ABSTRACT

LIAO, MOCHEN. Evaluating the Variability of Energy Consumption and Carbon Footprints of Activated Carbon Production Using Machine Learning Integrated Process Simulation. (Under the direction of Dr. Yuan Yao).

Understanding the environmental implications of activated carbon (AC) produced from diverse biomass feedstocks is critical for biomass screening and process optimization for sustainability. Many studies have developed Life Cycle Assessment (LCA) for biomass-derived AC. However, most of them either focused on individual biomass species with differing process conditions or compared multiple biomass feedstocks without investigating the impacts of feedstocks and process variations. Developing LCA for AC from diverse biomass is time-consuming and challenging due to the lack of process data (e.g., energy and mass balance). This study addresses these knowledge gaps by developing a modeling framework that integrates artificial neural network (ANN), a machine learning approach, and kinetic-based process simulation. The integrated framework is able to generate Life Cycle Inventory data of AC produced from 73 different types of woody biomass with 250 characterization data samples. The results show large variations in energy consumption and GHG emissions across different biomass species (43.4-277 MJ/kg AC and 3.96-22.0 kg CO_2-eq./kg AC). The sensitivity analysis indicates that biomass composition (e.g., hydrogen and oxygen content) and process operational conditions (e.g., activation temperature) have large impacts on energy consumption and GHG emissions associated with AC production.

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Evaluating the Variability of Energy Consumption and Carbon Footprints of Activated Carbon Production Using Machine Learning Integrated Process Simulation

by
Mochen Liao

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APPROVED BY:

Yuan Yao
Committee Chair

Stephen S Kelley

Sunkyu Park

BIOGRAPHY

Mochen Liao was born in the Hunan province of China. He was educated in Hunan province prior to the university. In 2013, he went to Guangzhou for his undergraduate and received a B.S. in Applied Chemistry from the South China University of Technology in 2017.

Mochen Liao has developed multiple academic interests since his undergraduate. Besides the Applied Chemistry major, he took a minor in Computer Science & Technology. He also proposed/took part in some research projects relevant to the biomass valorization and molecular simulation. These projects were funded by the National Undergraduate Training Program for Innovation and Entrepreneurship, and they were highly praised after finished. Mochen Liao won the scholarships awarded by the university in 2014 and 2015 based on his excellent academic performance. In 2016, Mochen Liao also participated in a summer research program at the University of California, Riverside.

From Fall 2017, Mochen Liao became a graduate research assistant in Dr. Yuan Yao's research group in the Department of Forest Biomaterials at North Carolina State University in Raleigh, NC. Mochen Liao has developed a machine learning-based framework to evaluate the energy consumption and greenhouse gas emissions of activated carbon production using diverse biomass species. The results of his research were presented in several conferences, including ACLCA 2018, ISSST 2019 and AIChE 2019 annual conference. After graduation, Mochen Liao will start his Ph.D. study at the School of Environment, Yale University, under the supervision of Dr. Yuan Yao.

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CHAPTER 1

LITERATURE REVIEW

Introduction

Activated carbon (AC) is a carbonaceous material with high porosity, absorptivity and surface reactivity, and has value-added applications in water purification, industrial processes, and flue gas cleanup.[1,2] AC also has many emerging applications such as functional materials used for electrode, catalyst, and carbon capture.[3] The worldwide consumption of AC was 12.8 million metric tons in 2015,[4] and the annual growth rate of AC market was projected as 6.31% from 2019 to 2024[5]. AC can be produced from diverse carbonaceous sources such as coal (the main current source of commercial AC) and biomass (e.g. agricultural waste, wood, and herbaceous plants).[3,6] Given a large number of potential feedstocks for AC production and rapid growth of AC demand, it is critical to understand the environmental implications of producing AC from alternative biomass feedstocks, especially given that AC production is one of the largest contributors to the overall environmental impacts of relevant technologies such as wastewater treatment based on previous Life Cycle Assessment (LCA) studies.[7–10] This understanding will enable more informed decision-making related to biomass selection, technology investment, process design, and optimization.

Many LCA studies evaluated the environmental implications of AC produced from diverse sources. A comprehensive literature review of previous studies is provided in the following section. The review indicates large variations in the environmental burdens associated with AC production from different biomass feedstocks (see Table 1.1). Given that most previous studies focused on a specific biomass feedstock, it is difficult to apply their results for other biomass feedstocks or make generic comparisons.[11–13] Developing LCAs for AC produced from a variety of biomass is challenging due to the lack of Life Cycle Inventory (LCI) data. Rapid and reliable estimation of LCI data for AC produced from diverse biomass sources is essential to screen different types of biomass feedstock and support early-stage technology development and process design for sustainable AC production. It also significantly reduces the time and efforts needed for the gate-to-gate LCI data collection for manufacturing processes that is usually the most time-consuming phase for LCA.[14] A few previous studies have investigated different approaches for the rapid generation of LCI data of production processes. For example, Parvatker and Eckelman[15] reviewed different methods that have been used for LCI estimation, such as process simulation tools[16,17], process design calculations[18,19], stoichiometry, proxy method[20], molecular structure-based models[21], hybrid LCI[22,23]. Other studies have used other process simulation in conjunction with other techniques such as dynamic model[24], kinetic model[25], network approaches[26] and knowledge-based models[27]. Applying previous approaches to estimate LCI for AC produced from diverse biomass feedstocks is challenging due to the lack of quantitative understandings of the relationships between LCI and large variations in biomass compositions and process operations, which are further discussed in the following two paragraphs. A few studies have tried to use machine learning (ML), a technique that does not rely on pre-known knowledge, to directly generate LCI data[21] or environmental impacts[28–30]. However, these applications of ML techniques are limited to commercialized chemicals/products with abundant LCI data. Thus it is challenging to apply ML alone to AC production that lacks LCI data for different biomass feedstocks.

Previous studies indicate that energy consumptions and GHG emissions are mainly driven by the AC production stage that usually has large variations due to differences in the types and composition of biomass, process operational conditions, and sources of energy.[9,13] A few studies have tried to explore such variations by investigating AC production scenarios by varying process parameters. For example, Sepúlveda-Cervantes et al. conducted a gate-to-gate LCA of soybean shell-based AC production using zinc chloride activation.[31] By varying the operational conditions (i.e., activation temperature, time and impregnation ratio), the electricity consumption of AC production changed from 17 to 50 MJ/kg AC, and the GHG emissions varied between 5.86 to 47.2 kg CO_2-eq./kg AC.[31] Arena et al. analyzed the impacts of different energy sources on the environmental footprints of coconut shell AC, which showed a significant reduction of most environmental impact categories (60-80%) by using electricity from renewable sources.[12] For feedstock variations, most studies[13,32,33] developed LCA for individual biomass with a limited set of operational conditions then made a comparative analysis. To the best of the authors' knowledge, none of the previous studies have correlated LCA results with parameters related to biomass characteristics and process operations. Thus, it is challenging to use previously developed LCA models to obtain quantitative understandings of the impacts of feedstocks and process variations or screen biomass and perform process optimization for AC production from an environmental perspective.

One additional, and significant, liability of many studies is that they have assumed a fixed composition for the gas and vapor product generated by the activation process[11,12,31], whose accuracy cannot be ensured in the scenarios with varying feedstocks and operating conditions. The composition of these gas and vapor can have a significant effect on LCI.[11,12,31] The composition of gases and vapors will vary depending on both the composition of the starting biomass and operational conditions.[31,34]

To address the gaps discussed above, this study integrated kinetic-based process simulation and artificial neural network (ANN), a machine learning approach, to estimate environmental footprints of AC produced from a variety of biomass feedstocks. Specifically, primary energy consumption and GHG emissions of AC production, two most commonly used indicators in previous LCAs for AC production[11–13], were parameterized by process models that used large datasets collected from literature (e.g., ultimate analysis of biomass, in total 250 data samples) and predicted by ANN (e.g., total AC yield). As the focus is to demonstrate the functionality of the integrated framework in generating the LCI data for AC produced from different biomass, the system boundary of this work is gate-to-gate. This system boundary is also consistent with most of the previous LCAs of AC.[9,10,38–42,11,12,31–33,35–37] The influences of biomass feedstock characteristics were investigated by correlating the feedstock compositions with energy consumption and GHG emissions.

This study can be used for screening a diverse array of biomass feedstocks useful for AC production, enhancing options for feedstock selection, process design, and process optimization. Although this work focuses on AC production, the integration of ANN and kinetic-based based simulation can be applied to other production systems to generate LCI data for rapid LCA analysis, especially those LCAs for emerging technologies whose LCI data is not available. These combined models will allow future research and production on biomass-based AC to clearly understand the environmental sustainability implications of their process choices. Furthermore, the sensitivity analysis was constructed to identify the key biomass properties and operational parameters driving the energy and GHG emissions.

Life Cycle Assessment of Activated Carbon Production

Previous studies have estimated the energy consumption and Global Warming Potential (GWP) of activated carbon (AC) produced from different feedstock and technological routes as shown in Table 1.1. All these data were normalized to the functional unit as 1 kg of AC product.

Since different energy sources are provided by different studies, the energy consumption from electricity is converted to primary energy consumption using the assumed efficiency of 32.9%.[43]

Table 1.1 Primary energy consumption (PEC) and global warming potential (GWP) of activated carbon production (Functional Unit: 1 kg of AC)

Ref.	System Boundaries	Feedstock	Activating Agent	PEC (MJ/kg)	GWP (kg CO_2-eq./kg)
[35]	Activation	Coal	Steam	30.71[a]	5.321
	Gate-to-gate	Coal	Steam	-	11.00
[36]	Gate-to-gate	Coal	Steam	196.2[a]	-
[9]	Gate-to-gate	Coal	Steam	-	8.292
[37]	Gate-to-gate	Coal	Steam	-	8.410
[10]	Gate-to-gate	Coal	Steam	-	9.423
[32]	Gate-to-gate	Coal	Steam	-	9.620
	Gate-to-gate	Wood	Steam	-	1.790
[11]	Drying	Olive Waste	H_3PO_4	47.47	2.777
	Pyrolysis	Olive Waste	H_3PO_4	43.67	3.388
	Impregnation	Olive Waste	H_3PO_4	52.15	3.317
	Gate-to-gate	Olive Waste	H_3PO_4	167.6	11.10
[12]	Gate-to-gate	Coconut shell	Steam	10.40-11.80[b]	0.8752-1.000
[31]	Drying	Soybean shell	$ZnCl_2$	0.3900[a]	-
	Pyrolysis	Soybean shell	$ZnCl_2$	7.560-10.25[a]	-
	Impregnation	Soybean shell	$ZnCl_2$	43.16-143.8[a]	-
	Gate-to-gate	Soybean shell	$ZnCl_2$	51.68-152.0[a]	5.860-47.15
[33]	Chipping	Wood waste	Steam	2.168	0.003246
	Drying	Wood waste	Steam	1.252[a]	0.05661
	Pyrolysis	Wood waste	Steam	7.613	0.01136
	Activation	Wood waste	Steam	2.271[a]	0.01652
	Gate-to-gate	Wood waste	Steam	13.30[a]	0.08814
	Gate-to-gate	Coconut shell	Steam	-	1.150
[38]	Chipping	Poplar	Steam	0.2564	-
	Drying	Poplar	Steam	11.36	1.564
	Pyrolysis	Poplar	Steam	1.325	0.1821
	Activation	Poplar	Steam	0.7791	0.1092
	Gate-to-gate	Poplar	Steam	13.72	1.853
[13]	Activation	Wood chip	Steam	106.4[a]	-
	Activation	Wood chip	Steam	73.50[c]	-
	Activation	Coal	Steam	141.9[a]	8.520
	Cradle-to-gate	Wood chip	Steam	158.3	8.600
	Cradle-to-gate	Coal	Steam	241.6	18.28
[39]	Pyrolysis	Hazelnut shell	Steam	23.18[d]	-
	Activation	Hazelnut shell	Steam	20.00[d]	-

Table 1.1 (Continued)

44	Pyrolysis	Coconut shell	Steam	85.64	-
	Activation[e]	Coconut shell	Steam	-7.821	-
41	Drying	Corn stover	Steam	5.950	-
	Pyrolysis[f]	Corn stover	Steam	18.45	-
	Activation	Corn stover	Steam	11.90	-
42	Gate-to-gate	Eucalyptus wood	$ZnCl_2$	118.6	8.581
	Gate-to-gate	Eucalyptus wood	H_3PO_4	153.8	5.575

[a] Assume the electricity is purchased from the grid and the grid average energy efficiency is 32.9%[43]
[b] The study assumed that flue gas is fully combusted to compensate the energy use
[c] Activation in an upscaled reactor with a capacity of 33.3 kg biochar per hour, the result fixed the yield from the LCI of the present study[13]
[d] The theoretical energy consumptions presented by the author are considered and normalized to the functional unit
[e] The activation step was mixed with some oxygen to achieve partial oxidation
[f] The carbonization step applied fast pyrolysis

Bayer et al. completed the first life cycle assessment (LCA) study of AC production from coal in 2005.[35] Steam activation was implemented to convert hard coal to granular activated carbon (GAC). In this study, 3 metric tons of hard coal and 1,600 kWh were needed to produce 1 ton of GAC. In addition, 330 m^3 of natural gas was combusted to provide 12 tons of steam as the activating agent for 1 ton GAC. The cradle-to-gate GWP of GAC production in this study was 11.0 kg CO_2 eq./kg AC.[35] However, if the GAC can be recycled and used as the feedstock of GAC production, the GWP of the process was reduced to 1.17 kg CO_2 eq./kg AC.[35]

Many studies then have developed LCA models for coal-based AC based on the process data by Bayer et al.[35] In these studies, the GWP of coal-based AC varied between 8.29-9.62 kg CO_2 eq./kg AC.[9,10,32,37] Manda et al. made a comparison between the coal-based GAC and wood-based GAC using the data from Azargohar.[45] The normalized results showed a significant reduction (81.4%) of GWP by changing the feedstock from coal to wood.[32]

A few studies have developed LCA models for AC from biomass. Hjaila et al. developed an LCA model for AC produced from olive waste cake using phosphoric acid as the activation agent.[11]

In this study, the system boundary is gate-to-gate, including all processes from the acquisition of olive waste cake to the production of AC.[11] The LCI was developed based on the experimental data and the results were compared to coal-based AC.[11] Arena et al. constructed the LCA of coconut shell based AC production via steam activation with a similar system boundary as Hjaila et al. Different scenarios were developed to compare different energy sources, coconut shell applications and different byproduct disposal strategies.[11,12] In this study, the life cycle inventory (LCI) data was developed based on the literature data.[12,46] The study highlighted the potential of low-carbon electricity energy sources and environmental management methods in reducing the environmental impact of AC production.[12]

Some researchers have tried to generate detailed process data using experimental studies. Sepúlveda-Cervantes et al. developed an LCA for AC from soybean shell using zinc chloride activation, and the LCI data were developed based on the lab-scale experiments. The experiments and optimal operational conditions for high AC yields were determined by response surface methodology (RSM).[31] A similar approach was used in another study for AC from corn pericarp by potassium hydroxide activation.[34] The brew waste-based AC produced by sulfuric acid activation is also studied by the lab-scale experiments and LCA.[47] In this study, it is concluded that the impact of AC disposal is ignorable and the impact of untreated brew waste disposal is significant.[47] Gu et al. used steam to activate wood chip derived biochar in a pilot-scale test calciner (1.54 or 1.13 kg/h biochar precursor) and an upscaled commercial calciner (33.6 kg biochar precursor).[13] The cradle-to-gate LCA results demonstrate that the cumulative energy demand (CED) and GWP of wood chip-based AC production are 158.33 MJ/kg AC product and 8.60 kg CO_2 eq,/kg AC product, respectively.[13] The CED and GWP were higher for AC from hard coal.[13] A similar process was established by Kim et al. with a larger scale (4 tons a day).[33] In this study, the steam AC production from wood waste showed lower energy consumption and environmental impact compared with previous LCA studies.[12,13,33]

Some studies have used simulations and/or experiments to quantify the energy consumption of AC production. Hung simulated the AC production using coconut shell and steam activation processes by ChemCAD for an industrial-scale fluidized bed reactor (14.5 tons a day).[44] Since the steam activation was implemented with high-pressure, the activation in the fluidized bed reactor was exothermic rather than endothermic.[44] Another study simulated an industrial scale steam AC production using corn stover feedstock and fast pyrolysis.[41] Sharifan used a lab-scale experiment to investigate the energy consumption of steam AC production from hazelnut shell.[39]

Table 1.1 shows large variations for both primary energy consumption and GWP of AC production. These variations could be caused by different system boundaries, feedstock, and technologies (e,g., activation agent as shown in Table 1.1). Note that a few studies estimated energy consumption based on theoretical energy demand without considering the energy efficiency of energy end uses such as boilers.[39] In this study, the energy and mass balance was simulated in Aspen Plus based on the input variables collected either from literature or ANN models. The energy efficiency of different energy end uses was considered. The energy efficiency of reactor was assumed to be 90%, the efficiency of boiler was assumed to be 82%.[48,49]

CHAPTER 2

MATERIALS AND METHODS

This study focuses on steam activation, a common technology for AC production.[3] The steam AC production process consists of two steps. In the first step, dried biomass is treated at high temperature (400-850℃) and inert atmosphere in a slow pyrolysis process that produces solid biochar, syngas and condensable bio-oil.[2] In the second step, the biochar is placed in a high-temperature reactor without air, and superheated steam is injected to activate the biochar. A series of complex chemical reactions are involved in both steps, and it is challenging to directly determine the yields and composition of the products of each step. Yet the yield and composition of the gases and vapors are required to estimate the energy consumption and GHG emissions of AC production.[50] To address this challenge, previous studies used either experiments or literature data for specific feedstocks with a limited set of activation conditions.[12,13,33,38,44] However, such data cannot be accurately extended to a broad array of different feedstocks. Although some recent studies tried to use ANN models to predict the LCI data or LCIA (life cycle impact assessment) results[21,28–30], it is very challenging to use ANN alone to estimate the environmental burdens of AC production that does not have sufficient data samples for different biomass feedstocks and process operation conditions. This work addressed this challenge by first using kinetic-based process models to estimate pyrolysis yield and gas composition, and then using trained ANN models to predict the activation yield, and Aspen Plus process simulation to generate gate-to-gate LCI data such as energy consumption and air emissions (see details in Figure 2.1).[51,52]

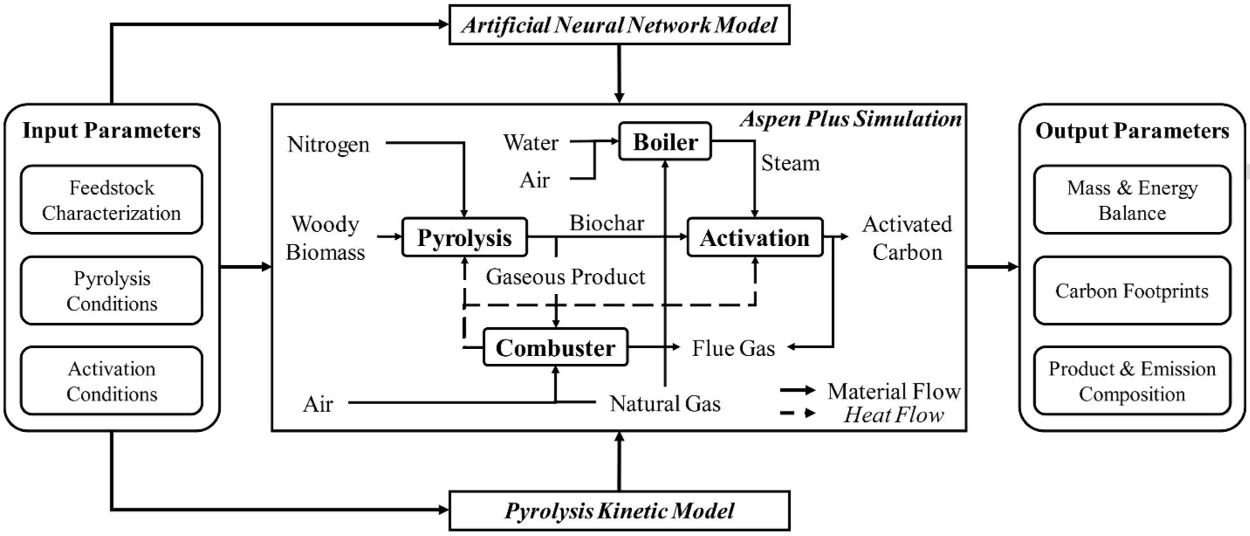


Figure 2.1 A schematic diagram of the integrated modeling framework in this study

Three types of input parameters were used in this modeling framework, including biomass characterization (i.e., ultimate analysis data), pyrolysis conditions (i.e., temperature and reaction time), and activation conditions (i.e., steam to biochar mass ratio, activation time and temperature). These data were used as the input of the ANN model to predict the total yield of AC production. The training process is detailed in our prior work.[51] This study focuses on woody biomass, given that it is one of the most abundant biomass resources in the world.[53] This also has the practical advantage of limiting the effects of ash, in particular active alkali, which can have a significant impact on the initial slow pyrolysis reactions, and be significant in herbaceous or agricultural feedstocks. The data of ultimate analysis (a type of chemical analysis commonly used for biomass and fuels, it provides composition information such as the contents of carbon, hydrogen and oxygen)[54] combined with the pyrolysis time and temperature were then used as the inputs to the pyrolysis kinetic model adapted from the previous study[52], producing data on the quantity and composition of pyrolysis products. Both ANN and kinetic models were run independently, although they used the same datasets for biomass characterization and operational conditions. Then the data generated by the kinetic model (gas and solid products from pyrolysis) and ANN model (total AC yield) were used in an Aspen Plus process simulation that ultimately provided the energy and mass balance data needed to estimate the environmental burdens of AC.[55] A list of input and output parameters is provided in Table 2.1. As this study mainly focused on energy and GHG emissions, energy consumption and GHG in the gas products were main tracked for the process simulation. However, the integrated modeling framework is capable to provide the full list of inputs and outputs that can be used as LCI to estimate other environmental impact categories such as acidification and eutrophication that other researchers may be interested in.

Table 2.1 Model input and output parameters

Input Parameters	
Parameters	Unit
Feedstock Properties	
Carbon Content	wt%, dry basis
Hydrogen Content	wt%, dry basis
Oxygen Content	wt%, dry basis
Ash Content	wt%, dry basis
Pyrolysis	
Pyrolysis Time	minute
Pyrolysis Temperature	K
Activation	
Activation Time	minute
Activation Temperature	K
Steam to Biochar Mass Ratio	kg/kg
Output Parameters	
Parameters	Unit
Pyrolysis Reactor	
Feedstock – Woody Biomass	kg/kg AC
Product – Biochar	kg/kg AC
Syngas – Carbon Dioxide	kg/kg AC
Syngas – Methane	kg/kg AC
Thermal Energy Consumption	MJ/kg AC
Combustor	
Flue Gas – Carbon Dioxide	kg/kg AC
Flue Gas – Methane	kg/kg AC
Thermal Energy Recovery	MJ/kg AC
Steam Boiler	

Table 2.1 (Continued)

Water Consumption	kg/kg AC
Thermal Energy Consumption	MJ/kg AC
Activation Furnace	
Flue Gas – Carbon Dioxide	kg/kg AC
Thermal Energy Consumption	MJ/kg AC
Biochar Properties	
Carbon Content	wt%, dry basis
Hydrogen Content	wt%, dry basis
Oxygen Content	wt%, dry basis
Ash Content	wt%, dry basis
Activated Carbon Properties	
Carbon Content	wt%, dry basis
Hydrogen Content	wt%, dry basis
Oxygen Content	wt%, dry basis
Ash Content	wt%, dry basis

Pyrolysis Kinetic Model

Many mechanistic studies have attempted to detail biomass thermochemical conversion processes. Four types of mechanisms were commonly used, including 1) three-step reaction mechanism, 2) two-stage semi-global reaction mechanism, 3) Broido-Shafizadeh reaction mechanism, and 4) multi-step reaction mechanism (MSRM).[56] The MSRM framework was chosen in this study given its capability of predicting the composition of the biochar solid, and the product gases and vapors.[56,57] MSRM assumes that biomass is composed of the lignocellulosic components (i.e., cellulose, hemicellulose, and lignin) and thermal degradations happen on these components and derived products. Then MSRM based model suggests a series of reactions, related to the decomposition of the individual biomass components, where the overall reaction rate can be determined by the kinetic equation shown in Equation 1:

$$r = k \times T^{n} \times e^{-\frac{E}{RT}} \tag{1}$$

Where *r* is the rate of reaction, *k* is the pre-exponential factor, *T* is the reaction temperature, *n* is the exponential factor of temperature, *E* is the activation energy of the reaction, and *R* is the ideal gas constant. The *k, n*, and *E* are given for each reaction included in the MSRM model[58], and thus the product compositions can be calculated based for a given combination of temperature, time and starting biomass composition. See Table 2.2 for parameters values associated with each reaction included in this model. In total, the kinetic model includes 5 reactions for cellulose, 10 for hemicellulose, 12 for lignin, 8 for metaplastic compounds and 13 for gas phase tar cracking.

Table 2.2 Pyrolysis kinetic model reactions and parameters[52,59,60]

Primary Kinetic Reactions (*T* = Pyrolysis Temperature, *t* = Pyrolysis Time)					
Reactions			*k* (s^{-1})	*n*	*E* (kJ/mol)
Cellulose (x_{CELL} = 0.1)					
CELL	→	CELLA	4×10^{13}	0	188.37
CELLA	→	$(1-x_{CELL})$*(0.45 HAA + 0.2 GLYOX + 0.3 C_3H_6O + 0.25 HMFU + 0.05 H_2 + 0.31 CO + 0.41 CO_2 + 0.4 CH_2O + 0.15 CH_3OH + 0.1 CH_3CHO + 0.83 H_2O + 0.02 HCOOH + 0.05 G-H_2 + 0.2 G-CH_4 + 0.61 Char)	2×10^{6}	0	80.0
CELLA	→	x_{CELL}*(5.5 Char + 4 H_2O + 0.5 CO_2 + H_2)	2×10^{6}	0	80.0
CELLA	→	$(1-x_{CELL})$*(0.45 HAA + 0.2 GLYOX + 0.3 C_3H_6O + 0.25 HMFU + 0.05 H_2 + 0.31 CO + 0.41 CO_2 + 0.4 CH_2O + 0.15 CH_3OH + 0.1 CH_3CHO + 0.83 H_2O + 0.02 HCOOH + 0.05 G-H_2 + 0.2 G-CH_4 + 0.61 Char)	4	1	41.86
CELLA	→	x_{CELL}*(5.5 Char + 4 H_2O + 0.5 CO_2 + H_2)	4	1	41.86
Hemicellulose (XYHW for hardwood; GMSW for softwood; x_{HCE} = 0.2)					
GMSW	→	0.7 HCE1 + 0.3 HCE2	1×10^{10}	0	129.70
XYHW	→	0.35 HCE1 + 0.65 HCE2	1.25×10^{11}	0	131.38
HCE1	→	$(1-x_{HCE})$*(0.5 CO + 0.5 CO_2 + 0.325 CH_4 + 0.8 CH_2O + 0.1 CH_3OH + 0.25 C_2H_4 + 0.125 ETOH + 0.025 H_2O + 0.025 HCOOH + 0.275 G-CO_2 + 0.4 G-COH_2 + 0.125 G-H_2 + 0.45 G-CH_3OH + 0.875 Char)	1.2×10^{9}	0	125.58
HCE1	→	x_{HCE}*(4.5 Char + 3 H_2O + 0.5 CO_2 + H_2)	1.2×10^{9}	0	125.58
HCE1	→	$(1-x_{HCE})$*(0.1 CO + 0.8 CO_2 + 0.3 CH_2O + 0.25 H_2O + 0.05 HCOOH + 0.15 G-CO_2 + 0.15 G-CO + 1.2 G-COH_2 + 0.2 G-H_2 + 0.625 G-CH_4 + 0.375 G-C_2H_4 + 0.875 Char)	0.15	1	33.5

Table 2.2 (Continued)

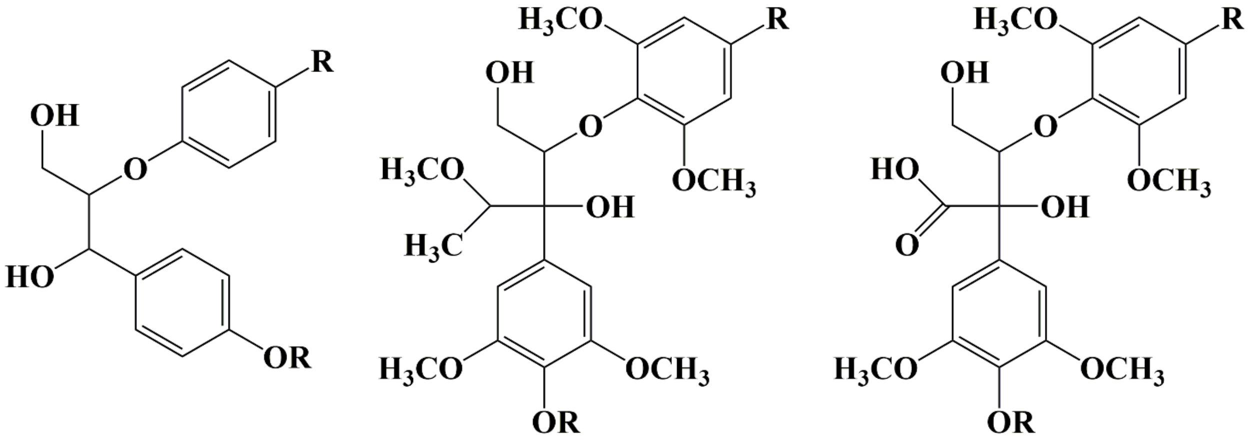
HCE1	→	x_{HCE}*(4.5 Char + 3 H_2O + 0.5 CO_2 + H_2)	0.15	1	33.5
HCE1	→	(1-x_{HCE})*(0.5 CO + 0.5 CO_2 + 0.325 CH_4 + 0.8 CH_2O + 0.1 CH_3OH + 0.25 C_2H_4 + 0.125 ETOH + 0.025 H_2O + 0.025 HCOOH + 0.275 G-CO_2 + 0.4 G-COH_2 + 0.125 G-H_2 + 0.45 G-CH_3OH + 0.875 Char)	3	1	46.05
HCE1	→	x_{HCE}*(4.5 Char + 3 H_2O + 0.5 CO_2 + H_2)	3	1	46.05
HCE2	→	(1-x_{HCE})*(0.2 HAA + 0.175 CO + 0.275 CO_2 + 0.5 CH_2O + 0.1 ETOH + 0.2 H_2O + 0.025 HCOOH + 0.4 G-CO_2 + 0.925 G-COH_2 + 0.25 G-CH_4 + 0.3 G+CH_3OH + 0.275 G-C_2H_4 + Char)	5×10^{9}	0	138.14
HCE2	→	x_{HCE}*(4.5 Char + 3 H_2O + 0.5 CO_2 + H_2)	5×10^{9}	0	138.14
Lignin (x_{LIG} = 0.3)					
LIG-C	→	0.35 LIG-CC + 0.1 pCoumaryl + 0.08 PHENOL +0.32 CO + 0.3 CH_2O + H_2O + 0.7 G-COH_2 + 0.495 G-CH_4 + 0.41 G-C_2H_4 + 5.735 Char	1.33×10^{15}	0	203.02
LIG-H	→	LIG-OH + 0.25 HAA + 0.5 C_3H_6O + 0.5 G-C_2H_4	6.7×10^{12}	0	156.97
LIG-O	→	LIG-OH + CO_2	3.3×10^{8}	0	106.74
LIG-CC	→	(1-x_{LIG})*(0.35 HAA + 0.3 pCoumaryl + 0.2 PHENOL + 0.4 CO + 0.65 CH_4 + 0.6 C_2H_4 + 0.7 H_2O + 0.4 G-CO + G-COH_2 + 6.75 Char)	3×10^{7}	0	131.86
LIG-CC	→	x_{LIG}*(15 Char + 4 H_2O + 3 H_2)	3×10^{7}	0	131.86
LIG-OH	→	LIG + 0.55 CO + 0.05 CO_2 + 0.1 CH_4 + 0.6 CH_3OH + 0.9 H_2O + 0.05 HCOOH + 0.6 G-CO + 0.85 G-COH_2 + 0.1 G-H_2 + 0.35 G-CH_4 + 0.3 G-CH_3OH + 0.2 G-C_2H_4 + 4.15 Char	1×10^{8}	0	125.58
LIG	→	(1-x_{LIG})*FE2MACR	4	1	50.2
LIG	→	x_{LIG}*(10.5 Char + 3 H_2O + 0.5 CO_2 + 3 H_2)	4	1	50.2
LIG	→	(1-x_{LIG})*(0.2 C3H6O + CO + 0.2 CH_4 + 0.2 CH_2O + 0.4 CH_3OH + 0.2 CH_3CHO + 0.95 H_2O + 0.05 HCOOH + 0.45 G-CO + 0.5 G-COH_2 + 0.4 CH_4 + 0.65 C_2H_4 + 5.5 Char)	4×10^{8}	0	125.58
LIG	→	x_{LIG}*(10.5 Char + 3 H_2O + 0.5 CO_2 + 3 H_2)	4×10^{8}	0	125.58
LIG	→	(1-x_{LIG})*(0.4 CO + 0.2 CH_4 + 0.4 CH_2O + 0.6 H_2O + 0.2 G-CO + 2 G-COH_2 + 0.4 CH_4 + 0.4 G-CH_3OH + 0.5 C_2H_4 + 6 Char)	0.083	1	33.5
LIG	→	x_{LIG}*(10.5 Char + 3 H_2O + 0.5 CO_2 + 3 H_2)	0.083	1	33.5
Metaplastic (x_G = 0.4)					

Table 2.2 (Continued)

G-CO_2	→	CO_2	4×10^5	0	100.46
G-CO	→	$(1-x_G)$*CO + x_G*(0.5 Char + 0.5 CO_2)	3×10^{13}	0	209.3
G-COH_2	→	0.75 G2-COH_2 + 0.25*(H_2 + 0.5 CO + 0.25 CO_2 + 0.25 Char)	1×10^6	0	100.46
G-H_2	→	H_2	1×10^{12}	0	313.96
G-CH_4	→	CH_4	2×10^{13}	0	300.0
G-CH_3OH	→	$(1-x_G)$*CH_3OH + x_G*(Char + H_2O + H_2)	1.2×10^{13}	0	209.3
G-C_2H_4	→	0.3 C_2H_4 + 0.7 CH_4 + 0.7 Char	1×10^6	0	100.46
G2-COH_2	→	0.2 G3-COH_2 + 0.8*(H_2 + CO)	1.5×10^9	0	209.3
Gas Phase Tar Cracking Reactions (*T* = Pyrolysis Temperature, *t* = Gas Residence Time)					
Reactions (with $k = 3.08\times10^3$ s^{-1}, $n = 0$, $E = 66.3$ kJ/mol)					
HAA	→	1.5 H_2 + 1.5 CO + 0.25 CO_2 + 0.25 CH_4			
GLYOX	→	H_2 + 2CO			
C_3H_6O	→	0.5 CO_2 + C_2H_4 + 0.5 CH_4			
$C_3H_4O_2$	→	CO_2 + C_2H_4			
HMFU	→	3 CO + 1.5 C_2H_4			
pCoumaryl	→	2 CO + 1.5 C_2H_4 + CH_4 + 3 Char			
PHENOL	→	CO + C_2H_4 + 0.5 CH_4 + 2.5 Char			
FE2MACR	→	4 CO + C_2H_4 + 2 CH_4 + 3 Char			
CH_2O	→	H_2 + CO			
CH_3OH	→	1.5 H_2 + 0.5 CO + 0.25 CO_2 + 0.25 CH_4			
CH_3CHO	→	CO + CH_4			
ETOH	→	H_2 + CO + CH_4			
HCOOH	→	H_2 + CO_2			

Note1 (Solid): CELL – Cellulose; CELLA – Activated cellulose; XYHW – Hardwood hemicellulose; GMSW – Softwood hemicellulose; HCEA1 or HCEA2 – Activated hemicellulose 1 or 2; LIG-C – Carbon rich lignin (Lignin-C); LIG-H – Hydrogen rich lignin (Lignin-H); LIG-O – Oxygen rich lignin (Lignin-O); LIG-CC – Carbon rich lignin 2; LIG-OH – OH rich lignin; LIG – Intermediate lignin; G-X – Trapped substance X; Char – Biochar.
Note2 (Volatiles): HAA – Hydroxyacetaldehyde acid; HCOOH – Formic acid; GLYOX – Glyoxal; C_3H_6O – Acetone; $C_3H_4O_2$ – Propanedial; HMFU – 5-hydroxymethyl-furfural; pCoumaryl – Paracoumaryl alcohol; PHENOL – Phenol; FE2MACR – Sinapaldehyde; CH_2O – Formaldehyde; ETOH – Ethanol.

From the reactions in Table 2.2, the biomass is decomposed to lignocellulosic components (cellulose, hemicellulose and lignin). Model compounds were chosen to represent major biomass lignocellulosic components based on literature.[57] Glucose ($C_6H_{10}O_5$) was chosen to represent cellulose and xylose ($C_5H_8O_4$) to represent hemicellulose. Given the complexity of lignin structure, three types of chemical compounds were chosen to present lignin: Lignin-C, lignin-O and lignin-H. The structures of these compounds are shown in Figure 2.2.



Lignin-C $C_{15}H_{14}O_4$ **Lignin-H** $C_{22}H_{28}O_9$ **Lignin-O** $C_{20}H_{22}O_{10}$

Figure 2.2 Structures and chemical formulas of lignin-C, lignin-O and lignin-H[57]

Since only ultimate analysis data were collected in the present study, the contents of these model compounds should be estimated by the ultimate analysis data. The triangle method developed by Debiagi et al. was used in this study as shown in Figure 2.3.[61] Considering the chemical composition of model compounds, the contents of different model compounds can be calculated by Equation 2-6. Then the triangle method was used to construct 3 reference components to replace 5 model compounds in order to reduce the degree of freedom in Equation 2-6 to be solvable.

$$x_{CELL}C_{CELL} + x_{HEMI}C_{HEMI} + x_{LIGC}C_{LIGC} + x_{LIGH}C_{LIGH} + x_{LIGO}C_{LIGO} = C_{BIOMASS} \tag{2}$$

$$x_{CELL}H_{CELL} + x_{HEMI}H_{HEMI} + x_{LIGC}H_{LIGC} + x_{LIGH}H_{LIGH} + x_{LIGO}H_{LIGO} = H_{BIOMASS} \tag{3}$$

$$x_{CELL}O_{CELL} + x_{HEMI}O_{HEMI} + x_{LIGC}O_{LIGC} + x_{LIGH}O_{LIGH} + x_{LIGO}O_{LIGO} = O_{BIOMASS} \tag{4}$$

$$x_{CELL} + x_{HEMI} + x_{LIGC} + x_{LIGH} + x_{LIGO} = 1 \tag{5}$$

$$x_{CELL}, x_{HEMI}, x_{LIGC}, x_{LIGH}, x_{LIGO} \geq 0 \tag{6}$$

Note for equations: x_t – Mass fraction of compound t; C_t – Carbon content of compound t; H_t – Hydrogen content of compound t; O_t – Oxygen content of compound t; *CELL* – Cellulose; *HEMI* – Hemicellulose; *LIGC* – Lignin-C; *LIGH* – Lignin-H; *LIGO* – Lignin-O.

However, some biomass samples in Figure 2.3 are outside the model compounds. In this study, the components of model compounds in the samples outside the range were determined by fixing the variables in Equation 2-6 (fix x_{CELL} and x_{HEMI}) by the experimental compositional analysis result of the corresponding biomass sample, and then solve the Equation 2-5. Since some solution may be negative when Equation 6 is not considered, these negative values are set as 0 and the remaining positive values are normalized to satisfy Equation 6.

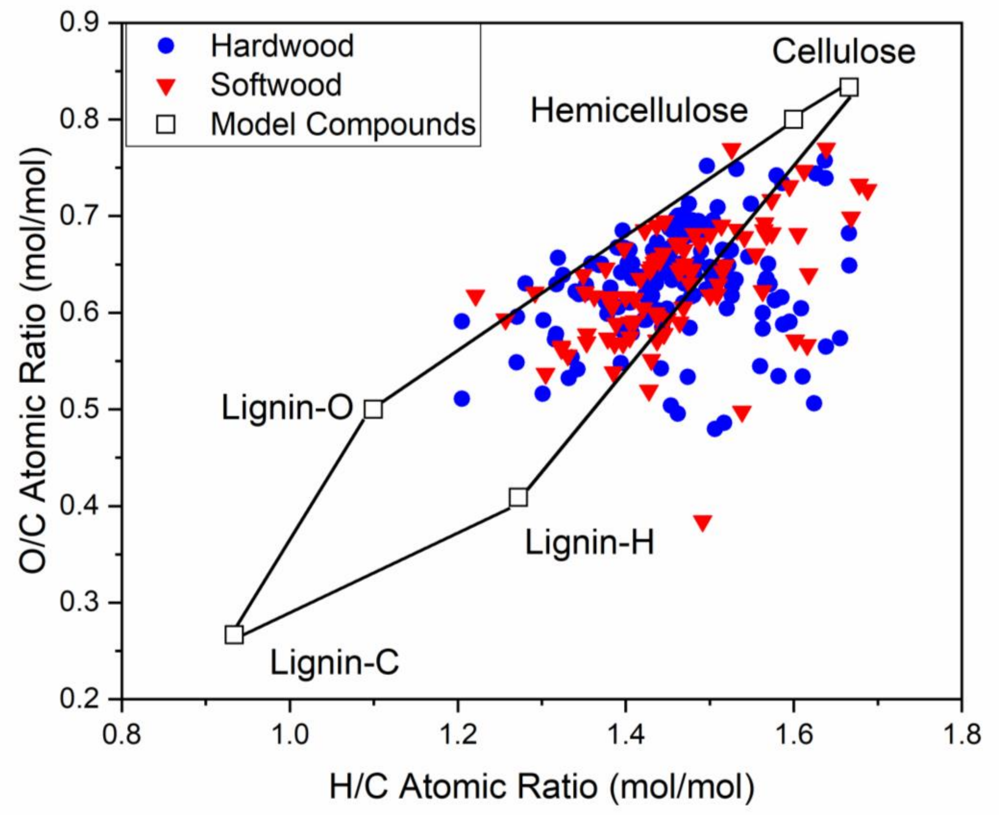


Figure 2.3 Biomass characterization representation for model compounds and collected woody biomass samples by Krevelen diagram

After determining the model compounds of the woody biomass samples, the kinetic model was developed based on the multi-step reaction mechanism that provides a series of reactions. The reactants are model compounds and corresponding products. In this study, the pyrolysis kinetic model was based on the model developed by Anca-Couce et al.[52], which was modified by adding gas-phase tar cracking reactions[59] and fitting the differences between different types of biomass.[60] The reactions, kinetic parameters, and other relevant parameters are listed in Table 2.2.

Artificial Neural Network for Steam Activation

A key parameter needed for the Aspen Plus process simulation is the yield of AC. The MSRM kinetic model provides the yield of the intermediate biochar (pyrolysis yield), it does not provide the final yield of AC from biochar (activation yield). In this study, the yield of the final AC product from the starting biomass (biomass yield) was estimated by using ANN as outlined in our prior work.[51] The ANN model was trained using 8 input variables, including 5 process variables (i.e., pyrolysis time, pyrolysis temperature, activation time, activation temperature and steam to biochar ratio) and 3 biomass characterization variables (i.e., biomass carbon content, hydrogen content, and oxygen content). The output variable is the total activation yield based on the total biomass input of the entire AC production process.[51] The ANN model demonstrated a high accuracy ($R^2 = 0.971$) and showed high consistency with independent experimental data through an additional model validation step.[51]

Based on the output data predicted from ANN, the yield of the biochar-to-AC process can be determined using Equation 7 and the biomass-to-biochar yield provided by the pyrolysis kinetic model. In addition, it was assumed that the ash content from the biomass feedstock is retained in the biochar and the AC. Hence, the burn-off rate of organic components in biochar, which is the ratio of mass loss in the activation stage to the ash-free biochar mass, should be calculated by Equation 7.

$$Burn-off = \left(1 - \frac{Total\ AC\ Yield\ -\ Ash\ Content}{Pyrolysis\ Yield\ -\ Ash\ Content}\right) \times 100\% \quad (7)$$

The main reaction in the steam activation is shown in Equation 8:

$$C + H_2O \rightarrow H_2 + CO \quad (8)$$

Previous LCA of steam AC production assumed that only steam-carbon reaction exists in the activation process. As a result, the activation flue gas should not contain any CO_2.[12] However, experimental studies showed significant carbon dioxide content in the activation flue gas, which contradicts this assumption.[13,33] One study indicated that different types of reactions may happen in the steam activation process, including water-gas shift reaction (Equation 9), methanation reactions (Equation 10), steam-reforming reactions (Equation 11), and Boudouard reaction (Equation 12).[62] However, the extent of these reactions in the specified temperature and time was hard to determine. Therefore, in this study, the reaction formula developed by Martín-Gullón et al. was used (see details in the following section), which covered all products occurred in Equation 9-12.[63] Even the aforementioned formula was established by fitting the data from bituminous coal-based AC production, it can be transferred to the biomass-based AC production due to the similar reaction mechanism of steam activation for coal and biochar.[62]

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (9)$$

$$C + 2H_2 \rightarrow CH_4; 2CO + 2H_2 \rightarrow CH_4 + CO_2 \quad (10)$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O; CO + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad (11)$$

$$C + CO_2 \leftrightarrow 2CO \quad (12)$$

Aspen Plus Process Simulation

In this study, the process simulation model was developed using Aspen Plus[55] (Aspen Plus V10) to generate energy and mass balances. One key parameter needed for the process simulation of steam activation is the activation yield that is defined as the AC produced divided by the total biochar input to the activation process.[64] The activation yield could have large variations depending on the quantity and quality of biochar (that are driven by pyrolysis process and biomass feedstock) and process operational conditions.[65] To take such variations into consideration, this study calculated the activation yield using Equation 13, where the total AC yield is given by the ANN model and the pyrolysis yield of biochar was provided by the kinetic model. The calculated activation yields range from 29.0-94.8%, which is consistent with the activation yields derived from literature.[65]

$$\text{Activation Yield} = \frac{\text{Total AC Yield}}{\text{Pyrolysis Yield of Biochar}} \times 100\% \qquad (13)$$

In addition to the data provided by the ANN and kinetic models discussed previously, another key piece of information is the composition of flue gas coming from the steam activation. This gas needs to be counted as an air emission. Previous LCA studies have assumed that the only a steam-carbon reaction occurs without CO_2 generation[12], which is not consistent with experimental measurements.[13,33] Other reactions such as water-gas shift reaction, methanation reactions, steam-reforming reactions, and Boudouard reaction (shown in Equation 9-12) also occur.[62,66] As described above, in this study, those reactions were considered by using the model from Martín-Gullón et al.[63] as shown in Equation 14.

$$\mathrm{C} + \alpha\mathrm{H_2O} \rightarrow (2-\alpha)\mathrm{CO} + (\alpha-1)\mathrm{CO_2} + \alpha\mathrm{H_2},\ \alpha = 3.4690 - 0.0019T(\mathrm{K}) \qquad (14)$$

The Aspen Plus database has property data, which can be used to model gas phase reactions and to estimate the reaction products including gases (e.g., hydrogen, methane, carbon monoxide and carbon dioxide) and vapors (e.g., alkanes, alkenes and oxygenates).[67,68] However, the property data for solid components (e.g., woody biomass, biochar, and AC), lignocellulosic components (e.g., cellulose, hemicellulose and lignin) and monosaccharides (e.g., glucose, xylose) are not included in Aspen databases. The relevant physical property parameters for lignocellulosic components and monosaccharides were collected from the literature.[69] For solid components, the thermodynamic data was calculated based on previous studies[60,70] and the details will be provided below. Key process parameters used in the Aspen Plus simulation are listed in Table 2.3.

Table 2.3 Key process parameters used in the process simulation model

Parameter	Value	Reference
Heat capacity of biomass feedstock (J/(kg*K))	1500 + T [a]	71
Heat capacity of biochar and AC (J/(kg*K))	$420 + 2.09*T - 6.85*10^{-4}*T^2$ [a]	71
Pyrolysis gas residence time (s)	2	58
Pyrolysis nitrogen gas mass flow	1/6 of feedstock mass flow	44
Pyrolysis thermal efficiency (%)	90	48
Combustor excess air rate (%)	30	12
Pyrolysis non-solid product combustion rate (%)	80	72
Steam boiler thermal efficiency	82	49
Activation furnace thermal efficiency (%)	90	48
Pyrolysis temperature (K)	773	-
Pyrolysis time (min)	60	-
Activation temperature (K)	1073	-
Activation time (min)	60	-
Steam to biochar ratio (kg/kg)	2	-

[a] T represents absolute temperature in Kelvin

In this study, the natural gas was combusted in the combuster to provide the heat for pyrolysis and activation, given that natural gas is the most commonly used fuel type to supply heat in the U.S. manufacturing industry.[73] A few studies used electricity to supply heat, but all of them were based on lab-scale AC production experiments.[11,31,39,42] Electricity could be used for ancillary facilities or purposes (e.g., process monitoring and control), but the electricity consumption for those purposes is generally negligible[13,33,38] and needs to be assessed on a case-by-case basis given the specific equipment used. Thus this study does not include ancillary electricity consumption and the primary energy consumption was in the form of natural gas. Meanwhile, all the gaseous byproducts from the initial pyrolysis process were combusted with an 80% combustion rate to produce process energy. The combustion rate is the ratio of pyrolysis products that can be fully combusted, and 80% was used based on the ratio of unidentified and hard-to-combust substances of non-solid pyrolysis products[72]. The energy content in the flue gases from the activation process are estimated to be minor[13], so they were not combusted. To understand the impacts of energy recovery, scenarios with and without burning gas products were evaluated using Energy Recovery Ratio (ERR) calculated by Equation 15:

$$\mathrm{ERR} = \frac{\text{Energy Recovered}}{\text{Total Energy Consumption}} \times 100\% \tag{15}$$

The pyrolysis kinetic model and ANN provide essential data inputs of Aspen Plus process simulation models. Aspen Plus software provides different types of reactors, including RYield, RGibbs, RCSTIR, RStoic and RBatch.[55] In this study, RBatch is chosen as it is a common reactor type for pyrolysis simulations.[72] The process flowsheet of pyrolysis was shown in Figure 2.4.

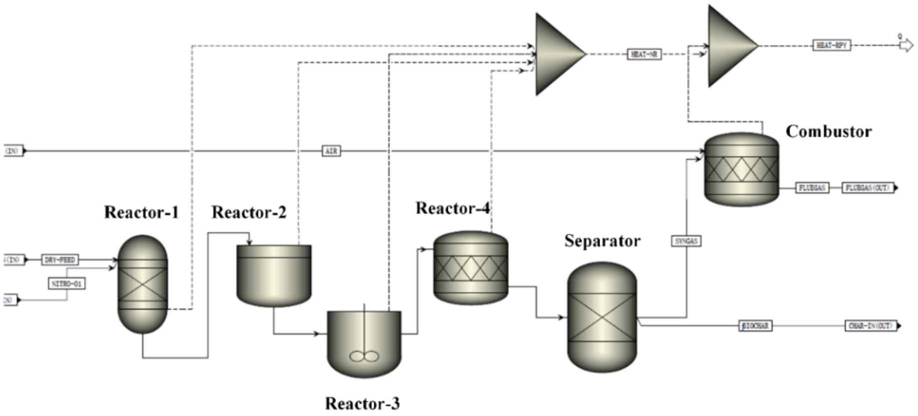


Figure 2.4 Process flowsheet of pyrolysis

The pyrolysis reaction process consists of four continuous sub-reactors. The Reactor-1, which is set as RYield reactor, decomposed the biomass feedstock into model compounds and ash content. Then the primary kinetic reactions mentioned in Table S3 were implemented in the Reactor-2 (RBatch). The Reactor-3 calculated gas-phase tar cracking reactions in Table 2.2. Finally, the RStoic Reactor-4 converted the remaining metaplastic components into biochar. After the pyrolysis kinetic reactions, the Separator unit moved the solid components out and the hot volatiles was sent to the Combustor unit. The Combustor unit was set as RStoic, which oxidized all of the combustible components in the syngas with the burn-off rate of 80%. The heat generated from the Combustor unit was recovered to compensate for the energy consumption of Reactor units. The components of output flows from Separator and Combustor were tracked to generate the Life Cycle Inventory (LCI) data.

The assumed reaction provided by Martín-Gullón et al. can be directly simulated by the RStoic reactor in Aspen Plus, thus the process flowsheet of steam activation of biochar can be constructed, which is shown in Figure 2.5. The steam boiler raises the temperature of water from the room temperature to the desired temperature in order to generate the superheated steam. The Activation Reactor unit was set as the RStoic reactor, which implemented the reaction between water and biochar with the predefined reaction extent. Detailed information on the unit operations presented in Figure 2.4 and 2.5 are given in Table 2.4.

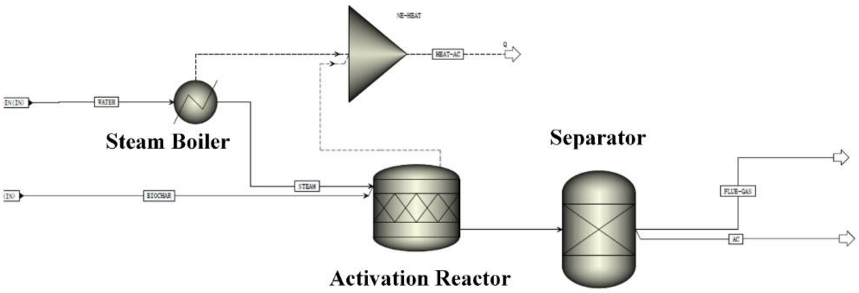


Figure 2.5 Process flowsheet of activation

Table 2.4 Parameter settings for unit operators in the Aspen process simulation

Parameters	Values
Figure 2.4 – Reactor-1	
Reactor Type	RYield
Temperature [a]	773 K
Pressure	1 atm
Reactions	Conversion of biomass to lignocellulosic components and ash
Figure 2.4 – Reactor-2	
Reactor Type	RBatch
Temperature [a]	773 K
Pressure	1 atm
Catalyst Loading	0 kg
Reaction time [b]	3600 s
Reactions	Primary kinetic reactions
Figure 2.4 – Reactor-3	
Reactor Type	RCSTR
Temperature [a]	773 K
Pressure	1 atm
Residence Time	2 s
Reactions	Gas phase tar cracking reactions
Figure 2.4 – Reactor-4	
Reactor Type	RStoic
Temperature [a]	773 K
Pressure	1 atm
Reactions	Conversion of trapped substances (see notes in Table 2.2) to biochar
Figure 2.5 – Activation Reactor	
Temperature [c]	1073 K
Pressure	1 atm
Reactions	Activation reactions

[a] Pyrolysis temperature in Table 2.1; [b] Pyrolysis time in Table 2.1; [c] Activation temperature in Table 2.1.
Note: The values for parameters that are indiced [a,b,c] are the default value.

The Aspen Simulation Workbook was used to automatically inputs the results of ANN models into the Aspen Plus simulation. Aspen Simulation Workbook was the plugin in the Microsoft excel which allows running simulations with different input parameters automatically. The thermal efficiencies of reactors and pyrolysis combustion rate can be seen in Table 2.3. The combustion rate is set as 80% due to the heavy oil products from slow pyrolysis that is hard to combust. By fitting the characterization of products from slow pyrolysis of beech at 500℃, around 20% of the non-solid products cannot be identified, which are considered as the heavy oil products.[72] Therefore the combustion rate is set as 80% in the present study.

When the simulation is finished, LCI of AC production can be established from the simulation results. An example representation of AC production process material and energy flow chart that is generated from Aspen Plus simulation data is shown in Figure 2.6, and additional LCI information of the simulation scenarios are summarized in Table A.1 and TableA.2 of Appendix A.

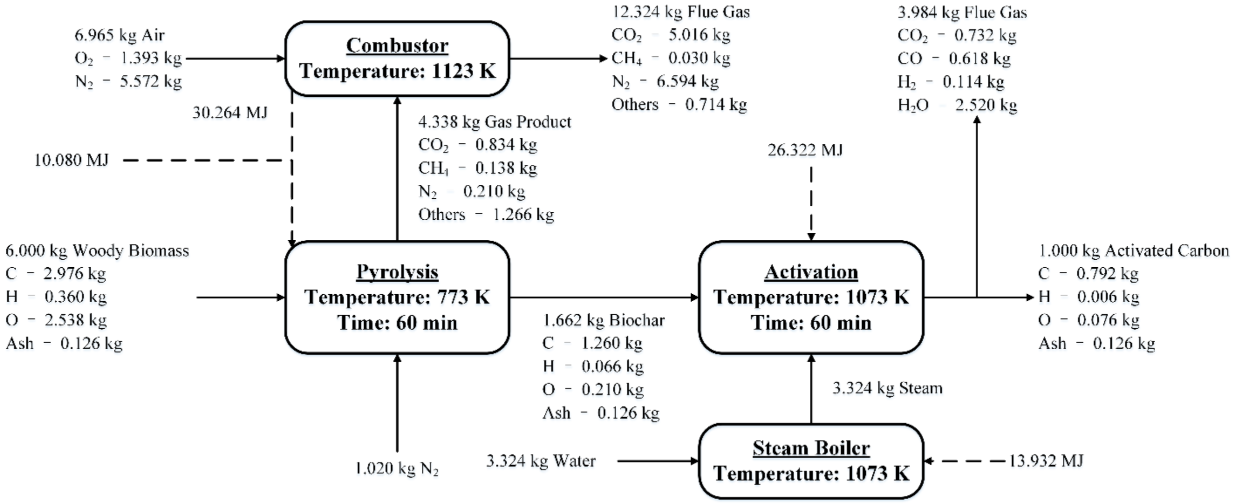


Figure 2.6 An example representation of material and energy flows of AC production

Other Assumptions

The thermodynamic properties of the substances were collected from the Aspen Plus databank or the report from National Renewable Energy Laboratory (NREL).[69,74] The higher heating value (HHV) of solid compounds, a key parameter needed to calculate the DHSFRM parameters for process simulation[75], was calculated by Dulong's equation (Equation 16), where m_C, m_H and m_O represent the weight percentage (wt.%) of carbon, hydrogen, and oxygen in the biochar or AC.[70]

$$HHV(MJ/kg) = 0.338m_C + 1.442m_H - 0.182m_O \tag{16}$$

For the HHV of woody biomass, the equation was modified by Demirbaş in order to reflects the effect of considerable nitrogen content in the biomass.[76] The updated equation was shown in Equation 17:

$$HHV(MJ/kg) = 0.335m_C + 1.423m_H - 0.154m_O - 0.145m_N \tag{17}$$

Based on the previous equations, the ultimate analysis data of biochar and AC are needed. The pyrolysis kinetic model generates some metaplastic substances which trap the volatile components into the biochar. Therefore, based on the method developed by Debiagi et al., the carbon, hydrogen and oxygen content of biochar can be determined by normalizing the elemental composition of char (elemental carbon) and trapped substances (containing carbon, hydrogen and oxygen).[60] In this study, the elemental compositions of AC were derived from the biochar by Equation 18-20, whose constants are fitted by the literature data.[77] All these data are in the dry-ash-free basis.

$$C_{AC} = 1.097 * C_{Biochar} \tag{18}$$

$$H_{AC} = 0.215 * H_{Biochar} \tag{19}$$

$$O_{AC} = 100 - C_{Biochar} - H_{Biochar} \tag{20}$$

With these equations, the produced AC contains higher carbon content and lower hydrogen content, which is consistent with the literature.[13,77] One limitation is that Equation 18-20 were derived based on activation temperature – 1073K, activation time – 60 min, and steam to biochar ratio – 2 kg/kg. More experimental data are needed if the operational conditions are changed.

Besides, the Aspen Plus software also requires the parameters for the calculation of viscosity, which are categorized as VSPOLY parameters. In the present study, the VSPOLY parameters for the substances were assumed to be either the default values in Aspen Plus database or from literature data.[69,74,78]

CHAPTER 3

RESULTS AND DISCUSSION

Results of Estimated Lignocellulosic Compositions

To investigate the impact of the composition of the woody biomass feedstock, a large dataset (250 data samples) containing the characterization data of woody biomass feedstocks was collected from 4 different data sources: The biomass feedstock composition and property database from National Renewable Energy Laboratory[79], the bioenergy feedstock library from Idaho National Laboratory[80], the Phyllis2 database for biomass and waste from ECN[81], and other literature references.[61] The entire dataset is provided in Table 3.1, which can be useful in replicating the results and becoming the basis of further researches. The Aspen Plus process simulation was run for each sample with the fixed operational conditions shown in Table 2.3, allowing for comparisons among different feedstocks, as well as an initial quantification of the variations in energy and GHG emissions for individual species of biomass sources.

Table 3.1 Woody biomass feedstock characterization dataset

		Raw Data (dry basis, wt%)					**Triangle Method Result (dry basis, wt%)**				
Feedstock	Type	C	H	O	N	Ash	CELL	HEMI	LIGC	LIGH	LIGO
Data from National Renewable Energy Laboratory[79]											
Ailanthus	HW	50.77	6.36	42.05	0.31	0.51	42.87	30.71	6.27	1.22	18.43
Pistachio	HW	48.79	5.91	43.41	0.56	1.28	45.08	32.04	2.44	0.49	18.66
White Ash	HW	49.75	6.91	43.04	0.00	0.30	45.22	32.06	2.88	0.54	19.00
Manzanita	HW	48.27	5.95	44.77	0.17	0.82	47.03	33.28	0.66	0.20	18.02
Robinia	HW	50.86	5.72	42.04	0.57	0.80	42.07	29.63	7.90	1.20	18.40
Teak	HW	51.60	6.00	40.04	0.26	2.10	39.62	26.58	14.33	1.21	16.17
Almond	HW	48.31	6.00	42.73	0.68	2.24	48.56	32.37	2.23	0.00	14.59
Oak	HW	49.83	6.23	42.99	0.13	0.82	44.42	29.57	4.67	0.27	20.25
Almond	HW	47.12	5.97	40.07	1.19	5.55	43.14	28.23	0.06	11.70	11.30
Cherry tree	HW	50.03	5.87	42.41	0.31	1.36	43.32	27.94	6.93	0.25	20.19
Mixed	HW	49.09	5.93	42.49	0.33	2.10	44.23	27.89	5.32	0.09	20.38
Prune	HW	50.35	6.69	39.66	1.30	1.90	41.51	25.40	12.58	0.24	18.36
Spruce	SW	49.60	5.63	40.81	0.20	3.66	39.85	23.64	0.13	9.52	23.20
Eucalyptus	HW	48.20	5.30	42.20	0.00	4.30	44.03	26.11	5.83	0.00	19.73

Table 3.1 (Continued)

Mixed	SW	50.30	5.80	40.65	0.42	2.80	37.87	21.77	0.18	6.82	30.57
Oak	HW	50.93	5.96	41.46	0.20	1.30	43.32	24.58	12.29	0.02	18.49
Spruce	SW	50.05	5.63	42.65	0.10	1.48	45.85	26.00	1.77	21.10	3.79
Olive	HW	51.38	6.32	40.02	0.45	1.69	39.01	22.06	4.29	31.71	1.25
Spruce	SW	50.90	6.40	42.00	0.00	0.70	44.95	25.07	2.99	21.57	4.72
Cedar	SW	48.80	6.40	44.40	0.00	0.40	53.77	29.55	0.00	11.95	4.33
Maple	HW	49.54	6.00	43.84	0.10	0.50	50.18	27.46	0.58	14.59	6.69
Larch	SW	50.67	6.38	42.51	0.00	0.45	46.46	25.18	2.99	17.77	7.16
Pine	SW	52.13	6.36	41.01	0.07	0.37	41.57	22.45	7.55	24.55	3.51
Douglas Fir	SW	52.30	6.30	40.32	0.10	0.98	39.97	21.35	9.67	26.08	1.94
Pine	SW	48.40	6.31	44.23	0.21	0.82	53.57	28.61	0.00	10.41	6.58
Olive	HW	45.15	5.63	37.56	1.55	10.01	41.45	22.09	3.66	15.70	7.10
Cotton	HW	48.48	6.12	41.48	0.97	2.85	46.80	24.91	2.14	14.66	8.64
Cotton	HW	48.48	6.12	41.48	0.97	2.85	46.80	24.91	2.14	14.66	8.64
Olive	HW	48.71	6.18	42.16	0.52	2.39	47.91	25.49	1.49	13.85	8.86
Pine	SW	50.10	6.00	38.17	0.10	5.63	37.33	19.84	10.39	26.02	0.80
Spruce	SW	48.82	5.84	42.44	0.17	2.73	47.44	24.95	1.85	13.46	9.57
Babassu	HW	50.38	5.38	42.35	0.26	1.59	44.75	23.44	5.31	16.83	8.08
Almond	HW	47.15	5.91	40.04	1.20	5.61	44.92	23.51	2.88	13.86	9.23
Cocoa	HW	46.31	5.57	36.12	3.21	8.60	38.30	19.99	9.70	20.21	3.20
Mulberry	HW	49.84	6.14	41.00	0.42	2.60	44.22	23.04	5.58	16.44	8.12
Ailanthus	HW	49.50	6.20	42.30	0.30	1.70	47.22	24.56	2.68	13.66	10.17
Birch	SW	48.74	6.26	44.09	0.19	0.54	52.28	26.98	0.00	9.83	10.38
Pine	SW	51.99	6.28	41.16	0.14	0.41	42.94	22.14	9.86	19.35	5.30
Olive	HW	50.77	5.90	37.07	1.36	4.61	34.30	17.53	13.78	29.78	0.00
Olive	HW	50.18	6.85	37.78	1.11	4.00	40.10	20.46	12.93	20.35	2.16
Willow	HW	49.29	5.98	42.72	0.57	1.38	48.03	24.39	2.42	11.89	11.89
Poplar	HW	50.19	6.06	40.43	0.60	2.70	43.33	21.81	8.95	15.67	7.54
Willow	HW	48.50	6.12	43.00	0.50	1.86	49.67	24.92	0.75	9.79	13.01
Douglas Fir	SW	50.63	6.23	42.54	0.12	0.47	46.78	23.38	5.02	12.79	11.56
Pine	SW	51.85	6.21	41.23	0.13	0.42	43.85	21.83	11.22	16.22	6.46
Pine	SW	51.48	6.16	41.14	0.16	0.97	43.97	21.75	10.86	15.29	7.16
Pistachio	HW	49.55	6.12	42.32	0.62	1.27	47.45	23.43	3.73	11.16	12.96
Peach	HW	51.21	6.14	41.14	0.40	1.07	44.27	21.78	10.43	14.56	7.89
Unidentified	SW	52.10	6.10	39.90	0.20	1.70	42.04	20.59	16.97	17.48	1.22
Cedar	SW	52.74	6.14	39.98	0.10	1.03	41.92	20.42	18.59	18.04	0.00
Almond	HW	48.60	5.70	37.51	0.62	7.46	40.05	19.49	15.30	15.39	2.31
Walnut	HW	51.00	6.04	40.31	0.78	1.78	43.46	21.13	13.01	14.68	5.94
Poplar	HW	49.93	6.10	42.26	0.29	1.36	46.94	22.76	4.97	10.80	13.18

Table 3.1 (Continued)

Poplar	HW	47.67	6.15	45.29	0.20	0.68	56.36	27.22	0.00	5.04	10.70
Camphor	HW	50.30	6.10	42.50	0.10	0.80	47.24	22.38	5.72	9.90	13.96
Willow	HW	48.98	5.99	42.09	0.65	2.24	47.46	22.47	3.90	8.97	14.96
Palm	HW	47.28	6.25	38.82	2.83	4.59	41.83	33.02	3.91	2.92	13.73
Unidentified	HW	47.10	5.52	36.92	0.43	9.94	40.16	18.97	14.36	12.11	4.45
Fir	SW	50.35	6.14	43.18	0.05	0.28	48.30	22.74	4.32	9.02	15.35
Peanut	HW	45.77	5.46	39.56	1.63	7.46	45.05	21.20	3.60	8.17	14.52
Beech	SW	48.37	6.10	44.51	0.34	0.65	53.12	24.94	0.00	5.77	15.52
Spruce	SW	50.17	5.94	40.44	0.42	3.01	44.29	20.78	11.70	11.30	8.91
Eucalyptus	HW	50.43	6.01	41.53	0.17	1.76	45.85	21.24	9.33	9.87	11.95
Eucalyptus	HW	50.50	6.02	41.59	0.27	1.58	45.95	21.28	9.33	9.86	12.00
Maple	HW	50.64	6.02	41.74	0.25	1.35	46.16	21.25	9.44	9.58	12.23
Olive	HW	52.70	5.90	38.04	1.05	2.06	38.29	17.50	23.43	18.72	0.00
Oak	HW	48.82	6.06	44.17	0.15	0.78	51.25	23.37	0.04	5.80	18.75
Maple	HW	50.60	6.00	41.70	0.30	1.40	46.27	21.04	9.84	9.04	12.40
Walnut	HW	53.66	6.50	36.04	1.34	2.36	37.83	29.83	14.76	12.40	2.81
Unidentified	HW	50.48	6.04	42.43	0.17	0.78	47.34	21.51	7.31	8.35	14.71
Birch	SW	49.85	6.72	42.54	0.10	0.29	49.02	22.25	3.82	7.23	17.38
Kenaf (italy)	HW	46.60	5.80	42.62	1.00	3.67	50.74	23.00	0.00	4.97	17.62
Tan Oak	HW	48.50	6.08	44.98	0.05	0.35	53.86	24.40	0.00	4.49	16.90
Pine	SW	52.55	6.08	41.25	0.00	0.12	45.59	20.65	17.77	10.70	5.17
Oak	HW	48.78	6.09	44.98	0.00	0.15	53.41	24.19	0.00	4.75	17.50
Palm	HW	48.11	6.64	36.79	2.81	5.50	43.19	19.55	16.44	10.02	5.30
Peanut	HW	46.97	5.64	40.11	1.85	5.25	45.93	20.74	5.27	7.18	15.63
Spruce	SW	49.53	6.06	43.92	0.11	0.37	50.23	22.65	1.73	6.22	18.80
Birch	SW	48.89	6.04	44.43	0.22	0.35	51.81	23.19	0.00	5.12	19.53
Spruce	SW	50.20	5.90	41.14	0.20	2.56	45.79	20.46	11.01	8.34	11.84
Oak	HW	49.89	5.98	42.57	0.21	1.29	47.89	21.37	5.83	7.10	16.52
Mixed	HW	50.00	5.97	42.80	0.21	0.95	48.18	21.49	5.53	7.01	16.84
Casuarina	HW	48.59	5.94	43.37	0.45	1.62	50.00	22.14	1.30	5.38	19.56
Grape	HW	47.57	5.85	43.14	0.81	2.61	50.42	22.31	0.03	4.80	19.84
Spruce	SW	48.46	5.84	44.88	0.21	0.60	53.12	23.48	0.00	4.12	18.68
Cocoa	HW	49.21	5.34	33.87	3.04	8.42	31.42	13.87	23.88	22.41	0.00
Cocoa	HW	48.23	5.23	33.19	2.98	10.25	30.79	13.60	23.40	21.96	0.00
Oak	HW	49.74	5.96	42.56	0.23	1.47	48.04	21.17	5.67	6.54	17.11
Spruce	SW	48.39	5.55	41.67	0.10	4.19	46.73	20.59	5.47	6.35	16.67
Oak	HW	49.90	5.97	42.88	0.36	0.88	48.49	21.37	5.25	6.46	17.55
Fir	SW	49.00	5.98	43.91	0.05	1.04	50.52	22.22	1.03	5.11	20.07
Coconut	HW	50.29	5.05	39.63	0.45	4.14	36.26	15.91	5.79	0.27	37.62

Table 3.1 (Continued)

Hazelnut	HW	51.00	5.40	40.50	1.30	1.80	31.13	13.66	7.08	0.32	46.01
Walnut	HW	53.52	6.52	35.37	1.53	2.95	34.14	14.98	6.18	40.81	0.94
Cypress	SW	54.98	6.54	38.08	0.00	0.40	33.42	14.66	6.65	42.56	2.31
Olive	HW	50.18	6.30	32.09	1.40	9.90	34.98	15.35	5.13	33.77	0.88
Grape	HW	54.01	6.83	35.00	1.46	2.50	39.85	17.48	5.18	34.95	0.04
Walnut	HW	47.86	5.75	34.60	1.07	10.62	32.77	14.38	5.44	36.56	0.23
Spruce	SW	51.10	5.50	42.30	0.10	1.00	38.88	17.06	5.71	0.23	37.12
Olive	HW	51.25	6.29	36.46	1.10	4.70	37.75	16.56	5.29	34.40	1.30
Almond	HW	48.55	5.33	40.74	0.81	4.50	37.73	16.55	5.46	0.19	35.56
Almond	HW	48.43	5.98	39.90	0.94	4.71	43.29	18.99	4.38	0.22	28.42
Grape	HW	45.72	5.05	38.95	1.07	9.13	38.46	16.87	4.71	0.24	30.58
Olive	HW	50.00	6.50	36.30	0.80	6.30	47.16	20.69	3.33	21.78	0.74
Peach	HW	53.15	7.19	35.86	0.60	3.20	55.60	24.39	2.17	14.59	0.06
Cherry	HW	53.41	7.04	38.05	0.30	0.90	52.35	22.97	3.07	20.07	0.64
Grape	HW	49.73	6.67	35.41	1.83	6.24	53.21	23.34	2.22	14.90	0.09
Pine	SW	52.60	7.02	40.07	0.00	0.31	56.99	25.00	2.28	15.31	0.11
Unidentified	SW	50.96	6.86	38.49	0.19	3.11	57.02	25.02	1.91	12.87	0.06
Olive	HW	49.85	6.59	39.06	0.70	3.40	54.14	23.75	2.41	15.91	0.39
Oak	HW	49.16	6.46	40.16	1.64	2.55	54.75	24.02	2.41	15.95	0.33
Elm	HW	50.35	6.57	42.34	0.00	0.74	55.07	24.16	2.58	17.45	0.00
Elm	HW	50.40	6.60	42.30	0.00	0.70	55.76	24.46	2.46	16.54	0.08
Oak	HW	50.44	6.59	42.73	0.00	0.24	55.91	24.53	2.49	16.29	0.54
Coconut	HW	50.64	5.09	39.91	0.45	3.75	40.33	31.54	8.13	5.05	11.21
Mixed	HW	50.09	5.94	42.30	0.26	1.31	47.63	20.87	7.48	6.76	15.95
Pistachio	HW	48.85	6.29	42.86	0.50	1.30	49.72	21.75	2.22	5.32	19.68
Poplar	HW	50.84	5.89	41.06	0.59	1.60	46.24	20.18	14.22	7.81	9.95
Peach	HW	53.00	5.90	39.14	0.32	1.59	42.36	18.43	25.69	11.93	0.00
Olive	HW	47.73	5.86	43.60	0.58	2.23	51.25	22.25	0.00	4.05	20.22
Fir	SW	51.36	5.99	42.20	0.06	0.36	47.35	20.52	11.79	7.17	12.82
Spruce	SW	50.25	5.99	43.36	0.10	0.30	49.09	21.24	5.11	5.77	18.49
Unidentified	SW	50.00	6.00	43.60	0.00	0.30	49.57	21.43	3.89	5.45	19.35
Almond	HW	48.04	5.79	42.32	0.72	3.06	48.66	21.04	2.75	5.03	19.47
Fir	SW	49.84	5.99	43.60	0.18	0.38	49.67	21.48	3.57	5.36	19.55
Eucalyptus	HW	48.29	5.93	44.28	0.39	1.10	52.18	22.53	0.00	3.81	20.37
Cotton	HW	44.88	5.54	41.57	1.04	6.66	50.16	21.64	0.00	3.20	18.34
Beech	SW	49.69	6.07	42.80	0.41	1.01	48.86	21.01	4.97	5.50	18.65
Peanut	HW	46.50	5.55	40.19	1.66	5.98	46.40	19.96	4.72	5.22	17.71
Prune	HW	49.47	6.25	42.67	0.58	0.96	49.13	21.12	4.31	5.33	19.15
Mixed	SW	49.73	5.95	43.40	0.22	0.67	49.45	21.25	3.89	5.23	19.50

Table 3.1 (Continued)

Pine	SW	49.45	5.95	43.59	0.30	0.61	49.96	21.47	2.80	4.94	20.22
Madrone	HW	48.56	6.02	44.99	0.05	0.36	53.64	23.00	0.00	3.24	19.76
Unidentified	HW	50.52	5.80	40.35	0.40	2.86	45.80	19.63	16.51	7.19	8.01
Pine	SW	52.30	5.80	38.76	0.20	2.90	42.61	18.20	26.03	10.25	0.00
Sequoia	SW	52.30	5.90	40.30	0.20	1.30	46.45	19.82	24.01	7.72	0.71
Mixed	HW	50.49	5.95	42.83	0.16	0.54	48.47	20.61	7.60	5.65	17.14
Mixed	HW	50.48	5.94	42.80	0.16	0.54	48.46	20.59	7.66	5.63	17.11
Pine	SW	52.19	5.67	37.37	0.41	4.30	39.21	16.47	27.77	12.25	0.00
Sequoia	SW	50.67	5.98	42.91	0.05	0.36	48.68	20.44	7.95	5.26	17.32
Fir	SW	50.55	5.82	41.22	0.10	2.21	46.89	19.60	13.84	5.81	11.66
Poplar	HW	48.51	5.88	44.29	0.29	1.00	51.75	21.53	0.00	3.17	22.54
Eucalyptus	HW	48.50	5.89	44.43	0.28	0.75	52.22	21.72	0.00	3.05	22.26
Ecoblock	HW	51.48	5.92	42.03	0.14	0.43	47.87	19.88	14.08	5.66	12.08
Oak	HW	49.47	5.73	44.03	0.45	0.26	50.58	20.94	2.69	3.83	21.69
Coconut	HW	51.27	5.88	41.78	0.23	0.65	47.84	19.75	14.52	5.47	11.78
Fir	SW	50.40	5.80	41.40	0.10	2.20	47.23	19.49	12.96	5.22	12.90
Sequoia	SW	53.50	5.90	40.15	0.10	0.30	45.78	18.84	27.56	7.52	0.00
Eucalyptus	HW	49.04	5.88	44.01	0.30	0.76	50.95	20.95	1.48	3.35	22.51
Hazelnut	HW	47.79	5.78	43.79	0.76	1.43	51.86	21.31	0.00	2.77	22.64
Sequoia	SW	53.50	5.90	40.30	0.10	0.20	46.29	18.93	27.60	6.98	0.00
Eucalyptus	HW	48.32	5.89	45.12	0.15	0.52	54.18	22.10	0.00	1.97	21.24
Oak	HW	49.50	5.70	41.30	0.20	3.30	47.29	19.14	10.81	4.27	15.19
Cherry tree	HW	49.52	5.81	42.97	0.31	1.35	49.36	19.95	5.46	3.62	20.26
Unidentified	HW	49.00	6.00	44.60	0.00	0.30	52.14	20.90	0.10	2.42	24.14
Robinia	HW	48.73	5.66	41.71	1.00	2.90	48.28	19.28	7.36	3.49	18.68
Walnut	HW	49.86	5.83	43.30	0.22	0.78	49.80	19.88	5.57	3.30	20.68
Walnut	HW	49.80	5.82	43.25	0.22	0.85	49.76	19.87	5.56	3.29	20.66
Oak	HW	47.81	5.93	44.12	0.12	2.00	52.61	20.95	0.00	1.76	22.69
Fir	SW	48.52	5.81	44.66	0.25	0.72	52.72	20.73	0.00	1.75	24.08
Apricot	HW	51.39	6.29	41.82	0.20	0.20	49.07	19.26	14.29	3.65	13.53
Palm	HW	47.98	5.26	36.61	1.17	8.81	44.16	17.28	25.77	3.98	0.00
Olive	HW	49.20	5.40	37.90	0.70	6.60	46.06	17.90	25.99	3.45	0.00
Almond	HW	46.49	5.44	41.22	0.97	5.87	48.24	18.65	3.24	2.06	21.95
Spruce	SW	49.53	5.77	44.01	0.19	0.48	51.27	19.44	3.36	1.72	23.73
Vine	HW	48.15	5.61	42.84	0.81	2.59	50.23	19.05	3.14	1.67	23.33
Almond	HW	50.30	5.62	41.71	0.64	1.72	49.04	18.54	13.77	2.44	14.49
Almond	HW	48.85	5.51	40.94	0.80	3.90	48.30	18.01	11.73	1.95	16.10
Hazelnut	HW	52.90	5.60	38.70	1.40	1.40	45.44	16.82	32.09	4.25	0.00
Walnut	HW	49.98	5.71	43.35	0.21	0.71	50.68	18.75	6.85	1.50	21.51

Table 3.1 (Continued)

Oak	HW	49.67	5.93	44.02	0.07	0.30	51.67	19.10	3.49	1.18	24.27
Spruce	SW	51.06	5.75	42.29	0.11	0.77	50.10	18.34	14.40	1.61	14.79
Cotton	HW	45.97	5.35	41.99	0.84	5.48	50.16	18.05	0.74	0.32	25.25
Oak	HW	49.76	5.40	39.29	0.15	5.30	48.48	17.44	23.89	1.00	3.89
Cherry tree	HW	46.93	5.97	39.29	1.11	6.63	47.74	17.12	9.47	0.92	18.12
Walnut	HW	49.74	5.63	43.16	0.37	1.08	50.93	18.25	7.25	0.81	21.69
Walnut	HW	49.72	5.63	43.14	0.37	1.07	50.94	18.25	7.25	0.81	21.69
Oak	HW	48.99	5.93	42.58	0.33	2.10	44.20	34.00	2.53	1.64	15.53
Kukui	HW	55.12	5.54	37.55	0.34	1.43	40.61	13.94	38.54	5.48	0.00
Leucaena	HW	47.89	5.84	43.29	0.41	2.50	50.29	21.72	0.43	4.30	20.78
Hickory	HW	49.70	6.50	43.10	0.00	0.70	45.14	34.61	2.22	1.47	15.86
Willow	HW	49.25	5.99	42.66	0.60	1.40	44.20	33.11	3.07	1.29	16.93
Maple	HW	49.88	6.09	43.26	0.14	0.60	44.59	33.22	3.09	1.21	17.30
Pine	SW	50.22	6.17	43.17	0.16	0.26	44.41	32.89	3.59	1.23	17.62
Data from Idaho National Laboratory[80]											
Eucalyptus	HW	50.87	5.70	41.99	0.22	1.22	39.80	11.90	8.86	7.52	30.16
Hybrid Poplar	HW	49.95	6.12	41.98	0.31	1.64	52.24	15.87	8.08	22.16	0.00
Juniper	SW	52.67	6.08	37.83	0.55	2.87	34.79	8.91	7.77	45.66	0.00
Lodge Pole Pine	SW	50.25	6.54	41.70	0.14	1.36	52.47	7.51	0.00	38.66	0.00
Pine	SW	50.80	6.22	41.01	0.54	1.43	45.25	9.89	0.00	43.43	0.00
Pinyon Juniper	SW	50.98	5.89	38.61	0.27	4.25	34.44	11.94	6.98	39.19	3.16
Pinyon Pine	SW	52.62	6.27	38.69	0.55	1.87	37.79	8.96	2.85	48.53	0.00
Shrub Willow	HW	49.20	6.09	42.71	0.31	1.69	46.79	16.97	0.10	32.60	1.81
Data from Phyllis2[81]											
Bamboo	HW	48.04	6.11	42.57	0.58	2.70	47.46	21.89	0.20	27.74	0.00
Bamboo	HW	44.16	5.64	44.08	0.75	5.37	45.78	20.01	0.00	11.13	17.70
Bamboo Sawdust	HW	46.06	5.75	46.18	0.19	1.83	43.37	28.03	0.00	1.90	24.86
Pine Wood	SW	48.23	6.30	43.75	0.13	1.59	45.15	39.36	2.92	10.97	0.00
Douglas Fir Wood	SW	49.95	6.31	42.80	0.17	0.77	56.93	14.03	3.77	24.49	0.00
Pyrenean Oak Wood	HW	48.87	6.37	38.01	2.70	4.05	49.79	12.31	0.20	33.65	0.00
Pyrenean Oak Wood	HW	48.71	6.53	39.25	2.51	3.00	51.44	17.21	0.00	28.35	0.00
Literature Data[58,76,90–99,82,100–109,83,110–116,84–89]											
Olive Branch	HW	48.77	6.08	40.59	1.06	3.50	34.67	24.02	0.00	37.81	0.00
Kiwi Branch	HW	49.01	5.59	42.42	0.78	2.20	32.98	34.24	14.30	0.00	16.27
Pine Bark	SW	51.00	5.19	42.02	0.69	1.10	32.81	14.46	12.69	0.00	38.94
Almond Tree Pruning	HW	50.63	6.42	40.82	0.79	1.34	42.19	25.17	2.88	28.42	0.00
Softwood bark	SW	51.87	5.85	39.39	0.39	2.50	22.40	22.28	7.13	31.92	13.52

Table 3.1 (Continued)

Hardwood rich in fibres	HW	49.00	5.89	43.01	0.29	1.80	43.27	30.00	14.31	7.78	2.79
Softwood	SW	51.67	6.05	40.67	0.20	1.41	45.98	24.50	17.22	10.89	0.00
Hardwood	HW	49.11	6.27	41.53	0.39	2.70	44.79	31.01	4.48	17.02	0.00
Wood Bark	SW	52.25	6.00	39.95	0.19	1.60	24.80	29.80	13.60	30.20	0.00
Spruce Wood	SW	51.54	6.06	40.61	0.29	1.50	50.29	20.99	16.70	10.52	0.00
Beech Wood	HW	50.67	6.35	42.17	0.41	0.40	45.84	31.83	6.93	14.99	0.00
Beech Wood	HW	46.90	6.20	45.90	0.30	0.70	50.53	24.83	0.00	21.26	2.69
Spruce Wood	SW	48.30	6.30	44.60	0.40	0.40	47.59	22.89	0.00	29.12	0.00
Wood Chips	SW	46.17	5.87	47.39	0.08	0.48	38.31	38.31	0.00	2.47	20.42
Jatropha De-oiled Cake	SW	56.78	7.06	29.10	5.56	1.51	55.47	17.21	8.38	17.43	0.00
Willow	HW	49.55	6.45	39.62	2.68	1.70	57.90	16.91	3.53	19.96	0.00
Silver Fir	SW	50.96	6.37	42.00	0.20	0.47	53.46	15.39	5.07	25.61	0.00
Holm Oak	HW	46.78	5.75	44.44	0.49	2.54	40.32	27.56	0.00	8.14	21.43
Stone Pine	SW	50.01	5.95	42.96	0.30	0.78	44.08	21.61	9.38	15.06	8.93
Pyrenean Oak	HW	47.19	5.74	43.88	0.49	2.70	36.41	27.39	0.00	11.14	22.37
Bonbogori	HW	54.05	6.00	38.37	0.22	1.36	62.94	10.66	23.51	1.53	0.00
Moj	HW	51.35	6.09	40.58	0.30	1.68	63.48	7.56	15.55	11.73	0.00
Woody Waste	SW	48.09	6.68	44.80	0.10	0.33	41.42	31.96	0.00	26.29	0.00
Waste Square Timber	SW	46.94	6.56	45.85	0.10	0.55	44.17	24.26	0.00	31.03	0.00
Plywood	SW	42.55	5.81	43.68	1.69	6.27	40.77	24.58	0.00	21.37	7.01
Spruce Wood	SW	49.03	6.13	44.55	0.08	0.21	48.78	13.74	0.00	25.85	11.42
Pine	SW	48.55	5.76	44.37	0.02	1.30	48.15	22.20	9.04	0.00	19.31
Birch	HW	47.00	6.19	46.50	0.11	0.20	39.92	38.92	0.00	17.51	3.45
Spruce	SW	47.37	6.30	46.17	0.07	0.10	43.96	26.97	0.00	24.99	3.98
Pine	SW	46.87	6.30	46.67	0.07	0.10	42.96	26.97	0.00	24.03	5.94
Pine	SW	48.33	5.88	43.23	0.49	2.07	46.81	17.33	1.11	18.34	14.09
Beech	SW	49.73	6.29	43.04	0.40	0.53	46.15	31.53	5.39	16.39	0.00
Pinewood Sawdust	SW	49.19	6.10	44.08	0.08	0.56	53.70	21.88	8.82	15.05	0.00
Spruce	SW	48.76	6.23	44.60	0.15	0.26	49.38	22.66	0.00	27.71	0.00
Salix	HW	47.23	5.94	44.65	1.03	1.16	49.98	23.20	0.00	15.07	10.58
Poplar - Sapwood	HW	51.47	6.13	42.20	0.00	0.20	48.82	17.30	13.06	20.62	0.00
Poplar - Heartwood	HW	51.21	6.51	42.16	0.00	0.12	50.91	13.79	0.10	35.08	0.00
Norway Spruce	SW	50.28	6.20	43.19	0.10	0.23	42.33	26.20	4.86	26.38	0.00
Spruce Bark	SW	46.39	6.21	42.16	0.00	5.24	41.89	26.93	0.00	25.93	0.00
Eucalyptus Sawdust	HW	49.35	5.72	43.90	0.17	0.86	42.31	30.89	13.37	0.00	12.56
Pine	SW	49.33	6.39	43.44	0.20	0.63	38.77	24.21	0.00	36.38	0.00
Hybrid Poplar	HW	50.05	5.91	42.54	0.30	1.20	50.34	21.04	19.11	6.17	2.11

Table 3.1 (Continued)

Subabul Wood	HW	48.16	5.89	45.06	0.00	0.89	44.57	26.88	2.51	7.00	17.83
Pine Chip	SW	47.19	6.64	45.74	0.17	0.27	53.87	16.85	0.00	29.01	0.00
Logging Residue Chip	SW	46.87	6.15	44.79	0.42	1.77	47.89	16.94	0.00	26.79	6.62
Fir Wood	SW	48.30	5.92	41.87	0.42	3.49	39.86	31.47	9.13	16.05	0.00
Pine Bark	SW	51.25	5.37	40.55	0.01	2.82	15.60	44.39	18.30	0.00	18.89
Bambusa vulgaris	HW	46.01	6.24	45.63	0.18	1.95	46.50	24.08	0.00	24.75	2.72
Bambusa vulgaris	HW	46.37	6.33	45.70	0.18	1.43	47.26	24.65	0.00	26.66	0.00
Bambusa vulgaris	HW	45.35	6.19	45.79	0.26	2.40	46.49	24.98	0.00	22.47	3.66
Lauan	HW	48.64	6.75	44.24	0.10	0.27	40.38	15.70	0.00	43.65	0.00
Patula Pine	SW	55.52	7.12	36.85	0.19	0.32	48.79	9.21	4.90	36.78	0.00

Note: db – dry basis; C – Carbon content; H – Hydrogen content; O – Oxygen content; N – Nitrogen content; Ash – Ash content; CELL – Cellulose content; HEMI – Hemicellulose content; LIGC – Lignin-C content; LIGH – Lignin-H content; LIGO – Lignin-O content; HW – Hardwood; SW – Softwood.

Results of Energy Consumption and GHG Emission for Activated Carbon Production

Fossil-based and biogenic GHG were tracked separately in this study given the debate of accounting biogenic GHG.[117] Some studies set the characterization factor of biogenic CO_2 as zero according to the carbon-neutral assumption.[13,118,119] Fossil-based GHG emissions were generated from burning natural gas that was assumed to be the sole fossil fuel used in the AC production.[120] Biogenic GHG emissions were generated from both energy recovery (burning pyrolysis gas products) and the activation process (GHG as byproducts). Both fossil-based and biogenic GHG are converted to the same unit (kg CO_2 eq./kg AC) by applying the latest 100-year Global Warming Potential conversion factors from IPCC, which distinguishes methane from biogenic and fossil sources (the GWP conversion factor is 30 for fossil methane and 28 for biogenic methane).[121]

Table 3.3 lists the average, minimum, maximum, and standard deviation (STD) for 250 data samples of different biomass feedstocks. These ranges are consistent with the results of previous LCA studies using woody biomass (Table 1.1). Some observations can be identified from Table

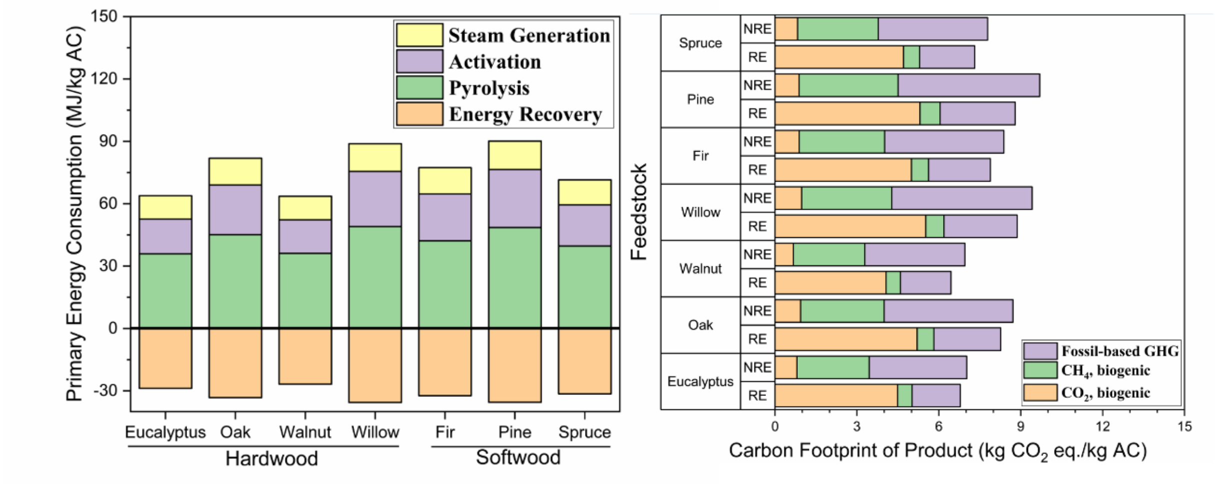
3.3. First, there are large variations in energy consumption and fossil-based/biogenic GHG emission of steam AC production across different types of biomass. Second, although the average energy consumption and GHG emission of softwood are higher than that of hardwood, there are large overlaps between the softwood and hardwood for the Min-Max results across all categories. The differences between hardwood and softwood could be more remarkable if more characterization data is available (e.g. textural properties, lignocellulose composition, morphology). Third, energy recovery reduces the primary energy consumption and fossil-based GHG emissions by burning gas byproducts as biogenic fuel sources (and as a result biogenic GHG emissions increases).

Table 3.2 Variability in primary energy consumption, fossil-based and biogenic GHG emissions

	Softwood		Hardwood		Total	
	Average (Min-Max)	STD[a]	Average (Min-Max)	STD[a]	Average (Min-Max)	STD[a]
E_{NRE} (MJ/kg AC)	101 (43-224)	32	88 (43-277)	32	93 (43-277)	33
E_{RE} (MJ/kg AC)	65 (25-155)	23	57 (23-208)	24	60 (23-207)	24
Fossil $\mathrm{GHG}_{\mathrm{NRE}}$ (kg CO_2-eq./kg AC)	8.7 (4.2-18.8)	2.6	7.4 (4.0-22)	2.4	7.9 (4.0-22)	2.6
Fossil $\mathrm{GHG}_{\mathrm{RE}}$ (kg CO_2-eq./kg AC)	4.0 (1.7-9.3)	1.4	3.5 (1.5-12)	1.4	3.7 (1.5-12)	1.4
Biogenic $\mathrm{GHG}_{\mathrm{NRE}}$ (kg CO_2-eq./kg AC)	5.1 (2.7-12)	1.5	4.3 (2.4-13)	1.4	4.6 (2.4-13)	1.5
Biogenic $\mathrm{GHG}_{\mathrm{RE}}$ (kg CO_2-eq./kg AC)	6.7 (3.4-14)	1.9	5.9 (3.4-16)	1.8	6.2 (3.4-16)	1.9

[a] STD: Standard deviation; RE: with energy recovery; NRE: without energy recovery

To understand the major contributors to both energy and GHG emissions results, the breakdown results of 4 types of common hardwood (i.e., eucalyptus, oak, walnut, willow) and 3 types of common softwood (i.e., fir, pine, spruce) were shown in Figure 3.1. Because more than one data sample of biomass characterization was collected from literature, the average values of the results for each type of wood were shown.



(a) (b)

Figure 3.1 Average primary energy consumption (a) and carbon footprint (b) of steam AC production from different woody biomass species

In Figure 3.1(a), the energy demand by different unit processes in the AC production is shown as positive and the energy recovered by burning flue gas is shown as negative. Figure 3.1(a) shows that across all the different biomass species, pyrolysis has the largest energy demand (53-57% without energy recovery), which is consistent with the literature.[33,41,44] Across seven feedstocks, 72-80% of the pyrolysis energy consumption can be supplied by the energy recovered from flue gas, which is also consistent with the previous study (~75%).[67] For the entire AC production process, at most 45% of the primary energy consumption can be recovered by burning flue gas from pyrolysis, indicating the importance of including energy recovery in AC production.

Figure 3.1(b) shows the average results of the carbon footprint of AC production from seven types of woody biomass. The CO_2 and CH_4 from pyrolysis and steam activation as byproducts, and in the case of energy recovery from flue gas combustion of the pyrolysis gases, are considered as biogenic as the carbon is originally from biomass. Figure 3.1(b) shows that without energy recovery most of the GHG emissions were from natural gas combustion. When energy recovery from pyrolysis gas combustion is included, most of the GHG emissions come from biogenic sources. The biogenic carbon emission can be sequestrated by the regrowth of the plant, which was not included in this study as the carbon sequestration capacity of different wood species is highly variable and depends on regional climate and forest management practices. However, carbon sequestration could be easily incorporated into this framework in future work. Given the large contribution of biogenic carbon in the results (69-74%) it is clear that the GHG emissions of AC production with energy recovery will be much lower if carbon sequestration from biomass is included.

Impacts of Biomass Feedstock Characteristics

To further understand the impacts of biomass feedstocks on AC production energy and carbon footprints, the results of 250 data samples were plotted with different biomass compositions (see Table 3.1). The results indicated that hydrogen content and hydrogen/carbon ratio (H/C ratio) are two parameters strongly correlated with GHG emissions (see Appendix B, figure B.1 and figure B.2) and primary energy consumption as shown in Figure 3.2(a) - (b). For both softwood and hardwood, increasing the hydrogen content increases the primary energy consumption, except for a few samples that show decreased energy consumption with hydrogen content higher than 6.5%. Since the carbon contents for these outliers are relatively higher than other data samples, figure 3.2(b) plots energy consumption and H/C ratio to eliminate the influence of the carbon content, which shows similar trends as Figure 3.2(a) but with a more scattered distribution of results. The results of the scenario without energy recovery have similar trends and shown in figures of Appendix B.

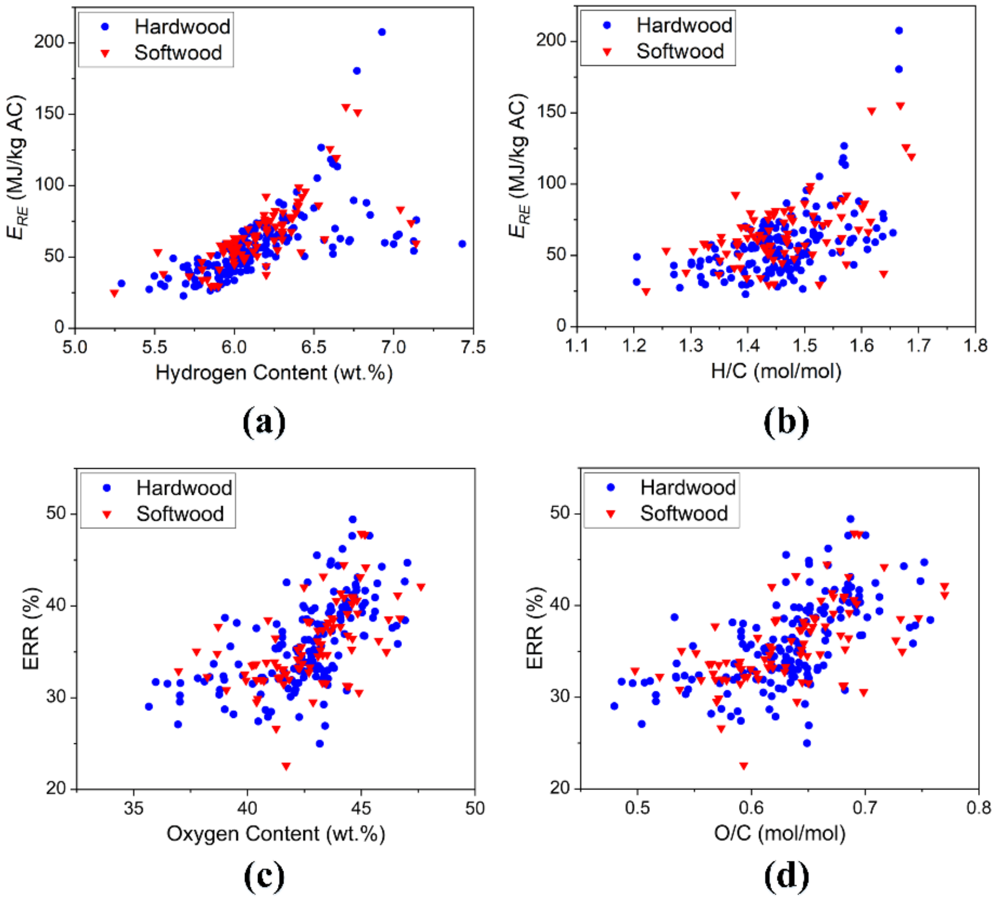


Figure 3.2 Impacts of feedstock characteristics on the primary energy consumption ((a) – impact of hydrogen content, (b) – impact of hydrogen to carbon ratio) and energy recovery potential ((c) – impact of oxygen content, (d) – impact of oxygen to carbon ratio) of AC production

The large impacts of hydrogen and H/C ratios can be explained by their impacts on the AC yields. A high H/C ratio in biomass feedstock usually indicates a lower percentage of aromatic carbon, which may lead to low AC yields given the important role of aromatic carbon in steam activation.[2,125] Such information could be helpful for future biomass selection and process design, it also demonstrates the unique capability of the modeling framework presented in this study.

A similar approach was applied to ERR, the indicator of energy recovery (see Figure B.4 of Appendix B). Two parameters, oxygen content and O/C ratio, show correlations with ERR as shown in Figure 3.3(c)-(d). For both hardwood and softwood, the higher oxygen content of biomass or atomic O/C ratio, the higher ERR in the steam AC production process. This higher O/C ratio is indicative of a higher carbohydrate content, and hemicellulose in particular are known to be less stable and generate more gas and vapor products under pyrolysis conditions.[126] Thus feedstocks with higher O/C ratios will produce more gases and vapors that are important for energy recovery. Based on the discussion above, one conclusion is that choosing biomass with lower hydrogen contents, H/C ratio and higher oxygen contents, O/C ratio is beneficial from energy and GHG emissions perspectives.

Sensitivity Analysis Results

In addition to biomass characteristics, another set of parameters that have large impacts on pyrolysis and steam activation processes are operational conditions. A sensitivity analysis was conducted to understand the impacts of varied biomass composition and operational conditions on the energy and GHG emissions of AC. The typical value and upper/lower bounds of all parameters were determined by the literature review and documented in Table 3.2.[51,65,122–124] The LCI data generated by the integrated model for 250 data samples were provided in Appendix A.

Table 3.3 The baseline and ranges of input parameters used in the sensitivity analysis

	Baseline	Lower Bound	Upper Bound	Ref.
Carbon Content (wt%)	49.59	42.55	55.52	[a]
Hydrogen Content (wt%)	6.02	5.05	7.19	[a]
Ash Content (wt%)	2.14	0.1	10.62	[a]
Pyrolysis Temperature (℃)	500	300	700	[122]
Pyrolysis Time (min)	60	10	120	[51]
Activation Temperature (℃)	800	750	900	[123]
Activation Time (min)	60	45	75	[124]
Steam to Biochar Ratio (kg/kg)	2	1.35	5.4	[65]

[a] Based on the dataset

The results of sensitivity analysis for primary energy consumption and biogenic GHG emissions are shown in Figure 3.3 (see Figure B.5 in Appendix B for the results without energy recovery and the results for fossil-based GHG emissions). Figure 3.3 indicates that among different biomass characteristics, hydrogen content and ash content are both important. The importance of hydrogen is already discussed previously. The effects of ash are complex. Active alkali ash species (e.g., sodium, potassium, calcium) can impact the decomposition of the biomass carbohydrate fraction in particular during the pyrolysis process, which in turn will affect the ratio of biochar to pyrolysis vapors and thus the final AC yield will also be affected.[127]

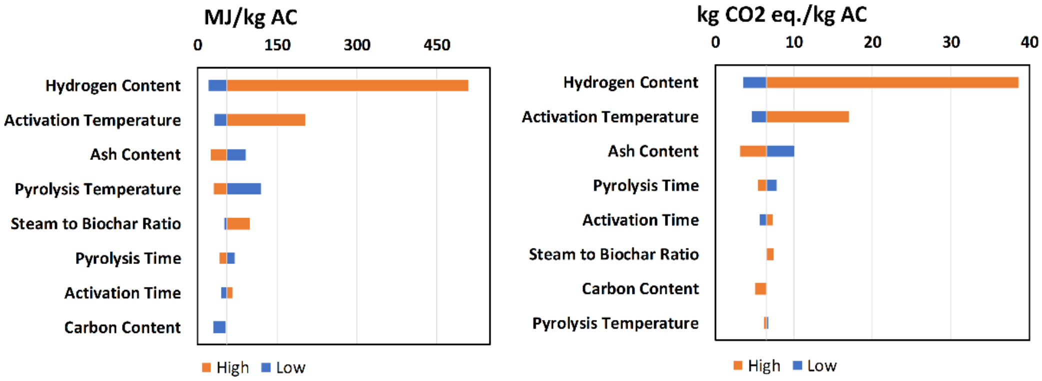


Figure 3.3 Sensitivity analysis for the energy consumption and biogenic GHG emission (with energy recovery) of the steam AC production process

Among different operating parameters, the activation temperature has the greatest impact. This is due to its large impact on the final AC yield, and associated heat duty on the furnace and boiler. In general, choosing biomass with low hydrogen contents and setting the low temperature for steam activation and pyrolysis processes are beneficial from energy and GHG emissions perspectives.

Limitations

There are some limitations of the modeling framework presented in this study. While understanding the primary energy consumption and GHG emissions for AC production are useful, the AC product must meet a series of performance specifications demanded by the market. For example, the adsorption capacity of AC is a key parameter determining the effectiveness of applications such as contamination removal in water and associated prices. This parameter was not included in this study due to the lack of data. The authors previously published a study to use ANN to predict the BET surface area of AC, which could be used as an initial proxy of the adsorption capacity of AC.[51] In that study, a contribution analysis was conducted to understand the impacts of variations in feedstocks and process operations on the yields and BET surface area of AC produced. The results indicated that both yields and BET surface area of AC are highly driven by the variations of feedstock composition (e.g., ash and carbon content) and operational conditions of steam activation (e.g., activation temperature and steam to carbon ratio). Depending on the applications, other performance specifications may be expected for AC such as iodine number and methylene blue index.[128] Previous literature indicated that these specifications are affected by process and feedstock variations, which could be the future research direction for the authors if sufficient experimental data are available. Another limitation is the procedure used to estimate the quality and heating value of the intermediate pyrolysis gases, which could be further improved with the improvement of pyrolysis kinetic models in the future. Finally, this study does not include other biomass-related parameters such as particle size due to their relatively low impacts on the results based on previous studies.[129] In addition, the oven-dried biomass used in the present study avoided the influence of the moisture content, which may have some impact and needs additional clarification when evaluating the cradle-to-gate AC production process that is a larger system boundary than this gate-to-gate study. This limitation can be addressed by adding additional drying processes in future work.

Conclusions

In conclusion, this work developed a modeling framework that integrates ANN and kinetic-based process simulation models to estimate the gate-to-gate primary energy consumption and GHG emissions across a variety of woody biomass. The LCI generated by the integrated models can be used as data sources for future LCAs of AC or industrial systems using AC materials. To understand opportunities for reducing energy consumption and GHG emissions from AC production, the key driving factors were identified and the impacts of variations were quantified. Furthermore, the results of this study indicated the importance of feedstock selection and operation of AC production from an environmental sustainability perspective. Both the results and modeling framework can be used by engineers and project managers to select biomass feedstocks and improve process operations. Although this study focused on woody biomass and AC production, the modeling framework can be applied to other types of biomass and other biomass utilization technologies. The ranges and distributions of the primary energy consumption and GHG emissions estimated in this study can also be used as transparent and reliable data sources for future LCA and Techno-Economic Assessment.

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APPENDICES

Appendix A

Table A.1 Life cycle inventory data generated for steam AC production using different biomass species (without energy recovery)

		Inputs				Outputs					
Case	Biomass feedstock type	Dry biomass	Water	Nitrogen	Natural gas	Biogenic CO_2	Biogenic CH_4	Fossil CO_2	Fossil CH_4	Fossil N_2O	Other gases
	Unit	kg/kg AC	kg/kg AC	kg/kg AC	MJ/kg AC	kg/kg AC	kg/kg AC	kg/kg AC	kg/kg AC	kg/kg AC	kg/kg AC
1	Ailanthus	7.0541	3.5390	1.1757	118.6958	1.9203	0.1347	5.9647	1.12E-04	1.12E-05	8.7137
2	Ailanthus	7.4586	3.8456	1.2431	132.5877	2.3058	0.1361	6.6628	1.26E-04	1.26E-05	9.1055
3	Almond	4.2082	2.3385	0.7014	52.1678	0.8234	0.0695	2.6216	4.94E-05	4.94E-06	5.3551
4	Almond	5.8310	2.8466	0.9718	85.3896	1.4703	0.0979	4.2910	8.09E-05	8.09E-06	7.0813
5	Almond	5.1030	2.6222	0.8505	70.6697	1.1450	0.0892	3.5513	6.69E-05	6.69E-06	6.3415
6	Almond	5.6445	3.1417	0.9407	89.5980	1.5286	0.1030	4.5025	8.49E-05	8.49E-06	7.0952
7	Almond	5.4764	3.0857	0.9127	86.4041	1.3905	0.1013	4.3420	8.18E-05	8.18E-06	6.9831
8	Almond	4.4711	2.5090	0.7452	60.9842	0.9125	0.0784	3.0646	5.78E-05	5.78E-06	5.7344
9	Almond	5.6539	3.2702	0.9423	94.2131	1.5690	0.0988	4.7344	8.92E-05	8.92E-06	7.1986
10	Almond	4.0809	2.5039	0.6801	54.8825	0.8842	0.0725	2.7580	5.20E-05	5.20E-06	5.3083
11	Almond	4.6005	2.4683	0.7668	63.1454	0.9177	0.0842	3.1732	5.98E-05	5.98E-06	5.8336
12	Almond	4.7507	3.1469	0.7918	81.2377	1.2188	0.0947	4.0824	7.69E-05	7.69E-06	6.3760
13	Almond Tree Pruning	6.8749	3.6198	1.1458	123.9690	1.8307	0.1491	6.2297	1.17E-04	1.17E-05	8.6608
14	American Ash (White Ash)	13.8696	6.7349	2.3116	276.7239	5.0478	0.2505	13.9060	2.62E-04	2.62E-05	16.6178
15	Apricot	7.1731	3.7207	1.1955	127.1450	2.0190	0.1350	6.3893	1.20E-04	1.20E-05	8.9354
16	Babassu	4.0867	2.1349	0.6811	50.3060	0.6616	0.0817	2.5280	4.76E-05	4.76E-06	5.1595
17	Bamboo (Bambusa Vulgaris)	6.4147	3.2453	1.0691	101.8727	1.5583	0.1317	5.1193	9.65E-05	9.65E-06	8.0391
18	Bamboo (Bambusa vulgaris) - Bottom	7.2704	3.6216	1.2117	111.2762	1.9321	0.1479	5.5919	1.05E-04	1.05E-05	9.0237
19	Bamboo (Bambusa vulgaris) - Middle	8.0372	3.9051	1.3395	126.8493	2.2061	0.1664	6.3745	1.20E-04	1.20E-05	9.9092
20	Bamboo (Bambusa vulgaris) - Top	6.9348	3.4820	1.1558	102.7037	1.8330	0.1391	5.1611	9.73E-05	9.73E-06	8.6005
21	Bamboo (Guadua amplexifolia Prestl)	4.7373	2.6022	0.7896	58.5346	1.0355	0.0848	2.9415	5.54E-05	5.54E-06	6.0087
22	Bamboo Sawdust	4.3309	2.2059	0.7218	47.8939	0.8472	0.0757	2.4068	4.54E-05	4.54E-06	5.3358

Table A.1 (Continued)

23	Beech	6.1384	2.6816	1.0231	85.5111	1.3774	0.1065	4.2971	8.10E-05	8.10E-06	7.3592
24	Beech	6.8183	3.2954	1.1364	110.5829	1.7922	0.1435	5.5571	1.05E-04	1.05E-05	8.3145
25	Beech	6.2501	3.0489	1.0417	97.1348	1.5637	0.1168	4.8813	9.20E-05	9.20E-06	7.6601
26	Beech Wood	5.8089	2.6579	0.9682	77.8270	1.2299	0.1150	3.9110	7.37E-05	7.37E-06	7.0901
27	Beech Wood	5.2785	2.6350	0.8797	81.4411	1.1611	0.1063	4.0926	7.71E-05	7.71E-06	6.5258
28	Birch	6.4063	3.1743	1.0677	91.9895	1.7298	0.1312	4.6227	8.71E-05	8.71E-06	7.7871
29	Birch	7.4642	3.2505	1.2440	115.5390	1.9359	0.1407	5.8061	1.09E-04	1.09E-05	8.8821
30	Birch	5.8629	2.5889	0.9771	80.9139	1.3040	0.1063	4.0661	7.66E-05	7.66E-06	7.0185
31	Birch	11.2368	5.4002	1.8728	215.1742	3.6244	0.2139	10.8130	2.04E-04	2.04E-05	13.6715
32	Bonbogori	4.8478	2.3905	0.8080	76.9446	0.8100	0.0846	3.8667	7.29E-05	7.29E-06	6.1517
33	Camphor	6.6868	3.3581	1.1145	110.4983	1.7585	0.1266	5.5528	1.05E-04	1.05E-05	8.2742
34	Casuarina	5.5849	2.6935	0.9308	79.1254	1.2683	0.0975	3.9762	7.49E-05	7.49E-06	6.8434
35	Cedar	8.7895	3.6973	1.4649	142.4139	2.4017	0.1673	7.1566	1.35E-04	1.35E-05	10.3828
36	Cedar	5.7018	3.2679	0.9503	102.5425	1.4033	0.1228	5.1530	9.71E-05	9.71E-06	7.3939
37	Cherry	5.1883	2.4021	0.8647	92.2282	0.9670	0.1022	4.6347	8.73E-05	8.73E-06	6.3859
38	Cherry tree	5.2156	2.6035	0.8693	73.3087	1.1369	0.0925	3.6839	6.94E-05	6.94E-06	6.4590
39	Cherry tree	5.6008	3.3125	0.9335	92.6093	1.5254	0.0938	4.6538	8.77E-05	8.77E-06	7.2276
40	Cherry tree	5.5286	2.9201	0.9214	84.4608	1.4100	0.0994	4.2444	8.00E-05	8.00E-06	6.8607
41	Cocoa	4.1121	2.7357	0.6853	61.7005	0.9086	0.0824	3.1006	5.84E-05	5.84E-06	5.5420
42	Cocoa	3.7169	2.9045	0.6195	62.0020	0.8578	0.0812	3.1157	5.87E-05	5.87E-06	5.3019
43	Cocoa	3.8563	2.9177	0.6427	64.7122	0.8822	0.0858	3.2519	6.13E-05	6.13E-06	5.4488
44	Coconut	5.6010	2.9734	0.9335	88.5331	1.3306	0.1069	4.4490	8.38E-05	8.38E-06	7.0704
45	Coconut	3.7956	2.3391	0.6326	50.1390	0.7599	0.0685	2.5196	4.75E-05	4.75E-06	4.9390
46	Coconut	3.8541	2.2113	0.6424	49.5396	0.7033	0.0687	2.4895	4.69E-05	4.69E-06	4.9358
47	Cotton	4.4637	2.4035	0.7440	55.0926	0.9134	0.0726	2.7685	5.22E-05	5.22E-06	5.6251
48	Cotton	3.9589	2.1069	0.6598	43.4498	0.6765	0.0633	2.1835	4.12E-05	4.12E-06	4.9859
49	Cotton	6.2491	3.2056	1.0415	100.4367	1.6088	0.1180	5.0472	9.51E-05	9.51E-06	7.7695
50	Cotton	6.2467	3.2044	1.0411	100.3839	1.6077	0.1180	5.0445	9.51E-05	9.51E-06	7.7665
51	Cypress	4.8688	2.8246	0.8115	92.4088	1.0121	0.1243	4.6438	8.75E-05	8.75E-06	6.3685

Table A.1 (Continued)

52	Douglas Fir	7.2381	3.5672	1.2063	123.5606	1.9614	0.1455	6.2092	1.17E-04	1.17E-05	8.9047
53	Douglas Fir	6.2374	3.4427	1.0396	114.8053	1.6212	0.1437	5.7692	1.09E-04	1.09E-05	7.9549
54	Douglas Fir Wood	7.5457	3.3471	1.2576	124.4555	1.7757	0.1536	6.2542	1.18E-04	1.18E-05	9.2211
55	Ecoblock	5.7086	3.0055	0.9514	91.0754	1.3680	0.1090	4.5768	8.63E-05	8.63E-06	7.1885
56	Elm	9.4754	4.1935	1.5792	171.7925	2.6190	0.1797	8.6330	1.63E-04	1.63E-05	11.4495
57	Elm	9.4818	4.1551	1.5803	171.3491	2.6607	0.1810	8.6107	1.62E-04	1.62E-05	11.3754
58	Eucalyptus	4.8996	2.1686	0.8166	58.7401	0.9219	0.0837	2.9518	5.56E-05	5.56E-06	5.8793
59	Eucalyptus	5.3217	2.4401	0.8869	69.9131	1.1087	0.0909	3.5133	6.62E-05	6.62E-06	6.4492
60	Eucalyptus	5.1756	2.3532	0.8626	66.4128	1.0367	0.0879	3.3374	6.29E-05	6.29E-06	6.2669
61	Eucalyptus	5.1607	2.4275	0.8601	68.4170	1.0650	0.0892	3.4381	6.48E-05	6.48E-06	6.2941
62	Eucalyptus	4.0960	2.2892	0.6827	50.6899	0.8070	0.0701	2.5473	4.80E-05	4.80E-06	5.1908
63	Eucalyptus	6.1465	3.2853	1.0244	102.5744	1.5953	0.1182	5.1546	9.71E-05	9.71E-06	7.7426
64	Eucalyptus	6.0476	3.2362	1.0079	100.3355	1.6084	0.1194	5.0421	9.50E-05	9.50E-06	7.5639
65	Eucalyptus	4.9816	2.8516	0.8303	76.4254	1.1735	0.0978	3.8406	7.24E-05	7.24E-06	6.3921
66	Eucalyptus Sawdust	4.7433	2.5948	0.7905	63.9878	1.0942	0.0893	3.2155	6.06E-05	6.06E-06	5.9451
67	Fir	4.7711	2.1221	0.7952	56.5370	0.8678	0.0832	2.8411	5.35E-05	5.35E-06	5.7373
68	Fir	5.9408	2.7540	0.9901	85.3932	1.3902	0.1106	4.2912	8.09E-05	8.09E-06	7.1842
69	Fir	5.8592	2.7637	0.9765	85.6611	1.3525	0.1090	4.3047	8.11E-05	8.11E-06	7.1379
70	Fir	6.8779	3.3927	1.1463	112.1677	1.7867	0.1333	5.6367	1.06E-04	1.06E-05	8.4969
71	Fir	6.0036	3.0788	1.0006	96.8588	1.5004	0.1203	4.8674	9.17E-05	9.17E-06	7.4623
72	Fir	5.5528	3.0008	0.9255	87.8040	1.3548	0.1069	4.4124	8.32E-05	8.32E-06	7.0174
73	Fir	5.6555	3.0914	0.9426	91.1498	1.4091	0.1100	4.5805	8.63E-05	8.63E-06	7.1704
74	Fir Wood	5.9114	3.3368	0.9852	95.5653	1.5976	0.1203	4.8024	9.05E-05	9.05E-06	7.5154
75	Grape	5.1016	2.4837	0.8503	67.5359	1.0802	0.0869	3.3938	6.40E-05	6.40E-06	6.2685
76	Grape	3.6640	2.4172	0.6107	46.3144	0.7614	0.0627	2.3274	4.39E-05	4.39E-06	4.8678
77	Grape	4.6999	2.4550	0.7833	79.8760	0.9166	0.0832	4.0140	7.56E-05	7.56E-06	5.9384
78	Grape	4.8854	2.7686	0.8142	94.5677	1.0439	0.1127	4.7523	8.96E-05	8.96E-06	6.3116
79	Hardwood	6.1781	3.2405	1.0297	102.8926	1.6108	0.1216	5.1706	9.74E-05	9.74E-06	7.7159
80	Hardwood rich in fibres	5.5268	3.1139	0.9211	84.6196	1.3889	0.1040	4.2523	8.01E-05	8.01E-06	7.0690

Table A.1 (Continued)

81	Hazelnut	4.6910	2.2054	0.7818	55.3871	0.8986	0.0806	2.7833	5.25E-05	5.25E-06	5.6989
82	Hazelnut	4.0283	2.5046	0.6714	56.6029	0.8903	0.0772	2.8444	5.36E-05	5.36E-06	5.2368
83	Hazelnut	4.3013	2.6752	0.7169	66.5840	0.8420	0.0854	3.3460	6.31E-05	6.31E-06	5.7660
84	Hickory	9.5517	4.6463	1.5919	173.3564	3.1344	0.1689	8.7116	1.64E-04	1.64E-05	11.4866
85	Holm Oak	4.6059	2.4846	0.7677	58.2615	1.0081	0.0852	2.9278	5.52E-05	5.52E-06	5.7649
86	Hybird Poplar	4.7151	2.5268	0.7858	66.4198	0.9105	0.0886	3.3378	6.29E-05	6.29E-06	6.0286
87	Hybrid Poplar	4.8783	2.4357	0.8130	70.7154	0.8583	0.0985	3.5536	6.70E-05	6.70E-06	6.1703
88	Juniper	4.4017	2.7138	0.7336	76.8186	0.8342	0.1110	3.8603	7.28E-05	7.28E-06	5.9039
89	Kenaf (italy)	5.0469	2.5055	0.8411	66.1081	1.0783	0.0846	3.3221	6.26E-05	6.26E-06	6.2307
90	Kiwi Branch	4.3093	2.6453	0.7182	59.5607	1.0324	0.0866	2.9931	5.64E-05	5.64E-06	5.5538
91	Kukui	4.1805	2.8454	0.6967	71.7546	0.8591	0.0870	3.6058	6.80E-05	6.80E-06	5.7765
92	Larch	7.9603	3.9104	1.3267	143.7662	2.2909	0.1727	7.2246	1.36E-04	1.36E-05	9.7338
93	Larch	8.2501	3.9676	1.3750	147.1256	2.3688	0.1727	7.3934	1.39E-04	1.39E-05	10.0512
94	Lauan	13.1345	6.8642	2.1891	260.6620	4.3354	0.3183	13.0989	2.47E-04	2.47E-05	16.5341
95	Leucaena	5.2620	2.5654	0.8770	71.5249	1.1512	0.0895	3.5943	6.77E-05	6.77E-06	6.4637
96	Lodge Pole Pine	5.4492	2.5877	0.9082	86.7515	0.9560	0.1206	4.3595	8.22E-05	8.22E-06	6.8685
97	Logging Residue Chip	5.6280	2.7722	0.9380	78.5448	1.1976	0.1190	3.9471	7.44E-05	7.44E-06	7.0217
98	Madrone	5.7292	2.5233	0.9549	76.7891	1.2299	0.0972	3.8588	7.27E-05	7.27E-06	6.8802
99	Manzanita	5.4142	2.5660	0.9024	72.6160	1.2601	0.0928	3.6491	6.88E-05	6.88E-06	6.5297
100	Maple	5.9632	2.7260	0.9939	86.5467	1.3412	0.1131	4.3492	8.20E-05	8.20E-06	7.2287
101	Maple	6.4200	3.1649	1.0700	101.0967	1.7970	0.1171	5.0804	9.57E-05	9.57E-06	7.7408
102	Maple	6.0484	3.2010	1.0081	99.4966	1.5388	0.1158	4.9999	9.42E-05	9.42E-06	7.6029
103	Maple	6.3040	3.3298	1.0507	105.4611	1.6544	0.1213	5.2997	9.99E-05	9.99E-06	7.9087
104	Mixed	5.8511	3.1216	0.9752	90.9341	1.5595	0.1027	4.5697	8.61E-05	8.61E-06	7.2857
105	Mixed	6.0143	3.0172	1.0024	93.1792	1.4707	0.1107	4.6825	8.82E-05	8.82E-06	7.4524
106	Mixed	5.8103	3.0162	0.9684	89.0589	1.4156	0.1086	4.4754	8.43E-05	8.43E-06	7.2706
107	Mixed	5.7139	2.8543	0.9523	86.9156	1.3694	0.1053	4.3677	8.23E-05	8.23E-06	7.0458
108	Mixed	5.8928	3.0395	0.9821	92.2614	1.4551	0.1093	4.6364	8.74E-05	8.74E-06	7.3500
109	Mixed	5.7144	2.7316	0.9524	82.9643	1.3154	0.1064	4.1692	7.86E-05	7.86E-06	6.9767

Table A.1 (Continued)

110	Mixed	5.3456	2.9653	0.8909	85.8205	1.4012	0.1026	4.3127	8.13E-05	8.13E-06	6.6980
111	Moj	6.1371	2.8901	1.0229	99.6314	1.2341	0.1114	5.0067	9.44E-05	9.44E-06	7.7045
112	Mulberry	6.4960	3.5019	1.0827	112.6690	1.7564	0.1286	5.6619	1.07E-04	1.07E-05	8.1955
113	Norway Spruce	6.8473	3.4596	1.1412	114.5299	1.7926	0.1548	5.7554	1.08E-04	1.08E-05	8.5008
114	Oak	5.7693	2.7153	0.9615	80.0579	1.3285	0.0953	4.0231	7.58E-05	7.58E-06	7.0223
115	Oak	6.1451	2.6898	1.0242	85.9821	1.3931	0.1062	4.3208	8.14E-05	8.14E-06	7.3598
116	Oak	6.1049	2.7956	1.0175	88.1285	1.4402	0.1088	4.4287	8.35E-05	8.35E-06	7.3690
117	Oak	4.5369	2.1237	0.7562	54.6397	0.7857	0.0800	2.7458	5.17E-05	5.17E-06	5.5510
118	Oak	5.5736	2.6087	0.9289	78.0551	1.2196	0.0961	3.9225	7.39E-05	7.39E-06	6.7955
119	Oak	5.8288	2.9829	0.9715	88.5294	1.5412	0.1020	4.4488	8.38E-05	8.38E-06	7.1399
120	Oak	7.3512	3.7350	1.2252	124.7602	2.1867	0.1319	6.2695	1.18E-04	1.18E-05	8.9926
121	Oak	5.7289	2.8337	0.9548	85.7410	1.3709	0.1065	4.3087	8.12E-05	8.12E-06	7.0401
122	Oak	6.5532	3.0540	1.0922	108.0878	1.5625	0.1214	5.4317	1.02E-04	1.02E-05	8.0156
123	Oak	5.9146	2.9970	0.9858	91.5275	1.4672	0.1082	4.5995	8.67E-05	8.67E-06	7.3220
124	Oak	9.8418	4.2355	1.6403	177.2212	2.7207	0.1852	8.9058	1.68E-04	1.68E-05	11.8117
125	Oak	6.0554	3.0805	1.0092	95.0755	1.5033	0.1113	4.7778	9.00E-05	9.00E-06	7.5305
126	Oak	5.8940	3.2550	0.9823	98.1213	1.6034	0.1092	4.9308	9.29E-05	9.29E-06	7.4187
127	Oak	4.5294	2.8002	0.7549	68.6427	1.0330	0.0832	3.4495	6.50E-05	6.50E-06	5.9683
128	Oak	5.1769	2.8727	0.8628	78.8182	1.2416	0.0938	3.9608	7.46E-05	7.46E-06	6.5771
129	Olive	5.1313	2.4507	0.8552	67.3052	1.0712	0.0869	3.3822	6.37E-05	6.37E-06	6.2790
130	Olive	6.8749	3.4374	1.1458	113.2028	1.8366	0.1289	5.6887	1.07E-04	1.07E-05	8.4926
131	Olive	4.6531	2.9818	0.7755	72.7386	1.1680	0.0845	3.6553	6.89E-05	6.89E-06	6.1580
132	Olive	6.6185	3.1860	1.1031	117.2413	1.6149	0.1207	5.8917	1.11E-04	1.11E-05	8.1719
133	Olive	5.5012	3.3466	0.9169	105.7390	1.4310	0.1157	5.3136	1.00E-04	1.00E-05	7.2179
134	Olive	6.2524	3.4630	1.0421	114.5977	1.6242	0.1409	5.7588	1.09E-04	1.09E-05	7.9923
135	Olive	4.5726	3.0092	0.7621	80.0833	1.0636	0.1050	4.0244	7.58E-05	7.58E-06	6.1753
136	Olive	4.8564	2.7599	0.8094	86.6689	1.0436	0.0933	4.3553	8.21E-05	8.21E-06	6.2888
137	Olive	4.6519	2.8414	0.7753	83.9548	1.0015	0.1046	4.2189	7.95E-05	7.95E-06	6.1625
138	Olive	4.6528	2.9546	0.7755	80.5780	1.0527	0.1065	4.0492	7.63E-05	7.63E-06	6.2237

Table A.1 (Continued)

139	Olive	4.2654	2.9506	0.7109	83.2539	1.0157	0.0930	4.1837	7.88E-05	7.88E-06	5.8183
140	Olive	4.3463	2.8481	0.7244	68.0105	0.9794	0.0810	3.4177	6.44E-05	6.44E-06	5.8584
141	Olive Branch	5.8779	3.4398	0.9796	101.1877	1.5555	0.1358	5.0849	9.58E-05	9.58E-06	7.6061
142	Palm	5.4408	3.0466	0.9068	86.8049	1.4775	0.0954	4.3622	8.22E-05	8.22E-06	6.8214
143	Palm	5.1604	3.2081	0.8601	92.3905	1.3275	0.0993	4.6428	8.75E-05	8.75E-06	6.8018
144	Palm	4.0290	2.7886	0.6715	61.8968	0.8960	0.0742	3.1105	5.86E-05	5.86E-06	5.5189
145	Patula Pine	4.7897	2.3765	0.7983	88.7947	0.8045	0.1116	4.4621	8.41E-05	8.41E-06	6.0483
146	Peach	6.2053	3.3425	1.0342	107.0077	1.6289	0.1270	5.3774	1.01E-04	1.01E-05	7.8261
147	Peach	4.9120	3.0172	0.8187	84.9795	1.1561	0.1058	4.2704	8.05E-05	8.05E-06	6.4860
148	Peach	4.7864	2.2417	0.7977	86.4931	0.8398	0.0860	4.3465	8.19E-05	8.19E-06	5.9002
149	Peanut	4.3680	2.4862	0.7280	57.7874	0.9075	0.0748	2.9040	5.47E-05	5.47E-06	5.5999
150	Peanut	4.2427	2.5646	0.7071	56.1541	0.9146	0.0743	2.8219	5.32E-05	5.32E-06	5.5256
151	Peanut	4.5043	2.5412	0.7507	61.0843	0.9637	0.0799	3.0696	5.79E-05	5.79E-06	5.7527
152	Pine	7.2361	3.4866	1.2060	108.4932	1.9314	0.1579	5.4520	1.03E-04	1.03E-05	8.8395
153	Pine	7.7999	3.3560	1.3000	121.3713	2.0401	0.1462	6.0992	1.15E-04	1.15E-05	9.2695
154	Pine	4.7381	2.4017	0.7897	60.2612	0.9777	0.0847	3.0283	5.71E-05	5.71E-06	5.8671
155	Pine	5.3574	2.7536	0.8929	76.3529	1.1593	0.1075	3.8369	7.23E-05	7.23E-06	6.7371
156	Pine	7.5068	3.8738	1.2511	131.1161	2.0766	0.1789	6.5889	1.24E-04	1.24E-05	9.3763
157	Pine	5.6109	2.6339	0.9352	79.0590	1.2644	0.1045	3.9729	7.49E-05	7.49E-06	6.8110
158	Pine	6.9272	3.3326	1.1545	111.9661	1.9731	0.1314	5.6266	1.06E-04	1.06E-05	8.3098
159	Pine	5.7911	2.9850	0.9652	97.1669	1.1985	0.1362	4.8829	9.20E-05	9.20E-06	7.4066
160	Pine	6.4455	3.4459	1.0742	112.8039	1.7250	0.1367	5.6687	1.07E-04	1.07E-05	8.1038
161	Pine	6.6176	3.4981	1.1029	117.4637	1.7546	0.1415	5.9028	1.11E-04	1.11E-05	8.3225
162	Pine	6.6656	3.5290	1.1109	119.9263	1.7742	0.1455	6.0266	1.14E-04	1.14E-05	8.3858
163	Pine	6.7567	3.5562	1.1261	122.8001	1.8474	0.1542	6.1710	1.16E-04	1.16E-05	8.4374
164	Pine	6.0630	3.2827	1.0105	104.7572	1.5399	0.1285	5.2643	9.92E-05	9.92E-06	7.6878
165	Pine	6.9278	2.8800	1.1546	125.4624	1.5637	0.1338	6.3048	1.19E-04	1.19E-05	8.2650
166	Pine	5.2775	3.3147	0.8796	96.4715	1.3815	0.1170	4.8479	9.14E-05	9.14E-06	6.9733
167	Pine	4.8348	2.9985	0.8058	82.9435	1.1420	0.1036	4.1681	7.86E-05	7.86E-06	6.3936

Table A.1 (Continued)

168	Pine	4.4277	2.9560	0.7380	76.8185	1.0023	0.0928	3.8603	7.28E-05	7.28E-06	6.0265
169	Pine Bark	3.5904	2.2171	0.5984	43.4386	0.6475	0.0718	2.1829	4.11E-05	4.11E-06	4.6866
170	Pine Bark	4.2835	3.0360	0.7139	69.1153	1.2917	0.0945	3.4732	6.55E-05	6.55E-06	5.6472
171	Pine Chip	11.0409	4.8323	1.8402	187.4516	3.1072	0.2343	9.4199	1.78E-04	1.78E-05	13.3719
172	Pine Wood	7.8770	3.7779	1.3128	129.3268	2.3311	0.1530	6.4990	1.22E-04	1.22E-05	9.4837
173	Pinewood Sawdust	6.2022	2.8847	1.0337	91.5482	1.3864	0.1246	4.6005	8.67E-05	8.67E-06	7.6097
174	Pinyon Juniper	4.1072	2.5816	0.6845	66.4517	0.7715	0.0993	3.3394	6.29E-05	6.29E-06	5.5025
175	Pinyon Pine	4.7958	2.7480	0.7993	84.0853	0.9096	0.1240	4.2255	7.96E-05	7.96E-06	6.3095
176	Pistachio	5.3734	2.6783	0.8956	75.6587	1.2925	0.0937	3.8020	7.17E-05	7.17E-06	6.5611
177	Pistachio	7.5887	3.6959	1.2648	126.6156	2.1250	0.1340	6.3627	1.20E-04	1.20E-05	9.2904
178	Pistachio	6.2998	3.2172	1.0500	101.3153	1.6240	0.1210	5.0913	9.60E-05	9.60E-06	7.8220
179	Poplar	6.3985	2.7106	1.0664	87.5905	1.4565	0.1085	4.4016	8.30E-05	8.30E-06	7.6105
180	Poplar	5.2220	2.4298	0.8703	68.2442	1.0757	0.0895	3.4294	6.46E-05	6.46E-06	6.3568
181	Poplar	6.5235	3.3155	1.0872	107.0837	1.7158	0.1240	5.3812	1.01E-04	1.01E-05	8.0865
182	Poplar	5.9311	3.3082	0.9885	101.5859	1.5501	0.1189	5.1049	9.62E-05	9.62E-06	7.5588
183	Poplar	5.4069	2.9702	0.9012	86.2528	1.2986	0.1053	4.3344	8.17E-05	8.17E-06	6.8745
184	Poplar - Heartwood	8.5983	3.9801	1.4330	158.0901	2.1773	0.1879	7.9444	1.50E-04	1.50E-05	10.6462
185	Poplar - Sapwood	6.6605	3.4370	1.1101	114.3397	1.6362	0.1402	5.7458	1.08E-04	1.08E-05	8.4313
186	Prune	7.0218	3.4356	1.1703	115.4063	1.8855	0.1260	5.7994	1.09E-04	1.09E-05	8.6162
187	Prune	6.5209	3.7118	1.0868	121.2708	1.9736	0.1218	6.0941	1.15E-04	1.15E-05	8.2241
188	Pyrenean Oak	4.6597	2.6212	0.7766	62.4198	1.0792	0.0898	3.1367	5.91E-05	5.91E-06	5.8885
189	Pyrenean Oak Wood (<20mm diameter, Dry)	5.2283	2.7145	0.8714	84.2738	1.0372	0.1096	4.2350	7.98E-05	7.98E-06	6.6674
190	Pyrenean Oak Wood (20-70mm diameter, Dry)	5.9324	2.9138	0.9887	97.4306	1.2873	0.1200	4.8961	9.23E-05	9.23E-06	7.4277
191	Robinia	4.6345	2.4693	0.7724	62.3890	0.9458	0.0819	3.1352	5.91E-05	5.91E-06	5.8485
192	Robinia	4.8101	2.5653	0.8017	68.9047	1.1131	0.0886	3.4626	6.53E-05	6.53E-06	5.9755
193	Salix	5.8557	2.7475	0.9759	78.9022	1.3056	0.1102	3.9650	7.47E-05	7.47E-06	7.1634
194	Sequoia	6.0935	2.9897	1.0156	94.8326	1.4866	0.1161	4.7656	8.98E-05	8.98E-06	7.4960

Table A.1 (Continued)

195	Sequoia	5.3315	3.0514	0.8886	89.2835	1.2728	0.1121	4.4867	8.46E-05	8.46E-06	6.8866
196	Sequoia	5.2237	2.9813	0.8706	88.0523	1.2007	0.1115	4.4248	8.34E-05	8.34E-06	6.7634
197	Sequoia	5.1748	2.9759	0.8625	87.4114	1.1895	0.1111	4.3926	8.28E-05	8.28E-06	6.7125
198	Shrub Willow	4.9911	2.5117	0.8319	72.1574	0.9219	0.1074	3.6261	6.83E-05	6.83E-06	6.3053
199	Silver Fir	7.6478	3.5514	1.2746	133.4881	1.8597	0.1609	6.7081	1.26E-04	1.26E-05	9.4533
200	Softwood	6.5562	3.5762	1.0927	116.3011	1.7940	0.1374	5.8444	1.10E-04	1.10E-05	8.2938
201	Softwood bark	4.9641	3.2685	0.8274	89.7752	1.3619	0.1183	4.5114	8.50E-05	8.50E-06	6.5797
202	Spruce	7.2856	3.4840	1.2143	110.9583	1.9255	0.1595	5.5759	1.05E-04	1.05E-05	8.8988
203	Spruce	4.8591	2.1228	0.8098	57.7157	0.8826	0.0867	2.9004	5.47E-05	5.47E-06	5.8224
204	Spruce	7.4776	3.4032	1.2463	117.6373	1.8503	0.1614	5.9116	1.11E-04	1.11E-05	9.1154
205	Spruce	6.3621	2.9097	1.0603	94.9417	1.5393	0.1183	4.7710	8.99E-05	8.99E-06	7.6746
206	Spruce	4.8617	2.2747	0.8103	61.6263	0.9254	0.0867	3.0969	5.84E-05	5.84E-06	5.9345
207	Spruce	5.6413	2.8133	0.9402	83.6936	1.3061	0.1051	4.2058	7.93E-05	7.93E-06	6.9837
208	Spruce	5.9855	2.8771	0.9976	90.0550	1.4263	0.1134	4.5255	8.53E-05	8.53E-06	7.3205
209	Spruce	4.7909	2.5922	0.7985	66.8715	1.0559	0.0885	3.3605	6.33E-05	6.33E-06	6.0372
210	Spruce	4.7860	2.3575	0.7977	64.3891	0.9155	0.1007	3.2357	6.10E-05	6.10E-06	5.9250
211	Spruce	5.1751	2.6591	0.8625	75.6886	1.1202	0.0976	3.8035	7.17E-05	7.17E-06	6.4790
212	Spruce	5.8099	3.1652	0.9683	95.2910	1.4846	0.1136	4.7886	9.02E-05	9.02E-06	7.3453
213	Spruce	5.0750	2.7969	0.8458	77.4586	1.2473	0.0977	3.8925	7.34E-05	7.34E-06	6.3726
214	Spruce	4.4568	2.4801	0.7428	61.8097	0.9710	0.0846	3.1061	5.85E-05	5.85E-06	5.6242
215	Spruce	5.7176	3.2136	0.9529	95.8654	1.4729	0.1154	4.8175	9.08E-05	9.08E-06	7.2958
216	Spruce Bark	7.2657	4.0058	1.2110	125.7862	2.1586	0.1530	6.3211	1.19E-04	1.19E-05	9.1708
217	Spruce Wood	6.7948	3.1735	1.1325	104.1510	1.6210	0.1491	5.2338	9.86E-05	9.86E-06	8.3306
218	Spruce Wood	6.3963	3.0109	1.0660	96.6091	1.4381	0.1350	4.8548	9.15E-05	9.15E-06	7.9001
219	Spruce Wood	6.4607	3.3838	1.0768	112.0250	1.6486	0.1309	5.6295	1.06E-04	1.06E-05	8.1418
220	Stone Pine	5.7248	3.0052	0.9541	88.2782	1.3874	0.1204	4.4362	8.36E-05	8.36E-06	7.1762
221	Subabul Wood	5.3245	2.6774	0.8874	72.3509	1.2319	0.0987	3.6358	6.85E-05	6.85E-06	6.5588
222	Tan Oak	6.0999	2.7722	1.0167	84.9885	1.3759	0.1047	4.2709	8.05E-05	8.05E-06	7.4081
223	Teak	5.5929	3.2708	0.9321	97.5213	1.5590	0.1061	4.9007	9.24E-05	9.24E-06	7.1307

Table A.1 (Continued)

224	Unidentified	5.6901	2.5636	0.9484	77.9843	1.2797	0.0991	3.9189	7.39E-05	7.39E-06	6.8233
225	Unidentified	6.2954	3.1883	1.0492	101.8602	1.6086	0.1192	5.1187	9.65E-05	9.65E-06	7.8052
226	Unidentified	5.3090	3.0684	0.8848	86.5634	1.2997	0.1020	4.3500	8.20E-05	8.20E-06	6.8605
227	Unidentified	4.5402	3.1253	0.7567	76.6758	1.1791	0.0852	3.8531	7.26E-05	7.26E-06	6.1579
228	Unidentified	6.1242	2.8764	1.0207	91.7303	1.4702	0.1148	4.6097	8.69E-05	8.69E-06	7.4363
229	Unidentified	6.1691	2.7792	1.0282	109.6708	1.3773	0.1131	5.5112	1.04E-04	1.04E-05	7.4861
230	Unidentified	5.6122	3.2262	0.9354	99.5208	1.4269	0.1235	5.0012	9.43E-05	9.43E-06	7.2234
231	Vine	4.3725	2.2041	0.7288	52.9053	0.7868	0.0737	2.6586	5.01E-05	5.01E-06	5.4449
232	Walnut	5.2044	2.5545	0.8674	72.4483	1.1175	0.0926	3.6407	6.86E-05	6.86E-06	6.4161
233	Walnut	5.2424	2.5683	0.8737	73.2817	1.1248	0.0931	3.6826	6.94E-05	6.94E-06	6.4665
234	Walnut	4.4974	2.2325	0.7496	56.3005	0.8164	0.0785	2.8292	5.33E-05	5.33E-06	5.5846
235	Walnut	4.5087	2.2375	0.7514	56.4796	0.8199	0.0789	2.8382	5.35E-05	5.35E-06	5.5988
236	Walnut	4.7794	2.3529	0.7966	62.0046	0.9531	0.0851	3.1159	5.87E-05	5.87E-06	5.8907
237	Walnut	5.6415	3.1763	0.9402	95.5258	1.4034	0.1153	4.8004	9.05E-05	9.05E-06	7.2394
238	Walnut	4.0955	2.9154	0.6826	72.3137	0.9389	0.0903	3.6339	6.85E-05	6.85E-06	5.6644
239	Walnut	4.6502	2.8002	0.7750	86.1990	1.0722	0.0930	4.3317	8.16E-05	8.16E-06	6.0602
240	Walnut	4.7058	2.8787	0.7843	90.4809	1.0059	0.1137	4.5469	8.57E-05	8.57E-06	6.2491
241	Waste Ordinary Plywood	4.9571	2.8500	0.8262	63.6931	1.1873	0.1005	3.2007	6.03E-05	6.03E-06	6.3455
242	Waste Square Timber	11.0642	5.3616	1.8440	193.5691	3.4564	0.2497	9.7273	1.83E-04	1.83E-05	13.5638
243	Willow	6.5046	3.1277	1.0841	100.3261	1.6653	0.1183	5.0416	9.50E-05	9.50E-06	7.9328
244	Willow	5.8285	2.9422	0.9714	88.2042	1.5217	0.1029	4.4325	8.35E-05	8.35E-06	7.1175
245	Willow	5.7640	2.8353	0.9607	85.9898	1.3380	0.1079	4.3212	8.14E-05	8.14E-06	7.1141
246	Willow	5.9027	3.0163	0.9838	91.3213	1.4591	0.1080	4.5891	8.65E-05	8.65E-06	7.3357
247	Willow	8.0639	3.6277	1.3440	139.4131	2.0053	0.1525	7.0058	1.32E-04	1.32E-05	9.8777
248	Wood Bark	6.4302	4.1447	1.0717	126.1166	2.0197	0.1577	6.3377	1.19E-04	1.19E-05	8.4693
249	Wood Chips	4.5681	2.2704	0.7613	51.1095	0.9787	0.0853	2.5684	4.84E-05	4.84E-06	5.5357
250	Woody Waste	12.1061	5.8715	2.0177	223.6846	4.0360	0.2703	11.2407	2.12E-04	2.12E-05	14.6890

Note: The biomass feedstock types of cases in Table A.1 are consistent with the cases in Table A.2

Table A.2 Life cycle inventory data generated for steam AC production using different biomass species (with energy recovery)

	Inputs					Outputs					
Case	Dry biomass	Water	Nitrogen	Air	Natural gas	Biogenic CO_2	Biogenic CH_4	Fossil CO_2	Fossil CH_4	Fossil N_2O	Other gases
Unit	kg/kg AC	kg/kg AC	kg/kg AC	kg/kg AC	MJ/kg AC	kg/kg AC	kg/kg AC	kg/kg AC	kg/kg AC	kg/kg AC	kg/kg AC
1	7.0541	3.5390	1.1757	6.8700	79.4781	6.9036	0.0269	3.9940	7.53E-05	7.53E-06	10.7082
2	7.4586	3.8456	1.2431	7.1966	95.6001	7.2211	0.0272	4.8041	9.05E-05	9.05E-06	11.4955
3	4.2082	2.3385	0.7014	3.9505	30.4804	3.6871	0.0139	1.5317	2.89E-05	2.89E-06	6.4976
4	5.8310	2.8466	0.9718	5.7300	56.8024	5.3098	0.0196	2.8545	5.38E-05	5.38E-06	9.0501
5	5.1030	2.6222	0.8505	4.9294	42.7427	4.7434	0.0178	2.1479	4.05E-05	4.05E-06	7.7439
6	5.6445	3.1417	0.9407	5.2957	60.7307	5.3116	0.0206	3.0519	5.75E-05	5.75E-06	8.6904
7	5.4764	3.0857	0.9127	5.1137	57.9661	5.0927	0.0203	2.9129	5.49E-05	5.49E-06	8.4756
8	4.4711	2.5090	0.7452	4.1816	37.4564	3.9825	0.0157	1.8823	3.55E-05	3.55E-06	6.9087
9	5.6539	3.2702	0.9423	5.2244	65.8377	5.3337	0.0198	3.3085	6.24E-05	6.24E-06	8.7374
10	4.0809	2.5039	0.6801	3.6776	34.9528	3.5479	0.0145	1.7565	3.31E-05	3.31E-06	6.3801
11	4.6005	2.4683	0.7668	4.3763	37.8645	4.1569	0.0168	1.9028	3.59E-05	3.59E-06	7.0381
12	4.7507	3.1469	0.7918	4.1305	56.5757	4.4034	0.0189	2.8431	5.36E-05	5.36E-06	7.3976
13	6.8749	3.6198	1.1458	6.5844	84.2409	6.7502	0.0298	4.2333	7.98E-05	7.98E-06	10.4449
14	13.8696	6.7349	2.3116	13.6528	207.5661	14.2163	0.0501	10.4307	1.97E-04	1.97E-05	21.3026
15	7.1731	3.7207	1.1955	6.9066	86.5355	7.1601	0.0270	4.3486	8.20E-05	8.20E-06	10.8088
16	4.0867	2.1349	0.6811	3.9251	27.3997	3.5514	0.0163	1.3769	2.59E-05	2.59E-06	6.2601
17	6.4147	3.2453	1.0691	6.2297	63.8844	6.2552	0.0263	3.2103	6.05E-05	6.05E-06	9.6772
18	7.2704	3.6216	1.2117	7.0975	69.1713	7.1791	0.0296	3.4760	6.55E-05	6.55E-06	10.9926
19	8.0372	3.9051	1.3395	7.9101	79.1309	8.0986	0.0333	3.9765	7.49E-05	7.49E-06	12.0599
20	6.9348	3.4820	1.1558	6.7519	63.2251	6.7858	0.0278	3.1772	5.99E-05	5.99E-06	10.5109
21	4.7373	2.6022	0.7896	4.4671	33.5580	4.2833	0.0170	1.6864	3.18E-05	3.18E-06	7.2959
22	4.3309	2.2059	0.7218	4.1964	26.4757	3.7021	0.0151	1.3305	2.51E-05	2.51E-06	6.7377
23	6.1384	2.6816	1.0231	6.2369	50.7781	5.8103	0.0213	2.5517	4.81E-05	4.81E-06	9.2483
24	6.8183	3.2954	1.1364	6.7218	72.4108	6.5875	0.0287	3.6388	6.86E-05	6.86E-06	10.3558
25	6.2501	3.0489	1.0417	6.1433	62.2880	6.0043	0.0234	3.1301	5.90E-05	5.90E-06	9.4563
26	5.8089	2.6579	0.9682	5.8240	43.3579	5.5080	0.0230	2.1788	4.11E-05	4.11E-06	8.7279

Table A.2 (Continued)

27	5.2785	2.6350	0.8797	5.1493	52.6301	4.8218	0.0213	2.6448	4.98E-05	4.98E-06	8.0994
28	6.4063	3.1743	1.0677	6.2649	58.9895	5.9926	0.0262	2.9644	5.59E-05	5.59E-06	9.8942
29	7.4642	3.2505	1.2440	7.5906	73.0482	7.3082	0.0281	3.6708	6.92E-05	6.92E-06	11.2130
30	5.8629	2.5889	0.9771	5.9390	47.7490	5.5230	0.0213	2.3995	4.52E-05	4.52E-06	8.8236
31	11.2368	5.4002	1.8728	11.0977	151.6659	11.6682	0.0428	7.6216	1.44E-04	1.44E-05	16.8965
32	4.8478	2.3905	0.8080	4.7483	47.1486	4.5132	0.0169	2.3693	4.47E-05	4.47E-06	7.2645
33	6.6868	3.3581	1.1145	6.5100	73.4433	6.4777	0.0253	3.6907	6.96E-05	6.96E-06	10.1663
34	5.5849	2.6935	0.9308	5.5095	48.6943	5.1955	0.0195	2.4470	4.61E-05	4.61E-06	8.5037
35	8.7895	3.6973	1.4649	9.0231	92.2078	8.7361	0.0335	4.6337	8.73E-05	8.73E-06	13.2052
36	5.7018	3.2679	0.9503	5.2882	69.8022	5.4743	0.0246	3.5077	6.61E-05	6.61E-06	8.7093
37	5.1883	2.4021	0.8647	5.1834	61.1523	4.8152	0.0204	3.0730	5.79E-05	5.79E-06	7.8029
38	5.2156	2.6035	0.8693	5.0881	44.5513	4.8301	0.0185	2.2388	4.22E-05	4.22E-06	7.9278
39	5.6008	3.3125	0.9335	5.1279	63.9855	5.3101	0.0188	3.2154	6.06E-05	6.06E-06	8.6458
40	5.5286	2.9201	0.9214	5.2891	57.1695	5.0402	0.0199	2.8729	5.41E-05	5.41E-06	8.5992
41	4.1121	2.7357	0.6853	3.5675	40.9454	3.6103	0.0165	2.0576	3.88E-05	3.88E-06	6.4738
42	3.7169	2.9045	0.6195	2.9440	43.6759	3.2363	0.0162	2.1948	4.14E-05	4.14E-06	5.9324
43	3.8563	2.9177	0.6427	3.1167	45.1355	3.3946	0.0172	2.2682	4.27E-05	4.27E-06	6.1217
44	5.6010	2.9734	0.9335	5.3486	57.2710	5.3014	0.0214	2.8780	5.42E-05	5.42E-06	8.5337
45	3.7956	2.3391	0.6326	3.4139	31.4858	3.2440	0.0137	1.5822	2.98E-05	2.98E-06	5.9235
46	3.8541	2.2113	0.6424	3.5731	31.4099	3.1535	0.0137	1.5784	2.97E-05	2.97E-06	6.1135
47	4.4637	2.4035	0.7440	4.2406	32.5005	3.9198	0.0145	1.6332	3.08E-05	3.08E-06	6.9174
48	3.9589	2.1069	0.6598	3.7771	22.7519	3.4053	0.0127	1.1433	2.15E-05	2.15E-06	6.0848
49	6.2491	3.2056	1.0415	6.0402	66.4987	5.9582	0.0236	3.3417	6.30E-05	6.30E-06	9.5547
50	6.2467	3.2044	1.0411	6.0379	66.4589	5.9555	0.0236	3.3397	6.29E-05	6.29E-06	9.5510
51	4.8688	2.8246	0.8115	4.4935	62.6002	4.5885	0.0269	3.1458	5.93E-05	5.93E-06	7.3829
52	7.2381	3.5672	1.2063	7.0908	82.3860	7.1380	0.0291	4.1401	7.80E-05	7.80E-06	10.9353
53	6.2374	3.4427	1.0396	5.8709	78.2363	6.1047	0.0287	3.9316	7.41E-05	7.41E-06	9.4572
54	7.5457	3.3471	1.2576	7.6338	78.0128	7.5095	0.0368	3.9203	7.39E-05	7.39E-06	11.2380

Table A.2 (Continued)

55	5.7086	3.0055	0.9514	5.4677	59.2255	5.4155	0.0218	2.9762	5.61E-05	5.61E-06	8.6959
56	9.4754	4.1935	1.5792	9.5922	115.3078	9.6492	0.0359	5.7945	1.09E-04	1.09E-05	14.1552
57	9.4818	4.1551	1.5803	9.6256	113.3707	9.8192	0.0362	5.6971	1.07E-04	1.07E-05	13.9874
58	4.8996	2.1686	0.8166	4.9599	30.7385	4.4885	0.0167	1.5447	2.91E-05	2.91E-06	7.3395
59	5.3217	2.4401	0.8869	5.3321	40.5409	4.8919	0.0182	2.0373	3.84E-05	3.84E-06	8.0707
60	5.1756	2.3532	0.8626	5.1987	37.7668	4.7255	0.0176	1.8979	3.58E-05	3.58E-06	7.8470
61	5.1607	2.4275	0.8601	5.1311	39.8639	4.7357	0.0178	2.0033	3.78E-05	3.78E-06	7.8259
62	4.0960	2.2892	0.6827	3.8368	31.0752	3.4544	0.0140	1.5616	2.94E-05	2.94E-06	6.4363
63	6.1465	3.2853	1.0244	5.8550	68.7811	5.9066	0.0236	3.4564	6.51E-05	6.51E-06	9.3809
64	6.0476	3.2362	1.0079	5.7584	66.0053	5.9277	0.0239	3.3169	6.25E-05	6.25E-06	9.0986
65	4.9816	2.8516	0.8303	4.6225	48.6798	4.6918	0.0196	2.4463	4.61E-05	4.61E-06	7.5746
66	4.7433	2.5948	0.7905	4.4797	40.3357	4.2146	0.0179	2.0270	3.82E-05	3.82E-06	7.3758
67	4.7711	2.1221	0.7952	4.8230	29.4673	4.3227	0.0166	1.4808	2.79E-05	2.79E-06	7.1720
68	5.9408	2.7540	0.9901	5.9330	51.9727	5.6412	0.0221	2.6118	4.92E-05	4.92E-06	8.9546
69	5.8592	2.7637	0.9765	5.8205	52.6840	5.5441	0.0218	2.6475	4.99E-05	4.99E-06	8.8540
70	6.8779	3.3927	1.1463	6.7361	73.2789	6.7018	0.0267	3.6824	6.94E-05	6.94E-06	10.4245
71	6.0036	3.0788	1.0006	5.8034	62.4259	5.8198	0.0241	3.1371	5.91E-05	5.91E-06	9.0426
72	5.5528	3.0008	0.9255	5.2682	57.3825	5.2394	0.0214	2.8836	5.43E-05	5.43E-06	8.4864
73	5.6555	3.0914	0.9426	5.3427	59.9956	5.3763	0.0220	3.0149	5.68E-05	5.68E-06	8.6339
74	5.9114	3.3368	0.9852	5.5159	65.3999	5.5083	0.0241	3.2865	6.19E-05	6.19E-06	9.2169
75	5.1016	2.4837	0.8503	5.0177	40.1231	4.6415	0.0174	2.0163	3.80E-05	3.80E-06	7.7945
76	3.6640	2.4172	0.6107	3.1921	29.5760	3.0627	0.0125	1.4863	2.80E-05	2.80E-06	5.8087
77	4.6999	2.4550	0.7833	4.5142	54.2136	4.2168	0.0166	2.7244	5.13E-05	5.13E-06	7.2190
78	4.8854	2.7686	0.8142	4.5514	64.5815	4.6791	0.0240	3.2454	6.12E-05	6.12E-06	7.3164
79	6.1781	3.2405	1.0297	5.9253	70.3625	5.7990	0.0243	3.5359	6.66E-05	6.66E-06	9.5503
80	5.5268	3.1139	0.9211	5.1608	56.4995	5.0692	0.0208	2.8392	5.35E-05	5.35E-06	8.6326
81	4.6910	2.2054	0.7818	4.6648	28.0008	4.3648	0.0161	1.4071	2.65E-05	2.65E-06	6.9620
82	4.0283	2.5046	0.6714	3.6088	36.5949	3.5312	0.0154	1.8390	3.47E-05	3.47E-06	6.2664

Table A.2 (Continued)

83	4.3013	2.6752	0.7169	3.8528	42.8874	3.8510	0.0171	2.1552	4.06E-05	4.06E-06	6.6782
84	9.5517	4.6463	1.5919	9.3971	126.6667	9.3740	0.0338	6.3653	1.20E-04	1.20E-05	14.7792
85	4.6059	2.4846	0.7677	4.3727	35.3068	4.0404	0.0170	1.7743	3.34E-05	3.34E-06	7.1734
86	4.7151	2.5268	0.7858	4.4872	39.9727	4.2686	0.0177	2.0087	3.79E-05	3.79E-06	7.2286
87	4.8783	2.4357	0.8130	4.7585	40.6117	4.5459	0.0198	2.0408	3.85E-05	3.85E-06	7.3198
88	4.4017	2.7138	0.7336	3.9582	49.8897	4.0757	0.0251	2.5071	4.72E-05	4.72E-06	6.7065
89	5.0469	2.5055	0.8411	4.9323	39.4429	4.5656	0.0169	1.9821	3.74E-05	3.74E-06	7.7434
90	4.3093	2.6453	0.7182	3.8826	40.1971	3.6665	0.0173	2.0200	3.81E-05	3.81E-06	6.8716
91	4.1805	2.8454	0.6967	3.5851	48.9570	3.7461	0.0174	2.4602	4.64E-05	4.64E-06	6.5442
92	7.9603	3.9104	1.3267	7.8066	95.9828	8.1509	0.0345	4.8234	9.09E-05	9.09E-06	11.8185
93	8.2501	3.9676	1.3750	8.1463	98.9318	8.3501	0.0345	4.9716	9.37E-05	9.37E-06	12.3543
94	13.1345	6.8642	2.1891	12.6132	180.4106	14.0952	0.0785	9.0661	1.71E-04	1.71E-05	19.6272
95	5.2620	2.5654	0.8770	5.1732	43.2380	4.8273	0.0179	2.1728	4.10E-05	4.10E-06	8.0324
96	5.4492	2.5877	0.9082	5.4020	53.3862	5.0682	0.0320	2.6828	5.06E-05	5.06E-06	8.2469
97	5.6280	2.7722	0.9380	5.5144	43.8124	5.4388	0.0245	2.2017	4.15E-05	4.15E-06	8.3893
98	5.7292	2.5233	0.9549	5.8078	44.7792	5.3399	0.0194	2.2503	4.24E-05	4.24E-06	8.6558
99	5.4142	2.5660	0.9024	5.3706	45.9354	4.8271	0.0186	2.3084	4.35E-05	4.35E-06	8.4075
100	5.9632	2.7260	0.9939	5.9802	52.6827	5.6192	0.0226	2.6474	4.99E-05	4.99E-06	9.0214
101	6.4200	3.1649	1.0700	6.2889	68.6565	6.0692	0.0234	3.4502	6.50E-05	6.50E-06	9.8511
102	6.0484	3.2010	1.0081	5.7823	66.2550	5.7789	0.0232	3.3295	6.27E-05	6.27E-06	9.2377
103	6.3040	3.3298	1.0507	6.0308	70.6270	6.0875	0.0243	3.5492	6.69E-05	6.69E-06	9.6035
104	5.8511	3.1216	0.9752	5.5774	62.2551	5.3918	0.0205	3.1285	5.90E-05	5.90E-06	9.1129
105	6.0143	3.0172	1.0024	5.8574	59.9343	5.7209	0.0221	3.0118	5.68E-05	5.68E-06	9.1482
106	5.8103	3.0162	0.9684	5.5928	55.1867	5.6712	0.0217	2.7733	5.23E-05	5.23E-06	8.6947
107	5.7139	2.8543	0.9523	5.5727	55.1660	5.4188	0.0211	2.7722	5.22E-05	5.22E-06	8.6533
108	5.8928	3.0395	0.9821	5.6850	59.7423	5.6116	0.0219	3.0022	5.66E-05	5.66E-06	8.9660
109	5.7144	2.7316	0.9524	5.6532	50.8696	5.3969	0.0213	2.5563	4.82E-05	4.82E-06	8.6335
110	5.3456	2.9653	0.8909	5.0219	58.3522	4.9856	0.0205	2.9323	5.53E-05	5.53E-06	8.2176

Table A.2 (Continued)

111	6.1371	2.8901	1.0229	6.0997	61.7384	5.9439	0.0254	3.1025	5.85E-05	5.85E-06	9.1805
112	6.4960	3.5019	1.0827	6.1686	77.0732	6.2823	0.0257	3.8731	7.30E-05	7.30E-06	9.9411
113	6.8473	3.4596	1.1412	6.6527	74.2402	6.7379	0.0310	3.7307	7.03E-05	7.03E-06	10.3320
114	5.7693	2.7153	0.9615	5.7351	48.6037	5.4078	0.0191	2.4425	4.60E-05	4.60E-06	8.7544
115	6.1451	2.6898	1.0242	6.2403	51.5841	5.7993	0.0212	2.5922	4.89E-05	4.89E-06	9.2788
116	6.1049	2.7956	1.0175	6.1193	54.0362	5.8019	0.0218	2.7154	5.12E-05	5.12E-06	9.2136
117	4.5369	2.1237	0.7562	4.5176	29.3834	4.0217	0.0160	1.4766	2.78E-05	2.78E-06	6.8967
118	5.5736	2.6087	0.9289	5.5500	46.9321	5.2128	0.0192	2.3584	4.44E-05	4.44E-06	8.4293
119	5.8288	2.9829	0.9715	5.6385	60.7412	5.2947	0.0204	3.0524	5.75E-05	5.75E-06	9.1067
120	7.3512	3.7350	1.2252	7.1288	88.2461	7.0360	0.0264	4.4346	8.36E-05	8.36E-06	11.3777
121	5.7289	2.8337	0.9548	5.6057	53.2214	5.4904	0.0213	2.6745	5.04E-05	5.04E-06	8.6115
122	6.5532	3.0540	1.0922	6.5341	69.8321	6.3622	0.0243	3.5092	6.61E-05	6.61E-06	9.8471
123	5.9146	2.9970	0.9858	5.7410	58.9310	5.6400	0.0216	2.9614	5.58E-05	5.58E-06	8.9768
124	9.8418	4.2355	1.6403	10.0412	118.3154	10.0493	0.0370	5.9456	1.12E-04	1.12E-05	14.6724
125	6.0554	3.0805	1.0092	5.8697	61.8626	5.7600	0.0223	3.1087	5.86E-05	5.86E-06	9.2326
126	5.8940	3.2550	0.9823	5.5464	68.1721	5.5355	0.0218	3.4258	6.46E-05	6.46E-06	9.1204
127	4.5294	2.8002	0.7549	4.0681	44.0659	4.1919	0.0166	2.2144	4.17E-05	4.17E-06	6.9440
128	5.1769	2.8727	0.8628	4.8628	51.1968	4.8188	0.0188	2.5728	4.85E-05	4.85E-06	7.9376
129	5.1313	2.4507	0.8552	5.0777	39.5641	4.6703	0.0174	1.9882	3.75E-05	3.75E-06	7.8272
130	6.8749	3.4374	1.1458	6.7031	75.6812	6.6405	0.0258	3.8032	7.17E-05	7.17E-06	10.4949
131	4.6531	2.9818	0.7755	4.1109	50.2030	4.1738	0.0169	2.5228	4.75E-05	4.75E-06	7.3307
132	6.6185	3.1860	1.1031	6.5332	79.5032	6.3906	0.0241	3.9952	7.53E-05	7.53E-06	10.0260
133	5.5012	3.3466	0.9169	4.9762	75.9194	5.2082	0.0231	3.8151	7.19E-05	7.19E-06	8.5095
134	6.2524	3.4630	1.0421	5.8771	78.0311	6.1172	0.0282	3.9213	7.39E-05	7.39E-06	9.4892
135	4.5726	3.0092	0.7621	3.9884	54.5000	4.2393	0.0210	2.7388	5.16E-05	5.16E-06	7.0719
136	4.8564	2.7599	0.8094	4.5194	59.9195	4.4457	0.0187	3.0111	5.67E-05	5.67E-06	7.4807
137	4.6519	2.8414	0.7753	4.2005	56.8656	4.3325	0.0209	2.8576	5.39E-05	5.39E-06	7.1156
138	4.6528	2.9546	0.7755	4.1282	54.5075	4.2949	0.0213	2.7391	5.16E-05	5.16E-06	7.1949

Table A.2 (Continued)

139	4.2654	2.9506	0.7109	3.6272	59.0780	4.0211	0.0186	2.9688	5.60E-05	5.60E-06	6.5144
140	4.3463	2.8481	0.7244	3.7989	46.1144	3.8572	0.0162	2.3174	4.37E-05	4.37E-06	6.8443
141	5.8779	3.4398	0.9796	5.4054	67.6142	5.6936	0.0272	3.3978	6.40E-05	6.40E-06	8.9820
142	5.4408	3.0466	0.9068	5.0928	61.9080	4.8826	0.0191	3.1110	5.86E-05	5.86E-06	8.5854
143	5.1604	3.2081	0.8601	4.6233	65.8388	4.7813	0.0199	3.3086	6.24E-05	6.24E-06	8.0506
144	4.0290	2.7886	0.6715	3.4251	42.3890	3.4956	0.0148	2.1301	4.01E-05	4.01E-06	6.4037
145	4.7897	2.3765	0.7983	4.6818	59.5773	4.4083	0.0317	2.9939	5.64E-05	5.64E-06	7.2063
146	6.2053	3.3425	1.0342	5.8943	71.8496	6.0385	0.0254	3.6106	6.80E-05	6.80E-06	9.4125
147	4.9120	3.0172	0.8187	4.4245	57.4350	4.6024	0.0212	2.8862	5.44E-05	5.44E-06	7.5488
148	4.7864	2.2417	0.7977	4.7652	59.1606	4.3031	0.0172	2.9730	5.60E-05	5.60E-06	7.2709
149	4.3680	2.4862	0.7280	4.0624	35.6734	3.8341	0.0150	1.7927	3.38E-05	3.38E-06	6.7956
150	4.2427	2.5646	0.7071	3.8486	33.9794	3.8118	0.0149	1.7075	3.22E-05	3.22E-06	6.5364
151	4.5043	2.5412	0.7507	4.2038	37.5549	4.0355	0.0160	1.8872	3.56E-05	3.56E-06	6.9487
152	7.2361	3.4866	1.2060	7.1406	66.5675	7.1225	0.0316	3.3452	6.30E-05	6.30E-06	10.9154
153	7.7999	3.3560	1.3000	7.9585	77.1410	7.6414	0.0292	3.8765	7.31E-05	7.31E-06	11.7437
154	4.7381	2.4017	0.7897	4.5984	34.2642	4.3181	0.0169	1.7219	3.25E-05	3.25E-06	7.1928
155	5.3574	2.7536	0.8929	5.1747	44.7498	5.0867	0.0215	2.2488	4.24E-05	4.24E-06	8.0704
156	7.5068	3.8738	1.2511	7.2409	85.6321	7.5763	0.0358	4.3032	8.11E-05	8.11E-06	11.2606
157	5.6109	2.6339	0.9352	5.5822	46.9917	5.3218	0.0209	2.3614	4.45E-05	4.45E-06	8.4194
158	6.9272	3.3326	1.1545	6.8392	76.5477	6.6107	0.0263	3.8467	7.25E-05	7.25E-06	10.6166
159	5.7911	2.9850	0.9652	5.5882	61.7196	5.5245	0.0342	3.1016	5.85E-05	5.85E-06	8.7708
160	6.4455	3.4459	1.0742	6.1393	75.4558	6.3649	0.0273	3.7918	7.15E-05	7.15E-06	9.7127
161	6.6176	3.4981	1.1029	6.3291	79.5709	6.4744	0.0283	3.9986	7.54E-05	7.54E-06	10.0450
162	6.6656	3.5290	1.1109	6.3715	81.3453	6.5528	0.0291	4.0878	7.70E-05	7.70E-06	10.0951
163	6.7567	3.5562	1.1261	6.4722	81.2008	6.8880	0.0312	4.0805	7.69E-05	7.69E-06	9.9920
164	6.0630	3.2827	1.0105	5.7481	69.7707	5.8965	0.0257	3.5061	6.61E-05	6.61E-06	9.1821
165	6.9278	2.8800	1.1546	7.1342	83.4052	6.7657	0.0268	4.1913	7.90E-05	7.90E-06	10.3042
166	5.2775	3.3147	0.8796	4.7063	67.6356	5.0033	0.0234	3.3989	6.41E-05	6.41E-06	8.1514

Table A.2 (Continued)

167	4.8348	2.9985	0.8058	4.3362	56.5012	4.4864	0.0207	2.8393	5.35E-05	5.35E-06	7.4683
168	4.4277	2.9560	0.7380	3.8347	53.1254	4.0180	0.0186	2.6697	5.03E-05	5.03E-06	6.9197
169	3.5904	2.2171	0.5984	3.2265	25.1763	3.0288	0.0144	1.2652	2.38E-05	2.38E-06	5.5892
170	4.2835	3.0360	0.7139	3.5951	53.4916	3.5557	0.0189	2.6881	5.07E-05	5.07E-06	7.0539
171	11.0409	4.8323	1.8402	11.2122	119.5649	11.4581	0.0559	6.0084	1.13E-04	1.13E-05	16.4116
172	7.8770	3.7779	1.3128	7.7844	88.9055	7.5969	0.0306	4.4677	8.42E-05	8.42E-06	12.1247
173	6.2022	2.8847	1.0337	6.1878	54.0677	6.0104	0.0249	2.7170	5.12E-05	5.12E-06	9.2732
174	4.1072	2.5816	0.6845	3.6613	41.3714	3.7901	0.0199	2.0790	3.92E-05	3.92E-06	6.2247
175	4.7958	2.7480	0.7993	4.4484	54.8140	4.4488	0.0309	2.7545	5.19E-05	5.19E-06	7.3118
176	5.3734	2.6783	0.8956	5.2445	49.4739	4.8007	0.0187	2.4862	4.69E-05	4.69E-06	8.3724
177	7.5887	3.6959	1.2648	7.4630	84.8740	7.4918	0.0268	4.2651	8.04E-05	8.04E-06	11.4937
178	6.2998	3.2172	1.0500	6.0985	65.7231	6.1219	0.0242	3.3027	6.22E-05	6.22E-06	9.5194
179	6.3985	2.7106	1.0664	6.5562	51.7350	6.0544	0.0217	2.5998	4.90E-05	4.90E-06	9.6556
180	5.2220	2.4298	0.8703	5.2092	39.3403	4.7952	0.0179	1.9769	3.73E-05	3.73E-06	7.9181
181	6.5235	3.3155	1.0872	6.3254	70.6940	6.3386	0.0248	3.5525	6.70E-05	6.70E-06	9.8883
182	5.9311	3.3082	0.9885	5.5601	69.1065	5.6775	0.0238	3.4728	6.54E-05	6.54E-06	9.0866
183	5.4069	2.9702	0.9012	5.0984	56.3727	5.0964	0.0211	2.8329	5.34E-05	5.34E-06	8.2593
184	8.5983	3.9801	1.4330	8.5908	105.3473	8.6516	0.0456	5.2940	9.98E-05	9.98E-06	12.9049
185	6.6605	3.4370	1.1101	6.4247	73.7265	6.6071	0.0280	3.7049	6.98E-05	6.98E-06	9.9972
186	7.0218	3.4356	1.1703	6.8952	76.7855	6.8433	0.0252	3.8587	7.27E-05	7.27E-06	10.6543
187	6.5209	3.7118	1.0868	6.0646	88.0062	6.3340	0.0244	4.4225	8.33E-05	8.33E-06	10.0257
188	4.6597	2.6212	0.7766	4.3538	39.4670	4.1098	0.0180	1.9833	3.74E-05	3.74E-06	7.2836
189	5.2283	2.7145	0.8714	5.0323	52.1121	4.9831	0.0248	2.6188	4.94E-05	4.94E-06	7.8385
190	5.9324	2.9138	0.9887	5.8182	60.8255	5.7705	0.0245	3.0566	5.76E-05	5.76E-06	8.8582
191	4.6345	2.4693	0.7724	4.4199	37.5752	4.1622	0.0164	1.8882	3.56E-05	3.56E-06	7.1174
192	4.8101	2.5653	0.8017	4.5857	45.1531	4.2674	0.0177	2.2691	4.28E-05	4.28E-06	7.4776
193	5.8557	2.7475	0.9759	5.8265	45.3907	5.5338	0.0220	2.2810	4.30E-05	4.30E-06	8.8498
194	6.0935	2.9897	1.0156	5.9782	60.5400	5.8353	0.0232	3.0423	5.73E-05	5.73E-06	9.2184

Table A.2 (Continued)

195	5.3315	3.0514	0.8886	4.9475	59.0760	5.0557	0.0224	2.9687	5.60E-05	5.60E-06	8.1409
196	5.2237	2.9813	0.8706	4.8530	58.4150	4.9048	0.0223	2.9355	5.53E-05	5.53E-06	8.0015
197	5.1748	2.9759	0.8625	4.7928	58.0328	4.8580	0.0222	2.9163	5.50E-05	5.50E-06	7.9257
198	4.9911	2.5117	0.8319	4.8559	41.4337	4.6710	0.0226	2.0821	3.92E-05	3.92E-06	7.4968
199	7.6478	3.5514	1.2746	7.6337	86.3955	7.6388	0.0362	4.3416	8.18E-05	8.18E-06	11.4325
200	6.5562	3.5762	1.0927	6.1986	79.6932	6.3984	0.0275	4.0048	7.55E-05	7.55E-06	9.9979
201	4.9641	3.2685	0.8274	4.3289	63.2700	4.6757	0.0237	3.1795	5.99E-05	5.99E-06	7.6894
202	7.2856	3.4840	1.2143	7.2067	68.1832	7.1986	0.0319	3.4264	6.46E-05	6.46E-06	10.9600
203	4.8591	2.1228	0.8098	4.9370	30.1350	4.3929	0.0173	1.5144	2.85E-05	2.85E-06	7.3185
204	7.4776	3.4032	1.2463	7.5088	71.5221	7.4693	0.0331	3.5942	6.77E-05	6.77E-06	11.1334
205	6.3621	2.9097	1.0603	6.3794	59.1038	6.0937	0.0237	2.9701	5.60E-05	5.60E-06	9.5942
206	4.8617	2.2747	0.8103	4.8417	34.2165	4.4222	0.0173	1.7195	3.24E-05	3.24E-06	7.3488
207	5.6413	2.8133	0.9402	5.5051	52.5366	5.2818	0.0210	2.6401	4.98E-05	4.98E-06	8.5971
208	5.9855	2.8771	0.9976	5.9110	55.9812	5.7345	0.0227	2.8132	5.30E-05	5.30E-06	9.0140
209	4.7909	2.5922	0.7985	4.5432	41.3018	4.3601	0.0177	2.0755	3.91E-05	3.91E-06	7.3471
210	4.7860	2.3575	0.7977	4.6894	36.5527	4.3715	0.0201	1.8369	3.46E-05	3.46E-06	7.2390
211	5.1751	2.6591	0.8625	4.9992	46.6893	4.8065	0.0195	2.3463	4.42E-05	4.42E-06	7.8699
212	5.8099	3.1652	0.9683	5.4955	63.5764	5.5314	0.0227	3.1949	6.02E-05	6.02E-06	8.8849
213	5.0750	2.7969	0.8458	4.7795	51.3536	4.6482	0.0195	2.5806	4.86E-05	4.86E-06	7.8294
214	4.4568	2.4801	0.7428	4.1817	38.1709	4.0287	0.0169	1.9182	3.62E-05	3.62E-06	6.8158
215	5.7176	3.2136	0.9529	5.3441	64.6131	5.4445	0.0231	3.2470	6.12E-05	6.12E-06	8.7606
216	7.2657	4.0058	1.2110	6.8417	86.3969	7.1485	0.0306	4.3417	8.18E-05	8.18E-06	11.1450
217	6.7948	3.1735	1.1325	6.7705	62.2731	6.7159	0.0306	3.1294	5.90E-05	5.90E-06	10.1247
218	6.3963	3.0109	1.0660	6.3580	57.1757	6.2694	0.0296	2.8732	5.42E-05	5.42E-06	9.5323
219	6.4607	3.3838	1.0768	6.1995	74.9536	6.2905	0.0262	3.7666	7.10E-05	7.10E-06	9.8041
220	5.7248	3.0052	0.9541	5.4889	55.2735	5.4975	0.0241	2.7776	5.23E-05	5.23E-06	8.6513
221	5.3245	2.6774	0.8874	5.1816	44.3379	4.8680	0.0197	2.2281	4.20E-05	4.20E-06	8.1832
222	6.0999	2.7722	1.0167	6.1279	50.6965	5.7654	0.0209	2.5476	4.80E-05	4.80E-06	9.2304

Table A.2 (Continued)

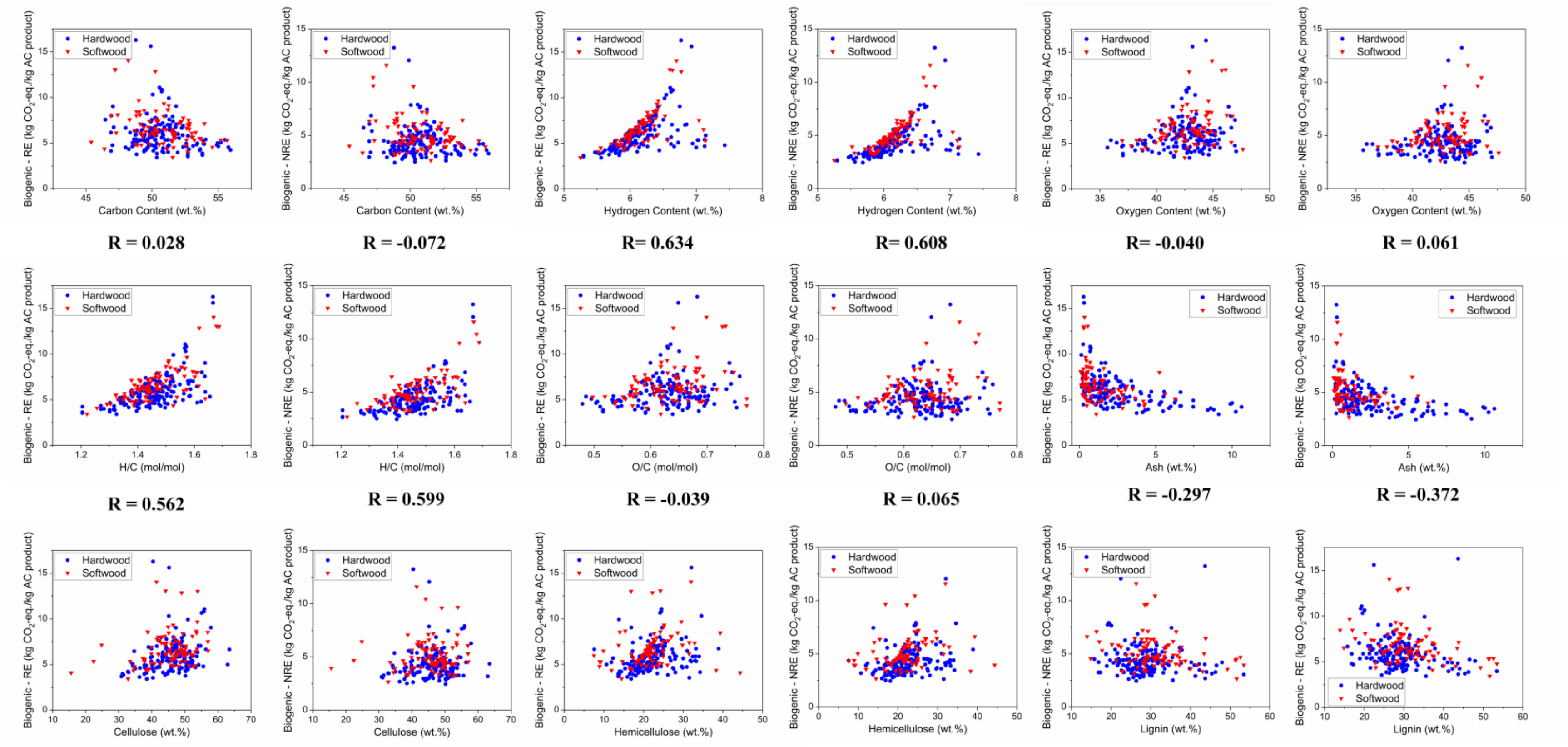
223	5.5929	3.2708	0.9321	5.1447	70.2989	5.1790	0.0212	3.5327	6.66E-05	6.66E-06	8.7404
224	5.6901	2.5636	0.9484	5.7308	45.4727	5.4151	0.0198	2.2851	4.31E-05	4.31E-06	8.4980
225	6.2954	3.1883	1.0492	6.1117	66.7709	6.0703	0.0238	3.3554	6.32E-05	6.32E-06	9.5506
226	5.3090	3.0684	0.8848	4.9072	58.0149	4.9662	0.0204	2.9154	5.49E-05	5.49E-06	8.1828
227	4.5402	3.1253	0.7567	3.8707	54.8443	4.0879	0.0170	2.7561	5.19E-05	5.19E-06	7.1880
228	6.1242	2.8764	1.0207	6.0917	57.1455	5.8584	0.0230	2.8717	5.41E-05	5.41E-06	9.2316
229	6.1691	2.7792	1.0282	6.2133	73.9509	5.8776	0.0226	3.7162	7.00E-05	7.00E-06	9.2896
230	5.6122	3.2262	0.9354	5.1988	67.7204	5.3841	0.0247	3.4031	6.41E-05	6.41E-06	8.5639
231	4.3725	2.2041	0.7288	4.2516	29.4094	3.8429	0.0147	1.4779	2.79E-05	2.79E-06	6.6994
232	5.2044	2.5545	0.8674	5.1052	43.5033	4.8247	0.0185	2.1861	4.12E-05	4.12E-06	7.8883
233	5.2424	2.5683	0.8737	5.1458	44.2280	4.8497	0.0186	2.2226	4.19E-05	4.19E-06	7.9619
234	4.4974	2.2325	0.7496	4.3955	31.2303	4.0302	0.0157	1.5694	2.96E-05	2.96E-06	6.8291
235	4.5087	2.2375	0.7514	4.4068	31.3403	4.0418	0.0158	1.5749	2.97E-05	2.97E-06	6.8470
236	4.7794	2.3529	0.7966	4.6838	34.1676	4.4681	0.0170	1.7170	3.24E-05	3.24E-06	7.1275
237	5.6415	3.1763	0.9402	5.2693	64.3203	5.3468	0.0231	3.2322	6.09E-05	6.09E-06	8.6575
238	4.0955	2.9154	0.6826	3.4291	50.3695	3.7074	0.0181	2.5312	4.77E-05	4.77E-06	6.3972
239	4.6502	2.8002	0.7750	4.2251	62.8461	4.1192	0.0186	3.1582	5.95E-05	5.95E-06	7.3127
240	4.7058	2.8787	0.7843	4.2464	61.9542	4.4452	0.0227	3.1133	5.87E-05	5.87E-06	7.1472
241	4.9571	2.8500	0.8262	4.5917	37.4732	4.5500	0.0201	1.8831	3.55E-05	3.55E-06	7.6548
242	11.0642	5.3616	1.8440	10.8985	125.8296	11.6777	0.0499	6.3232	1.19E-04	1.19E-05	16.4407
243	6.5046	3.1277	1.0841	6.4230	64.0239	6.2966	0.0237	3.2174	6.06E-05	6.06E-06	9.8192
244	5.8285	2.9422	0.9714	5.6647	59.9677	5.3073	0.0206	3.0135	5.68E-05	5.68E-06	9.0789
245	5.7640	2.8353	0.9607	5.6503	54.2088	5.3957	0.0216	2.7241	5.13E-05	5.13E-06	8.7930
246	5.9027	3.0163	0.9838	5.7129	59.3963	5.5693	0.0216	2.9848	5.63E-05	5.63E-06	9.0248
247	8.0639	3.6277	1.3440	8.1251	89.5868	8.1530	0.0319	4.5020	8.48E-05	8.48E-06	11.9759
248	6.4302	4.1447	1.0717	5.6652	92.5208	6.2430	0.0315	4.6494	8.76E-05	8.76E-06	10.0373
249	4.5681	2.2704	0.7613	4.4627	29.5720	3.8782	0.0171	1.4861	2.80E-05	2.80E-06	7.1673
250	12.1061	5.8715	2.0177	11.9215	155.2827	12.5428	0.0541	7.8033	1.47E-04	1.47E-05	18.3200

Appendix B

Correlations between Simulation Results and Biomass Feedstock Properties

The correlations between different biomass characteristics and other indicators for AC production energy and carbon footprints are summarized in Figure B.1-B.4. The biomass characteristics used in Figure B.1-B.4 include the main elements of biomass ultimate analysis (Carbon, hydrogen and oxygen content), lignocellulosic components (cellulose, hemicellulose and lignin content), ash content and two other indicators derived from ultimate analysis (Hydrogen to carbon ratio (H/C) and oxygen to carbon ratio (O/C)). The value of all these variables can be found or deduced from the data given in Table 3.1. The indicators for Figure B.1-B.4 are biogenic GHG emission, total GHG emission, primary energy demand and energy recovery ratio (ERR), respectively.

Besides the main insights that are concluded in the article, some additional findings can be summarized from Figure B.1-B.4 with the given R-value (correlation coefficient) of each plot. Overall the correlation between most of the biomass characterization data and the proposed indicators are weak (with R-value < 0.2), except the hydrogen content, H/C ratio and ash content. In addition, the ash content is negatively correlated to all the proposed indicators, which is because ash has no reactions in the AC production process and retained in final AC production. However, the high ash content may reduce the quality of AC in some specific applications (e.g., adsorbent, supercapacitor), thus the consideration of ash content in selecting biomass feedstock for AC production is still determined yet.

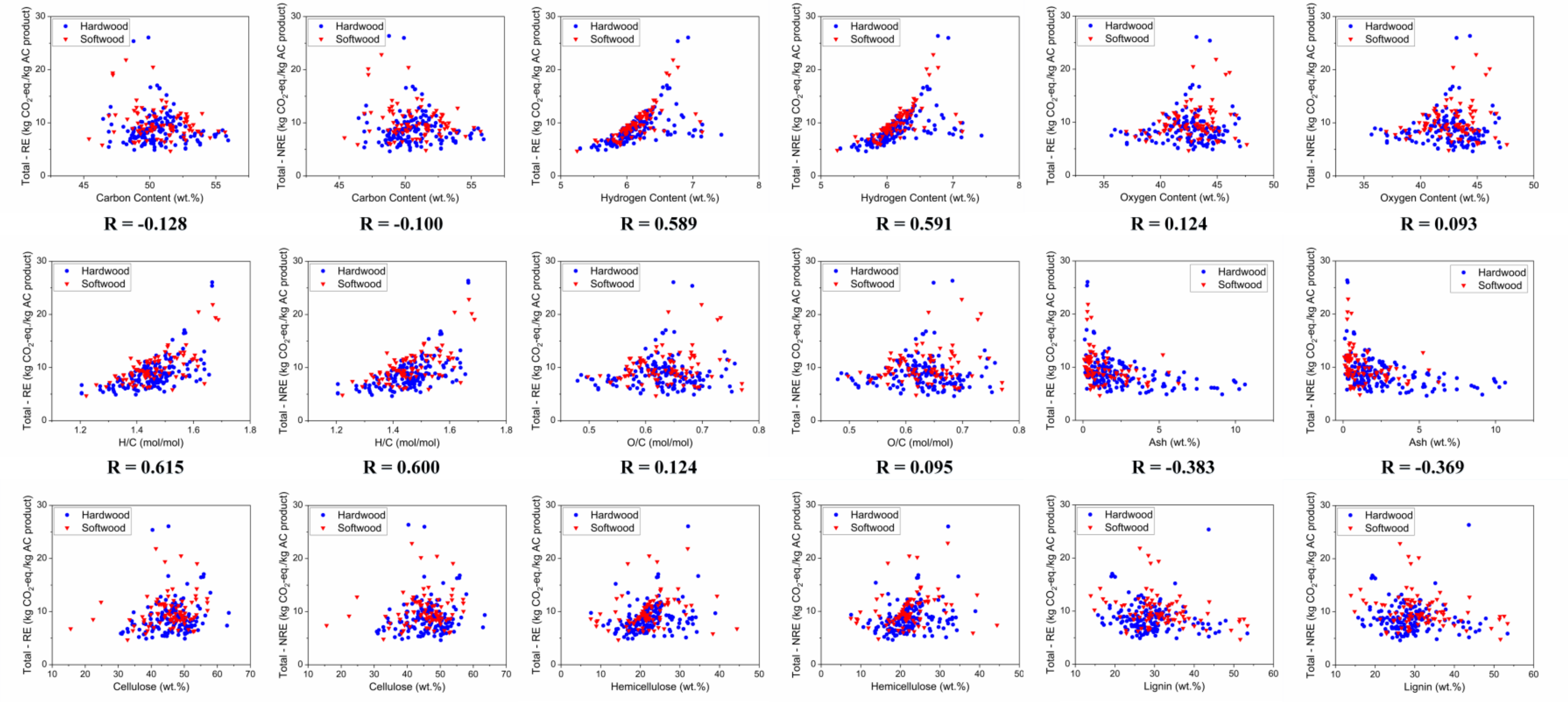


R = 0.028 R = -0.072 R= 0.634 R= 0.608 R= -0.040 R = 0.061

R = 0.562 R = 0.599 R = -0.039 R = 0.065 R = -0.297 R = -0.372

R = 0.025 R = 0.089 R = 0.183 R = 0.172 R = -0.073 R = -0.098

Figure B.1 Correlations between the biogenic GHG emission of steam AC production and feedstock composition (RE: process with energy recovery; NRE: process without energy recovery)

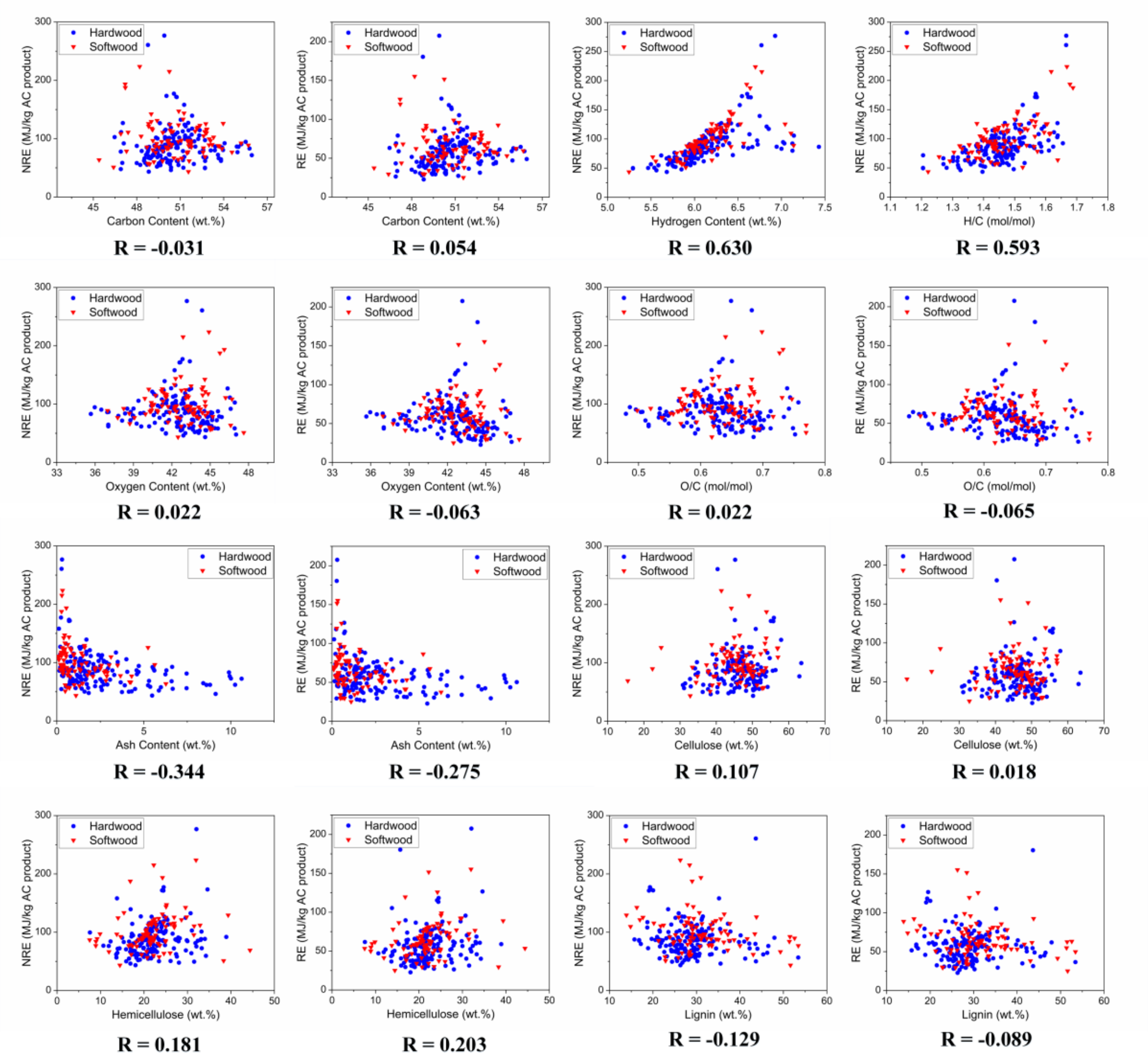


R = -0.128 **R = -0.100** **R = 0.589** **R = 0.591** **R = 0.124** **R = 0.093**

R = 0.615 **R = 0.600** **R = 0.124** **R = 0.095** **R = -0.383** **R = -0.369**

R = 0.150 **R = 0.087** **R = 0.209** **R = 0.204** **R = -0.175** **R = -0.122**

Figure B.2 Correlations between the total GHG emission of steam AC production and biomass feedstock composition (RE: process with energy recovery; NRE: process without energy recovery)



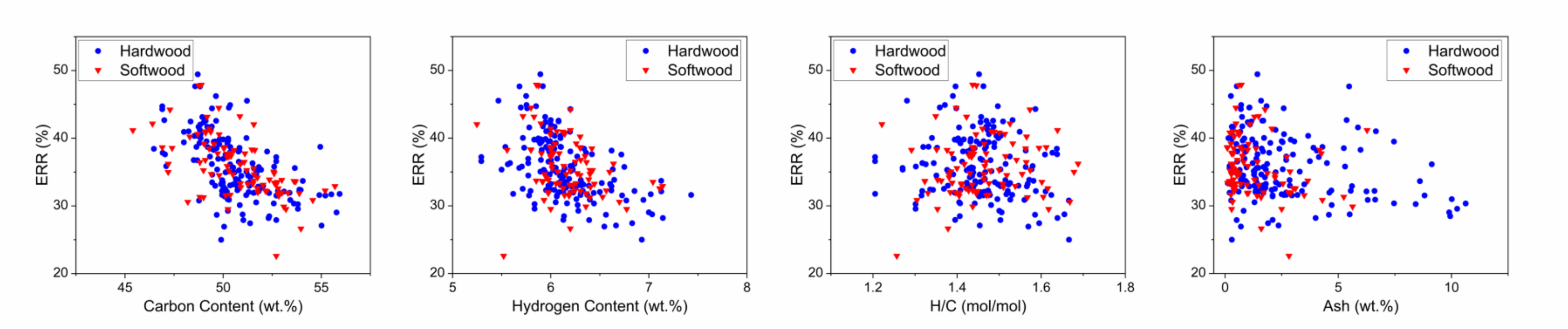
R = -0.031 **R = 0.054** **R = 0.630** **R = 0.593**

R = 0.022 **R = -0.063** **R = 0.022** **R = -0.065**

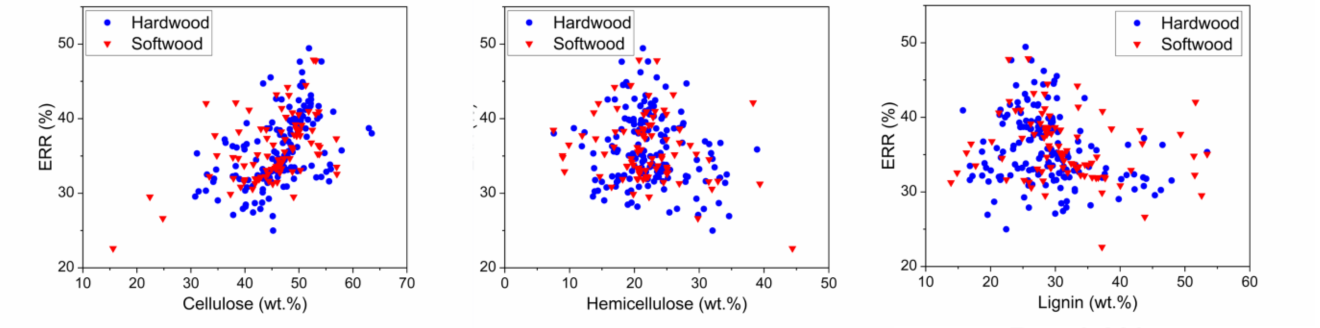
R = -0.344 **R = -0.275** **R = 0.107** **R = 0.018**

R = 0.181 **R = 0.203** **R = -0.129** **R = -0.089**

Figure B.3 Correlations between primary energy demand of steam AC production and feedstock composition (RE: process with energy recovery; NRE: process without energy recovery)



R = 0.018　**R = 0.289**　**R = 0.229**　**R= -0.529**



R = 0.678　**R = -0.125**　**R = -0.330**

Figure B.4 Correlations between energy recovery ratio of steam AC production and biomass feedstock composition

Additional Sensitivity Analysis Results

Figure B.5 Sensitivity analysis for the energy consumption, biogenic GHG emission (without energy recovery) and fossil-based GHG emission (with/without energy recovery) of steam AC production process