

BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Achieving carbon-negative bioenergy systems from plant materials

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Contents

Series list	ix
Acknowledgements	xv
Introduction	xvi

Part 1 Technologies

1	Biomass gasification for bioenergy	3
	<i>Maria Puig-Arnavat, Technical University of Denmark, Denmark; Tobias Pape Thomsen, Roskilde University, Denmark; and Zsuzsa Sárossy, Rasmus Østergaard Gadsbøll, Lasse Røngaard Clausen and Jesper Ahrenfeldt, Technical University of Denmark, Denmark</i>	
	1 Introduction	3
	2 Fundamentals of biomass gasification	6
	3 Biomass gasification for heat and power generation	15
	4 Fuel synthesis from biomass gasification synthesis gas	19
	5 Carbon balance value of by-products from thermal gasification of biomass	26
	6 System integration for polygeneration	30
	7 Conclusion	33
	8 Where to look for further information	34
	9 References	34
2	Fast pyrolysis for biofuel production	43
	<i>David Shonnard, Olumide Winjobi and Daniel Kulas, Michigan Technological University, USA</i>	
	1 Introduction	43
	2 Chemical reaction kinetics of fast pyrolysis	46
	3 Fast pyrolysis process technologies	48
	4 From hydroprocessing to catalytic upgrading	50
	5 Co-products and uses in the market	53
	6 Techno-economic analysis (TEA) and life cycle assessment (LCA) review	55

7	Commercialization and demonstration of biomass fast pyrolysis	61
8	Conclusion and future trends	63
9	Where to look for further information	64
10	References	65
3	Producing biofuels with torrefaction <i>Donald R. Fosnacht, Natural Resources Research Institute – University of Minnesota, USA</i>	71
1	Introduction	71
2	Biomass as a sustainable energy source	76
3	The development of biomass pretreatment technologies	81
4	Biomass densification technologies	85
5	Pretreatment technologies: an overview	87
6	Steam explosion	88
7	Dry torrefaction	92
8	Pelleting/briquetting	101
9	Hydrothermal carbonization (wet torrefaction)	105
10	Advantages and limitations of biomass pretreatments	105
11	Use of torrefied biomass in power plants	108
12	Case study: use of torrefied wood pellets at Portland General Electric's Boardman Facility	114
13	Summary	129
14	Acknowledgements	130
15	References	131
16	Appendix: key sources on torrefaction	132

Part 2 Materials

4	Production of biodiesel from renewable sources <i>Dan Zeng, Daidi Fan, Le Wu and Yuqi Wang, Northwest University, China</i>	151
1	Introduction	151
2	Types of feedstocks for biodiesel production	153
3	Understanding transesterification for biodiesel production	155
4	Optimizing operating conditions for biodiesel synthesis	166
5	Optimizing supercritical transesterification technology for biodiesel production: a case study	168
6	Improving biodiesel quality	183
7	Conclusions	185
8	Where to look for further information	186
9	References	186

5	Production of biodiesel from oilseeds: <i>Jatropha curcas</i> <i>Rahmath Abdulla, Universiti Malaysia Sabah, Malaysia</i>	193
	1 Introduction	193
	2 Characteristics of <i>Jatropha curcas</i> L.	195
	3 <i>Jatropha curcas</i> as a biodiesel feedstock: transesterification	198
	4 Factors affecting enzymatic transesterification using immobilized lipase	201
	5 Life cycle assessment of <i>Jatropha curcas</i> for biodiesel production	204
	6 Economic analysis of biodiesel production	208
	7 References	211
6	Production of biodiesel from oilseeds: canola/rapeseed <i>B. Brian He and Dev Shrestha, University of Idaho, USA</i>	217
	1 Introduction	217
	2 Current technologies and constraints of biodiesel production	221
	3 Life cycle assessment of canola/rapeseed biodiesel	231
	4 Future trends and conclusion	235
	5 Where to look for further information	237
	6 References	238
7	Sustainable use of <i>Miscanthus</i> for biofuel <i>Paul Robson, University of Aberystwyth, UK; Astley Hastings, University of Aberdeen, UK; John Clifton-Brown, University of Aberystwyth, UK; and Jon McCalmont, University of Exeter, UK</i>	243
	1 Introduction	243
	2 The energy balance	246
	3 Nutrient-use efficiency	249
	4 Water use/water-use efficiency	252
	5 Carbon flux	254
	6 Life cycle assessment (LCA) for different end uses	256
	7 Traits and/or agronomy for improved sustainability	259
	8 Conclusion and future trends	261
	9 Acknowledgements	263
	10 Where to look for further information	264
	11 References	264
8	Sustainable use of switchgrass for biofuel <i>John Fike, Virginia Tech, USA; Vance Owens, South Dakota State University, USA; David Parrish, Virginia Tech, USA; and Rana Genedy, Cairo, Egypt</i>	275
	1 Introduction	275
	2 Switchgrass and environmental sustainability metrics	276

3	Challenges in becoming a primary feedstock resource	281
4	Switchgrass production and agronomics in the context of sustainability	286
5	Economic, policy and social issues	290
6	Case study	292
7	Conclusion	293
8	Future trends	294
9	Where to look for further information	294
10	References	295
9	Sustainable production of willow for biofuel use <i>M. Weih, P.-A. Hansson, J. A. Ohlsson, M. Sandgren, A. Schnürer and A.-C. Rönnberg-Wästljung, Swedish University of Agricultural Sciences, Sweden</i>	305
1	Introduction	305
2	Feedstock quality for biofuel use	309
3	Feedstock productivity	311
4	Cropping security	313
5	Biodiversity	315
6	Nutrient uptake and use	316
7	Carbon accumulation and sequestration	317
8	Ecosystem services and environmental impact	318
9	Case study	319
10	Summary and future trends	322
11	Acknowledgements	326
12	Where to look for further information	326
13	References	327
10	Sustainable use of seaweed for biofuel <i>Jay Liu, Boris Brigljević and Peyman Fasahati, Pukyong National University, South Korea</i>	341
1	Introduction	341
2	Seaweed as a feedstock for third-generation biofuels	342
3	Conversion technologies for biofuel production from seaweed: biochemical conversion by anaerobic digestion	351
4	Biochemical conversion by fermentation	357
5	Thermochemical conversion routes	358
6	Chemical conversion routes	364
7	Large-scale production case studies and technoeconomical assessments	365
8	Conclusion and future trends	373
9	References	374
	Index	383

Introduction

There is a need to develop next-generation bioenergy systems that exhibit net carbon capture. Biomass removes carbon dioxide from the atmosphere during growth and, if converted to biofuel, has the potential to be 'carbon negative', especially if combined with carbon capture and storage. Accurately accounting for below-ground soil carbon, owing to root exudation and decay in the plant's rhizosphere, is also important for achieving net carbon capture. To achieve ambitious targets for global reductions in greenhouse gas emissions, biomass crops should generate high yield from minimal input energy while minimising environmental impacts that could make crop production less sustainable. This collection reviews advances in producing next-generation biofuels from non-food plant materials. Part 1 discusses key technologies to achieve this goal such as biomass gasification, fast pyrolysis and torrefaction. Chapters 1-3 address advances in technology, applications and commercial development. Part 2 assesses advances in the production of biofuels from non-food crops: *Jatropha*, oilseeds (such as canola and rapeseed), *Miscanthus*, switchgrass, willow and seaweed.

Part 1 Technologies

The first chapter in the book reviews developments in thermal gasification. This very flexible technique allows many different biomass feedstocks to be converted into a wide variety of products such as heat, electricity, chemicals and transport fuels as well as high value ash and biochar co-products. The chapter reviews current research to optimize process performance, fuel and product flexibility, including types of gasifier and gasification operating variables. It assesses developments in biomass gasification for heat and power generation as well as biofuel production. The chapter concludes by assessing developments in flexible biorefineries with integrated systems capable of polygeneration of different core and co-products.

Chapter 2 discusses the use of fast pyrolysis for biofuel production. Pyrolysis is a thermal depolymerization and fragmentation process carried out at moderate temperatures in the absence of oxygen and with a wide range of reaction residence times. It can convert a wide range of solid materials, ranging from woody biomass and algae to waste plastics, into complex mixtures of low molecular weight organic molecules. The chapter begins by examining the chemical reaction kinetics of fast pyrolysis as well as fast pyrolysis process technologies, including the transition from hydroprocessing to catalytic upgrading. It then describes pyrolysis co-products and their uses. The chapter

also reviews the use of both technoeconomic assessment (TEA) and life-cycle assessment (LCA) to assess process efficiency and sustainability. Finally, the chapter looks at the developments in commercialization of biomass fast pyrolysis.

The final chapter in Part 1, Chapter 3, discusses how biofuels can be produced using torrefaction. Significant investments have been made around the world to accommodate the use of dried and pelleted biomass materials in power plants. Substituting biomass for coal in coal-based boiler systems without degrading boiler capacity requires pretreatment to make its properties similar to the coal that it is displacing. The pretreatment technologies currently under active development include: torrefaction, steam explosion, and hydrothermal carbonization (wet torrefaction). This chapter reviews the factors associated with biomass pretreatment and the use of the advanced biomass-based fuels in power plants. It also provides a case study which describes the use of torrefied wood pellets at the Portland General Electric Boardman Facility in Oregon in the US.

Part 2 Materials

Part 2 of the book begins with a review of how biodiesel can be produced from renewable sources. There is increasing interest in the production of biodiesel from non-edible oil sources such as waste or recycled oil and animal fats. Transesterification is the most used method to convert triglycerides (TG) from different types of lipids. After reviewing the range of available feedstocks, Chapter 4 uses thermodynamic analysis to investigate the main three transesterification reaction systems: triolein and supercritical methanol (T&SCM), triolein and supercritical ethanol (T&SCE), and triolein and supercritical isopropanol (T&SCI). Using a case study, it identifies ways of optimizing supercritical transesterification technology for biodiesel production, as well as ways of improving the quality of the biodiesel manufactured from the process.

The subject of Chapter 5 is the production of biodiesel from oilseeds, in particular *Jatropha curcas*. The importance of edible oils for food applications makes non-edible oils a key feedstock for biodiesel production, including the seeds of *J. curcas*. The chapter begins by reviewing the characteristics of *Jatropha curcas* L. and how it can be used as a biodiesel feedstock through the use of transesterification. It then discusses the factors affecting the efficiency of enzymatic transesterification using immobilised lipase and provides a section on the life cycle assessment (LCA) of *Jatropha curcas* for biodiesel production. The chapter concludes by providing an economic analysis of biodiesel production using this feedstock.

Chapter 6 also reviews the production of biodiesel from oilseeds but instead focuses on canola and rapeseed. Currently, rapeseed oil is the dominant

feedstock for biodiesel production in Europe, while canola oil is also extensively used for biodiesel production in the Pacific Northwest of North America. The chapter describes current technologies and constraints of biodiesel production and examines life cycle assessment of canola/rapeseed biodiesel production. Finally, the chapter looks ahead to future trends of research in this area and provides guidance on further reading.

Chapter 7 discusses the sustainable use of *Miscanthus* for biofuel. The chapter focuses on research demonstrating that *Miscanthus* embodies a range of attributes (e.g. C4 photosynthesis combined with cold tolerance, high energy output/input ratios, efficient nutrient recycling and high yield from minimal agronomic input) that make it an ideal sustainable biomass crop for biofuels. Sections on both nutrient use efficiency and water use/water use efficiency are included. The chapter also discusses carbon flux and life cycle assessments for different end uses to improve the efficiency and sustainability of the process.

The next chapter addresses the sustainable use of switchgrass for biofuel. Switchgrass, a productive, perennial warm-season grass, native to much of North America, has significant potential as a sustainable biofuel crop. Chapter 8 begins by discussing switchgrass and environmental sustainability metrics. It then reviews the challenges that switchgrass faces in becoming a primary feedstock resource and provides a section on the production and agronomics of switchgrass in the context of sustainability. The chapter also reviews the economic, policy and social issues associated with the development of a sustainable biofuel industry. The chapter also includes a case study on burning switchgrass as a biofuel to illustrate biofuel production in practice.

Chapter 9 reviews the sustainable production of willow for biofuel use. Intensively managed plantations of willow (*Salix* spp.) are gaining interest worldwide, mainly due to their efficient and sustainable land use along with an increasing demand for biofuel resources. Willows have traditionally been used as biofuel in the form of wood chips for direct combustion in heat and power plants, but there is an increasing interest in using willow biomass as raw material for other biofuel supply chains. The chapter provides an overview of the challenges and key issues in the sustainable production and use of willow as feedstock for biofuel production in northern-temperate regions, including the issues of feedstock quality for biofuel use, feedstock productivity, cropping security, biodiversity, nutrient uptake and use, carbon accumulation and sequestration, and environmental impact. Finally, the chapter looks ahead to future research trends in this area and provides useful sources for further reading.

The final chapter of the book addresses the sustainable use of seaweed for biofuel. Chapter 10 describes the biological advantages and disadvantages of

seaweed in terms of its use as an energy crop and examines global production trends. The chapter reviews methods of seaweed cultivation, together with harvesting and supply chain logistics. It provides a systematic review of conversion routes to producing biofuels and other value-added products from seaweed. Finally, the chapter includes detailed case studies of potential industrial-scale processes for three different conversion routes and looks ahead to future research trends in this area.

Part 1

Technologies

Chapter 1

Biomass gasification for bioenergy

Maria Puig-Arnavat, Technical University of Denmark, Denmark; Tobias Pape Thomsen, Roskilde University, Denmark; and Zsuzsa Sárossy, Rasmus Østergaard Gadsbøll, Lasse Røngaard Clausen and Jesper Ahrenfeldt, Technical University of Denmark, Denmark

- 1 Introduction
- 2 Fundamentals of biomass gasification
- 3 Biomass gasification for heat and power generation
- 4 Fuel synthesis from biomass gasification synthesis gas
- 5 Carbon balance value of by-products from thermal gasification of biomass
- 6 System integration for polygeneration
- 7 Conclusion
- 8 Where to look for further information
- 9 References

1 Introduction

Gasification is a partial thermal oxidation of carbon-rich materials yielding a non-condensable gas product (CO_2 , CO , H_2 , H_2O and other gaseous hydrocarbons) and smaller quantities of by-products such as char, ash and condensable fractions including water, tars and oils. Biomass gasification platforms are most commonly designed for conversion of wood in the form of wood pellets, wood chips or waste wood. However, it is possible to extend the potential range of organic material fractions converted in thermal gasification to cover various organic secondary resources. This includes agricultural, municipal and industrial by-products and residues such as cereal straw, fibre residues, sludge and organic waste fractions.

Biomass-based energy systems have a unique potential for genuine carbon-negative energy production. There are two main routes that may be pursued individually or in a complementary combination: (i) combination with carbon capture and storage (CCS) and (ii) processes with co-production of carbon-rich char/ash fractions as well as other by-products to replace current, fossil-based products in the market. CCS has a huge potential, but the technology

has to mature and the economic feasibility needs to improve for it to penetrate market barriers (Álamo et al., 2018). The technical potential for carbon sequestration via bioenergy processes with carbon-rich residuals is smaller than via CCS, but it is cheaper, robust and readily applicable. The potential to produce carbon-negative energy in this way, arise from a combination of high net energy efficiency and a potential for carbon sequestration via the ash/char fraction as illustrated in Fig. 1. Emissions from peripheral unit processes and upstream inputs influence the net potential of this approach. The level of direct carbon negativity will be given by the amount of long-term sequestered carbon minus all emissions related to biomass fuel procurement and pre-treatment, production and use of utilities (water, chemicals, fuels) as well as the production and maintenance of the plant and peripheral systems (Thomsen et al., 2011).

Additional contribution from downstream CCS added to this system will have a substantial potential to increase the level of carbon negativity. Even CCS processes with low coverage and/or efficiency may provide a sizable net contribution when combined with efficient low-carbon biomass-based energy

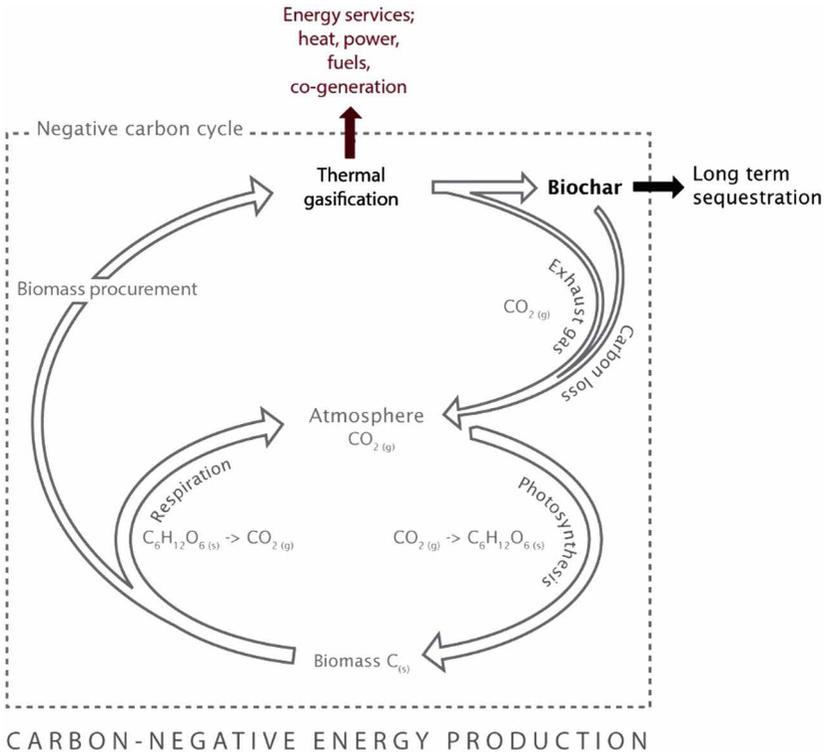


Figure 1 Schematics of the ideal carbon-negative biomass-based CHP system. Source: adapted with permission from Thomsen et al. (2011).

systems. Systems with high net energy efficiency will have the highest abatement potential. In thermal systems, these are most often cases with utilization of the inevitable heat production, that is biomass-based heat systems or biomass-based co-generation systems. Thermal gasification of biomass is unique in this regard, since the platform excels in overall efficiency and flexibility.

Gasification is no new invention. First steps in the development of gasification started in the late 1600s. Hundred years later, in 1792, coal producer gas was reported to be used for lighting and later on for cooking and heating. Almost simultaneously, the water-gas-shift reaction was described and within a few decades, the first commercially used gasifier was built. Since the early 1900s, application of producer gas rapidly spread into power production, combined heat and power (CHP) production and operation of vehicle motors as well as into gasification of wood and other biomasses (Behera and Varma, 2019).

Despite the advantages that biomass gasification offers, it has not yet been able to consolidate its role and become a fully mature technology. Thus, a majority of biomass gasification projects remain at the pilot or demonstration scale. This is due to inherent challenges of biomass as a fuel and insufficient resources allocation to address operational issues related to the following (Asadullah, 2014a; Heyne et al., 2013; Sansaniwal et al., 2017; Zhang et al., 2013a):

- Supply chain management (transportation and storage due to low-energy density);
- Handling, pre-treatment and fuel feeding;
- Optimizing the energy efficiency to high moisture content feedstock;
- Addressing variations in biomass fuel properties;
- Unrealistic fuel flexibility expectations;
- Unrealistic product property expectations;
- Upscaling of specific gasifier reactors;
- Problems with gas cleaning, conditioning and impurities such as sulphur compounds (e.g. H_2S , CO_2), hydrogen chloride, alkali and ammonia;
- Tar-related issues, for example condensation at lower temperatures which can lead to fouling and plugging of the plant pipelines, filters, catalyst units or engines; and
- Ash-related problems such as sintering, agglomeration, deposition, erosion and corrosion.

There is a firm belief in academia and industry that all mentioned technical problems can be overcome and that most of the solutions already exist. However, the foremost barrier for biomass gasification is associated with the

economic risk in a rapidly changing energy market. Thus, policy measures ensuring long-term economic viability of the projects should be implemented.

The aim of this chapter was to provide an insight into the versatility and benefits of biomass gasification processes and its products in relation to production of carbon-negative bioenergy from plant-based materials. General key issues related to designing a gasification plant are reviewed and discussed, and several new concepts and solutions in the form of process integration schemes, polygeneration strategies and biochar uses are described.

2 Fundamentals of biomass gasification

Biomass gasification involves a sequence of several stages occurring at different temperatures: drying (100–200°C), pyrolysis (200–700°C), partial combustion (>800°C) and reduction or gasification (700–900°C). These stages, depending on the specific gasifier design, often overlap.

- **Drying:** Evaporation of the moisture contained in the feedstock. The amount of heat required in this stage is proportional to the feedstock moisture content. The drying often takes place as a preliminary step in the pyrolysis stage and the required heat for both sets of processes is usually supplied from the oxidation stage.
- **Pyrolysis:** Thermal decomposition of biomass in the absence of oxygen/air. The cracking of chemical bonds takes place, resulting in the formation of molecules with a lower molecular weight. Thus, different fractions are obtained: solid char, liquid/condensed tars and a gaseous fraction. The condensable fraction of the pyrolysis gas will usually mix with the evaporated water from the drying stage as well as released cell bound water. Product weight and energy ratios will depend on the nature of the biomass, the reactor design and operating conditions of the process. Pyrolysis is a net endothermic stage and the heat required comes from the oxidation stage of the process.
- **Oxidation:** Usually, gasification involves a stage with partial oxidation to provide heat for the drying, pyrolysis and char gasification. During the partial oxidation, a part of the organic material in the fuel is oxidized and heat is released from the net exothermic reactions in the process. A partial oxidation is conducted by supplying, for example, air or pre-heated air to the gas/tar or to the char in a sub-stoichiometric ratio.
- **Reduction or gasification:** During the reduction/gasification step, the carbon matrix of the pyrolysis char is decomposed by reaction with gasification agents CO_2 and/or H_2O at elevated temperatures under a reducing atmosphere leading to formation of combustible gases. The gas from pyrolysis and char gasification can be mixed subsequently or

prior to the char gasification stage. The reduction step is endothermic, and the temperature at which it takes place has a fundamental role in determining the composition of the final gas and its characteristics (LHV, tar presence).

The quality of the gas produced in biomass gasification varies according to the gasifying agent used, the feedstock, bed material, operational conditions (temperature, pressure, air-to-fuel ratio) and gasification technology.

2.1 Biomass resources

Biomass is a broad concept that includes 'the biodegradable fraction of products, waste and residues of biological origin from agriculture (including vegetal and animal substances), forestry and related industries, including fisheries and the aquaculture as well as the biodegradable fraction of industrial and municipal wastes' (2009/28/EC European Directive). Even though gasification platforms are often designed for conversion of conventional biomass types, primarily wood, the global increase in demand for bioenergy has facilitated growing efforts to extend the potential range of organic material fractions converted in thermal processes. As a result, there is a growing focus on thermal utilization of various secondary organic resources including: (Thomsen et al., 2016):

- Agricultural by-products and residues: For example, crop residues (stalk, leaf, cob etc.), manure fibres, muck and bedding and fibres from biogas slurry;
- Municipal by-products and residues: For example, source segregated organic waste, used textiles, grass and cuttings from road and park maintenance, beach cleaning waste and sewage sludge; and
- Industrial by-products and residues: For example, residues from breweries, food packaging, food retail, food preparation or residues from production of non-food products based on the partial conversion of animal and vegetable raw materials.

Optimized treatment of secondary resources has great potentials from an economic, environmental and resource political point of view (Thomsen et al., 2016). However, the diversity of biomass resources makes it essential to characterize them thoroughly, as their physical-chemical properties will have a direct impact on the design of the gasification plant as well as on the technical and economic feasibility of the process. This characterization should be carried out before choosing the gasification technology to avoid subsequent problems. The biomass properties that have the highest impact on gasification technology are:

- *Biomass particle size* (Molino et al., 2018; Sansaniwal et al., 2017; Sikarwar et al., 2016): Reducing the biomass particle size increases the pre-treatment cost of the feedstock, but it increases the surface area and decreases the diffusion resistance. This results in improved heat and mass transfer, increased reaction rates, fuel conversion, carbon conversion efficiency and decreased char and tar yields. Conventional gasifiers can take particle sizes in the range of 0.15–51 mm. Particles of 0.15 mm are required for entrained flow gasifiers while fixed-bed reactors, with longer residence times, can tolerate particles up to 51 mm. Usually, bubbling fluidized-bed (BFB) reactors can take particles of up to 6 mm.
- *Moisture content* (Molino et al., 2016, 2018; Ruiz et al., 2013; Sansaniwal et al., 2017; Sikarwar et al., 2016): High moisture contents increase the energy required for water evaporation and steam gasification reactions that, in turn, may lower the gasifier operating temperature especially in the first stages. Reducing the moisture content may in some cases increase the energy efficiency, especially if low-temperature heat cannot be utilized. In addition, a dryer fuel will increase syngas quality, syngas HHV and decrease the conversion emissions. Fluctuations in biomass moisture content lead to variations in bed temperature, and this causes changes in the composition of the syngas generated.

The required moisture content of the biomass depends on the gasifier design; updraft fixed-bed gasifiers can operate with moisture contents up to 60% (w/w), while downdraft fixed gasifiers can take maximum moisture contents of 25% (w/w). However, values around 10–20% (w/w) are generally recommended for conventional gasification technologies and will keep bed temperatures moderately stable.

- *Ash content* (Molino et al., 2018; Sansaniwal et al., 2017; Sikarwar et al., 2016): The ash content in biomass plays a significant role in thermal biomass utilization, especially if it contains alkali metals such as potassium or halides such as chlorine. Slagging, fouling and corrosion are important – and potentially critical, issues that may be caused by the inorganic species present in the biomass. It is not possible to give any general biomass criteria related to ash content as the potential problems relate to a combination of process design, process temperature profile, ash quantity and ash composition. However, generally, biomass with ash content lower than 2% (w/w) can be used as feedstock material in all types of gasifiers even though there may still be issues related to corrosion and long-term deposit build-up.
- *Bulk density*: Bulk density will have a strong influence on the transportation costs, handling and feeding of the biomass in the gasification plant. Biomass with a low bulk density might cause severe feeding problems to the gasification units because of getting stuck in the feeding line. These

problems can be overcome by densifying the bulky biomass; however, this will result in higher energy consumption and cost.

Organic resources that are initially found to be unsuited for thermal gasification may still have a fuel potential through fuel design or thermal pre-treatment. Torrefaction is a well-known process used to pre-treat biomass resources for various purposes and may render organic material more coal like. Many other problematic issues may be overcome by fuel design, for example through proper mixing. Recent studies on these issues have indicated many potential benefits related to moisture content, ash melting-related issues and ash/char by-product quality (Skoglund et al., 2016; Thomsen et al., 2016, 2017a,b,c).

2.2 Types of gasifiers

The design of a biomass gasifier depends ideally on the fuel characteristics (size, shape, moisture content, ash content) and the marketability of the end products. The principal design concepts, even though there are others available, can be classified in fixed beds, fluidized beds and entrained flow reactors (Table 1).

Fixed-bed reactors are often considered the best choice for small-scale plants of up to 10 MW. Within fixed-bed reactors, it is possible to distinguish updraft and downdraft configurations. In updraft gasifiers, the biomass is supplied from the top and the gasifying agent from the bottom (counter-current). For these gasifiers, the sequence for biomass is drying → pyrolysis → reduction → combustion. Instead, in downdraft gasifiers, the biomass and gasifying agent are supplied from the top (co-current). Thus, the sequence is drying → pyrolysis → combustion → reduction. The main difference is that in downdraft gasifiers the decomposition products from drying and pyrolysis go through thermal cracking in the oxidation zone, thus produce less tar and a higher-quality gas than updraft gasifiers, where the pyrolysis gas goes directly into the producer gas. Fixed-bed gasifiers are simple in construction and operate at low gas velocity with high carbon conversion and long residence time.

Fluidized-bed reactors, including BFB and circulating fluidized-bed (CFB) reactors, are based on the principle of fluidization in which both the fuel and the hot bed material (inert inorganic material and/or catalyst) is made to behave as a fluid by mixing the high-density bed and fuel material with a low-density fluidization agent, for example, air, steam or other gas. The semi-suspended conditions are kept by means of the gasifying agent added at the appropriate velocity. These gasifiers provide an excellent gas-solid mixing, a uniform temperature and solid/gas concentration in the entire bed. It is not possible to distinguish the different zones in single-reactor fluidized-bed systems (drying,

Table 1 Comparison of different types of gasifiers (Basu, 2018; E4tech, 2009; Molino et al., 2016, 2018; Ruiz et al., 2013)

Gasifier	Downdraft	Updraft	Bubbling fluidized bed	Circulating fluidized bed	Entrained flow bed
Technology	Simple, reliable and proven. relatively low investment cost	Simple reactor with	Plants with higher investment and maintenance costs. Good ability to scale-up	Plants with higher investment and maintenance costs.	Complex. High investment and maintenance costs
Fuel specifications	<51 mm	<51 mm	<6 mm	<6 mm	<0.15 mm
Tar (g/Nm ³)	0.015-3.0	30-150	3.7-61.9	4-20	0.01-4
Ash and particles in syngas	Low	High	High	High	Low
Gasification temperature	900-1050°C	950-1150°C	800-1000°C	800-1000°C	1300-1500°C
Syngas exit temperature	700°C	150-400°C	800-1000°C	800-1000°C	>1260°C
Capacity	<5 MWe	<10 MWe	1-20 MWe	2-100 MWe	5-100 MWe
Carbon conversion efficiency	High	High	High. Loss of carbon in ash	High	High
Process flexibility	Very limited. Any change in the process variables needs a new design	Very limited. Any change in the process variables needs a new design	Flexible to loads less than design	Flexible to loads less than design	Very limited. Size and energy content of the fuel must be in a narrow range
Hot gas efficiency	85-90%	90-95%	89%	89%	80%

pyrolysis, reduction and combustion) due to the intense gas-solid mixing. Fluidized-bed gasifiers usually operate at relatively low temperatures (700–900°C) to prevent ash sintering and agglomeration and are the preferred option for large-scale plants due to superior scalability characteristics compared to fixed-bed systems.

Entrained flow reactors operate at high temperatures (1400°C) and high pressure (20–70 bar) by injecting powdered fuel into a high-speed stream of the gasifying medium and into the reactor. Thus, the gas stream entrains the fuel particles and directs the flow direction and speed through the reactor system.

2.3 Gasification operating variables

The operating parameters such as temperature, pressure, gasifying agent and equivalence ratio (ER) will have a very important role in determining the gasification performance, syngas yield and gas composition.

2.3.1 Temperature

Temperature is a crucial parameter in biomass gasification which, to a large extent, controls the gas composition, reaction rate, tar concentration, ash-related problems and so forth. Low temperatures generally result in higher tar content and low CO and H₂ content in the product gas. High-temperature gasification, on the other hand, leads to a desired high yield of CO and H₂ while reducing the tar content. However, high gasification temperatures present two major potential drawbacks: ash-melting problems, especially for high ash-containing biomass, and rigorous reactor specifications.

2.3.2 Pressure

Biomass gasification can be operated at atmospheric pressure or at higher pressures usually depending on the downstream application of the product gas. If the product gas is used in turbines or in Fischer-Tropsch synthesis, then pressurized gasification can be convenient even though it is more technologically complex. A reduction in the tar yield and in light hydrocarbons can be achieved by operation at higher pressures (Asadullah, 2014a; Molino et al., 2018).

2.3.3 Gasifying agent

Air, steam, pure oxygen, carbon dioxide or mixtures of them can be used as gasifying agents. The selection will depend on the gas quality requirements for

the downstream applications and the economics of the overall process. Air is the cheapest and most cost-effective gasifying agent and has been extensively applied for heat and power generation purposes. It results in a highly nitrogen diluted and low-quality gas with low H₂ content (8–14 vol. %) and a heating value in the range of 4–7 MJ/Nm³ (Matas Güell et al., 2012). Pure oxygen is the most expensive gasifying agent because it requires an air-separation unit, but it leads to a syngas with a heating value up to 28 MJ/m³, higher concentrations of CO, H₂ and low concentration of tars (Asadullah, 2014a; Molino et al., 2018). The cost of steam is somewhere between air and oxygen and leads to a product gas with a heating value around 10–18 MJ/Nm³ and with a higher concentration of H₂ as a result of the water-gas-shift reaction, but it reduces the thermal efficiency of the gasification. Steam-only gasification requires an external energy supply due to the endothermic reactions involved in the process. CO₂ gasification results in a product gas rich in CO because of the reaction of CO₂ and carbon; however, this reaction is slow and external heat supply is required.

2.3.4 Equivalence ratio (ER)

The ER can be defined as the ratio between air-to-fuel ratio of the gasification process and the air-to-fuel ratio for complete stoichiometric combustion. ER is a relevant parameter because it defines the degree of combustion and, thus, the temperature and distribution of gas, tar and char in the gasifier. ER optimal values are in the range of 0.2–0.3 for fixed-bed and fluidized-bed gasifiers, while entrained flow gasifiers usually require a 20% higher ER (Molino et al., 2018). ER lower than 0.2 results in an incomplete gasification, while ER higher than 0.4 approach the combustion. Decreasing the ER results in higher concentrations of H₂ and CO and higher calorific value of the product gas. Increasing the ER has the opposite effect and increases the CO₂ concentration but it reduces the tar yield. Thus, it is necessary to optimize the process depending on the downstream applications.

2.4 Synthesis gas requirements for further applications

The gas produced from biomass gasification is rarely used directly in downstream applications. Usually the gas needs to be cooled and cleaned to ensure smooth and efficient operation. The gasifier design, feedstock type, gasifying agent and other operating parameters will influence the gas composition and the quantity and type of impurities. The gas quality is a key driver in the technical and economic feasibility of different application schemes. In Table 2, a range of generalized quality measures accepted by engine, gas turbine and fuel-cell applications are provided.

Table 2 Acceptable range of impurities for different applications (Hasler and Nussbaumer, 1999; Sansaniwal et al., 2017; Singh et al., 2014)

	IC engine	Gas turbine	Fuel cell
Particles (mg/Nm ³)	<50	<30	-
Particulate matter (µm)	<100	<5	<1
Tar (mg/Nm ³)	<10	<5	<1
Alkali metals (mg/Nm)	-	<0.24	-

In fuel synthesis from gasification producer gas, the gas quality requirements may be even higher than for direct production of electricity and heat. The catalysts used in Fischer-Tropsch synthesis are sensitive to even very small amounts of impurities. In commercial operation, catalysts are replaced or regenerated after a certain operational period. Thus, the definition of the gas cleaning is therefore based on economic considerations: investment in gas cleaning versus accepting decreasing production due to poisoning of the catalyst. Requirements for feed gas quality of different downstream applications can be found elsewhere (Boerrigter et al., 2004; Molino et al., 2018; Tijmensen et al., 2002).

2.5 Gas cleaning processes

As previously mentioned, cleaning and conditioning of the product gas may be required to remove contaminants and potential catalyst poisons as well as to achieve the qualitative composition required by, for example, biofuel production processes. There are several papers available in the literature that have recently addressed and analysed the different possible cleaning processes (Abdoulmoumine et al., 2015; Asadullah, 2014b; Woolcock and Brown, 2013). In this section, a brief summary of commonly applied physical, thermal and catalytic gas cleaning technologies is presented.

2.5.1 Physical gas cleaning

Physical gas cleaning is one of the simplest cleaning methods and includes filtration and wet scrubbing to remove tar and particulate matter from the gas through gas/solid or gas/liquid interactions. Filtration can be conducted at high or low temperatures. High-temperature filtration requires temperature tolerable materials such as ceramics, fibre glass, composites or sand. Low-temperature filtration processes can use charcoal, cotton fibres as filtration media. Filtration techniques often face the problem of clogging and deposition of gas particles causing a pressure drop across the filtration. Back-flushing the filtration media with, for example, nitrogen may revitalize the performance of the filter.

Wet scrubbing is usually done at low or ambient temperature using water, oil or another solvent but faces the problem of producing high amounts of contaminated liquid that needs to be treated.

2.5.2 Thermal gas cleaning

Thermal decomposition consists of degrading (cracking) heavy aromatic tar compounds into smaller, lighter and non-condensable gas species such as methane, hydrogen and carbon dioxide at temperatures around 1000°C. The most problematic aspects of high-temperature cracking relate to the required temperature resistance of the setup that needs a complex and highly controllable heating system and intensive cooling system for the gas afterwards as well as possible ash-melting-related problems (Asadullah, 2014a).

2.5.3 Catalytic gas cleaning

It is possible that physical and thermal gas cleaning steps are not enough to fulfil stringent requirements of some downstream applications. Thus, the utilization of effective catalysts is often considered a method to decrease the concentration of tar and ammonia in the product gas. Catalytic decomposition usually occurs at much lower temperatures (600–800°C) than thermal cracking (>1000°C). Catalysts for tar removal have been tested and used directly in the gasifier reactor as well as in secondary catalytic reactors. Sometimes, additional oxidant (O₂ or H₂O) is injected into the secondary catalytic bed. Tars can be cracked or hydrocracked into light hydrocarbons or converted into CO and H₂ through steam and dry reforming reactions. The spectrum of studied catalytic materials covers acidic solids for cracking, basic solids for 'reforming' reactions and metal oxides with both acidic and metal sites for cracking and hydrocracking reactions (Torres et al., 2007). Desirable properties of a good catalyst for any of these reactions are (Sutton et al., 2001): (i) capability to efficiently convert tars into useful gas products in an environment containing high concentrations of H₂, CO, CO₂ and H₂O at temperatures of 600–800°C at ambient pressure (or even higher temperatures for pressurized reactors); (ii) resistance to deactivation and poisoning by species in the gas, such as sulphur-containing compounds; and (iii) resistance to attrition. It is also desirable to carry out the tar conversion process in such a way as to keep the deposition of carbonaceous materials on the catalyst surface under control.

In biomass gasification, most of the nitrogen ends up as ammonia (NH₃) and N₂ with lower concentrations of hydrogen cyanide (HCN), isocyanic acid (HNCO) and nitrogen oxides (NO_x). Nitrogen-containing species are undesirable because they can poison catalysts or serve as precursors for NO_x in downstream burners, gas engines or gas turbines. Most of the literature on

Index

- ABC. *see* Ammonium bicarbonate (ABC)
- Acetogens 353
- Acidogenesis 353
- Acid thermal hydrolysis (ATH) 358
- Acid value (AV) 183-184
- Activated carbon 54-55
- Activation energy determination 179-182
- Agroecological zones (AEZs) 232-233
- Ambrose method 157
- American Oil Chemists' Society (AOCS) 170
- Ammonium bicarbonate (ABC) 355
- Ammonium carboxylate salts 356
- Anaerobic digestion 309
- Analysis of variance (ANOVA) 172
- Animal fats 155
- ANOVA. *see* Analysis of variance (ANOVA)
- AOCS. *see* American Oil Chemists' Society (AOCS)
- Arbaflame 90
- Arrhenius equation 179-180
- Ash content 8
- Aspen Plus software 369, 370
- ATH. *see* Acid thermal hydrolysis (ATH)
- Atikokan Power Plant 112
- Australia 196
- AV. *see* Acid value (AV)

- BBD. *see* Box-Behnken design (BBD)
- BECCS. *see* Bioenergy with Carbon Capture and Storage (BECCS)
- Benson's Group Method 159
- BETO. *see* Bioenergy Technologies Office (BETO)
- Binders
 - additives, used in biomass pellet production 103-104
 - to improve mechanical durability 103
 - natural 102-103
 - types 102
 - water-resistant, need in biomass production 104
- Biochar 53-55, 58
 - microbial fuel cell electrodes 55
 - renewable 55
- Bioenergy Technologies Office (BETO) 53
- Bioenergy with Carbon Capture and Storage (BECCS) 256, 262
- Biomass gasification 3-6
 - by-products carbon balance value 26-30
 - fundamentals of 6-15
 - for heat and power generation 15-16
 - case studies 16-19
 - synthesis gas, fuel synthesis from 19-26
 - system integration for
 - polygeneration 30-33
- Biomass Gasification Group 16, 18
- Biomass kinetic modeling 46-47
- Biomass particle size 8
- Biomass recalcitrance 309, 311
- Biomass resources 7-9
- Biomass Strategy (2007) 245
- Bio-oil 50-53, 56, 361, 363
 - properties comparison between
 - crude oil and 51
- Biorefineries 364
- Boiler with fire box view port 117
- Box-Behnken design (BBD) 171
- Brazil 63, 197
- Brown seaweeds 343, 344, 345
- Brundtland report 308
- Bubbling fluid bed reactor 48
- Bulk density 8-9

- CAAA. *see* Clean Air Act Amendments (CAAA)
- Canada 63
- Canola/rapeseed 217-221

- biodiesel, life cycle assessment of 231-235
- current technologies and constraints of
biodiesel production 221-222
- chemistry 222-227
- fuel properties from canola and rapeseed oil 230-231
- off-grade canola oil processing 229-230
- processes 227-229
- future trends 235, 237
- Carbon capture and storage (CCS) 3-4
- Carbonization 44
- Carbon mitigation 248
- Catalytic vapor cracking. *see* Hydrocracking
- Catalytic water-gas-shift reactor 24
- CAWES. *see* Consortium for Advanced Wood to Energy Solutions (CAWES)
- CCS. *see* Carbon capture and storage (CCS)
- Center for Agricultural and Rural Development (FAPRI-CARD) 232
- Chemical binders 102
- China 196, 197, 344
- Circulating fluid bed reactor 48, 49
- Circulating fluidized bed pyrolysis system 362
- CJO. *see* Crude jatropha oil (CJO)
- Clean Air Act Amendments (CAAA) 78, 80
- Coal and briquette, comparison of 124
- Co-firing, with biomass 71, 78
- Consortium for Advanced Wood to Energy Solutions (CAWES) 73
- Constant-pressure heat capacity in liquid state, calculation coefficients of 161
- Constraint mapping approach 245
- Continuously stirred tank reactors (CSTRs) 229
- Conventional pyrolysis 44, 54
- CropSyst model 233
- Crude jatropha oil (CJO) 208-210
- CSGC-AF method 157
- CSTRs. *see* Continuously stirred tank reactors (CSTRs)
- Danish Fluid Bed Technology A/S 18
- DDGS. *see* Dried distillers grains with solubles (DDGS)
- Desulphurizing, of gas 23-24
- Dewatering 351
- Diglycerides (DGs) 176
- DOE. *see* US Department of Energy (DOE)
- DONG Energy A/S 18
- Downdraft gasifiers 9
- Drax Power Plant (United Kingdom) 81
- Dried distillers grains with solubles (DDGS) 366
- Drop-in biofuel 44, 51
- Drying 6
- EDOX. *see* Electrochemical deoxygenation (EDOX)
- EISA. *see* Energy Independence and Security Act (EISA) (2007)
- Electrochemical deoxygenation (EDOX) 52, 58
- Energy concentration beyond dried wood and fuel properties enhancement 81-85
- Energy Independence and Security Act (EISA) (2007) 221, 276
- Ensyn 61, 63
- Enthalpy and entropy formation, in gas state 159 formation, in liquid state 159-160
- Entrained flow reactors 11
- Enviva Partners 81
- ES. *see* Esterification strategy (ES)
- Esterification 356
- Esterification strategy (ES) 355
- Ethanol 202, 251 process flow diagram for seaweed biomass fermentation to 366
- European Union 219
- Eyring-Polanyi equation 182
- FAMEs. *see* Fatty acid methyl esters (FAMEs)
- FAPRI-CARD. *see* Center for Agricultural and Rural Development (FAPRI-CARD)
- Farm to Fuel project 292
- FASOM. *see* Forestry and Agricultural Sector Optimization Model (FASOM)
- Fast pyrolysis 43-46 chemical reaction kinetics of 46-48 commercialization and demonstration of biomass 61, 63 co-products and uses in market 53-55 future trends 63-64 hydroprocessing and catalytic upgrading 50-53 life cycle assessment (LCA) 56-60 process technologies for 48-50 techno-economic analysis (TEA) 58, 61

- Fatty acid methyl esters (FAMES) 153, 159, 168, 170, 172
- FCC. *see* Fluid catalytic cracking (FCC)
- FDC Enterprises (FDCE) 292, 293
- FFAs. *see* Free fatty acids (FFAs)
- Fibers 103
- Film type binders 102
- Filtration 13
- Finland 63
- Fischer-Tropsch process, for hydrocarbon production 19–20
 CO₂ use in 21
 economic feasibility 21–22
 products via 20–21
 reaction mechanism, environment, and catalysts 20
- Fischer-Tropsch synthesis 13
- Fixed-bed reactors 9
- Flexible biorefineries 30–32
- Floating raft cultivation 347–348
- Fluid catalytic cracking (FCC) 52
- Fluidized-bed reactors 9, 11
- Forestry and Agricultural Sector Optimization Model (FASOM) 232
- Fortum-Valmet 63
- Fram Renewable Fuels 81
- Free fatty acids (FFAs) 152, 183
- Fuel flexibility 18–19
- Future Metrics 79
- GANI method 157, 159
- Gas chromatography-mass spectrometry (GC-MS) 170, 172
- Gas cleaning processes 13
 catalytic 14–15
 physical 13
 thermal 14
- Gasification operating variables
 equivalence ratio 12
 gasifying agent 11–12
 pressure 11
 temperature 11
- Gasifiers, types of 9–11
- Gas turbine combined cycle (GTCC) 56
- GC-MS. *see* Gas chromatography-mass spectrometry (GC-MS)
- Georgia Biomass 81
- Germany 63
- Green Circle 81
- Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) 234
- Green seaweeds 343
- GREET. *see* Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET)
- Grinder, in pulverizer 116
- GTCC. *see* Gas turbine combined cycle (GTCC)
- Harboøre updraft gasifier 17–18
- HDO. *see* Hydrodeoxygenation (HDO)
- Highland Pellets 81
- HTC. *see* Hydrothermal carbonization (HTC)
- HTL. *see* Hydrothermal liquefaction (HTL)
- Hydrocracking 51–52, 372
- Hydrodeoxygenation (HDO) 51–53, 57
- Hydrologic fracking 254
- Hydrolysis 353
- Hydro-pyrolysis 44
- Hydrothermal carbonization 88
- Hydrothermal carbonization (HTC) 105
- Hydrothermal liquefaction (HTL) 363
- IEA Bioenergy 72
- India 196, 197
- Indonesia 197, 344
- Industrial-scale bioconversion platform 365–366
- Industrial-scale integrated platform 369–373
- Industrial-scale thermochemical platform 367–369
- Internal rate of return (IRR) 61
- International Energy Agency 78
- IRR. *see* Internal rate of return (IRR)
- Jatropha curcas* 193–195
 as biodiesel feedstock 198–204
 characteristics of 195–198
 economic analysis of biodiesel production 208–210
 life cycle assessment of 204–207
 see also Transesterification
- Karlsruhe Institute of Technology (Germany) 63
- Ketonization strategy (KS) 355
- Laminaran 357, 358
- Land-use change (LUC) 256, 258
- Leaf phenology 320
- Lignin 103, 260
- Limestone 103

- Line and net cultivation techniques 347
- Low-grade feedstocks 153, 155
- Low temperature circulating fluidized bed (LT-CFB) gasifier 18-19
- LUC. *see* Land-use change (LUC)
- Lydersen method 157
- Macroalgae 342-343
- Malaysia 63, 196
- Mannan 343
- Mannitol 357, 358
- Manual harvesting 350
- Matrix type binders 102
- Mauritius 196
- Maximum dry seaweed price (MDSP) 365
- Medium pressure steam (MPS) 369
- MESP. *see* Minimum ethanol selling price (MESP)
- Methanation 26
- Methanogenesis 353
- Methanol 163, 167, 176, 222, 223, 227
synthesis 22-24
- Methano-pyrolysis 46
- Methoxides 225
- Mexico 196
- MGs. *see* Monoglycerides (MGs)
- Micropyrolysis, with gas chromatography/
mass spectroscopy 48
- Minimum ethanol selling price (MESP) 365
- Minimum product selling price (MPSP)
367, 369
- Minimum selling price (MSP) 61
- Minnesota Power 73-74
- MiscanFor model 247
- Miscanthus*, sustainable use of 243-246
carbon flux 254-256
energy balance 246, 248-249
future trends 261-263
life cycle assessment for different end
uses 256-259
nutrient-use efficiency 249-252
traits/agronomy for improved
sustainability 259-261
water use/water-use efficiency 252-254
- Mississippi State University 104
- Moisture content 8
- Molasses 104
- Monoglycerides (MGs) 176
- Monte-Carlo simulation modeling 281, 372
- MPSP. *see* Minimum product selling price (MPSP)
- MPS. *see* Medium pressure steam (MPS)
- MSP. *see* Minimum selling price (MSP)
- Myanmar 196, 197
- Mycorrhizal fungi 314
- Natural Resources Research Institute (NRRI) 87, 92, 95, 101, 104
- Net Energy Service 27
- Netherlands 63
- Net present value (NPV) 61
- New Biomass Energy 73, 74, 81, 122
- New England Wood Pellet 81
- Nitrogen fixation 289
- NMR. *see* Nuclear magnetic resonance (NMR)
- Non-edible oils 152, 153
- Non-edible sources, for biodiesel
production 194-195
- NPV. *see* Net present value (NPV)
- NRRI. *see* Natural Resources Research Institute (NRRI)
- Nuclear magnetic resonance (NMR) 234
- Oilseed, biodiesel production from. *see*
Canola/rapeseed; *Jatropha curcas*
- Ontario Power (Canada) 75
- Ontario Power Generation (OPG) 111-112
- Operational flexibility 17-18
- OPG. *see* Ontario Power Generation (OPG)
- Oxidation 6
- PCC. *see* Pulverized coal combustion (PCC)
- PFRs. *see* Plug-flow reactors (PFRs)
- Philippines 344
- Phosphorous 289-290
- PHP. *see* Pyrolysis heat and power (PHP)
- Plug-flow reactors (PFRs) 229
- Portland General Electric (PGE) Boardman (Oregon) 74-76, 114-117
assessment and adjustment 119
biomass as carbon neutral substitute
for coal use in power plants
128-129
briquette blends use in stationary hearths
at Milwaukee Zoo 121-127
conventional pellet use versus
torrefied pellet use economics
comparison 127-128
fire in pulverizer 118-119
hundred percent biomass test
burn 120-121
plant emissions as normal 118
preliminary test 117

- pressure differential concern
 - resolving 119-120
- pulverizer plugged using torrefied biomass 118
- torrefied biomass yielding good burn 118
- Power plant conversion costs
 - comparison 75
- Pressure swing absorption (PSA) 369, 371
- Product flexibility 16-17
- Propagule production 345, 346
- PSA. *see* Pressure swing absorption (PSA)
- Pulverized coal combustion (PCC) 80
- Py-oil 44, 50
- Pyrolysis 6
- Pyrolysis heat and power (PHP) 367

- Ram briquettes, flame character using 125
- Ram briquetting equipment 123
- Rapid Thermal Processing (RTP™) 63
- Reactive distillation column (RDC) 356
- Rectisol process 24
- Red Arrow Products (USA) 50
- Red seaweed 343-345
- Reduction/gasification 6-7
- Renewable fuel oil (RFO) 63
- Renewable Fuel Standard (RFS) 54, 235
- Renewable Fuel Standard (RFS2) 221
- Renewable Identification Numbers (RINs) 221
- Renewable Portfolio Standards (RPS) 77
- Renewable sources, biodiesel production
 - from 151-153
 - feedstock types for 153-155
 - operating conditions optimization 166-168
 - quality improvement 183-185
 - see also* Transesterification
- Republic of Korea 344
- Response surface methodology (RSM) 168-169, 183
- Reverse water-gas-shift (RWGS) 21
- RFO. *see* Renewable fuel oil (RFO)
- RFS. *see* Renewable Fuel Standard (RFS)
- RFS2. *see* Renewable Fuel Standard (RFS2)
- RINs. *see* Renewable Identification Numbers (RINs)
- River Basin Energy 81
- Rotary kiln pyrolysis reactor 50
- Rotating cone pyrolysis reactor 49-50
- Rotavapor 234
- RPS. *see* Renewable Portfolio Standards (RPS)

- RSM. *see* Response surface methodology (RSM)
- Ruhrchemie Company 19
- RWGS. *see* Reverse water-gas-shift (RWGS)

- S-52 model (Hander Oil Machinery, Osaka, Japan) 233
- SCF. *see* Supercritical fluid (SCF)
- Schiller Station (Portsmouth, New Hampshire) 81
- Scholz Power Plant 75, 76, 108-111
- Seafloor cultivation 348
- Seaweed 341-342
 - anaerobic digestion 351
 - to methane 352-354
 - through MixAlco® process 355-357
 - to volatile fatty acids 354-355
 - chemical conversion routes 364
 - as feedstock for third-generation biofuels
 - classification and composition 342-343
 - current production trends 343-345
 - seaweed cultivation and supply chain 345, 347-351
 - fermentation 357-358
 - future trends 373
 - large-scale production case studies and techno-economical assessments 365-373
 - thermochemical conversion routes 358-359
 - gasification 359-361
 - liquefaction 363-364
 - pyrolysis 361-362
- Short-rotation coppice (SRC) 248, 306, 315, 318-319
- SNG. *see* Synthetic natural gas (SNG)
- Soapstock 153, 155
- SOC. *see* Solid oxide cells (SOC)
- SOEC. *see* Solid oxide electrolysis cells (SOEC)
- SOFC. *see* Solid oxide fuel cells (SOFC)
- Soil amendment 54
- Soil organic carbon 258, 278
- Soil priming 258
- Solid oxide cells (SOC) 30
 - pressurization and internal methanation in 32-33
- Solid oxide electrolysis cells (SOEC) 30
- Solid oxide fuel cells (SOFC) 30, 31
- Solvent type binders 102

- Southern Company 73, 108-111
SRC. *see* Short-rotation coppice (SRC)
Stack opacity comparison, for coal and
 biocoal 127
Starch 103
Statistics Canada 218
Strong acids 224
Strong bases 225
Supercritical fluid (SCF) 152, 155
Switchgrass 275-276
 case study 292-293
 challenges in becoming primary
 feedstock resource 281
 competing feedstock supplies
 282, 284
 logistics and conversion issues
 284-285
 economic policy and social issues
 290-292
 and environmental sustainability
 metrics 276-277
 biodiversity 280-281
 greenhouse gases 277-278
 soil carbon 278
 water quality 279
 water quantity 278-279
 future trends 294
 production, and agronomics in
 sustainability context 286
 ecotypes and cultivars 286-287
 establishment 287
 fertility 287-290
 harvest management 290
Syngas 21
Syngas Technologies 87
Synthesis gas requirements, for
 applications 12-13
Synthetic natural gas (SNG) 24-26

Taconite Harbor Energy Center (THEC)
 73, 112-114
Tank/pond cultivation 348
Tar 23
TGA. *see* Thermogravimetric analysis (TGA)
TGs. *see* Triglycerides (TGs)
Thailand 196
THEC. *see* Taconite Harbor Energy Center
 (THEC)
Thermogravimetric analysis (TGA) 48
Third-generation biofuel feedstocks 341
Thunder Bay plant 111
Tobacco Commission 292

Torrefaction, biofuels production with 71-73
 biomass as sustainable energy
 source 76-81
 biomass densification technologies 85
 pelleting/briquetting process 85-87
 biomass pretreatment technologies
 81-85
 biomass pretreatments advantages and
 limitations 105-108
 technology developments 108
 dry torrefaction 92-101
 pelleting/briquetting 101-104
 pretreatment technologies 87-88
 steam explosion 88-92
 torrefied biomass use in power
 plants 108-114
 torrefied fuels in power plants 73-76
 torrefied wood pellets use case
 study 114-129
Trait-to-ecosystem perspective 322
Transesterification 155-156, 198-200,
 222-224, 227, 364
 acid catalyst 200
 alkali catalyst 200
 enzymatic, factors affecting 201
 alcohol selection 201-202
 immobilized lipase
 pretreatments 203
 lipase enzyme 202-203
 water content 203-204
 enzyme catalyst (lipase) 200-201
Gibbs free energy and chemical
 equilibrium constant
 calculation 161-164
of oil/fat with methanol 222
proceeds, step-wise 223
process kinetic study 177-182
reaction 199
results 164-166
standard formation values calculation
 based on temperature 157,
 159-161
supercritical technology
 optimizing 168-169
 catalyst amount effect 176-177
 experimental design 171
 materials and methods 169-170
 methanol-to-oil molar ratio
 effect 176
 process optimization 172-174
 raw material properties 170
 statistical analysis 171-172

- temperature effect 175-176
- thermodynamic analysis 182-183
- thermodynamic parameters calculation
 - for individual compounds 156-157
- Triglycerides (TGs) 152, 153, 156, 199, 217
- Triolein 156, 157, 165, 166
- TSMR. *see* Two-stage micropyrolysis reactor (TSMR)
- TwoStage downdraft gasifier 16-17
- Two-stage micropyrolysis reactor (TSMR) 48

- Ultra pyrolysis 44
- Ulvan 343
- UN Food and Agricultural Organization 193
- United States 63
- Updraft gasifiers 9
- USDA Foreign Agricultural Services 219
- US Department of Energy (DOE) 357

- Vacuum pyrolysis 44
- Valmet 15, 18

- Vaporization enthalpy 159
- Vaporization entropy 159

- Wet scrubbing 14
- Wet torrefaction. *see* Hydrothermal carbonization (HTC)
- Willow 305-309
 - biodiversity 315-316
 - carbon accumulation and sequestration 317-318
 - case study 319-322
 - cropping security 313-315
 - ecosystem services and environmental impact 318-319
 - feedstock productivity 311-312
 - feedstock quality for biofuel use 309-311
 - future trends 322-325
 - nutrient uptake and use 316-317
- Wood pelleting 72, 81

- Zhao's empirical formula 159
- Zilkha 81, 90