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Toward a common classification approach for biorefinery systems

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Received June 19, 2009; revised version received July 16, 2009; accepted July 16, 2009
Published online in Wiley InterScience (www.interscience.wiley.com); DOI: 10.1002/bbb.172;
***Biofuels, Bioprod. Bioref.* (2009)**

Abstract: This paper deals with a biorefinery classification approach developed within International Energy Agency (IEA) Bioenergy Task 42. Since production of transportation biofuels is seen as the driving force for future biorefinery developments, a selection of the most interesting transportation biofuels until 2020 is based on their characteristics to be mixed with gasoline, diesel and natural gas, reflecting the main advantage of using the already-existing infrastructure for easier market introduction.

This classification approach relies on four main features: (1) platforms; (2) products; (3) feedstock; and (4) processes. The platforms are the most important feature in this classification approach: they are key intermediates between raw materials and final products, and can be used to link different biorefinery concepts. The adequate combination of these four features represents each individual biorefinery system. The combination of individual biorefinery systems, linked through their platforms, products or feedstocks, provides an overview of the most promising biorefinery systems in a classification network. According to the proposed approach, a biorefinery is described by a standard format as 'platform(s) – products – and feedstock(s)'. Processes can be added to the description, if further specification is required. Selected examples of biorefinery classification are provided; for example, (1) one platform (C6 sugars) biorefinery for bioethanol and animal feed from starch crops (corn); and (2) four platforms (lignin/syngas, C5/C6 sugars) biorefinery for synthetic liquid biofuels (Fischer-Tropsch diesel), bioethanol and animal feed from lignocellulosic crops (switchgrass).

This classification approach is flexible as new subgroups can be added according to future developments in the biorefinery area. © 2009 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: biorefinery; bioenergy; biofuels; biochemicals; classification; platform; feedstock

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Introduction

Background

The main fraction of worldwide energy carriers and material products, especially chemicals, is derived from fossil fuels, mainly oil and natural gas. Due to the expected price increase of fossil resources and their environmental impacts, the feasibility of their exploitation is predicted to decrease in the near future.[1,2]

There is clear scientific evidence that emissions of greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), arising from fossil fuel combustion and land-use change as a result of human activities, are perturbing the Earth's climate.[3] Over the past ten years, the transportation sector has shown the highest rates of growth in GHG emissions. By 2030, energy use and carbon emissions from transport are predicted to be 80% higher than current levels.[4] Concerning the existing chemical industry (based on oil refinery), about 4% of worldwide oil consumption is due to the production of chemicals and plastics, which are responsible of about 2% of the total oil-derived CO_2 emissions.[5]

In addition to the necessary increase of energy efficiencies on both the supply and demand sides, the amount of renewable energy must be increased in all sectors (electricity, heat, transportation and chemical industry), while at the same time securing the sustainability and affordable production of biomass for food and feed taking into account a strongly growing world population. Electricity and heat can be provided from different renewable resources like wind, solar, hydropower and biomass, while the only renewable carbon source is biomass.

The replacement of fossil-based carbon with renewable carbon from biomass leads to the development of biorefinery facilities, where transportation biofuels, bioenergy, biochemicals, biomaterials, food and feed are efficiently coproduced.

Among several definitions of biorefinery, the most exhaustive was recently formulated by International Energy Agency (IEA) Bioenergy Task 42*: 'Biorefining is the sustainable processing of biomass into a spectrum of marketable products and energy.'[6] Within this Task, a broad spectrum of different biorefinery systems is currently under study, some of which are already competitive in the market while others are still under development. The number of different types of biorefineries is growing, and a few general categories have been identified. A standard classification for the different existing and emerging biorefinery systems is not yet available, so the classification topic is still under debate. This paper addresses this issue, providing an approach for biorefinery system classification. This classification arises from the needs of IEA Bioenergy Task 42 for a common way to describe energy-driven biorefineries, i.e., systems that focus on the production of liquid or gaseous transportation biofuels as their main product. Following an overview of the classification issue, this new classification approach is presented, discussed and applied to some examples.

Classification issue

The problem of classification was of interest to Aristotle as well.[7] He thought that an all-embracing system of thought must be built up around certain novel theoretical conceptions, which could provide a logical skeleton for scientific explanation. For him, the logical backbone of science was to be provided by classification. Aristotle treated matter as species of a genus: instead of asking questions about the units of which matter is composed, he was concerned with the characteristic qualities distinguishing one substance from another. The challenge was to discover the properties of different substances, which can best be used as a basis of classification.

Two main attempts to classify biorefinery systems are recognized in the literature.[8,9] Several other papers mention classification schemes for individual biorefineries set-ups such as the 'liquid phase catalytic processing biorefinery' concept[10] and the 'forest-based biorefinery'.[11–13] The major different biorefinery types are:

1. The lignocellulosic feedstock biorefinery – uses nature-dry raw material, such as cellulose-containing biomass and wastes.
2. The whole crop biorefinery – uses raw materials, such as cereals or maize.
3. The green biorefinery – uses nature-wet biomasses, such as green grass, alfalfa, clover or immature cereal.

*Biorefinery: co-production of fuels, chemicals power and material from biomass (http://www.biorefinery.nl /ieabioenergy-task42/)

4. The two-platform concept biorefinery – includes the sugar and the syngas platforms.
5. The conventional biorefinery–based on existing industries, such as the sugar and starch industry.
6. The thermochemical biorefinery – based on a mix of several technologies.
7. The marine biorefinery – based on marine biomass.
8. The liquid-phase catalytic processing biorefinery – based on the production of functionalized hydrocarbons from biomass-derived intermediates.
9. The forest-based biorefinery – based on the full integration of biomass and other feedstocks (including energy), for simultaneous production of pulp, (paper) fibers, chemicals and energy.

Examples on how biorefinery systems can be classified are shown in Table 1. These classifications are broad and generic, and provide little information on the specific characteristics. Some of the limitations include:

- Classification criterion is not homogeneous: some of these systems refer to the type of feedstock (e.g., lignocellulosic feedstock biorefinery, marine biorefinery and others), while others focus on the technologies involved (e.g., thermochemical, conventional and two-platform concept biorefinery). The possibility to apply technological processes to different feedstocks is missing. For instance, a biorefinery system in which wood is gasified to syngas (like the production of Fischer-Tropsch (FT) fuels and chemicals from wood) can be categorized both as a lignocellulosic feedstock biorefinery (since lignocellulosic biomass is used) and a two-platform concept biorefinery (because syngas is produced).
- Biorefinery systems which use the grain and/or straw portions of a crop (like the conventional production of bioethanol from corn) can be indistinctly classified as whole crop biorefineries.
- The possibility to combine different biorefinery systems by linking different technologies is not taken into consideration. For example, if the carbohydrate fraction of a lignocellulosic feedstock is used to produce cellulose and xylose, the system is classified as a lignocellulosic feedstock biorefinery; but can also be classified as a forest-based biorefinery and, if the lignin fraction is pyrolyzed, the same biorefinery is also suitable for classification as a two-platform concept biorefinery.

The main reason for these contrasting results is that these classifications are based on a too large generalization in which each individual biorefinery system must fit, as only a limited number of generic types are formulated.

Therefore, a comprehensive approach for biorefinery system classification is needed and seen as essential to advance the ongoing discussion and development of biorefinery systems. It is expected that a sound and flexible classification approach will be able to deal with the various aspects of the biorefinery systems (both today's and future ones), and make the biorefinery area more accessible for stakeholders by improving the understanding of different biorefinery concepts. The aim of this paper is to describe a

Table 1. Classification of biorefinery systems using the existing methods.

		Classification	
	Biorefinery system	Kamm and Kamm[8]	Ree and Annevelink[9]
1	Production of bioethanol and animal feed from starch	Whole crop biorefinery (?)	Conventional biorefinery
2	Production of biodiesel, animal feed and glycerine from oil	Whole crop biorefinery (?)	Conventional biorefinery
3	Production of FT fuels and chemicals from wood	Lignocellulosic biorefinery	Thermochemical biorefinery
4	Production of biomethane, organic acids and biomaterials from grasses	Green biorefinery	Green biorefinery
5	Production of FT fuels and bioethanol from wood	Two-platform concept biorefinery	Two-platform concept biorefinery

(?) Uncertain classification

classification approach in which each individual biorefinery system is dealt with autonomously and classified according to its own individual characteristics (features). The most important individual biorefinery systems are then combined in a network. The classification described here was recently adopted within the IEA Bioenergy Task 42.

The four features of classification

The increase of the biofuel share in the transportation sector is a driving factor for the development of advanced processes to produce liquid and gaseous biofuels in biorefineries. In Europe, according to the directive for renewable energy, a target of 10% biofuel is set for 2020 and IEA and Intergovernmental Panel on Climate Change (IPCC) expect a 10–20% worldwide contribution of biofuels on the transportation market in 2030. For biomass-derived materials and chemicals, several procurement programs have been set but no specific targets have been established. Therefore, the main driver for the development of the energy-driven biorefinery can be seen in the efficient and cost-effective production of transportation biofuels, with coproduced biomaterials and biochemicals providing additional economic and environmental benefits.

With this perspective, a classification method for biorefinery systems was developed focusing mainly on concepts that are already commercial today, or might become of interest within the next few years (up to 2020), for the production of large volumes of transportation biofuels. The first selection of the most interesting bioenergy carriers is based on their chemical characteristics to be mixed with gasoline, diesel and natural gas. This reflects the main advantage of using the already-existing infrastructure (such as pipes, fuelling stations and vehicles) for easier market introduction (e.g., in Austria, blending of bioethanol and biodiesel with gasoline and diesel had already reached a share of 5.75% in 2008). These transportation biofuels include bioethanol, biodiesel, biomethane, and FT fuels. In addition, some final products like biohydrogen can be used both as an energy carrier and as an important auxiliary chemical for various processing technologies. To some extent, the same is the case with bioethanol (green ethylene) and biodiesel (triglyceride usage in lubricants and surfactants).

The basic idea of this classification approach is that each individual biorefinery system can be classified using the following four main features (listed in order of importance):

1. Platforms
2. Products
3. Feedstock
4. Processes

A biorefinery system is described as a conversion pathway from feedstock to products, via platforms and processes. The platforms are intermediates from which final products are derived. They are the most important feature in specifying the type of biorefinery.

Each feature consists of several subgroups, which are listed in Table 2 and are described in the following sections.

Platforms

Platforms are intermediates which link feedstocks and final products. The platform concept is similar to that used in the petrochemical industry, where the crude oil is fractionated into a large number of intermediates that are further processed to final energy and chemical products.

These platforms are recognized as the main 'pillars' of this biorefinery classification, since they might be reached via different conversion processes applied to various raw materials. Conversion of these platforms to marketable products can be carried out using the different processes described later.

The most important platforms which can be recognized in energy-driven biorefineries are the following:

- Biogas (a mixture of mainly CH_4 and CO_2), from anaerobic digestion.
- Syngas (a mix of CO and H_2), from gasification.
- Hydrogen (H_2), from water-gas shift reaction, steam reforming, water electrolysis and fermentation.
- C6 sugars (e.g., glucose, fructose, galactose: $C_6H_{12}O_6$), from hydrolysis of sucrose, starch, cellulose and hemicellulose.
- C5 sugars (e.g., xylose, arabinose: $C_5H_{10}O_5$), from hydrolysis of hemicellulose and food and feed side streams.
- Lignin (phenylpropane building blocks: $C_9H_{10}O_2(OCH_3)_n$), from the processing of lignocellulosic biomass.
- Pyrolysis liquid (a multicomponent mixture of different size molecules), from pyrolysis.

Table 2. Features (and relative subgroups) used in the proposed classification approach.

Platforms	Products	Feedstocks	Processes (selected)
I.) C5 sugars	***I.) Energy products***	***I.) Dedicated crops***	***I.) Thermochemical***
	I.1) Biodiesel	I.1) Oil crops	I.1) Combustion
II.) C6 sugars	I.2) Bioethanol	I.2) Sugar crops	I.2) Gasification
	I.3) Biomethane	I.3) Starch crops	I.3) Hydrothermal upgrading
III.) Oils	I.4) Synthetic biofuels	I.4) Lignocellulosic crops	I.4) Pyrolysis
	I.6) Electricity and heat	I.5) Grasses	I.5) Supercritical
IV.) Biogas		I.6) Marine biomass	***II.) Biochemical***
	II.) Material products		II.1) Fermentation
V.) Syngas	II.1) Food	***II.) Residues***	II.2) Anaerobic digestion
	II.2) Animal feed	II.1) Lignocellulosic residues	II.3) Aerobic conversion
			II 4) Enzymatic processes
VI.) Hydrogen	II.3) Fertilizer	II.2) Oil based residues	***III.) Chemical processes***
	II.4) Glycerin	II.3) Organic residues & others	III.1) Catalytic processes
VII.) Organic juice	II.5) Biomaterials		III.2) Pulping
	II.6) Chemicals and building blocks		III.3) Esterification
VIII.) Pyrolytic liquid	II.7) Polymers and resins		III.4) Hydrogenation
	II.8) Biohydrogen		III.5) Hydrolysis
IX) Lignin			III.6) Methanisation
			III.7) Steam reforming
X) Electricity and heat			III.8) Water electrolysis
			III.9) Water gas shift
			IV.) Mechanical/physical
			IV.1) Extraction
			IV.2) Fiber separation
			IV.3) Mechanical fractionation
			IV.4) Pressing / disruption
			IV.5) Pretreatment
			IV.6) Separation

- Oil (triglycerides: RCOO-CH_2CH(-OOCR')CH_2-OOCR") from oilseed crops, algae and oil based residues.
- Organic juice (made of different chemicals), which is the liquid phase extracted after pressing of wet biomass (e.g., grass).
- Electricity and heat, which can be internally used to meet the energy needs of the biorefinery or sold to the grid.

Products

Biorefineries produce both energetic and non-energetic products, and can be broadly grouped into two main classes:

1. Energy-driven biorefinery systems, where the biomass is primarily used for the production of secondary energy carriers (transportation biofuels, power and/or heat); products as feed are sold (current situation), or even better can be upgraded to added-value biobased products, to optimize economic and ecological performances of the full biomass supply chain.
2. Material-driven biorefinery systems, which primarily generate biobased products (biomaterials, lubricants, chemicals, food, feed etc.) and process residues that can be further processed or used to produce energy (for internal use or sale).

In this classification approach, biorefinery products are divided into energy products and material products. Some products like biohydrogen or bioethanol might be used either as an energy or as a material product. In this classification approach, the main market targets must be identified; for instance, the chemical market for H_2 and the transportation sector for bioethanol.

Besides electricity and heat, the energy products include the most promising transportation biofuels until 2020: bioethanol, biodiesel, synthetic biofuels (FT fuels and others) and biomethane.

Material products include fine chemicals (such as amino acids, organic acids and extracts) used in the food, chemical or pharmaceutical industry, and animal feed and fiber products, among others. The selected subgroups of material products are:

- Fertilizers.
- Biohydrogen.
- Glycerin (from the transesterification of triglycerides).
- Chemicals and building blocks (b.b.) (e.g., fine chemicals, aromatics, amino acids, xylitol, polyols, succinic-, lactic-, levulinic- and itaconic acid, phenols, furan dicarboxylic acid, furfural, etc.).
- Polymers and resins (produced by (bio)chemical conversion of biomass via monomeric intermediates (e.g., PHA, resins, PLA).
- Food.
- Animal feed.
- Biomaterials (fiber products, polysaccharides, pulp and paper, panels).

Feedstock

Feedstock is the renewable raw material (biomass) that is converted into marketable products in a biorefinery. The biomass feedstock can be subdivided into primary, secondary or tertiary.[14*]

Today, renewable carbon-based feedstocks for biorefinery are typically provided from four different sectors:

1. Agriculture (dedicated crops and crop residues).
2. Forestry (wood, short-rotation poplar, logging residues).
3. Industry (process residues and wastes) and domestic activities (organic residues).
4. Aquaculture (algae, seaweed).

A further distinction is made between those feedstocks which come from dedicated crops, produced on agriculture or forestry land or in aquatic systems, and those that come from residues, from agricultural, forestry and industrial activities.

Biomass feedstocks vary in composition, with different shares of basic components (cellulose, hemicellulose, lignin, starch, triglycerides, and proteins) and three chemical elements: carbon, oxygen and hydrogen (plus smaller percentages of S, N and ashes). Other important characteristics are water content, heating value and specific volume. In this classification approach, the following subgroups of biomass feedstocks are assumed (Fig. 1):

1. Dedicated feedstocks:
- Sugar crops (e.g., sugarbeet, sugarcane)
- Starch crops (e.g., wheat, corn, sweet sorghum)
- Lignocellulosic crops (e.g., wood, short rotation poplar, switchgrass and *Miscanthus*)
- Oil-based crops (e.g., rapeseed, soya, palm oil, *Jatropha curcas*)
- Grasses (e.g., green plant materials, grass silage, immature cereals and plant shoots)
- Marine biomass (e.g., micro and macro algae, seaweed)

2. Residues
- Oil-based residues (animal fat from food industries, used cooking oil from restaurants, households and others)
- Lignocellulosic residues (crop residues, saw mill residues etc.)
- Organic residues and others (e.g., organic urban waste, manure, wild fruits and crops)

Processes

In order to produce biofuels, biochemicals, biomaterials, food and/or feed, the feedstock is transformed into final products using different conversion processes. Dependent on their products (e.g., fuels, chemicals, materials, food, feed), biorefineries can be divided in systems where operations like

*Primary feedstocks include primary biomass that is harvested from forest or agricultural land. Secondary feedstocks are process residues, such as sawmill residues or black liquor generated by the forest products industry. Tertiary feedstocks are postconsumer wastes or residues such as waste greases, wastewaters, municipal solid waste (MSW), etc.

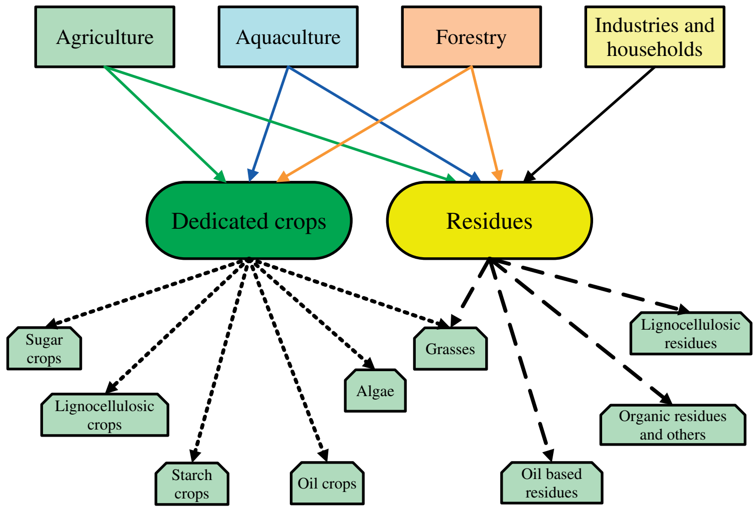

Figure 1. Types of feedstocks selected for the classification.

fractionation/separation into polymeric products (food, feed, biomaterials) are the main processes and systems for biofuels and biochemicals in which depolymerization and chemical, thermochemical and/or biochemical conversion are the major processes. The aim of the biofuel processes is both to depolymerize and deoxygenate the biomass components. Deoxygenation is particularly important, especially for producing transportation biofuels, as the presence of oxygen may reduce the heat content of the molecules and usually gives them higher polarity, thus decreasing blending possibilities with existing fossil fuels. By contrast, the presence of oxygen in chemical products (e.g., polyols and organic acids) often provides valuable physical and chemical properties to the compound.[15]

In biorefinery systems, several technological processes can be applied to convert biomass feedstock into marketable products. This classification approach identifies four main subgroups of processes:

1. Mechanical/physical (e.g., pressing, pre-treatment, milling, separation, distillation), which do not change the chemical structure of the biomass components, but they only perform a size reduction or a separation of feedstock components.
2. Biochemical (e.g., anaerobic digestion, aerobic and anaerobic fermentation, enzymatic conversion), which occur at mild conditions (lower temperature and pressure) using microorganisms or enzymes.
3. Chemical processes (e.g., hydrolysis, transesterification, hydrogenation, oxidation, pulping), where a chemical change in the substrate occurs.
4. Thermochemical (e.g., pyrolysis, gasification, hydrothermal upgrading, combustion), where feedstock undergoes extreme conditions (high temperature and/or pressure, with or without a catalytic mean).

All these processes need auxiliary energy and auxiliary materials. The long-term goal is to minimize the auxiliary energy and materials for conversion and to use auxiliary inputs from renewable sources (hydropower, solar, biomass process residues). For instance, when lignocellulosic feedstocks are used to produce bioethanol, the process residue lignin is combusted to provide the heat and electricity required by the biorefinery plant. Given its importance in the overall environmental assessment, this classification also specifies the source of heat and power for the energy needed by the system.

Biorefinery classification

Application to individual biorefinery systems

These four features, with their subgroups, are used for the classification of biorefinery systems. Figure 2 shows an example of how these features are combined in a biorefinery pathway. The generic biorefinery pathway starts with a feedstock which is converted to one of the platforms, from which final energy and material products are produced (Fig. 2(a)). In Fig. 2(b) an example of a biorefinery

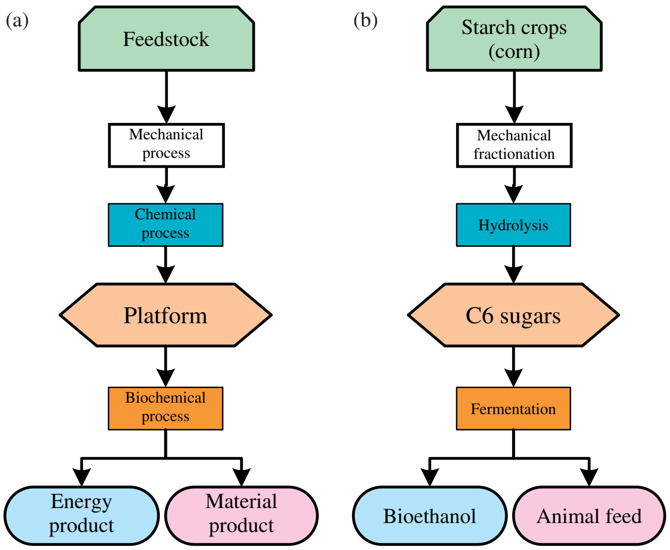

Figure 2 Example on the combination of the features for the classification of a biorefinery system: generic system (a) and example (b).

system producing bioethanol from corn is shown. After the mechanical treatment, corn is hydrolyzed to C6 sugars (the platform) and then fermented to bioethanol (the energy product), with animal feed as coproduct (the material product).

Biorefinery systems are classified according to this procedure:

1. Identify the main features of the biorefinery system and list them.
2. Draw the scheme of the biorefinery system using the involved features, i.e., platform(s), feedstock, products and processes.
3. Label the biorefinery system by quoting the involved number of platforms, marketable products, feedstocks and, if necessary, the processes, i.e.: number of platform (*platforms*) biorefinery for *products* from *feedstocks*.

Table 3. Application of the classification to selected biorefinery systems.

			Products				Source of auxiliary energy	
#	Name	Platforms	Energy	Material	Feedstock	Processes	Heat	Power
1	One-platform (C6 sugar) biorefinery for bioethanol and animal feed from starch crops	C6 sugars	Bioethanol	Animal feed	Starch crops (corn)	Hydrolysis, fermentation	Natural gas	Grid
2	One-platform (oil) biorefinery for biodiesel, animal feed and glycerine from oil crops	Oil	Biodiesel	Animal feed (rape cake), glycerine	Oil crops (rapeseed)	Pressing, transesterification	Natural gas	Grid
3	One-platform (syngas) biorefinery for synthetic biofuels and chemicals from lignocellulosic residues	Syngas	Synthetic biofuels (FT-fuels)	Chemicals (alcohols)	Lignocellulosic residues (straw)	Pre-treatment, gasification, FT synthesis, alochol synthesis	Natural gas	Grid
4	Two-platform (biogas and organic juice) biorefinery for biomethane, chemical b.b., biomaterials and fertilizer from grasses	Biogas, organic juice	Biomethane	Chemical b.b. (lactic acid, amino acid), biomaterials (fibers)	Grasses	Pressing, fiber separation, anaerobic digestion, upgrading (…)	Natural gas	Grid
5	Four-platform (C6/C5 sugars and lignin/syngas) biorefinery for synthetic biofuels, bioethanol and animal feed from lignocellulosic crops	C6/C5 sugars, lignin, syngas	Synthetic biofuels (FT-fuels), bioethanol	Animal feed	Lignocellulosic crops (switchgrass)	Pre-treatment, hydrolysis, fermentation, gasification, FT synthesis	Natural gas	Grid

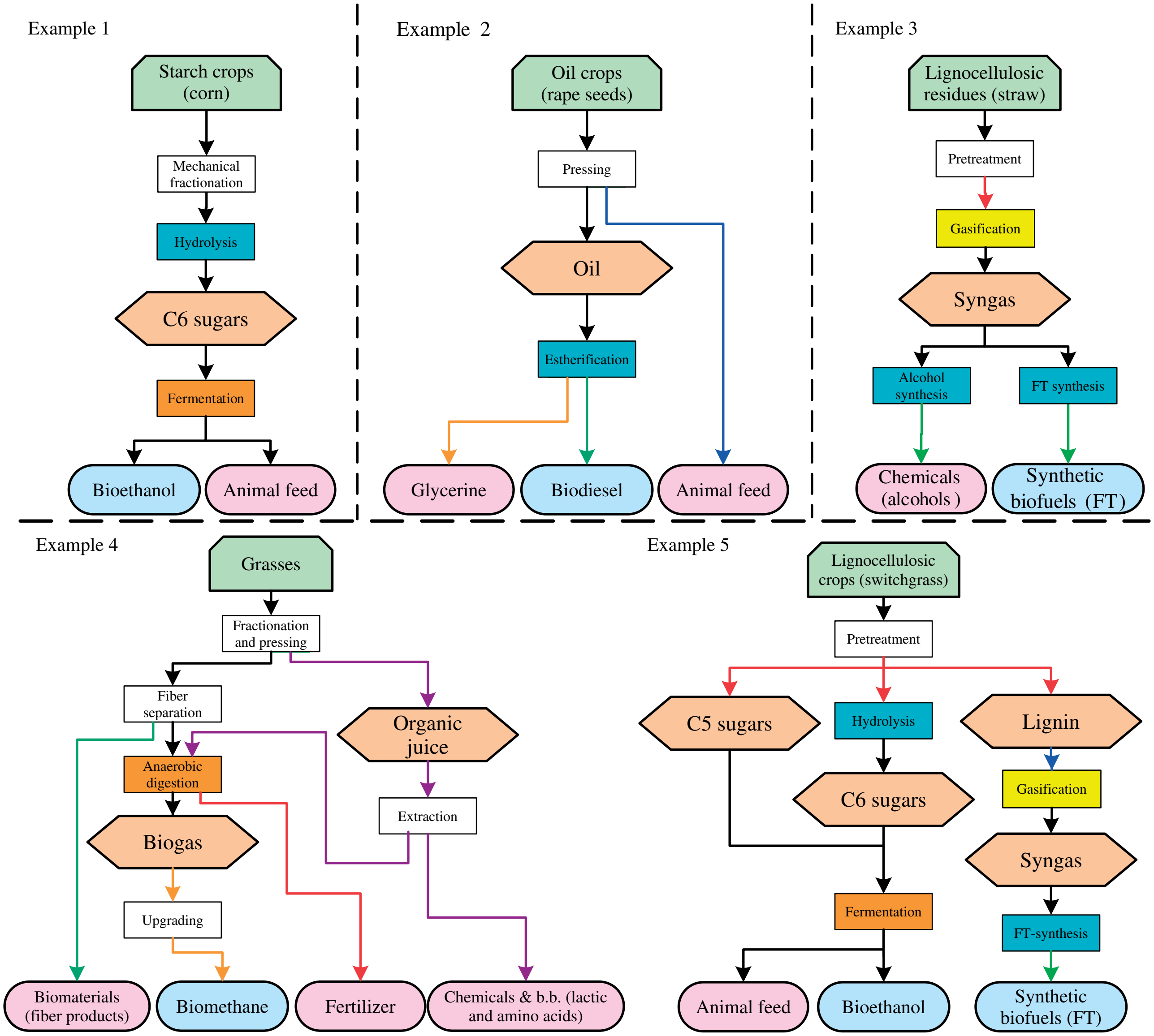

Figure 3. Schemes for the classification of biorefinery systems.

4. Set-up a table for the classified biorefinery systems with their features and the source of internal energy demand (i.e., heat and power).

This classification procedure is applied in the following examples, where the biorefinery systems of Table 1 are classified (their schemes are shown in Fig. 3 and their classification in Table 3):

- Example 1: One-platform (C6 sugar) biorefinery for bioethanol and animal feed from starch crops (corn).
- Example 2: One-platform (oil) biorefinery for biodiesel, animal feed and glycerin from oil crops (rape seeds).
- Example 3: One-platform (syngas) biorefinery for synthetic biofuels (FT diesel) and chemicals (alcohols) from lignocellulosic residues (straw).
- Example 4 – Green Biorefinery: Two-platform (biogas and organic juice) biorefinery for biomethane, chemical building blocks (lactic acid and amino acids), biomaterials (fiber products) and fertilizer from grasses.
- Example 5: Four-platform (lignin/syngas, C5/C6 sugar) biorefinery for synthetic liquid biofuels (FT diesel), animal feed and bioethanol from lingocellulosic crops (switchgrass).

This classification approach was also tested with further existing biorefinery systems taken from the literature; for example, four concepts from the *Bioenergy Network of Excellence*,[16] three referenced case studies[17] and one biorefinery commercial plant.[18] These biorefineries are classified according to this approach and shown in Table 4: each system properly fits in the classification and is clearly classified and described.

Network – Combination of individual biorefinery systems

The features, with their subgroups, are linked in a network which describes the most promising individual biorefinery systems toward the 2020s with a transportation biofuel orientation, from feedstock to products (Fig. 4). The network provides an overview of the most representative individual biorefinery systems which can be classified.

The upper level of the network of Fig. 4 shows the different types of feedstocks converted to platforms and/or products by combining different processes. Since there are some processes which are suitable for more than one platform, some platforms and conversion processes are linked together as well, thus combining two or more individual biorefinery systems. As a consequence, the number of involved platforms is an indication of biorefinery system complexity. In Fig. 4, this possibility is shown by dotted lines. A particular role is played by the electricity and heat platform, which can be reached from almost all the biomass feedstocks and other

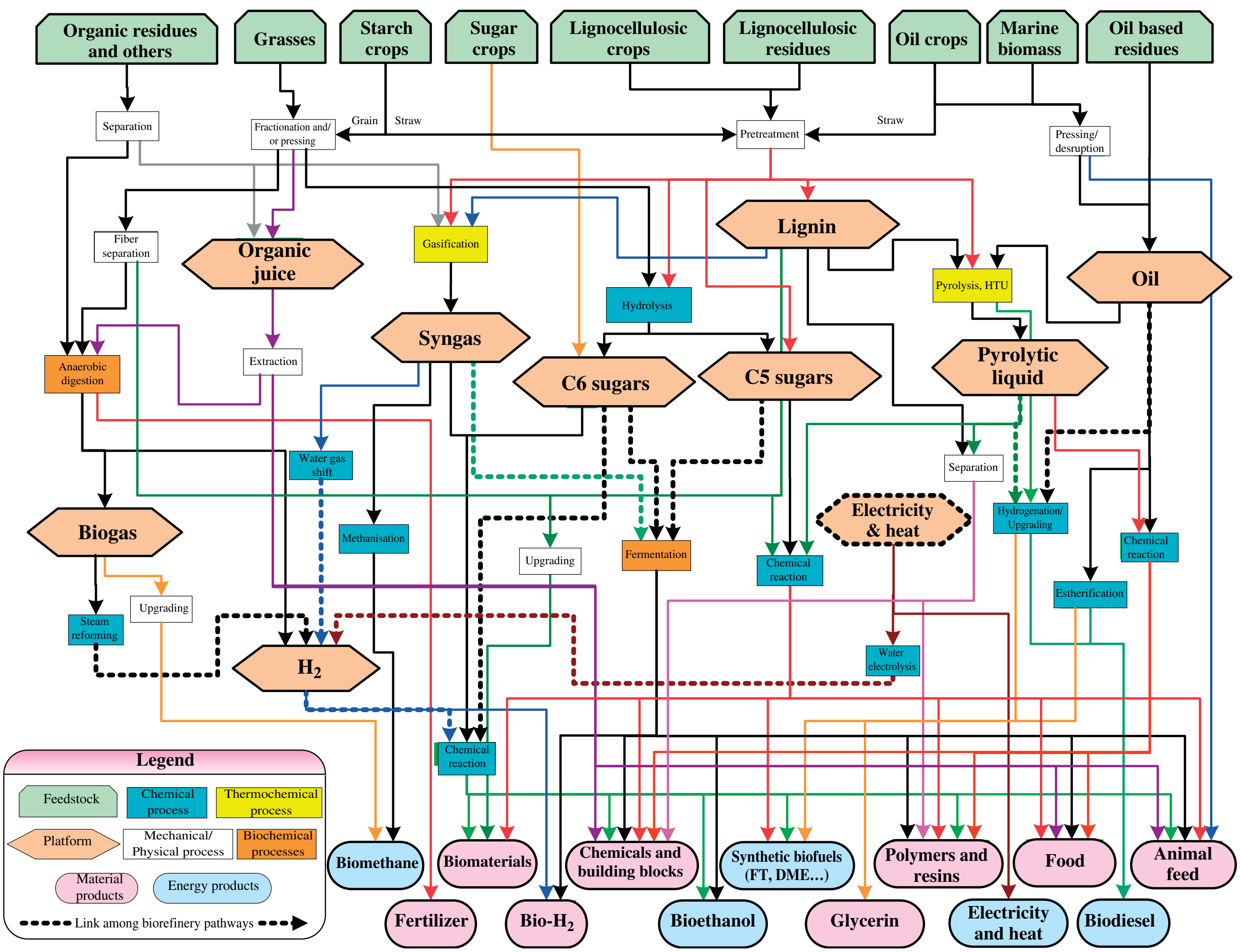

Figure 4 Network where the individual biorefinery systems are combined.

Table 4. Application of the classification to biorefinery systems taken from the literature. Systems from 1–4 from Bioenergy NoE,[15] 5–7 from Cherubini[16] and 8 from Modahl *et al*.[17]

#	Name	Platforms	Products		Feedstock	Processes	Source of auxiliary energy	
			Energy	Material			Heat	Power
1	Two-platform (C5 and C6) biorefinery for bioethanol from lignocellulosic residues	C6 sugars, C5 sugars	Bioethanol	Biomaterials (pulp and paper)	Lignocellulosic residues (from pulp & paper industry)	Pre-treatment, hydrolysis, fermentation, distillation	Unspecified	
2	One-platform (pyrolytic liquid) biorefinery for chemicals from lignocellulosic residues	Pyrolytic liquid	Chemicals (unspecified)		Lignocellulosic residues (lignin)	Pre-treatment, pyrolysis, separation	Unspecified	
3	One-platform (syngas) biorefinery for synthetic biofuels and chemicals from lignocellulosic residues	Syngas	Synthetic biofuels (FT fuels)	Chemicals (activated carbon and others)	Lignocellulosic residues (forest)	Pre-treatment, gasification, FT synthesis, chemical reactions	Unspecified	
4	One-platform (oil) biorefinery for biodiesel and chemicals from oil based residues	Oil	Biodiesel	Chemicals (brassylic and pelargonic acid)	Oil based residues	Pressing, estherification, chemical reactions	Natural gas	Grid
5	Six-platform (electricity & heat, C5/C6 sugars, biogas, lignin/pyrolytic oil) biorefinery for bioethanol, biomethane, electricity and heat and chemicals from lignocellulosic residues	C6/C5 sugars, lignin, pyrolytic oil, biogas, electricity and heat	Bioethanol, biomethane, electricity and heat	Chemicals (phenols)	Lignocellulosic residues (corn stover)	Pre-treatment, hydrolysis, fermentation, pyrolysis, combustion, separation (…)	Process residues	
6	Six-platform (electricity & heat, C5/C6 sugars, lignin, H2 and biogas) biorefinery for bioethanol, biomethane, synthetic biofuels, chemicals, resins, electricity and heat from lignocellulosic residues	C5/C6 sugars, lignin, H2, biogas, electricity and heat	Bioethanol, biomethane, synthetic biofuels (MTHF), electricity and heat	Chemicals (fumaric acid, O2), resins (furanic)	Lignocellulosic residues (from forestry)	Pre-treatment, hydrolysis, water electrolysis, fermentation, anaerobic digestion (…)	Process residues	
7	Six-platform (electricity & heat, C5/C6 sugars, lignin/pyrolytic oil and H2) biorefinery for synthetic biofuels, chemicals, electricity and heat from lignocellulosic crops	C5/C6 sugars, lignin, pyrolytic oil, H2, electricity and heat	Synthetic biofuel (ethyl levulinate), electricity and heat	Chemicals (formic, succinic acid, phenols)	Lignocellulosic crops (switchgrass)	Pre-treatment, acid hydrolysis, hydrogenation, combustion, flash pyrolysis (…)	Process residues	
8	Four-platform (C5/C6 sugars, biogas and lignin) biorefinery for bioethanol, biomaterials, chemicals from lignocellulosic residues	C5/C6 sugars, biogas and lignin	Bioethanol	Biomaterials (specialty cellulose), chemicals (vanillin)	Lignocellulosic residues	Pre-treatment, pulping, fermentation, anaerobic digestion	Biogas & residues	Hydro, MSW, oil

platforms via combustion. This heat and power can be used to meet the energy demand of the biorefinery itself, used as an energy source from a nearby individual biorefinery system or sold to the public grid.

The biorefinery network of Fig. 4 leads to the possibility to replace fossil-energy-based products, both energy carriers and materials, in the most efficient way. Regarding bioenergy, a biorefinery competes with energy services from fossil fuels (e.g., gasoline, diesel, heating oil, coal and natural gas) with the production of transportation biofuels and bioenergy from processing of biomass feedstocks. Concerning biomass-derived chemicals, this objective is met by producing the same chemical molecule from biomass instead of from fossils (e.g., phenols), or producing a molecule having a different structure but an equivalent function.

Discussion

According to IEA Bioenergy Task 42 priorities, this classification method was developed for biorefinery systems which focus on the large-volume production of transportation biofuels which can be blended with gasoline, diesel or natural gas.

Furthermore, biorefinery systems can be classified at different levels of details (e.g., processes and subgroups can be detailed step by step). An important characteristic of this classification approach is that it can be expanded to include future developments in the research and development of biorefinery activities: new feedstocks, platforms, processes or products can be added to features and to the network of Fig. 4.

Limitations of this current classification might arise when it is applied to biorefinery systems with a main focus on chemical, food and feed products. Compared to the energy-driven biorefineries, the classification of material-driven biorefinery systems might need further specification as the subgroup ‘chemicals and building blocks’ is very large and with heterogenous composition.

Another limitation may be recognized in the final denomination, which might become too long in cases with more than one platform. However, an acronym notation can be elaborated to resolve this issue.

At present, the selection of the energy products is limited to those transportation biofuels identified as most important until 2020. New transportation biofuels can be added following the future developments of research activities.

The network description does provide a valuable overview of the most important systems, identifying possible alternative pathways for exploiting all the different biomass components. Similarly, biomass conversions can be driven in order to reach the desired products and biological, chemical and thermal processes can be integrated and optimized to extract maximum value.

Conclusions

Energy and material production from biomass is maximized when raw materials are used with a biorefinery approach, where several technological processes are jointly applied to different kinds of biomass feedstock for producing a wide range of bioproducts for energy and material products. A large number of biorefinery pathways, from feedstock to products, may be established, according to the different types of feedstock, conversion technologies and products. Therefore, a sound and flexible classification approach able to take into account the most telling features of biorefinery systems is required.

This paper provides a classification approach for individual biorefinery systems and their possible combination. This classification was developed to meet the need of IEA Bioenergy Task 42 ‘Biorefinery’ to have a practical classification tool for biorefineries in general and energy-driven biorefineries in particular. The method is based on four features (platforms, products, feedstocks and processes) and their subgroups, which are used to classify and describe the different biorefinery systems. These features are also utilized to identify and label the individual biorefinery systems.

The main remarks arising from the application of this classification approach are the following:

- It is a classification with a relatively simple and schematic approach.
- Individual biorefinery systems are classified without an attempt to fit in *a priori* generic systems and this classification is based on systematic and homogeneous criteria, which results in no overlaps, inconsistencies and misunderstandings, as previous classification methods have done.
- Unlike previous methods, this classification approach offers the possibility to combine different biorefinery

systems into the so-called industrial 'bioclusters' or 'biorefinery complexes', due to the fact that some processes, platforms or feedstocks are able to join two or more individual biorefinery systems.

- The classification approach is flexible as further subgroups of the four features may be specified.
- Every biorefinery system can be classified and described at the required level of detail.
- The classification network that links different individual biorefinery systems promotes an understanding of the whole biomass system by displaying all the different conversion alternatives of each biomass component.
- The classification of some biorefinery systems with multiple platforms may result in relatively long names; this will be overcome with the further development of a proper acronym notation.
- Application of this classification approach to biorefinery systems with a focus on biomaterials and chemicals might lack the needed refinement. In such a case, additional platforms, product groups and processes may be added to specify the required details.
- Finally, this classification can be easily updated together with the future results of the ongoing activities of research and development in the biorefinery area by adding new platforms, processes or products.

Acknowledgments

This paper was funded by IEA Bioenergy Task 42 'Biorefineries: co-production of fuels, chemicals power and material from biomass'. The Task is constituted by the following countries (and representatives): Austria (Gerfried Jungmeier and Michael Mandl), Canada (Kirsty Piquette and Maria Wellisch), Denmark (Henning Jorgensen and Ioannis Skiadas), France (Leonard Boniface and Jean-Cristoph Pouet), Germany (Thomas Willke), Ireland (Patrick Walsh), and the Netherlands (Ed de Jong and René Van Ree).

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