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Biomass Gasification: A Review of Its Technology, Gas Cleaning Applications, and Total System Life Cycle Analysis

Kenji Koido and Takahiro Iwasaki

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Abstract

Gasification technology presents one option for energy-conversion technique from woody biomass contaminated by radionuclides released in March 2011 during the Fukushima Dai-ichi Nuclear Power Plant accident. The gasification process converts carbonaceous materials into combustible gases, carbon dioxide, and residues. Owing to their small-scale distributed configuration, woody biomass gasification plants are suitable for gasifying Japan's biomass and have been installed increasingly in Japan recently. This chapter reviews current trends of gasification and life cycle assessment (LCA) of total systems, including gas cleaning.

Keywords: biomass gasification, gas cleaning, desulphurisation, radioactive materials, life cycle assessment

1. Introduction

Lignin is a crosslinked macromolecular material based on a phenylpropanoid monomer structure. Vascular plant species such as fern-related plants, gymnosperms, and angiosperms have lignin structures. Woody plants such as softwoods and hardwoods are composed, respectively, of 25–35% and 20–25%. Recently, small-scale woody biomass power generation plants have been installed increasingly in Japan. Such plants are suitable for gasifying Japan's biomass because of their small-scale, distributed characteristics.

To utilise small-scale biomass more effectively, biomass plants must be installed near energy source and demand sites in order to shorten transport distances. This is especially effective for small-scale woody biomass plants. Here small scale is defined as a plant scale of at most

2 MWe. Power generation in such small-scale plants requires biomass gasification technology in order to obtain higher thermal efficiency. Gasification is a process that converts carbonaceous materials into carbon monoxide, hydrogen, carbon dioxide, and gaseous hydrocarbons (producer gas). Producer gas can be supplied as fuel to internal combustion engines and power generators. To maximise the efficiency of woody biomass conversion, producer gas should be utilised not only for power generation but also for thermal production from the producer gas' sensible heat. Cogeneration system for heat and power production is called combined heat and power (CHP).

Recently, many kinds of biomass gasification combined heat and power (BGCHP) systems have been developed (mainly in Europe). These micro/small-scale CHP systems can be connected and integrated to achieve an appropriate plant scale according to the biomass supply and heat and power demands. Further description of BGCHP is presented in section 2.4.

Woody biomass in Fukushima was contaminated by radionuclides released between 12 and 31 March 2011 due to the Fukushima Dai-ichi Nuclear Power Plant accident. To safely utilise the contaminated woody biomass in Fukushima as biomass gasification (BG) fuel, the radioactivity of products and by-products such as offgas and ashes in ash bins and on filters must be investigated.

This chapter reviews current trends of gasification and life cycle assessment (LCA) of total systems, including gas cleaning. Previously, there have been no reviews of small-scale gasification process for hydrogen production and CHP and no critical review of LCA of BG processes. Gas cleaning is one of the most important processes in BG systems for controlling contaminants in producer gases and preserving the catalysts of fuel cells and gas engines.

2. Gasification technology

A biomass gasifier is comprised of four reaction zones, i.e. drying, pyrolysis, combustion, and reduction. The produced gas (syngas) contains impurities to be cleaned utilising a bag filter, activated carbon, scrubber, etc. This chapter describes the fates of two contaminants, radionuclides and sulphur, during the gasification process. The radioactivity of caesium-137 (^{137}Cs) and caesium-134 (^{134}Cs) in fly ash over a bag filter was observed using a germanium semiconductor detector. The fate of sulphur was also reviewed because sulphur often triggers fuel cell catalyst poisoning and gas engine erosion. The LCA of a total system based on the energy profit ratio and environmental impact is then reviewed.

2.1. Biomass feedstock

Biomass feedstocks are classified based on several factors: moisture content, material, and form, as presented in **Table** 1. Biomass is broadly divided into three groups: dry, wet, and other. Dry biomass is classified as woody or herbaceous and wet biomass as sludge/excreta, common food, or other. Each classification has three sub-categories: waste, unutilised, and produced.

Moisture	Classification	Wastes	Unutilised	Produced
Dry	Woody	Construction wastes, Timber offcuts	Forest thinnings, Remaining forest timbers, Damaged trees	Short-rotation woody crops (eucalyptus, willow, etc.)
	Herbaceous		Crop residues (rice / wheat straw, rice husk)	Grasses (Napier grass, sorghum, Miscanthus etc.)
Wet	Sludge /Excreta	Sewage sludge, Livestock excreta		
	Common food	Food-processing wastes, Kitchen wastes		
Other	Other	Molasses, Waste food oil	Landfill gas	Cultivated maize, Cultivated sugar cane

Table 1. Classification of biomass feedstocks.

Among these, dry woody/herbaceous biomasses are used as feedstocks for BG plants in Japan. For instance, woody biomasses contain waste woods (construction wastes and timber offcuts) and unutilised woods (forest thinnings, remaining timbers, and damaged trees) composed of cedar, cypress, pine, etc. Short-rotation woody crops (eucalyptus, willow, etc.) are categorised as produced woods. Energy crops such as willow are expected to be cultivated in land fallow and used as biomass because non-food-producing farmlands have been recently abandoned in Japan [1].

For unutilised herbaceous biomass, crop residues such as rice/wheat straw and rice husks [2] are available, while for produced herbaceous biomass, grasses such as Napier grass, sorghum, and Miscanthus are usable. Above all, rice husks contain abundant silica. The ash by-product from gasifiers has potential use in nanomaterials [3].

2.2. Gasifier

There are various kinds of gasifiers (e.g., fixed-bed, fluidised, pressurised, etc.). This chapter describes the simplest fixed-bed gasifiers. Fixed-bed gasifiers have a long history and have established confidence through experience with small-scale biomass gasification reactors [4]. **Figure 1** schematically illustrates fixed-bed updraft and downdraft gasifiers. The flows of biomass and producer gases are counter-current for updraft and co-current for downdraft. The gasification reaction is comprised of four main reaction zones. Heat released during the combustion process is used for drying, pyrolysis, and reduction processes in the gasifier.

For both gasifier types, biomass fuels are supplied into each gasifier followed by a drying process. The dried biomass is then pyrolysed to release volatiles and gases. These products are combusted partially or completely using air fed with heat released from the combustion process. The gases, tars, and chars resulting after combustion are reduced in the reduction zone. The positional relationship of these processes is shown schematically in **Figure 2**.
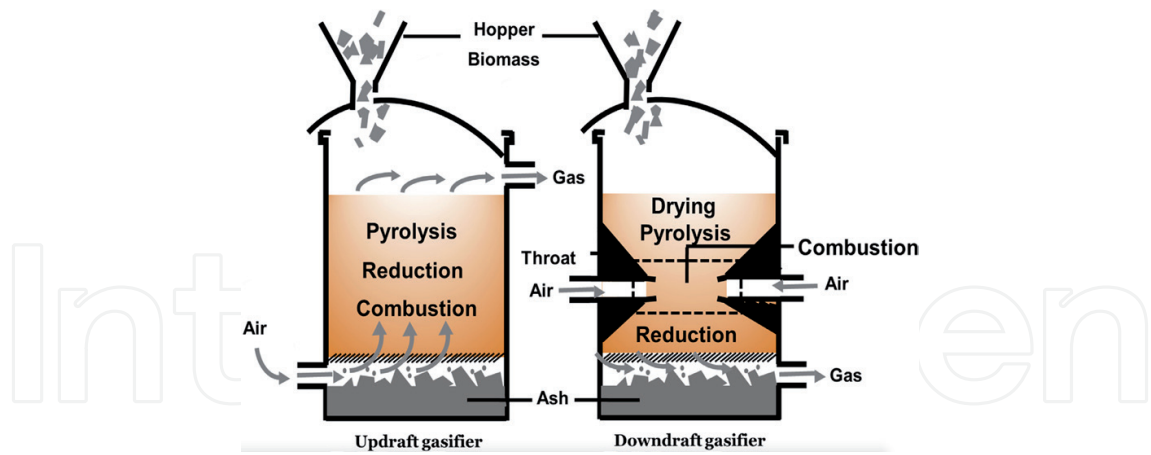
Figure 1. Schematic of updraft and downdraft fixed-bed gasifiers [5].

2.3. Gasification mechanisms

Gasification proceeds through many kinds of simultaneous or consecutive complex reactions. Reactions corresponding to each reaction zone are shown in this section. **Figure 3** represents several main reaction pathways in biomass gasification reactions. The reactions for each pathway (or reaction zone) are presented in **Table 2** based on the literature [7, 8].

2.3.1. Drying

Biomass moisture at ordinary temperatures becomes water vapour during the drying process at about 100–250 °C. The conversion occurs owing to heat transfer between hot gases from the oxidation and biomass in the drying zone [4]. First, the moisture on the biomass surface evaporates followed by inherent moisture evaporation. The vapour produced is used for reduction reactions in the reduction zone, including the water-gas reaction.
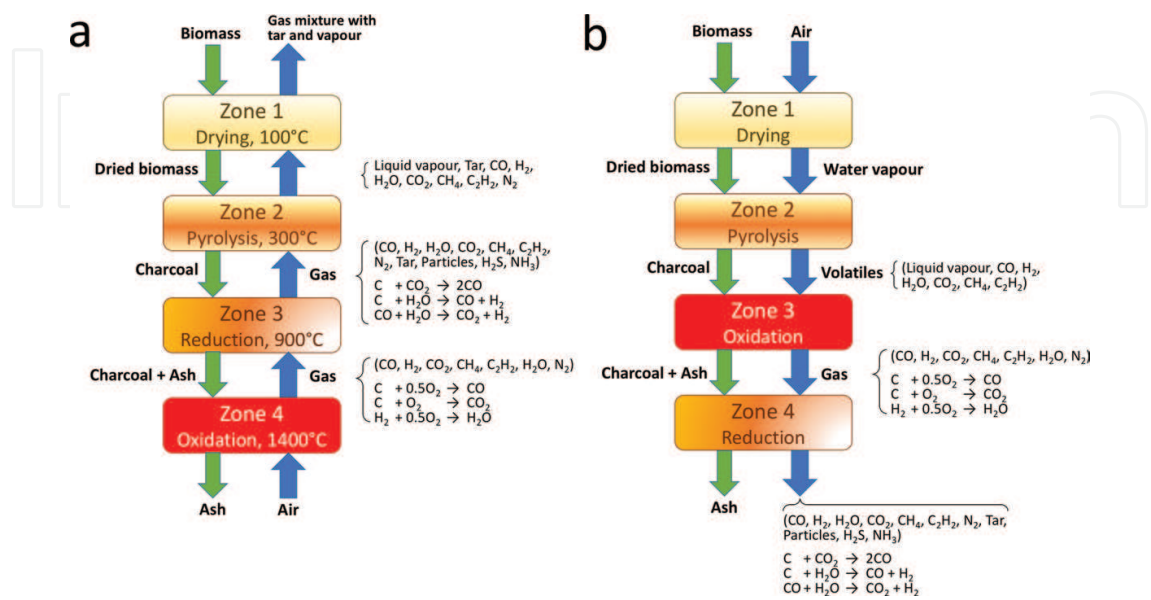

Figure 2. Conceptual diagram of multiple steps in fixed-bed (a) updraft and (b) downdraft gasifiers [6].
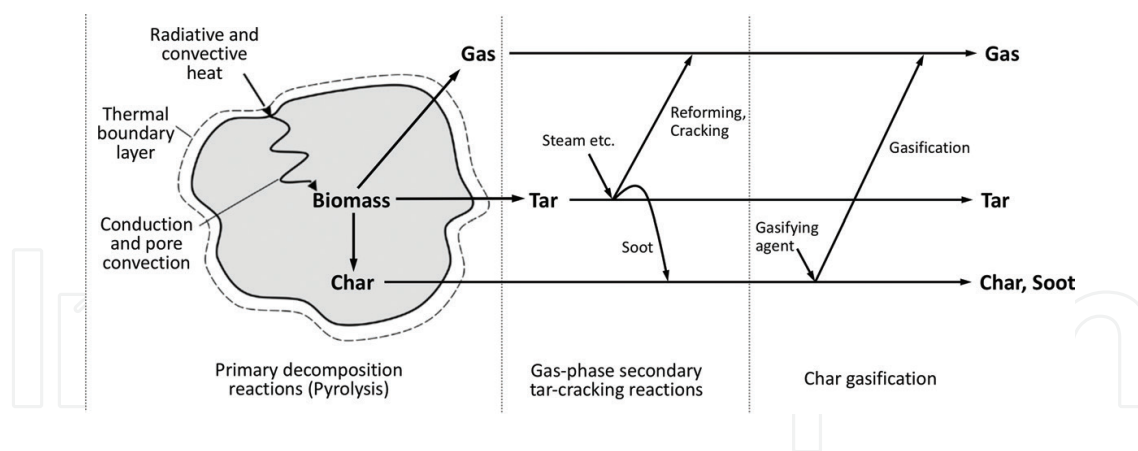
Figure 3. Biomass gasification pathway proposed based on Ref. [10, 11].

2.3.2. Pyrolysis

In the absence of oxygen, volatiles with weaker molecular bonds begin to be thermally decomposed at 200–240 °C; this continues up to 400 °C. The volatiles are vaporised to produce gases, tars, and chars. The chars are also pyrolysed with gas production and weight loss of about 30% [9]. Pyrolysis takes place owing to heat transfer from radiation, convection, and conduction to the biomass as shown in **Figure 3a**. The pyrolysis reactions are represented as Reaction (R1) in **Table 2**.

Name of reaction	Chemical reaction	$\Delta H^0_{r(298)}$ (kJ/mol)	$\Delta G^0_{r(298)}$ (kJ/mol)	No.
Pyrolysis	$C_xH_yO_z \rightarrow aCO_2 + bH_2O + cCH_4$ $+ dCO + eH_2 + fC_{2+} + char + tar$			(R1)
Partial oxidation	$C + 0.5\,O_2 \rightarrow CO$	−111		(R2)
Complete oxidation	$C + O_2 \rightarrow CO_2$	−394		(R3)
Steam-tar reforming	$C_nH_m + 2nH_2O \rightarrow (2n + m/2)\,H_2 + nCO_2$			(R4)
Hydrogenating gasification	$C + 2H_2 \leftrightarrow CH_4$	123.7	168.6	(R5)
Boudouard equilibrium	$C + CO_2 \leftrightarrow 2CO$	205.3	140.1	(R6)
Water-gas shift (WGS)	$CO + H_2O \leftrightarrow CO_2 + H_2$	−41.47	−28.5	(R7)
Heterogeneous WGS	$C + H_2O \leftrightarrow CO + H_2$	130.4	89.8	(R8)
Steam reforming of methane	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	172.6	118.4	(R9)
Dry reforming of methane	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	−74.9	−50.3	(R10)
Ethylene	$2CO + 4H_2 \leftrightarrow C_2H_4 + 2H_2O$	−104.3	−111.6	(R11)
Ethane	$2CO + 5H_2 \leftrightarrow C_2H_6 + 2H_2O$	−172.7	−212.7	(R12)
Propane	$3CO + 7H_2 \leftrightarrow C_3H_8 + 3H_2O$	−165.1	−293.2	(R13)
Butane	$4CO + 9H_2 \leftrightarrow C_4H_{10} + 4H_2O$	−161.9	−376.7	(R14)
H₂S formation	$S + H_2 \rightleftarrows H_2S$			(R15)
H₂S-COS equilibrium	$H_2S + CO \rightleftarrows COS + H_2$			(R16)

Table 2. Chemical reactions occurring in biomass gasification (gasifying agent: steam).

2.3.3. Oxidation

Heat is released during the oxidation of gases and of gaseous volatiles and chars produced in pyrolysis under supplied air. The heat is used for drying, pyrolysis, and other endothermic reactions [4]. Partial oxidation (R2) and complete oxidation (R3) occur. Reaction temperatures are around 600–900 °C for partial oxidation and around 800–1400 °C for complete oxidation. Partial oxidation releases 111 kJ/mol of heat while complete oxidation releases 394 kJ/mol.

2.3.4. Reduction

During the reduction process, the char and tar produced from oxidation release gases at around 600–950 °C via several reactions. The typical reactions include the heterogeneous water-gas shift (HWGS: $C + H_2O \rightarrow H_2 + CO$) and water-gas shift reaction (WGS: $CO + H_2O \leftrightarrows CO_2 + H_2$). Via the endothermic HWGS reaction, char or tar reacts with water vapour (derived from biomass and air) to produce CO and H_2 at temperatures greater than 750 °C. The WGS reaction is an exothermic reversible reaction and has an equilibrium point for CO, H_2O, CO_2, and H_2 concentrations. The higher the reaction temperature, the greater the amount of gaseous products produced on the equation's right-hand side. Reduction is a totally endothermic reaction because the water-gas reaction is dominant.

2.4. Combined heat and power gasification

Gasification power generation systems are different in terms of gasifier type, gas cleaner for dust/tar/hydrogen sulphide removal (as described in sections 3.2 and 3.3), heat exchanger type, and power generator type (gas turbine, internal combustion engine, fuel cell, etc.). A BGCHP requires seven elemental processes: (i) pretreatment, (ii) storage, (iii) gasifier, (v) gas cleaner, (iv) gas cooler, (vi) gas engine, and (vii) power generator, as shown in **Figure 4**. BGCHP is a process that cogenerates heat and power from syngas produced in the gasifier. **Figure 4** shows a simplified schematic of BGCHP. Generally, biomass power generation from direct combustion has an efficiency of ca. 30% at most. However, via BGCHP, a total efficiency of ca. 85% is attained with thermal-load-following operation.

There are many kinds of small-scale gasifiers manufactured by European companies such as in Germany (e.g., Burkhardt [12], Spanner [13], Entrade [14], etc.), Finland (e.g., Volter [15]), and Sweden (e.g., Cortus Energy AG [16]).

2.5. Biohydrogen production via gasification

Biohydrogen via thermochemical conversion is obtained by gasifying woody biomass followed by a gas cleaning process. Biomass gasification typically yields producer gases such as H_2 (14–25%), CO (15–24%), CO_2 (12–15%), CH_4 (2.0–2.5%), H_2S (<100 ppmv), and COS (50 ppmv) [6]. For H_2 production, gas cleaning is required for gases other than H_2. Generally, CO is converted into H_2 and CO_2 with steam by a shift converter packed with nickel or nickel oxide catalysts.
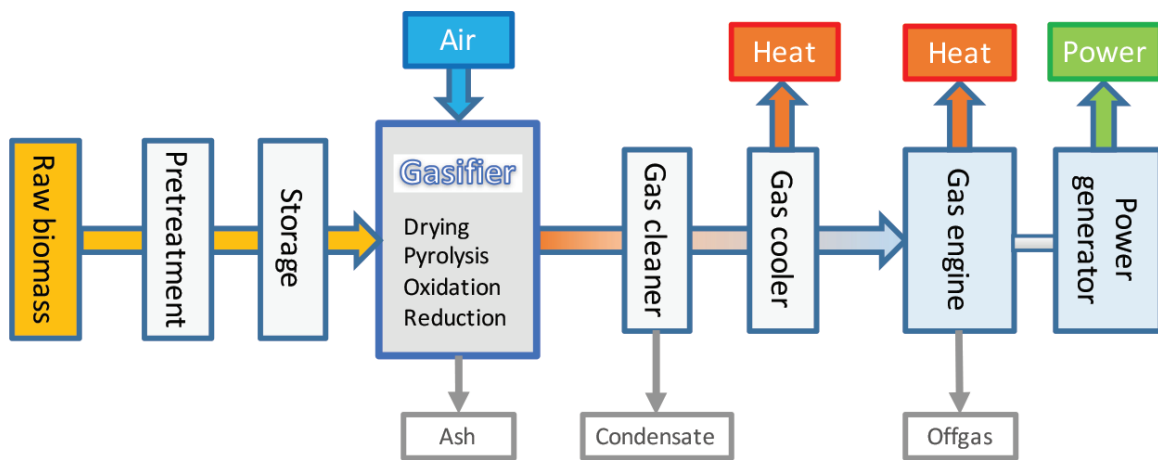
Figure 4. Flow diagram of power generation from biomass gasification.

3. Gas cleaning

3.1. Contaminants

Contaminants in syngas generally include particulate matter, condensable hydrocarbons (i.e. tars), sulphur compounds, nitrogen compounds, alkali metals (primarily potassium and sodium), hydrogen chloride (HCl), and radioactive nuclides. In this review, the sulphur compounds and radioactive nuclides in Fukushima, Japan are the focus.

Syngas ($CO + H_2$) has many uses ranging from heat and/or power applications (e.g., CHP) to many kinds of synthetic fuels and chemicals as shown in **Figure 5**. During production, each contaminant triggers process inefficiencies, including not only corrosion pipe blockages but also rapid and permanent deactivation of catalysts [17].
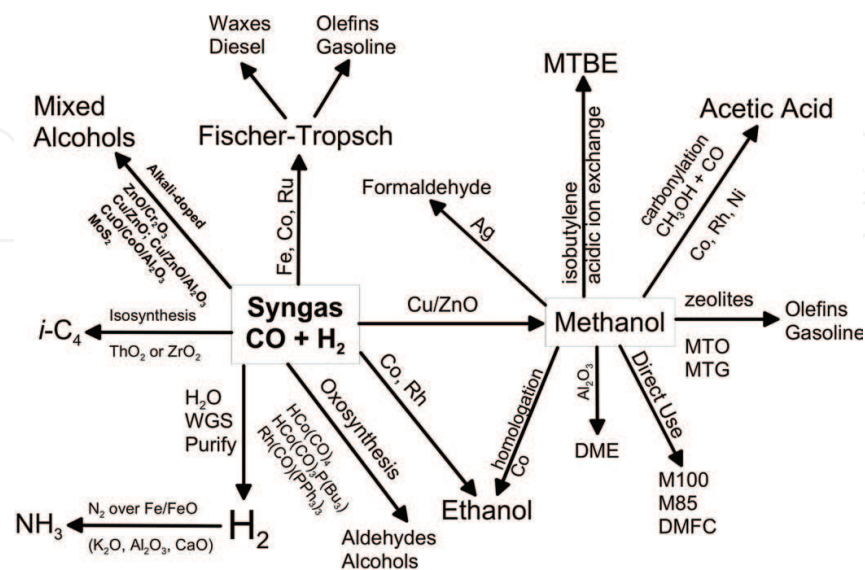

Figure 5. Different syngas transformation routes for synthesising fuels and other chemicals [18].

Contaminant levels depend on feedstock impurities and the syngas generation method used. The level of cleaning required may also be influenced substantially by end-use technology and/or emission standards [17]. **Table 3** shows the syngas cleaning requirements for some typical end-use applications.

3.2. Sulphur

There are several gas cleaning technologies: absorption, adsorption, conversion, and biological transformation. Wiheeb et al. has described the adsorption process of H_2S. **Table 4** presents a summary of the characteristics of sulphur removal technologies [19]. In gasification processes, absorption and adsorption are employed well as gas/bag filter and scrubber processes, respectively.

3.2.1. Fate of sulphur during gas cleaning over adsorbents

The fate of sulphur during the gasification of lignin slurry was investigated by Koido et al. [20]. In their study, hydrogen sulphide removal from bio-synthesis gas over a nickel oxide catalyst supported by calcium aluminate ($NiO/CaAl_2O_4$) was investigated at high temperatures. They investigated the sulphur balance of the process at different operating temperatures ($T = 750–950\ °C$), moisture contents of the lignin slurry (MC = 73–90 wt%), and catalyst loadings (CL = 0.00–0.61 g-catalyst/g-feedstock). The sulphur balance was 0.79, 0.04, 0.003, and 0.378 mmol/g-lignin for the gas, char, water-soluble fraction, and $NiO/CaAl_2O_4$ catalyst surface, respectively.

3.3. Radionuclides

3.3.1. Introduction

Radionuclides including [134]Cs and ^{137}Cs were released into the environment after the Fukushima Dai-ichi Nuclear Power Plant accident in March 2011. After the accident, decontamination was

Contaminants	Applications			
	Methanol synthesis (mg m^{-3})	FT synthesis (μL L^{-1})	Gas turbine (μL^{-1})	IC engine (mg m^{-3})
Particulate (soot, dust, char, ash)	<0.02	Not-detectable	<0.03 (PM$_5$)	< 50 (PM$_{10}$)
Tars (condensable)	—[a]	<0.01[b]	—	—
Tars (heteroatoms, BTX)	<0.1	<1	—	<100
Alkalis	—	<0.01	<0.024	—
Nitrogen (NH$_3$, HCN)	<0.01	<0.02	<50	—
Sulphur (H$_2$S,COS)	<1	<0.01	<20	—
Halides (primarily HCl)	<0.1	<0.01	1	—

[a]Data are not available in the original literature.
[b]All values are at STP unless explicitly specified.

Table 3. Syngas cleaning requirements for some typical end-use applications [17].

Classification [19]	Technology [19]	Characteristics [19]	Reference
Absorption (wet desulphurisation)	Conventional absorption process	• Absorption has been used in petroleum and gas industries to remove H_2S and CO_2 from sour natural gas and refinery gas. • The removal is called gas sweetening, which involves transferring of H_2S from a gaseous phase (feed) into a liquid phase (solvent). • The conventional process has higher sulphur removal but requires strict pH control of chemical concentrations and wastewater treatment, which could cause corrosion problems.	Taheri et al., [21]
	Membrane reactor	• Membranes can be used to purify biogas. • Membranes are not usually used for selective removal of H_2S, but rather to upgrade biogas to natural gas standards.	Dolejš et al., [22]
Adsorption (dry desulphurisation)	Carbonaceous adsorbents	• Activated carbon has a high specific surface area of more than 1000 m^2/g. • The surface area, pore volume, and surface chemistry promote numerous catalytic reactions.	Kazmierczak-Razna et al., [23]
	Metal oxide adsorbents	• The removal of H_2S at high temperature has received much attention owing to its potential in reducing H_2S concentration to 10 ppm. • Metal oxide: FeO, Cu_2O, MnO, ZnO CoO, NiO and MoO, alkaline earths (CaO, SrO, and BaO), and alkalis (Li_2O, K_2O and Na_2O). • The process has higher thermal efficiency through sensible heat utilisation and easy treatment of wastewater but requires either catalyst exchange or regeneration.	Abdoulmoumine et al., [24]
Conversion	Claus process	• The Claus process is used in oil and natural gas refining facilities and removes H_2S by oxidising it to elemental sulphur. • Removal efficiency is about 95% using two reactors and 98% using four reactors.	Ibrahim et al., [25]
	Selective catalytic oxidation	• The selective catalytic oxidation of H_2S into elemental sulphur is one of the treatment methods employed for the removal of H_2S from Claus process tail gas. • The catalytic oxidation of H_2S can be performed above or below the sulphur dew point (180 °C).	Tasdemir et al., [26]
	Liquid redox sulphur recovery	• Liquid-phase oxidation systems convert H_2S into elemental sulphur through redox reactions by electron transfer from sources such as vanadium or iron reagents.	Kim et al., [27]
Biological transformation	Biological methods	• Microorganisms have been used for the removal of H_2S from biogas. • Ideal microorganisms would have the ability to transform H_2S to elemental sulphur.	Tóth et al., [28]

Table 4. Characteristics of each sulphur removal technology [20].

implemented in resident areas, and was completed over all residential area surfaces at the end of March 2017 [29, 30]. However, for utilisation of Fukushima's forest resources, which are contaminated by radioactive nuclides, utilisation of woody biomass as fuel for bioenergy production from gasification (such as heat, power, hydrogen, etc.) in the near future is a possible option. For this purpose, the mass balance of radionuclides must be revealed.

In particular, ^{137}Cs is almost distributed in argilliferous soils and fallen leaves in Fukushima. Of all the local ^{137}Cs in 2015, 87% was distributed in soil with 10% in fallen leaves in Japanese cedar forests, while 87% was distributed in soils with 11% in fallen leaves in *Quercus serrata* forests [31]. Moreover, 3% of ^{137}Cs was in Japanese cedar timbers (bark: 0.5%; boards: 0.4%; branches: 0.7%; and leaves: 0.6%), while 2% of ^{137}Cs was found in *Quercus serrata* timber (bark: 0.7%; boards: 0.2%; branches: 0.5%; and leaves: 0.1%) [31].

The radioactivity of gasification pellet fuel, products, and by-products was measured to clarify the fate of ^{134}Cs and ^{137}Cs from Fukushima's woody biomass during the biomass gasification process.

3.3.2. Material and methods

The measured samples were woody pellet fuel, gasification residue in ash bins (main ash), soot on ash filters (fly ash), and exhaust gas, which are produced from woody BGCHP systems (E3 unit, Entrade Energy) at the Spa Resort Abukuma in Nishigo village, Fukushima. The woody pellets are comprised of a mixture of Japanese cedar and *Quercus serrata* obtained from the Yamizo Mountains. Using these pellets, the radioactivity of products/by-products for each BGCHP process was observed. The exhaust gas was filtered by means of a high-volume air sampler (Shibata Scientific Technology Ltd., HV-500RD) for 30 min at suction flow rate of 500 L/min.

A germanium semiconductor detector (CANBERRA GC4020) was used to detect the radioactivity arising from radionuclides such as ^{134}Cs and ^{137}Cs. To minimise measurement errors, each measurement was taken over 3 h for the pellet fuels, the gasification residues, and the soot on filters, while 12 h for the filter of high-volume air sampler. Each radioactivity concentration was calculated by dividing the measured radioactivity by the sample mass/volume. The solid samples were placed into a vessel (100 mL) and measured.

3.3.3. Results and discussion

For ^{137}Cs, the radioactivity levels of solid samples were 20.6 Bq/kg (standard error, SE: 1.01 Bq/kg) for the woody pellets, 1333 Bq/kg (SE = 10.4 Bq/kg) for residue, and 5432 Bq/kg for soot from bag filters as presented in **Table 5**. The offgas radioactivity was not detectable when the limit of detection (LOD) was 0.002 Bq/m^3. All of the by-products were smaller than the criterion. For ^{134}Cs, the solid sample radioactivity levels were less than 4.10 Bq/kg for the woody pellets, 207 Bq/kg (SE = 7.58 Bq/kg) for residue, and 849 Bq/kg for soot from bag filters as presented in **Table 5**. The offgas radioactivity was not detectable. All of the by-products were smaller than the criterion. In this study, the biomass gasification plant was capable of keeping the radioactive nuclides (in the residue and the filters) within the plant. However, radionuclides should be monitored periodically.

Sample	^{137}Cs			^{134}Cs			Sample amount
	Mean	SE[a]	LOD[b]	Mean	SE[a]	LOD[b]	
Woody pellet (Bq/kg)	20.6	1.01	3.50	< 4.10	na	3.55	70.5 g
Residue (Bq/kg)	1333	10.4	15.0	207	7.58	15.4	39.6 g
Bag filter (Bq/kg)	5432	na	43.0	849	na	46.8	11.6 g
Offgas (Bq/m³)	nd	na	0.002	nd	na	0.003	14.9 m³

[a]SE = standard error.
[b]LOD = limit of detection.
na = not available.
nd = not detectable.

Table 5. Radioactivity levels in the E3 biomass gasification process.

4. Life cycle assessment of the biomass gasification process

Life cycle assessment (LCA) is a methodology that examines products and services "from cradle to grave" with a view to understanding system-wide environmental impacts. A cradle-to-grave LCA study of a product considers all life cycle stages from extraction or primary production of materials and fuels ('cradle') through production and use of the product to its final disposal ('grave'). The framework has been standardised by the International Organisation as ISO 14,044:2006 [32].

Recent studies concerning biomass gasification are summarised in **Table 6**. Recent LCA studies concerning biomass gasification are categorised into four groups: (i) biomass-based hydrogen (bio-H_2) production [33–38], (ii) biomass gasification combined heat and power (CHP) [39–44], (iii) other energy systems [45–48], and (iv) dynamic LCA [49]. This chapter covers the review of the LCA studies about biomass gasification.

4.1. Biomass gasification for hydrogen production

To evaluate the environmental performance of H_2 production via indirect gasification of short-rotation poplar, a LCA was implemented using process simulation for normal BG processes [33] and for BG with CO_2 capture by pressure swing adsorption [34]. From a life-cycle perspective, H_2 from poplar gasification generally arose as a good alternative to conventional, fossil-derived H_2 produced via steam methane reforming.

Moreno and Dufour [35] examined the environmental feasibility of four Spanish lignocellulosic wastes (vine and almond pruning, and forest wastes coming from pine and eucalyptus plantation) for the production of H_2 through gasification via LCA methodology using global warming potential, acidification, eutrophication and the gross energy necessary for the production of 1 Nm³ of hydrogen as impact categories.

Kalinci et al. [36] performed LCA for stages from biomass production to the use of the produced hydrogen in proton exchange membrane fuel cell vehicles. Two different gasification

Study	Methodology				Economic impact	Environmental impact category												
	Location	FU	System boundary	Products		EC	AC	EP	GWP	HT	LU	OD	PO	RC	WC	ET	PM	IR
Susmozas et al. [33]		1 kg of H$_2$ produced from the plant with 99.9 vol% purity	Cradle-to-gate	Bio-H$_2$ from BG with CCS		X	X	X	X		X	X	X					
Susmozas et al. [34]	EU	1 kg of H$_2$ produced from the plant with 99.9 vol% purity	Cradle-to-gate	Bio-H$_2$ from indirect BG with CO$_2$ capture		X	X	X	X		X	X	X					
Moreno and Dufour [35]			Cradle-to-gate	H$_2$, CO$_2$, other emissions, wastes		X	X	X	X									
Kalinci et al. [36]			Cradle-to-gate	Bio-H$_2$	X				X									
Iribarren et al. [37]		1 m³ stp of purified H$_2$	Cradle-to-gate	Bio-H$_2$		X	X	X	X		X	X	X					
El-Emam, et al. [38]		1 TJ of produced energy	Cradle-to-gate	Bio-H$_2$					X									
Elsner et al. [39]	Poland		Cradle-to-gate	CHP	X													
Adams and McManus [40]	UK	1 MJ (or kWh) of energy produced	Cradle-to-gate	Small-scale BG CHP		X		X	X					X	X	X	X	
Patuzzi et al. [41]	South-Tyrol, Italy	Thermal efficiencies	Cradle-to-gate	Small-scale BG CHP		X												
Oreggioni et al. [42]	EU		Cradle-to-gate	Small-scale BG CHP			X				X				X		X	
Klavina et al. [43]	Latvia	1 kg of untreated forest residue woodchips	Cradle-to-gate	Small-scale BG CHP		X	X	X	X		X	X				X		X
Kimming et al. [44]	EU	1 y supply of heat and power to a modern village of 150 households	Cradle-to-gate	Small-scale BG CHP		X	X		X			X						

Study	Methodology				Economic impact	Environmental impact category												
	Location	FU	System boundary	Products		EC	AC	EP	GWP	HT	LU	OD	PO	RC	WC	ET	PM	IR
Sreejith et al. [45]	State of Kerala in India	1 MJ energy content in the gaseous fuel	Cradle-to-gate	Producer gas generated from coconut shell gasification					X			X			X			
Parvez et al. [46]			Cradle-to-gate	Heat and syngas produced from gasification		X			X									
Kalina [47]	Poland	Cold/hot gas efficiency	Cradle-to-gate	Integrated BG dual fuel combined cycle power plant	X	X												
Wang et al. [48]	Harbin, China	1 y operation	Cradle-to-gate	Building cooling heating and power	X	X			X					X				
Yang and Chen [49]	China	1 MJ of primary energy produced in a BG plant (dynamic LCA)	Cradle-to-grave	Producer gases (CO_2, H_2, CO and CH_4) from BG	X				X									

Abbreviation: CCS: carbon dioxide capture; na: not available; CHP: combined heat and power; BG: biomass gasification; EC: energy consumption; AC: acidification; EP: eutrophication; GWP: global warming potential; HT: human toxicity; LU: land use; OD: ozone depletion; PO: photochemical oxidation; RC: resource consumption; WC: water consumption; ET: ecotoxicity; PM: particulate matter; IR: ionising radiation.

Table 6. Recent life cycle assessment studies on biomass gasification.

systems, a downdraft gasifier and a circulating fluidised bed gasifier (CFBG), are considered and analysed for H_2 production using actual data taken from the literature. Functional unit was 1 MJ/s H_2 production. Then, the costs of GHG emissions reduction are calculated.

Iribarren et al. [37] assessed environmental and thermodynamic performance of H_2 production via BG through a LCA and an exergetic analysis. The case study involves poplar gasification in a low-pressure char indirect gasifier, catalytic tar destruction, cold wet gas cleaning, syngas conversion and hydrogen purification. The system boundary covers from poplar cultivation to H_2 purification.

El-Emam et al. [38] focused on efficiency and environmental impact assessments of steam biomass gasification and gasification-solid oxide fuel cell (SOFC) integrated system for power and H_2 production. The environmental assessment is performed based on the carbon dioxide produced from the system with respect to the generated useful products.

4.2. Biomass gasification for CHP

Experimental and numerical analyses of a CHP installation (75 kWe of electrical power) was investigated by Elsner et al. [39], which is equipped with a biomass downdraft gasifier, gas purification system, and gas piston engine. The economic analysis was performed taking into account policies and regulations in the Polish energy market sector. They revealed that it is more profitable to consume the generated power and heat for its self-consumption rather than selling it on the market.

Using the techniques of LCA and net energy analysis, the study by Adams and McManus [40] quantified the energy, resource, and emission flows, to assess the net energy produced and potential environmental effects of BG using wood waste. The paper conducted a case study that uses waste wood from a factory for use in an entrained flow gasification CHP plant. Overall, small-scale biomass gasification is an attractive technology if the high capital costs and operational difficulties can be overcome, and a consistent feedstock source is available.

Patuzzi et al. [41] did an investigation resulting in an overview of the actual state-of-the-art of small-scale biomass gasification technology in Italy in terms of energy efficiency of the plants, effectiveness of the adopted solutions and characteristics of the products and by-products. In the study by Oreggioni et al. [42], a combined heat and power via BG, CHP with pre-combustion adsorptive carbon capture unit, and CHP with post combustion absorptive carbon capture unit were environmentally assessed.

Klavina, et al. [43] performed environmental performance analysis of biochar from woodchip pyrolysis, and woodchip CHP through midpoint category impact comparison using LCA. Kimming et al. [44] conducted a simplified LCA over four scenarios for supply of the entire demand of power and heat of a rural village. Three of the scenarios are based on utilisation of biomass in 100 kW$_e$ CHP systems and the fourth is based on fossil fuel in a large-scale plant.

4.3. Biomass gasification for other energy systems

Sreejith et al. [45] investigated the suitability of coconut shell-derived producer gas as a substitute for coal gas from an environmental perspective using LCA. Thermochemical gasification in

an air-fluidised bed with steam injection is the gaseous fuel production process. The study indicates that coconut shell-derived producer gas life cycle is capable of saving 18.3% of emissions for global warming potential, 64.1% for ozone depletion potential, and 71.5% for nonrenewable energy consumption. The analysis of energy and exergy consumptions is 62.9% for producer gas life cycle, while it is only 2.8% for coal gas life cycle.

In the study of Parvez et al. [46], air, steam, and CO_2-enhanced gasification of rice straw was simulated using Aspen Plus™ and compared in terms of their energy, exergy, and environmental impacts. The maximum exergy efficiency occurred in 800–900 °C. For CO_2-enhanced gasification, exergy efficiency was found to be more sensitive to temperature than CO_2/Biomass ratios. In addition, the preliminary environmental analysis showed that CO_2-enhanced gasification resulted in significant environmental benefits compared with steam gasification.

Kalina [47] presents theoretical study of the concept of a small-scale combined cycle system composed of natural gas fired micro turbine and Organic Rankine Cycle, integrated with thermal gasification of biomass. The main issues addressed in the paper are configuration of the ORC technology and allocation of generated electricity between natural gas and biomass. Energy and exergy allocation keys are demonstrated. An initial cash flow calculations are presented in order to assess financial performance of the plant.

Wang et al. [48] proposed a combined methodology of optimisation method and life cycle inventory for the biomass gasification based building cooling, heating, and power (BCHP) system. The system boundary of life cycle models includes biomass planting, biomass collection-storage-transportation, BCHP plant construction and operation, and BCHP plant demolition and recycle. Economic cost, energy consumption and CO_2 emission in the whole service-life were obtained. Then, the optimisation model for the biomass BCHP system including variables, objective function and solution method are presented.

Prior to large-scale crop-residue gasification application, the lifetime environmental performance should be investigated to plan sustainable strategies. As traditional static LCA does not include temporal information for dynamic processes, Yang and Chen [49] proposed a dynamic life cycle assessment approach, which improves the static LCA approach by considering time-varying factors, e.g., greenhouse gas characterization factors and energy intensity. Results show that the crop residue gasification project has high net global warming mitigation benefit and a short global warming impact mitigation period, indicating its prominent potential in alleviating global warming impact.

5. Conclusions

After the nuclear power plant accident in Fukushima, nearby forests were contaminated by the released radionuclides. Gasification technology can gasify the contaminated woody biomass and produce syngas and ash. Current trends in biomass gasification technologies and the subsequent gas cleaning process including desulphurisation and separation of radioactive substances were reviewed.

Life cycle assessment of the total gasification system is receiving increasing attention. It analyses the energy profit ratio and environmental impacts of a process of interest (e.g. greenhouse gas emission, acidification potential, photochemical oxidation, eutrophication potential, land competition, etc.).

The radioactivity of the syngas produced was quite low, and that of ash was high (within acceptable levels), implying that the gasification technology can be utilised as an option for energy conversion of contaminated woody biomass in Fukushima.

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