		0.501
	OrA_4	LA	0.020	0.477
		Xylose		0.178
		Residue		0.556
ESTER	LA	EL	0.071	0.791
LA Hy	LA	GVL	0.097	0.338
BN Sy	GVL	Butene	0.103	0.415
OLIGO	Butene	Alkene	0.009	0.565
FERM	Sugar_1	Broth1	0.014	1.031
	Sugar_2	Broth2	0.014	1.031
	Sugar_3	Broth3	0.016	0.945
	Sugar_4	Broth4	0.016	0.945
	Sugar_5	Broth5	0.012	1.028
	Sugar_6	Broth6	0.012	1.028
	Sugar_7	Broth7	0.012	1.110
	Sugar_8	Broth8	0.011	1.068
	Sugar_9	Broth9	0.014	1.031
	Sugar_10	Broth10	0.014	1.031
	Sugar_11	Broth11	0.012	1.042
	Sugar_12	Broth12	0.012	1.036
	Sugar_13	Broth13	0.001	1.019
	Sugar_14	Broth14	0.001	1.019
	Sugar_15	Broth15	0.001	0.982
	Sugar_16	Broth16	0.001	0.982
	Sugar_17	Broth17	0.001	0.982
	Sugar_18	Broth18	0.001	0.982
DISTI	Broth1	Ethanol	0.154	0.044
		Residue1		0.108
	Broth2	Ethanol	0.164	0.041
		Residue1		0.112
	Broth3	Ethanol	0.130	0.043
		Residue1		0.090
	Broth4	Ethanol	0.157	0.038
		Residue1		0.095
	Broth5	Ethanol	0.185	0.025
		Residue2		0.109
	Broth6	Ethanol	0.200	0.023
		Residue2		0.111
	Broth7	Ethanol	0.206	0.018
		Residue2		0.082
	Broth8	Ethanol	0.148	0.021
		Residue2		0.081
DISTI	Broth9	Ethanol	0.150	0.037
		Residue3		0.133

Table S1. Continued

Name	In	Out	UPC	Yield
	Broth10	Ethanol	0.162	0.034
		Residue3		0.136
	Broth11	Ethanol	0.167	0.028
		Residue3		0.102
	Broth12	Ethanol	0.121	0.032
		Residue3		0.099
	Broth13	Ethanol	0.297	0.028
		Residue4		0.258
	Broth14	Ethanol	0.317	0.026
		Residue4		0.261
	Broth15	Ethanol	0.329	0.017
		Residue5		0.215
	Broth16	Ethanol	0.356	0.015
		Residue5		0.217
	Broth17	Ethanol	0.290	0.024
		Residue6		0.261
	Broth18	Ethanol	0.313	0.022
		Residue6		0.263
PERV	Broth1	Ethanol	0.224	0.045
		Residue7		0.106
	Broth2	Ethanol	0.240	0.041
		Residue7		0.110
	Broth3	Ethanol	0.204	0.050
		Residue7		0.101
	Broth4	Ethanol	0.227	0.044
		Residue7		0.107
	Broth5	Ethanol	0.263	0.025
		Residue8		0.108
	Broth6	Ethanol	0.240	0.041
		Residue8		0.110
	Broth7	Ethanol	0.293	0.025
		Residue8		0.108
	Broth8	Ethanol	0.237	0.028
		Residue8		0.105
	Broth9	Ethanol	0.224	0.037
		Residue9		0.131
	Broth10	Ethanol	0.242	0.034
		Residue9		0.134
	Broth11	Ethanol	0.229	0.036
		Residue9		0.132
	Broth12	Ethanol	0.202	0.042
		Residue9		0.127
	Broth13	Ethanol	0.378	0.028
		Residue10		0.254
	Broth14	Ethanol	0.404	0.025
		Residue10		0.256
	Broth15	Ethanol	0.428	0.017
		Residue10		0.212
	Broth16	Ethanol	0.463	0.016
		Residue11		0.213
	Broth17	Ethanol	0.375	0.024

Table S1. Continued

Name	In	Out	UPC	Yield
		Residue12		0.257
	Broth18	Ethanol	0.405	0.022
		Residue12		0.259
SMR	Syngas1	Syngas	0.048	0.543
	Syngas2	Syngas	0.047	0.543
	Syngas3	Syngas	0.069	0.631
	Syngas4	Syngas	0.067	0.631
ME Sy	Syngas	Methanol	0.036	0.862
FT Sy	Syngas	Gasoline	0.457	0.133
		Diesel		0.110
BA Sy	Syngas	Alcohols	0.812	0.555
AA Sy	AA	Ethanol	0.255	0.764
MTG	Methanol	Gasoline	0.246	0.323
		LPG		0.176
WGS	Biooil	H_2	0.537	0.058
Hyd T	Biooil	Rawoil	0.107	0.458
Hyd C	Rawoil	Gasoline	0.160	0.411
		Diesel		0.552
CHP	Residue1	Elec.	0.077	0.544
	Residue2	Elec.	0.094	0.397
	Residue3	Elec.	0.077	0.470
	Residue4	Elec.	0.065	0.334
	Residue5	Elec.	0.083	0.250
	Residue6	Elec.	0.074	0.289
	Residue7	Elec.	0.066	0.643
	Residue8	Elec.	0.069	0.471
	Residue9	Elec.	0.059	0.561
	Residue10	Elec.	0.048	0.388
	Residue11	Elec.	0.061	0.296
	Residue12	Elec.	0.054	0.342