The Biorefinery Complexity Index

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Working document

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Summary

Based on the classification system of biorefineries and the "Nelson´s complexity index" for oil refineries a Biorefinery Complexity Index (BCI) is developed. For each of the four features of a biorefinery the Technology Readiness Level (TRL) is assessed using level description between 1 ("basic research") to 9 ("system proven and ready for full commercial deployment"). Based on the TRL the Feature Complexity (FC) for each single feature of a biorefinery is calculated. With the number of features and the FC of each single feature the Feature Complexity Index (FCI) for each of the four features (platforms, feedstocks, products and processes) is calculated. The BCI is the sum of the four FCIs. The Biorefinery Complexity Profile (BCP) is a compact format to present the complexity of a biorefinery by giving the BCI and the four FCIs of each feature.

The BCP, which includes the BCI and the four FCI has the following format:

BCP: BCI ($FCI_{platforms}$/$FCI_{Feedstocks}$/$FCI_{Products}$/$FCI_{Processes}$),

with an example 8 (1/1/3/3).

The calculation method of the BCI is applied to 7 different biofuel-driven biorefineries. For each of these biorefinery concepts the BCP and the BCI are presented and compared to each other. The BCI and BCP of the analysed selected biofuel-driven biorefinery concepts are:

- 8 (1/1/3/3) of "1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed"
- 9 (1/1/4/3) for "1-platform (oil) biorefinery using oil based residues for biodiesel, glycerin, bio oil and fertilizer"
- 9 (1/1/2/5) of "1-platform (C6 sugars) biorefinery using starch crops for bioethanol and feed"
- 29 (8/1/4/16) of "3-platform (C5&C6 sugars, electricity&heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat and phenols"
- 25 (8/2/4/11) of "3-platform (pyrolysis oil, syngas, electricity&heat) biorefinery using straw for FT-biofuels and methanol with oxygen gasification"
- 16 (2/1/7/6) of "2-platform (electricity&heat, syngas) biorefinery using wood chips for FT-biofuels, electricity, heat and waxes with steam gasification"
- 35 (5/6/12/12) of "4-platform (biogas, biomethane, oil, electricity&heat) biorefinery using algae for biodiesel, biomethane, electricity, heat and glycerin, omega 3 and fertilizer".

The basic assumptions on the complexity of a biorefinery are the following:

- The number of different features of a biorefinery influences the complexity. The complexity increases by the number of features in a biorefinery.
- The state of technology of a single feature influences the complexity. The complexity decreases the closer a technology is to a commercial application.

This means a high "Technology Readiness Level" of a feature has lower technical and economic risks and a lower complexity.

- This leads to the basic assumption for the calculation procedure of the Biorefinery Complexity Index that the complexity is directly linked to the number of features and the Technology Readiness Level of each single feature involved.

The following conclusions on the BCI and BCP are drawn:

1. They give an indication for the relative comparison of different biorefinery concepts and their development potential
2. They present a benchmark of the "complexity" of a biorefinery in terms of involved platforms, feedstocks, processes and products, and their specific and overall "Technology Readiness Level"
3. The higher the Biorefinery Complexity Index the more beyond "state of the art" is the biorefinery
4. The BCI of a biorefinery producing biodiesel from vegetable oil which is fully deployed, with 8 (1/1/3/3) is a benchmark to compare the complexity of other current and future biorefinery systems:
   a. The complexity of producing biodiesel from vegetable oil and waste cooking oil is 1.25 more complex than using just vegetable oil
   b. The complexity of producing FT-Biofuel from wood is 3.125 more complex than producing biodiesel from vegetable oil
   c. The complexity of producing bioethanol from wood is 2.0 more complex than producing biodiesel from vegetable oil
   d. The complexity of producing biodiesel from algae is 4.375 more complex than producing biodiesel from vegetable oil.
5. The BCI will change in the future if the Technology Readiness Level has changed, e.g. if a demonstration plant for FT-Biofuels will go in to operation.
6. The Biorefinery Complexity Profile show the most relevant features contributing to the complexity of a biorefinery
7. The BCP of a biorefinery gives an indication on the technological and economic risks.
8. The first results and conclusions of a critical review by the country representatives in IEA Bioenergy Task 42 show that the "Biorefinery Complexity Index" adds additional relevant information on the assessment and comparison of different biorefinery systems
9. In future the BCI and BCP might also become a part of the "Biorefinery Fact Sheet" is developed by IEA Bioenergy Task 42 (Jungmeier et al. 2013, Jungmeier et al. 2014).

The results might become relevant for industry, decision makers and investors as additional information to assist them in their strategies to implement the most promising biorefinery systems by minimising technical and economic risks.

1 Aim of the work

The IEA Bioenergy Task 42 „Biorefining“ made the following definition on biorefinery: *“Biorefining is the sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, materials) and bioenergy (biofuels, power and/or heat)”*.

Currently many different and various biorefinery concepts are being developed, and are already implemented. On one hand some of these biorefinery concepts are simple, using one feedstock (e.g. vegetable oil) and producing two or three products (e.g. biodiesel, animal feed, glycerine) with current available commercial technologies. On the other hand biorefinery concepts are sometimes very complex using many different feedstocks (e.g. algae, miscanthus and wood chips from short rotation) to co-produce a broad spectrum of different products (e.g. bioethanol, phenol, omega 3 fatty acidy, biodiesel) using technologies that might become commercial in several years. Each of these different biorefinery concepts has a different degree of complexity, which makes it difficult for industry, decision makers and investors to decide, which of these concepts are the most promising options on the short, medium and long term, and to judge on the technological and economic risks.

The aim of this working document is to present the current status of an approach to develop a “Biorefinery Complexity Index (BCI)” and to calculate the BCI for some selected biorefinery concepts. The approach was developed in IEA Bioenergy Task 42 since 2010 and started with the analogy to the “Nelson´s complexity index” used for oil refineries. The results of this development are presented here after its continuously critical review by the country representatives of IEA Bioenergy Task 42 “Biorefineries”.

2 Approach

Based on the principles of the calculation of the “Nelson´s complexity index” for oil refineries, which are published for oil refineries in the “Oil and Gas Journal”, and the unique classification system for biorefineries developed in IEA Bioenergy Task 42, the principles for the calculation of a “Biorefinery Complexity Index (BCI)” are developed. These principles are applied to a selected number of different biorefinery concepts to calculate and compare the Biorefinery Complexity Index for these different biorefinery concepts.

For each of the four features of the classification system for biorefineries (Cherubini et al 2009) - 1) platforms, 2) feedstocks, 3) products and 4) processes (Figure 1) – a “Feature Complexity Index (FCI)” is developed to assess the technical and economic state of the art, and potential risks of using these features in a biorefinery. The “Feature Complexity Index” is developed based on the assessment of the “Technology Readiness Level (TRL)” for each single feature of the considered biorefineries. As “Products” and “Feedstocks” are or will be commodities on the market, they are assessed in accordance to their “Market Readiness Level (MRL)”, which is applied in analogy to the TRL.

The adequate combination of the Feature Complexity Index deriving from of each single feature gives the “Biorefinery Complexity Index”.

In the whole development process a critical review and discussion of the results was done by the members of IEA Task 42 from the participating countries and relevant stakeholders during internal meetings, stakeholder workshops and international conferences e.g. European Biomass Conference, Australian Bioenergy Conference (Jungmeier 2010, Jungmeier 2010a, Jungmeier 2011, Jungmeier 2011a, Jungmeier 2011b, Jungmeier et al. 2012, Jungmeier 2012a).

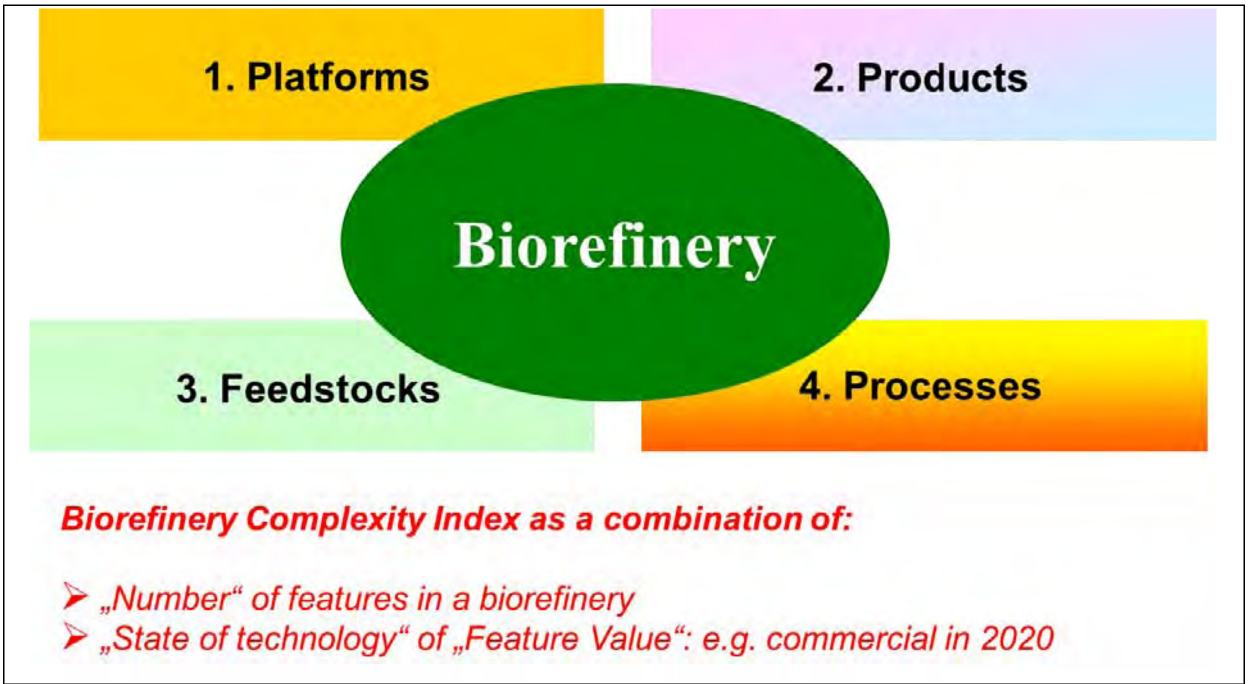

Figure 1: Classification system of a biorefinery with the 4 features – platforms, products, feedstocks and processes (based on Cherubini et al. 2009)

3 Nelson´s Complexity Index of oil refineries

In this chapter a short summary of the complexity index of oil refineries is given by also using 4 different oil refineries (A, B, C and D), for which some main characteristics are given in Figure 2.

- Nelson`s (complexity) index was developed by Wilbur L. Nelson and published in the “Oil and Gas Journal” (1960-61) to quantify the costs of the refinery´s components
- Nelsons`s Index:
  - indicator for the investment intensity
  - cost index of the refinery
  - value addition potential of a refinery

  - o refers to the refinery's ability to process feedstocks, such as high-sulfur crude, into value-added products
  - o the higher the complexity the more flexible it is
- Basic idea: assign the factor 1 to the primary crude distillation and all other components are rated relative to primary distillation (Figure 3)
- The Nelson Complexity Index assigns a complexity value to each major refining unit based on its complexity and cost in comparison to crude distillation, which is assigned a complexity factor of 1.0.
- The complexity of each refining unit is then calculated by multiplying its complexity factor by its throughput ratio as a percentage of crude distillation capacity.
- Adding the complexity values assigned to each unit, including crude distillation, determines a refinery's complexity. In Figure 4 the Nelson Complexity Index is shown for these 4 refineries.
- Another aspect of the complexity consideration of oil refineries is that the complexity can be normalized to an "Equivalent distillation unit". This "Equivalent distillation unit" compares the complexity of an oil refinery based on the capacity of the distillation unit. An example is given in Figure 5.
- A refinery with a complexity of 10.0 on the Nelson Complexity Index is considered 10 times more complex than crude distillation for the same amount of throughput.

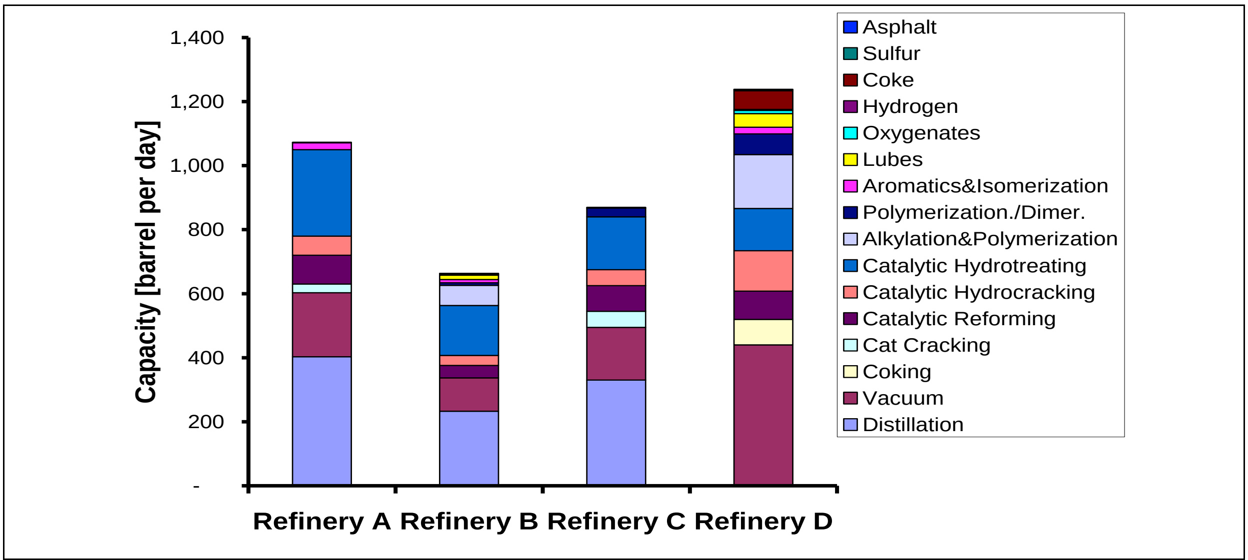

Figure 2: Characteristics of four refineries A, B, C and D

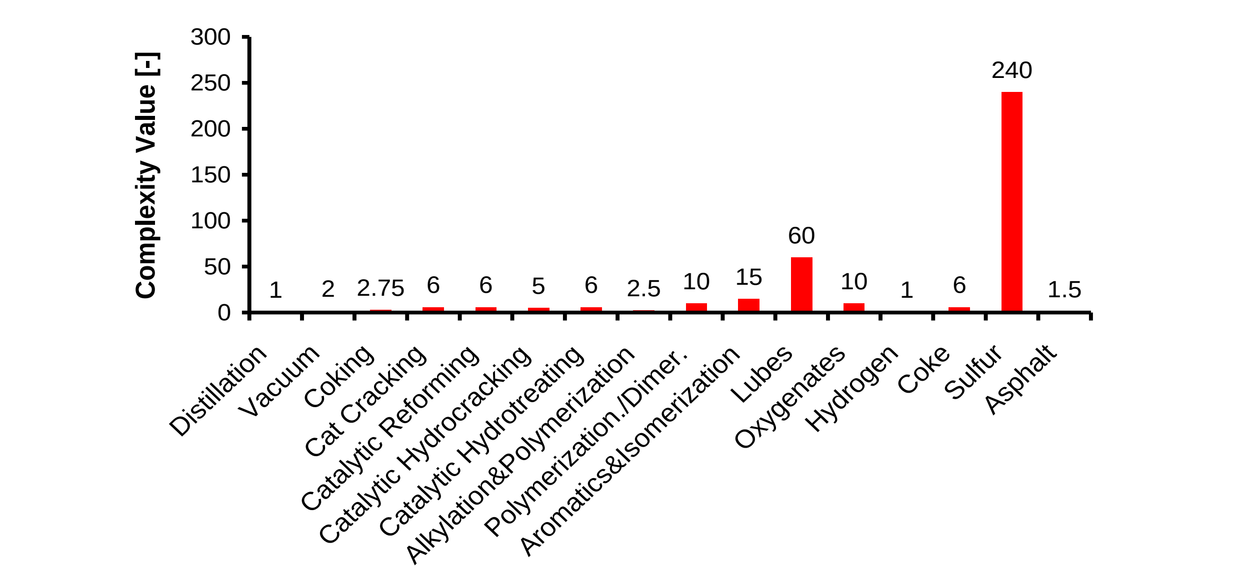

Figure 3: Complexity value of refining units

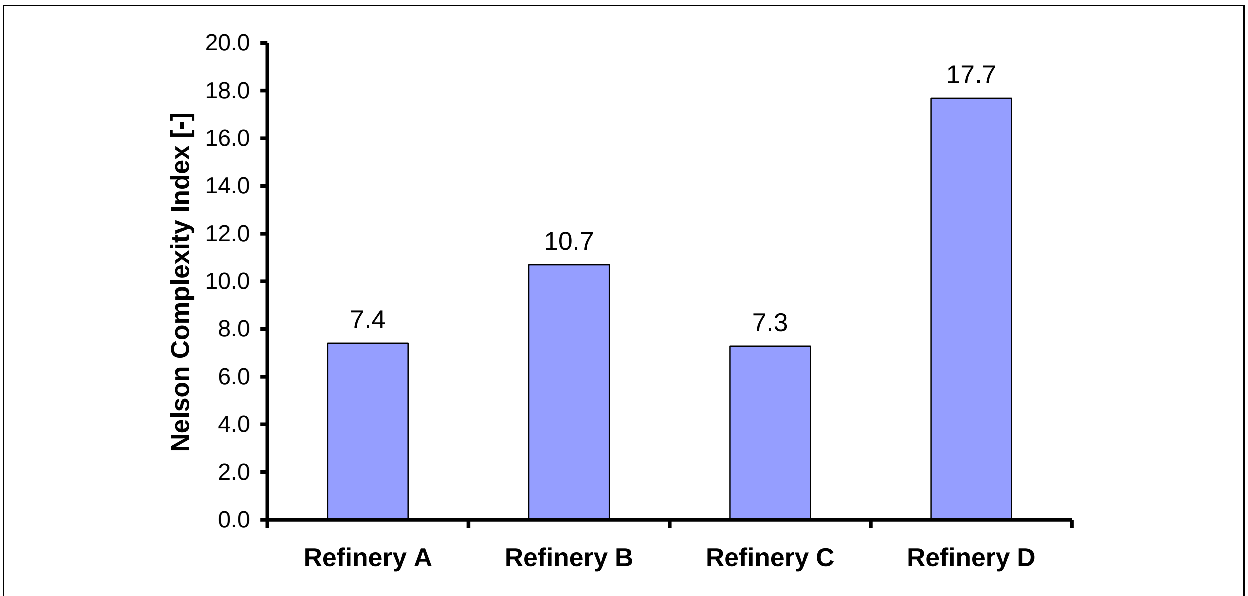

Figure 4: Nelson Complexity Index

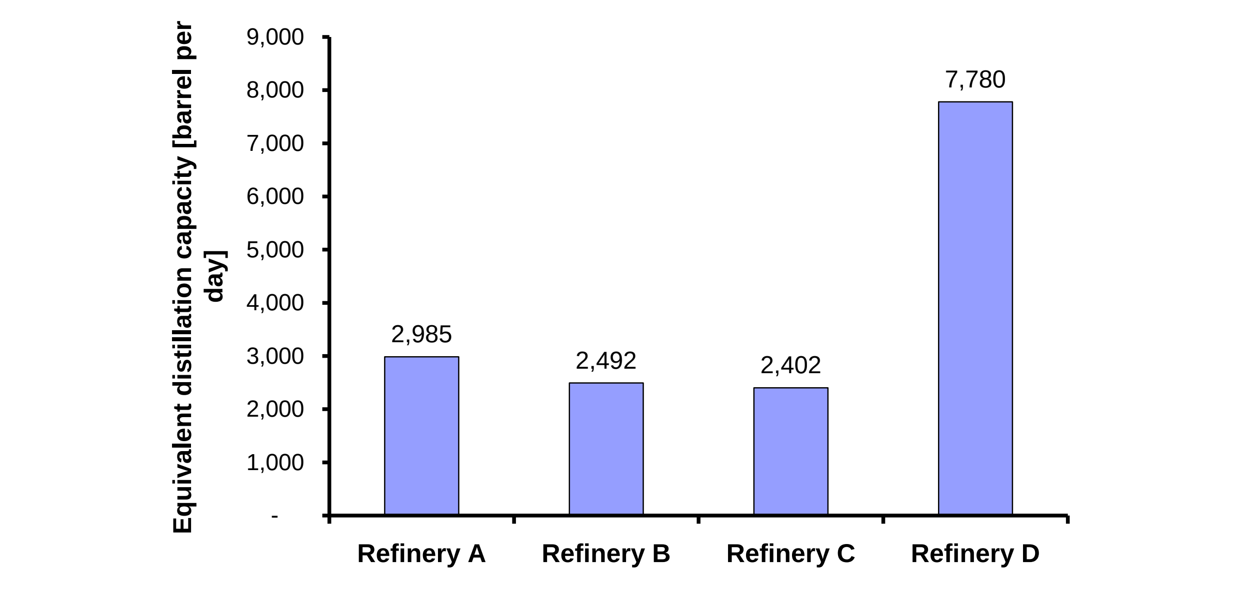

Figure 5: Equivalent distillation capacity

4 Biorefinery Complexity Index (BCI)

After an introduction of the basic assumptions the calculation of the BCI is shown, which is then applied to an example.

4.1 Basic assumptions

The basic assumptions on the complexity of a biorefinery are the following:

1. The number of different features of a biorefinery influences the complexity. The complexity increases by the number of features in a biorefinery.
2. The state of technology of a single feature influences the complexity. The complexity decreases the closer a technology is to a commercial application, meaning a high “Technology Readiness Level” of a feature has lower technical and economic risks, and so a lower complexity.
3. For the products and feedstock the “Market Readiness Level” is applied in analogy to the TRL of the processes and platforms. Therefore in the following document only the TRL is used.
4. This leads to the basic assumption for the calculation procedure of the Biorefinery Complexity Index that the complexity is directly linked to the number of features and the Technology Readiness Level of each single feature involved.
5. This means that the complexity of a commercial application, which means that all features are commercially available, is then only determined by the number of features; whereas in non-commercial application the TRL increase additionally the complexity of the biorefinery system.

4.2 Calculation of the Biorefinery Complexity Index (BCI)

Based on the classification system of biorefineries and the “Nelson´s complexity index” for oil refineries a Biorefinery Complexity Index (BCI) is developed. For each of the four features of a biorefinery the Technology Readiness Level (TRL) is assessed using a level description between 1 (“basic research”) to 9 (“system proven and ready for full commercial deployment”).

Based on the TRL the Feature Complexity (FC) for each single feature of a biorefinery is calculated. With the number of features and the FC of each single feature the Feature Complexity Index (FCI) for each of the four features (platforms, feedstocks, products and processes) is calculated. The BCI is the sum of the four FCIs. The Biorefinery Complexity Profile (BCP) is a compact format to present the complexity of a biorefinery by giving the BCI and the four FCIs of the composing features.

The calculation formulas of the BCI are:

$$BCI = \sum_{i=1}^{4} FCIi = \sum_{i=1}^{4} \sum_{j=1}^{m} NFij$$

or

$BCI = NF_{Plattforms} * FC_{Platforms} + NF_{Feedstocks} * FC_{Feedstocks} + NF_{Products} * FC_{Products} + NF_{Processes} * FC_{Processes}$

with

$$FCIi = \sum_{j=1}^{m} NFij$$

and

$FC_i = 10 - TRA_i$

BCI…..Biorefinery Complexity Index
NF_i…..Number of features
FC_i…..Feature Complexity
i…..Index for the four features: 1) Platforms, 2) Feedstocks, 3) Products and 4) Processes
m…
FCI_i…..Feature Complexity Index
TRA…..Technology Readiness Level of feature assessed between 1 and 9 (see Table 1)

The Technology Readiness Level of the feature is assessed using the description of technology levels in Table 1:

Table 1: Description of technology levels

Level	Technology Readiness Level (TRL)	Description	Feature Complexity (FC)
1	TRL1	basic research	9
2	TRL2	applied research	8
3	TRL3	critical function or proof of concept established	7
4	TRL4	lab testing/validation of Alpha prototype	6
5	TRL5	laboratory testing of integrated/semi-integrated system	5
6	TRL6	prototype system verified	4
7	TRL7	integrated pilot system demonstrated	3
8	TRL8	system incorporated in commercial design	2
9	TRL9	system proven and ready for full commercial deployment	1

The "Biorefinery Complexity Profile (BCP)" of a biorefinery is described by the Biorefinery Complexity Index by giving also the calculated "Feature Complexity Index (FCI)" for the four features:

$$BCP = BCI\ (FCI_{Platforms}/FCI_{Feedstocks}/FCI_{Products}/FCI_{Processes})$$

Some additional remarks:

1. Platforms and processes that are not directly linked to the biomass feedstock, e.g. electricity and heat, conversion of fossil fuels to electricity, are not considered in the BCI calculation.
2. The theoretical lowest BCI of a biorefinery is 5 (1/1/2/1), as a biorefinery must have as a minimum 2 products, 1 feedstock, 1 platform and 1 process.
3. So far the relevance of the FCI for all features is the same, but it might be for future development to be considered that the contribution of one feature to the BCI might be weighted higher than of another feature.
4. As biorefineries can also be an integrated part of an oil refinery, it may be possible in future to apply the Nelsons Complexity Index also to the processes of the biorefinery.

4.3 Example

The BCI and the BCP are calculated and shown for a biorefinery as an example. The biorefinery has

- 2 platforms with the $TRL_{platforms}$ of 7 and 9 ($NF_{platforms}$ = 2)
- 3 feedstocks with the $TRL_{feedstocks}$ 3, 8 and 9 ($NF_{feedstocks}$ = 3)
- 3 products with the $TRL_{products}$ of 9 and ($NF_{products}$ = 3)
- 4 processes with the $TRL_{processes}$ of 4, 8, 9 and 9 ($NF_{processes}$ = 4).

The Feature Complexities are

- $FC_{platform1}$ = (10 – 7) = 3; $FC_{platform2}$ = (10 – 9) = 1
- $FC_{feedstock1}$ = (10 – 3) = 7; $FC_{feedstock2}$ = (10 – 8) = 2; $FC_{feedstock3}$ = (10 – 9) = 1
- $FC_{product1\&2\&3}$ = 10 – 9 = 1
- $FC_{process1}$ = (10 – 4) = 6; $FC_{process2}$ = (10 – 8) = 2; $FC_{process3\&4}$ = (10 – 9) = 1

The Feature Complexity Index for the four features are

- $FCI_{platforms}$ = (1 * 3 + 1 * 1) = 4
- $FCI_{feedstocks}$ = (1 * 7 + 1 * 2 + 1 * 1) = 10
- $FCI_{products}$ = (3 * 1) = 3 and
- $FCI_{processes}$ = (1 * 6 + 1 * 2 + 2 * 1) = 10

The Biorefinery Complexity Index is

- BCI = 4 + 10 + 3 + 10 = 27

The Biorefinery Complexity Profile of the biorefinery is (Figure 6)

- BCP = 27 (4/10/3/10)

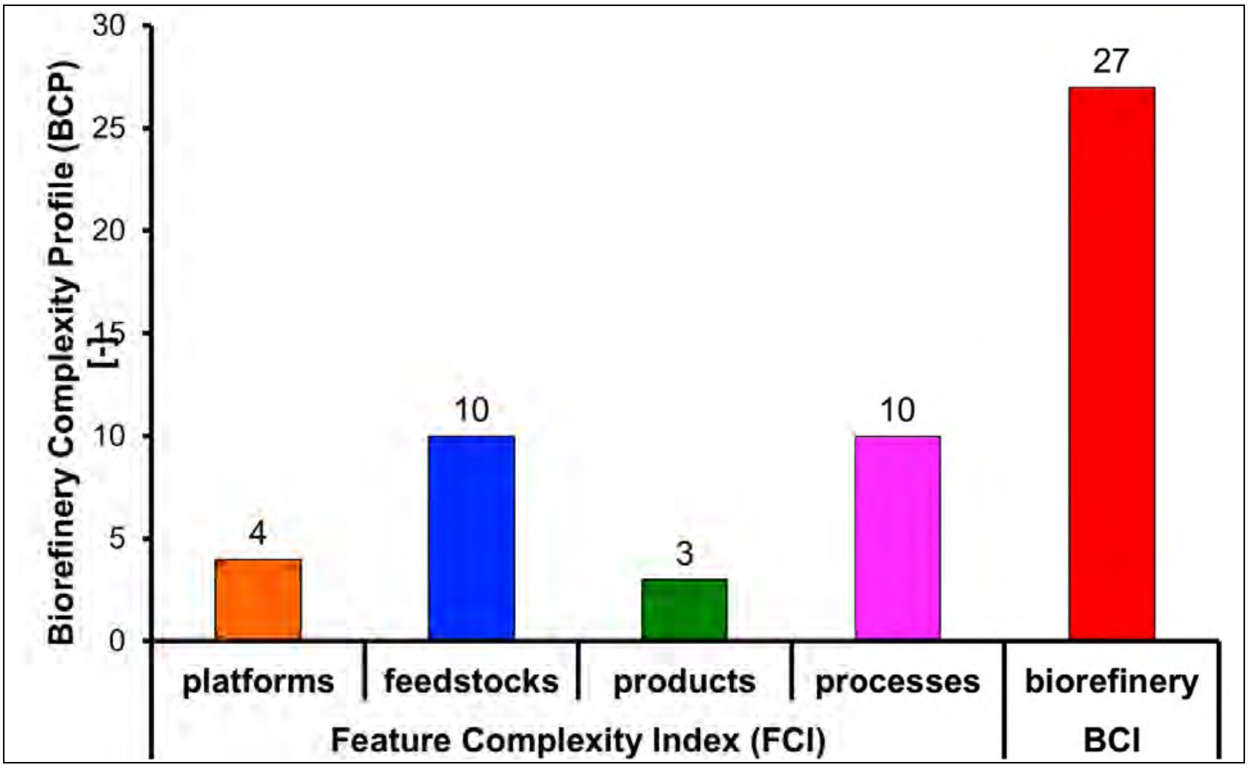

Figure 6: Example of a biorefinery with a "Biorefinery Complexity Profile" 27 (4/10/3/10)

5 Assessment of the Technology Readiness Level (TRL)

The assessment of the Technology Readiness Level of the different features is done using the description of the technology levels shown in Table 1. The assessment is done for all the features of the biofuel-driven biorefinery concepts that were identified by IEA Bioenergy Task 42 "Biorefining" to be the most promising biorefinery concepts to produce large volumes of road transportation biofuels by 2025. The selection and the description of the 15 biorefinery concepts are published in the report "Biofuel-driven Biorefineries – A Selection of the most promising biorefinery Concepts to produce large volumes of road transportation biofuels by 2025" (IEA Bioenergy Task 42 2013), which can be downloaded from the webpage of IEA Bioenergy Task 42 "Biorefining" (www.IEA-Bioenergy.Task42-Biorefineries.com).

The Technology Readiness Levels are shown for

- Platforms in Figure 7
- Feedstocks in Figure 8
- Products
    - Energy products in Figure 9
    - Material products in Figure 10
- Processes
    - Thermo-chemical processes in Figure 11
    - Bio-chemical processes in Figure 12
    - Chemical processes in Figure 13 and

- o Mechanical processes in Figure 14 and Figure 15

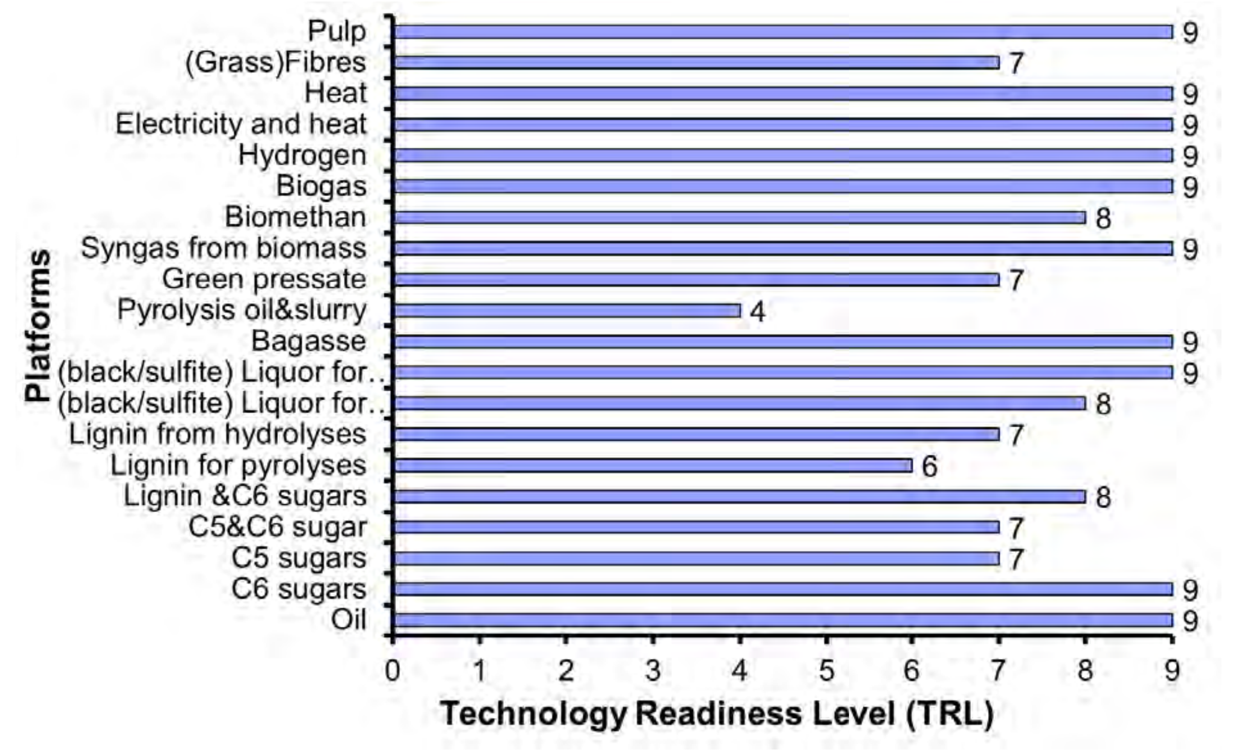

Figure 7: Technology Readiness Level of platforms

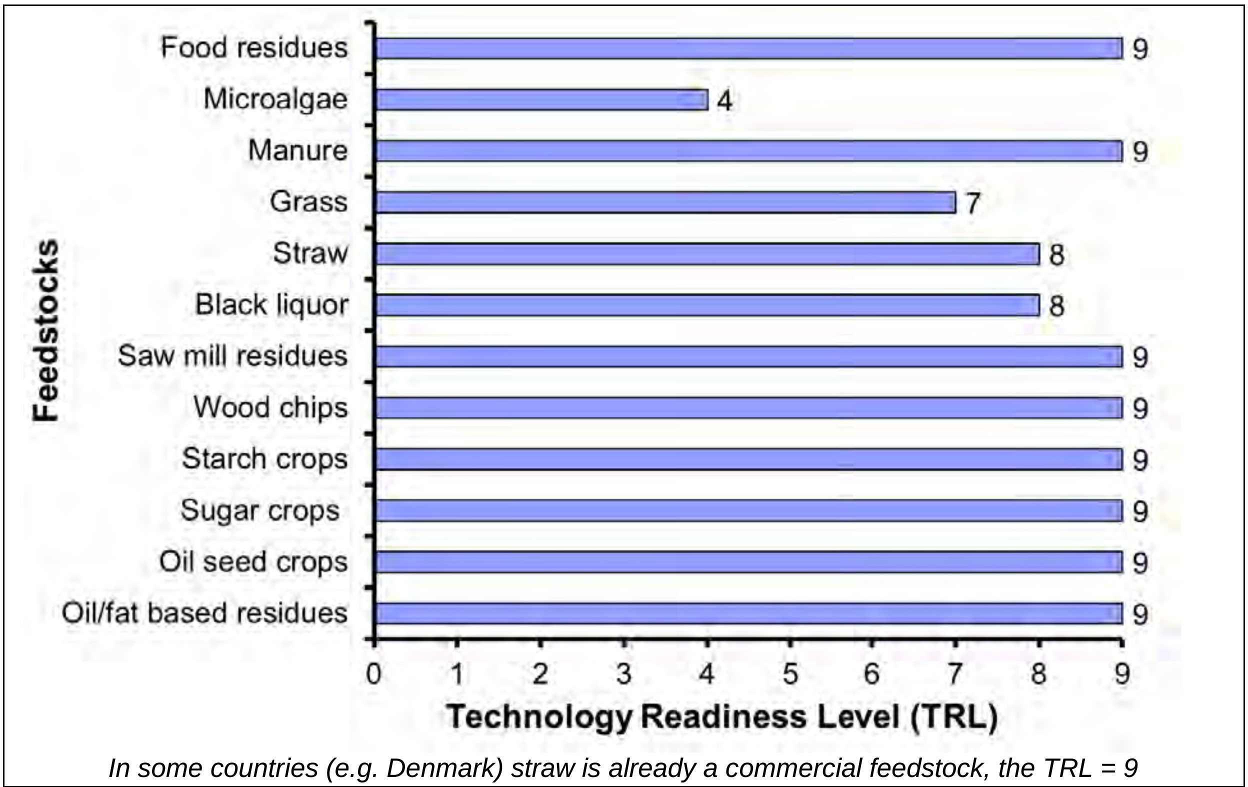

Figure 8: Technology Readiness Level of feedstocks

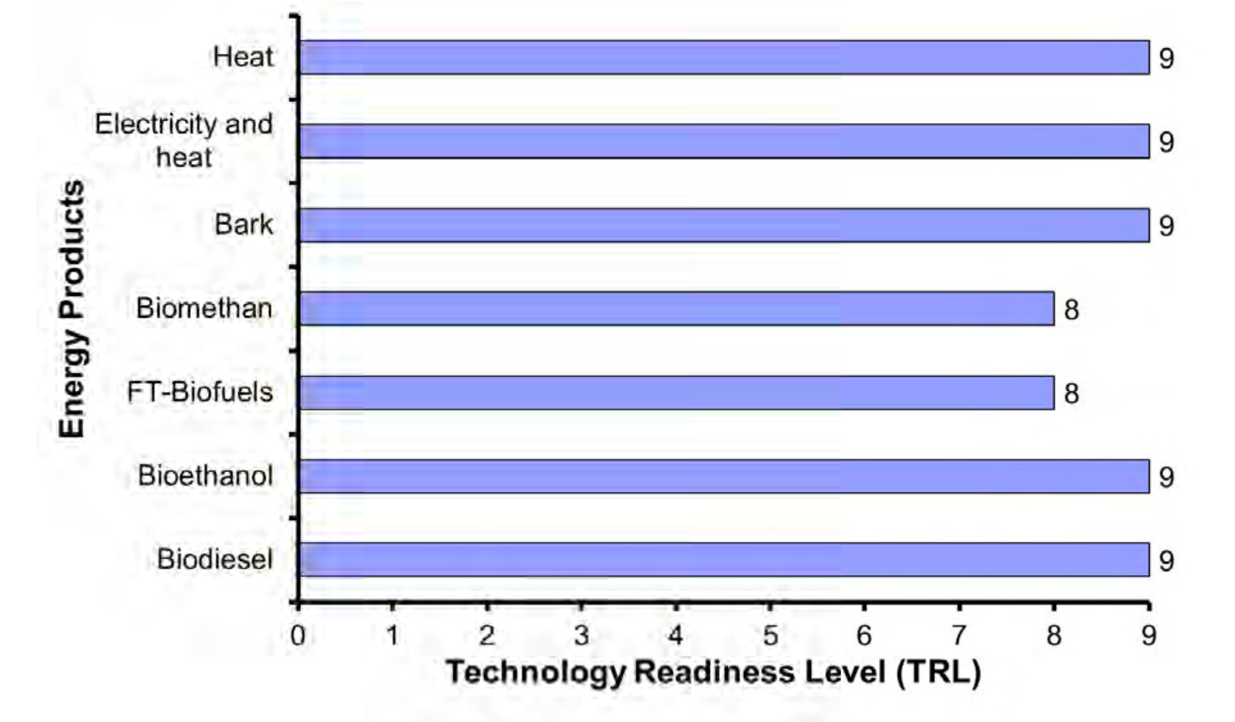

Figure 9: Technology Readiness Level of energy products

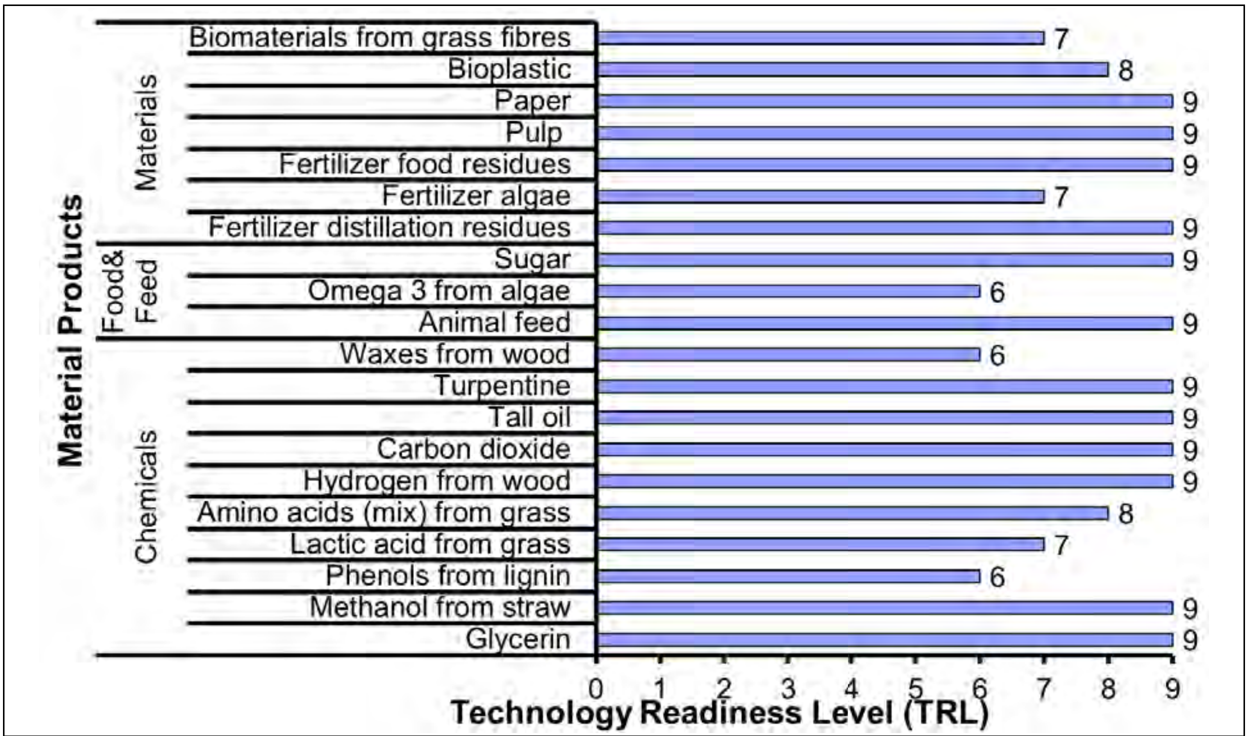

Figure 10: Technology Readiness Level of material products

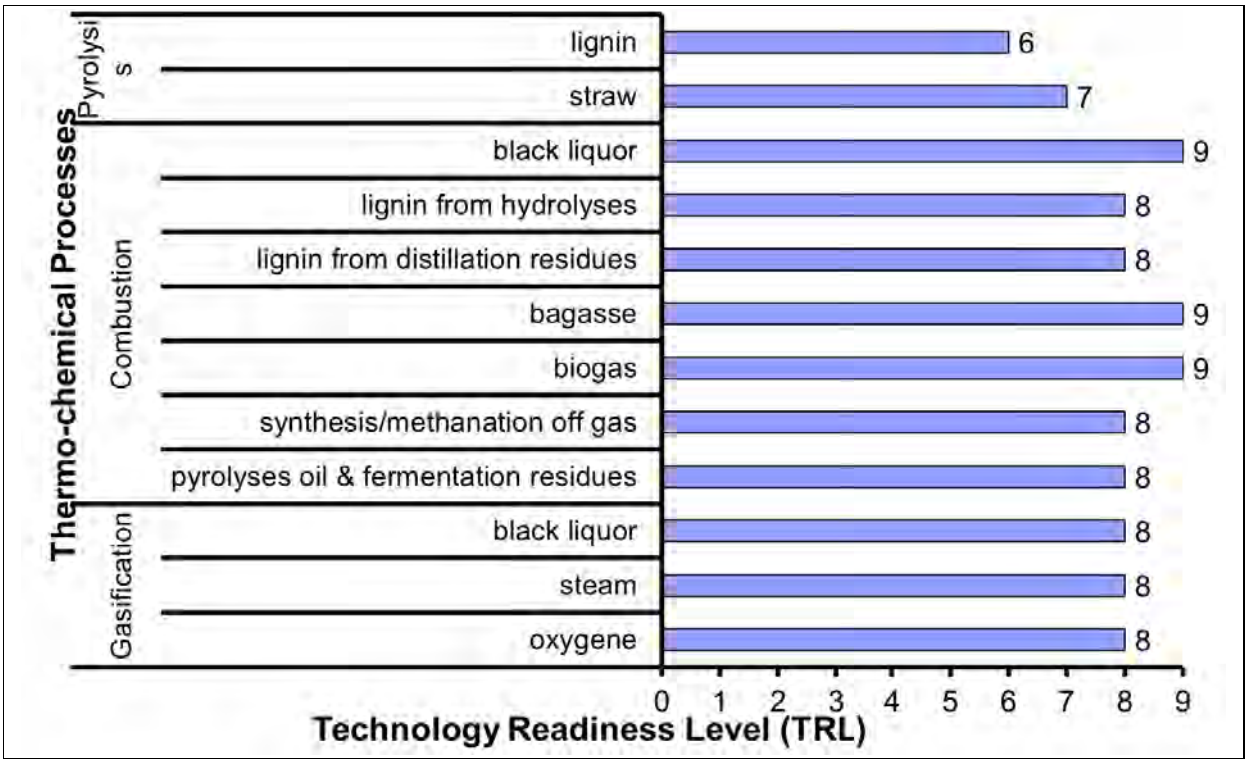

Figure 11: Technology Readiness Level of thermo-chemical processes

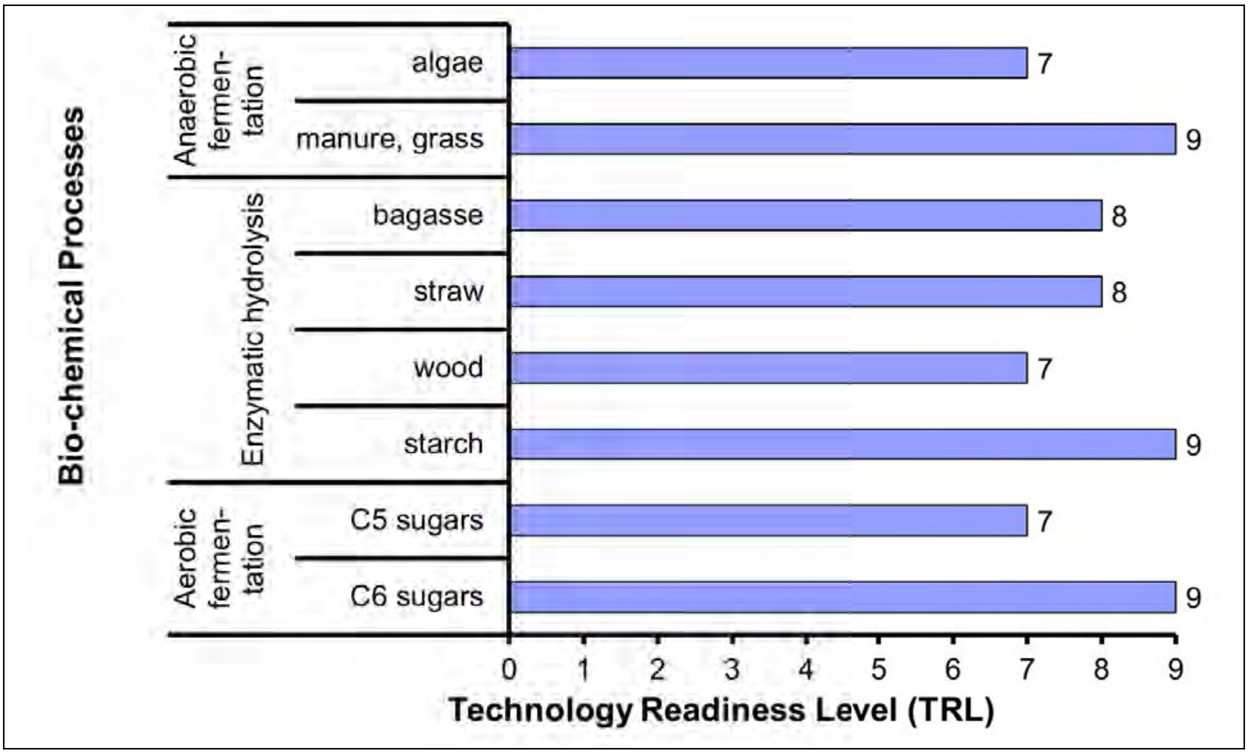

Figure 12: Technology Readiness Level of bio-chemical processes

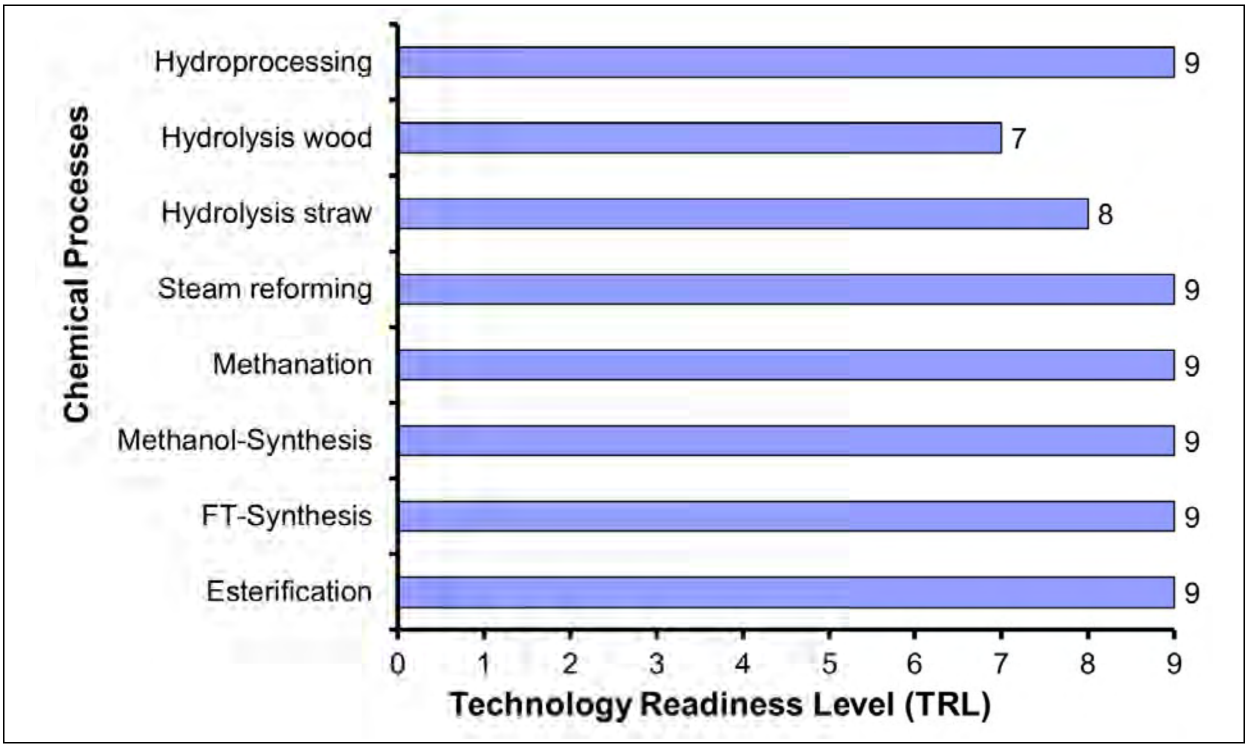

Figure 13: Technology Readiness Level of chemical processes

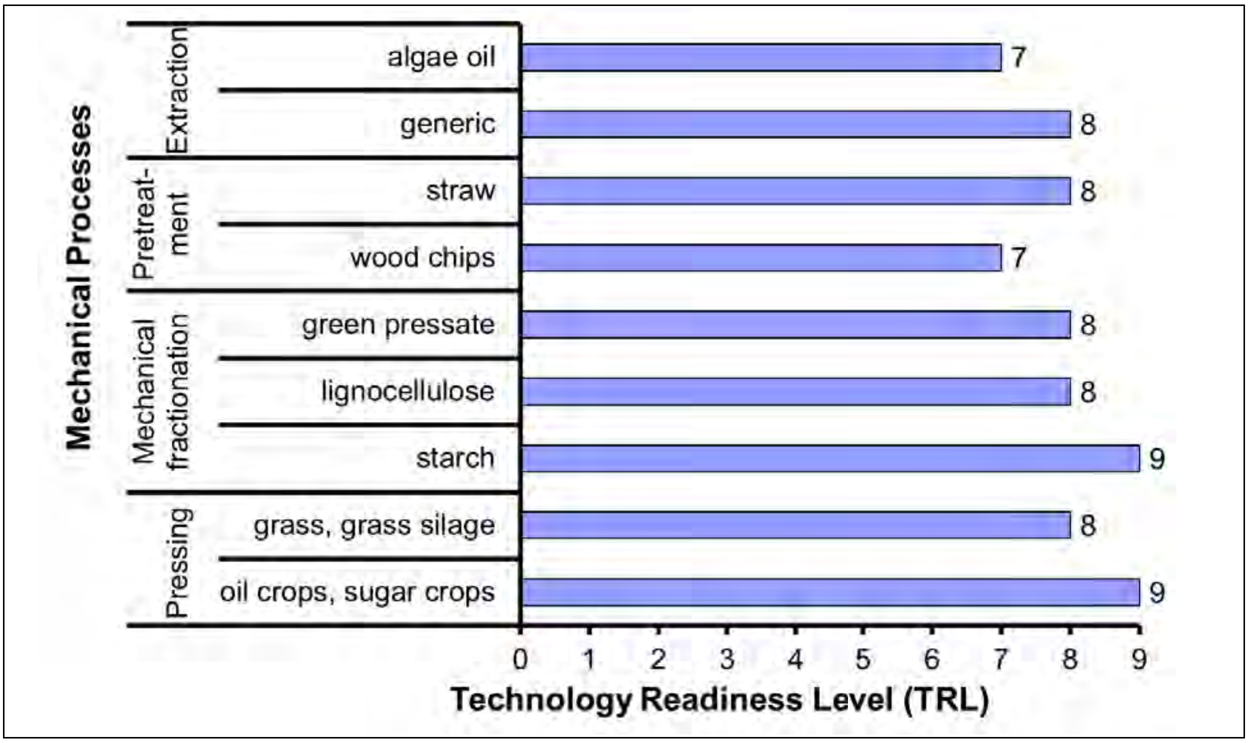

Figure 14: Technology Readiness Level of mechanical processes I

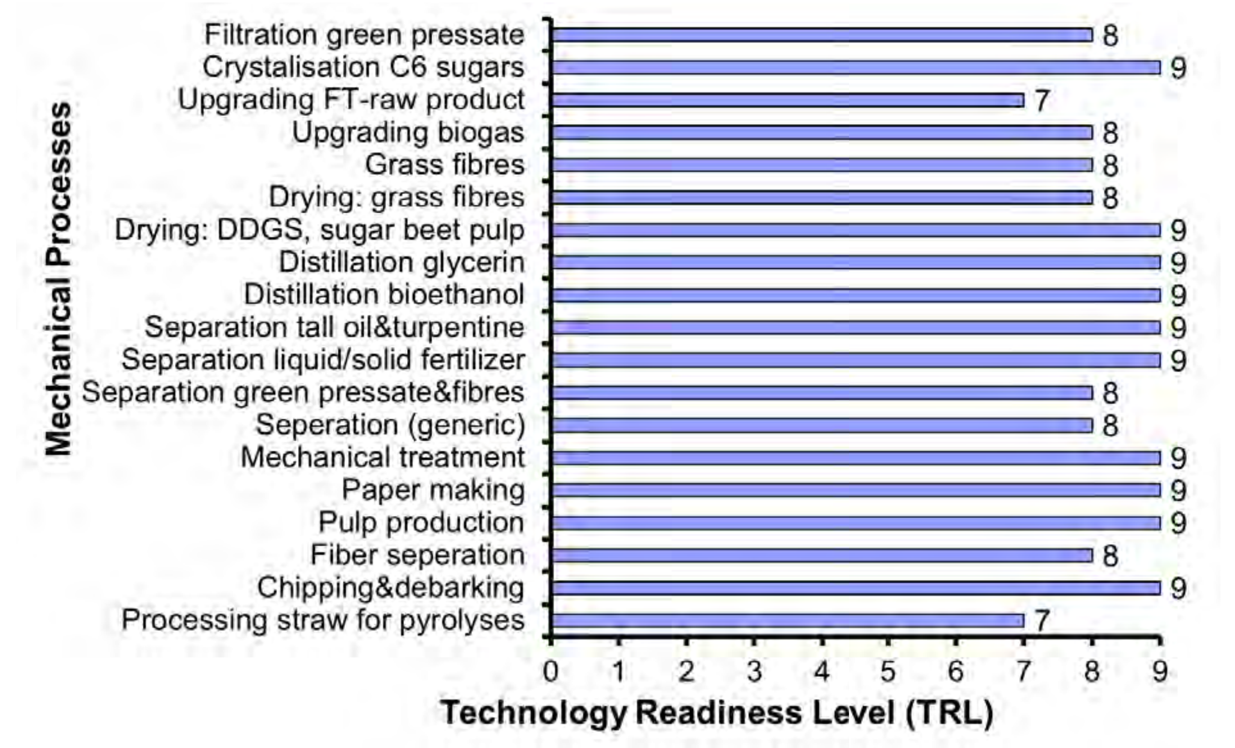

Figure 15: Technology Readiness Level of mechanical processes II

6 Biorefinery Complexity Index of selected biorefinery concepts

In this chapter the Biorefinery Complexity Index (BCI) and the Biorefinery Complexity Profile (BCP) for the following selected biofuel-driven biorefinery concepts are presented:

- "1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed"
- "1-platform (oil) biorefinery using oil based residues for biodiesel, glycerin, bio oil and fertilizer"
- "1-platform (C6 sugars) biorefinery using starch crops for bioethanol and feed"
- "3-platform (C5&C6 sugars, electricity&heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat and phenols"
- "3-platform (pyrolysis oil, syngas, electricity&heat) biorefinery using straw for FT-biofuels and methanol with oxygen gasification"
- "2-platform (electricity&heat, syngas) biorefinery using wood chips for FT-biofuels, electricity, heat and waxes with steam gasification"
- "4-platform (biogas, biomethane, oil, electricity&heat) biorefinery using algae for biodiesel, biomethane, electricity, heat and glycerin, omega 3 and fertilizer"

6.1 "1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed"

The commercial scale energy driven "1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed" is shown in Figure 16. The oilseed crops are transported to the biorefinery, where the vegetable oil and the animal feed are produced in the pressing step. The oil is considered as a platform, and it is esterified, producing FAME biodiesel and raw glycerin. To derive pure glycerin for pharmaceutical purposes the glycerin is subsequently distilled. The heat and electricity are typically supplied by fossil fuel energy carriers.

This biorefinery is state of the art, and commercial production facilities have an annual biodiesel production capacity between 50,000 up to 150,000 t per year. Many of the successful biorefineries operating today are multi feedstock plants that are able to use different oilseed crops, fat and oil based residues. The oil platform and the glycerin platform offer the possibilities for a wide range of biochemicals and biomaterials that are currently under development and partly at the beginning of commercialization. For example, the oil from certain oilseeds can be further processed via hydrolysis to long-chain fatty acids for lubricants; and the glycerin can be converted to softening agents, such as propandiol by fermentation or to triacetin by chemical conversion.

In Figure 17 the Biorefinery Complexity Profile 8 (1/1/3/3) of the "1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed" is shown. In the biorefinery one platform, one feedstock, three products and three processes are involved each of them with a feature complexity of 1. So the Biorefinery Complexity Index is 8.

REMARK: Platforms and processes that are not directly linked to the biomass feedstock, e.g. electricity and heat, conversion of fossil fuels to electricity, are not considered in the BCI calculation.

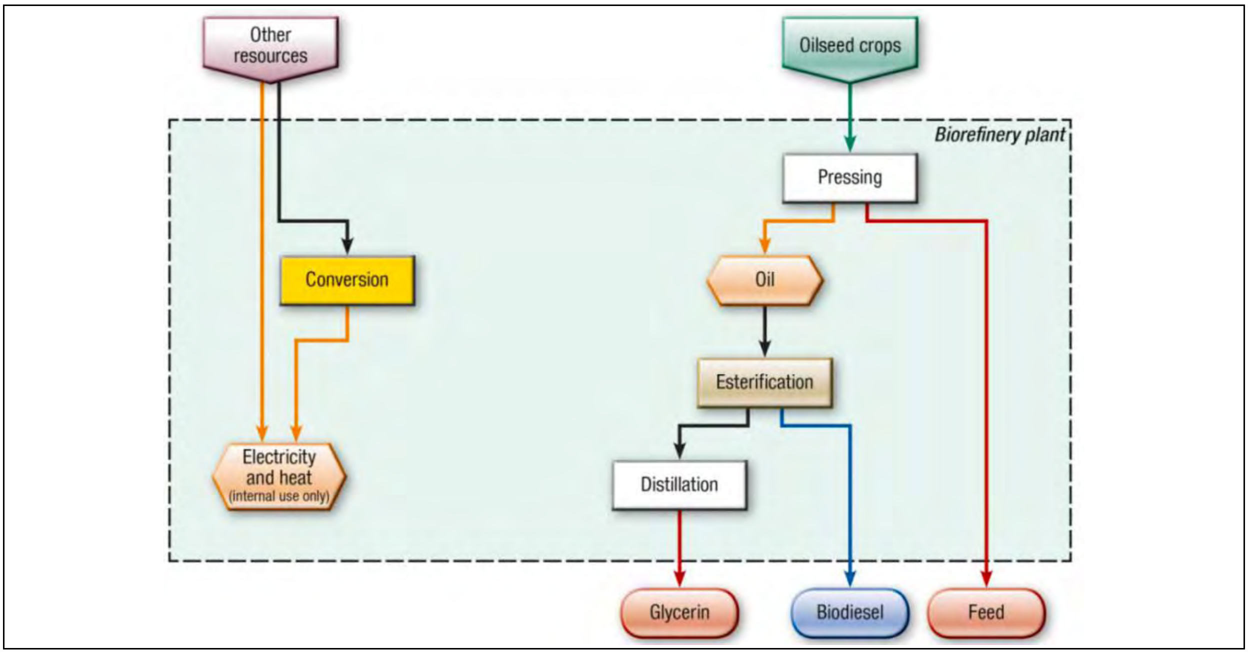

Figure 16: 1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed

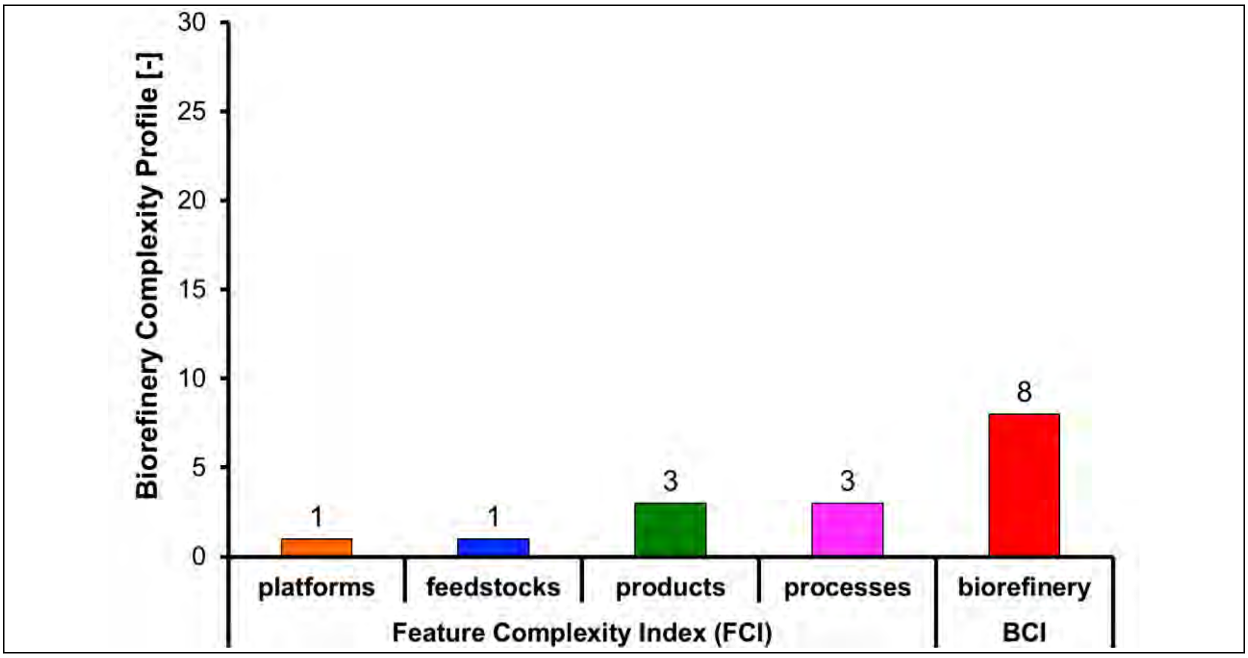

Figure 17: Biorefinery Complexity Profile 8 (1/1/3/3) of "1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed"

6.2 "1-platform (oil) biorefinery using oil based residues for biodiesel, glycerin, bio oil and fertilizer"

The commercial scale energy driven "1-platform (oil) biorefinery using oil based residues for biodiesel, glycerin, bio oil and fertilizer" is shown in Figure 18, which is similar to the biorefinery in the chapter before. The bio oil is a fraction of the oil based residues that cannot be used for biodiesel but can be used as heating fuel or as feedstock for biogas production.

This biorefinery is state of the art, and commercial production facilities have an annual biodiesel production capacity between 20,000 up to 100,000 t per year.

In Figure 19 the Biorefinery Complexity Profile 9 (1/1/4/3) is shown. In the biorefinery one platform, one feedstock, four products and three processes are involved each of them with a feature complexity of 1. So the Biorefinery Complexity Index is 9.

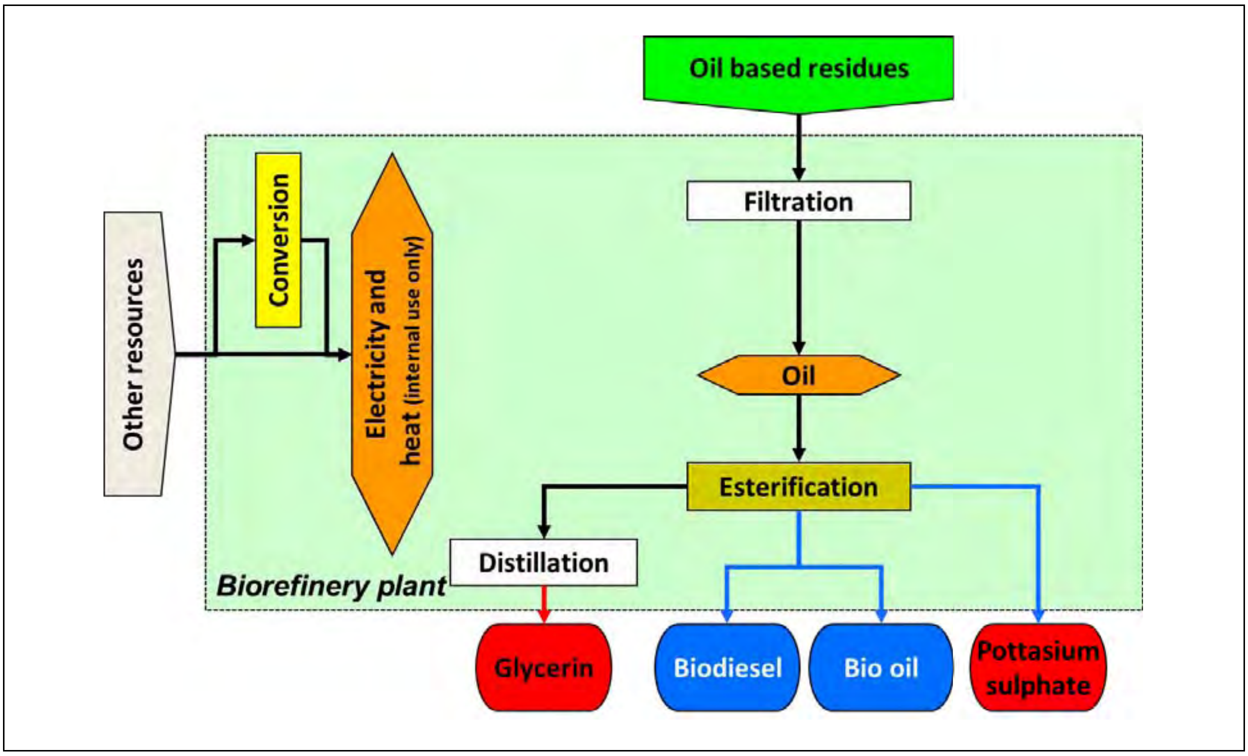

Figure 18: 1-platform (oil) biorefinery using oil based residues for biodiesel, glycerin, bio oil and fertilizer

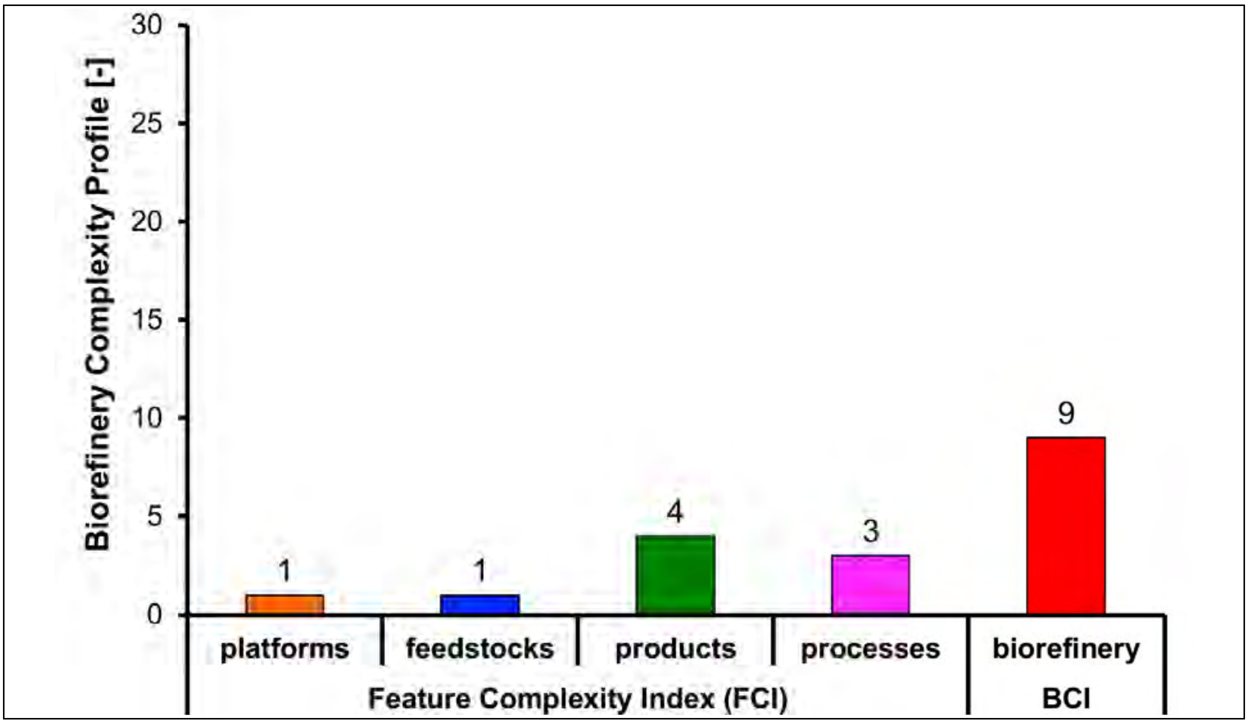

Figure 19: Biorefinery Complexity Profile 9 (1/1/4/3) of "1-platform (oil) biorefinery using oil based residues for biodiesel, glycerin, bio oil and fertilizer"

6.3 "1-platform (C6 sugars) biorefinery using starch crops for bioethanol and feed"

The commercial scale energy driven "1-platform (C6 sugars) biorefinery using starch crops for bioethanol and feed" is shown in Figure 20. The starch and/or crops are transported to the biorefinery, where the starch is converted to C6 sugars in the enzymatic hydrolysis step. The sugar crop e.g. from sugar beet is used to produce C6 sugars via mechanical pressing. The co-product, sugar beet pulp, is dried and used as animal feed. The C6 sugars are fermented to bioethanol which is purified using distillation. The fermentation solids, mainly proteins, are dried and pelleted for animal feed e.g. DDGS (Dried Distillers Grains with Solubles). In the fermentation CO_2 is produced, which can be separated and used in the food industry (e.g. beverage industry) or as an industrial gas (e.g. pH control of waste water). The heat and electricity are often supplied by fossil fuel energy

This biorefinery is state of the art and commercial production facilities have an annual bioethanol production capacity between 100,000 up to 300,000 t per year. Many of the successful operating biorefineries in Europe are multi feedstock plants using different starch and sugar crops. In America most biorefineries use sugar cane or starch crops e.g. maize. The C6 sugars platform offers the possibilities to produce a wide range of biochemicals based on sugars. Such processes are currently under development or just starting to become commercialized.

There will be a diversification of products from sugar and starch-derived C6 sugars (hexoses) towards other alcohols, chemicals and organic acids, as new biological and chemical processes are being developed to produce platform chemicals. A specific route currently under development, and likely to be commercialized in a medium term perspective is the fermentation of sugars to lipids. These lipids could be used by the oleochemical industry or to produce jet fuels, providing further integration potential between existing value chains. Also the sugar and starch based biorefinery offers interesting perspectives to integrate cereal straw (crop residues) into the supply chain, to produce C6 and C5 sugars. The use of dedicated lignocellulosic crops from agriculture is expected to increase when lignocellulosic conversion becomes more affordable.

Also, as new configurations are developed, the external energy sources can be partially or fully replaced by bioenergy produced from within the process to reduce the GHG resp. Carbon Footprint.

In Figure 21 the Biorefinery Complexity Profile 9 (1/1/2/5) is shown. In the biorefinery one platform, one feedstock, two products and five processes are involved each of them with a feature complexity of 1. So the Biorefinery Complexity Index is 9.

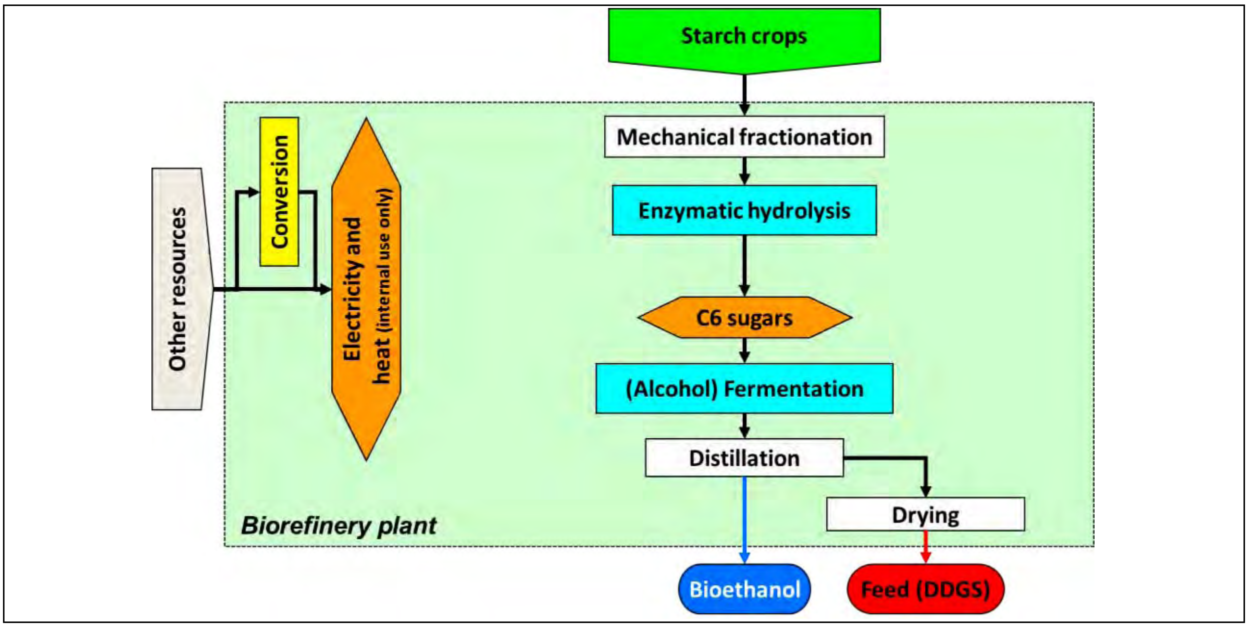

Figure 20: 1-platform (C6 sugars) biorefinery using starch crops for bioethanol and feed

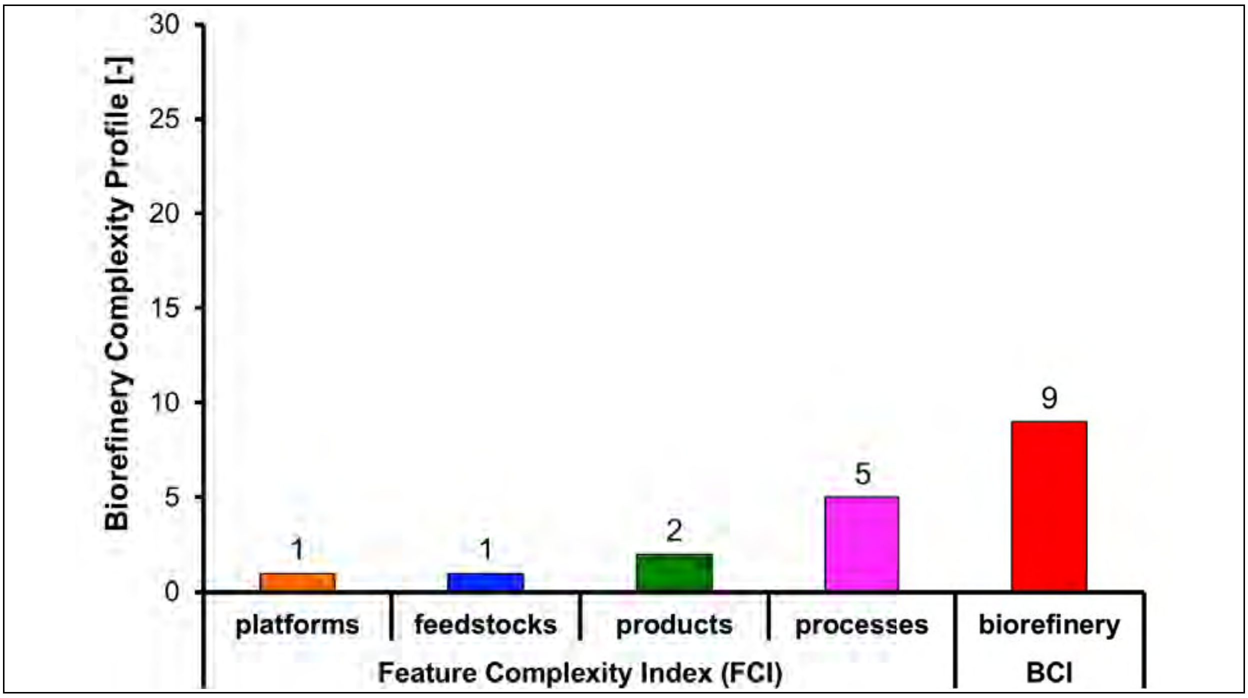

Figure 21: Biorefinery Complexity Profile 9 (1/1/2/5) of "1-platform (C6 sugars) biorefinery using starch crops for bioethanol and feed"

6.4 "3-platform (C5&C6 sugars, electricity&heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat and phenols"

The scheme of the energy driven "3-platform (C5&C6 sugars, electricity&heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat and phenols" is shown in Figure 22. The wood chips (without bark) are transported to the biorefinery, where the wood chips are pretreated for the hydrolysis to separate the sugars and the lignin. The C5&C6 sugars are fermented to bioethanol and the lignin is used to produce bio-oil via a pyrolysis step. The phenols from the bio-oil are separated and the residues are combusted to produce electricity and heat.

This biorefinery system is partly demonstrated. The production of bioethanol is demonstrated in Sweden, and the pyrolysis of the lignin was tested on laboratory scale. So far the production of bioethanol from hard wood is easier to be developed than from soft wood. Recent R&D results show that the integration of a bioethanol production from wood in a pulp and paper production plant offers promising synergies like handling and logistic of wood, water and waste water treatment, electricity and steam infrastructure and personal sharing. Realising these synergies would enable a commercial bioethanol production from wood by 2025.

In Figure 23 the Biorefinery Complexity Profile 29 (8/1/4/16) is shown. In the biorefinery the following features are involved:

- three platforms of which two (lignin and C5&C6 sugars) have a feature complexity of 3 and one (electricity&heat) of 1
- one feedstock with a feature complexity of 1
- three products of which the phenol has a feature complexity of 6 and the other products of 1 and

- seven processes with a feature complexity between 3 and 1.

The Biorefinery Complexity Index is 29.

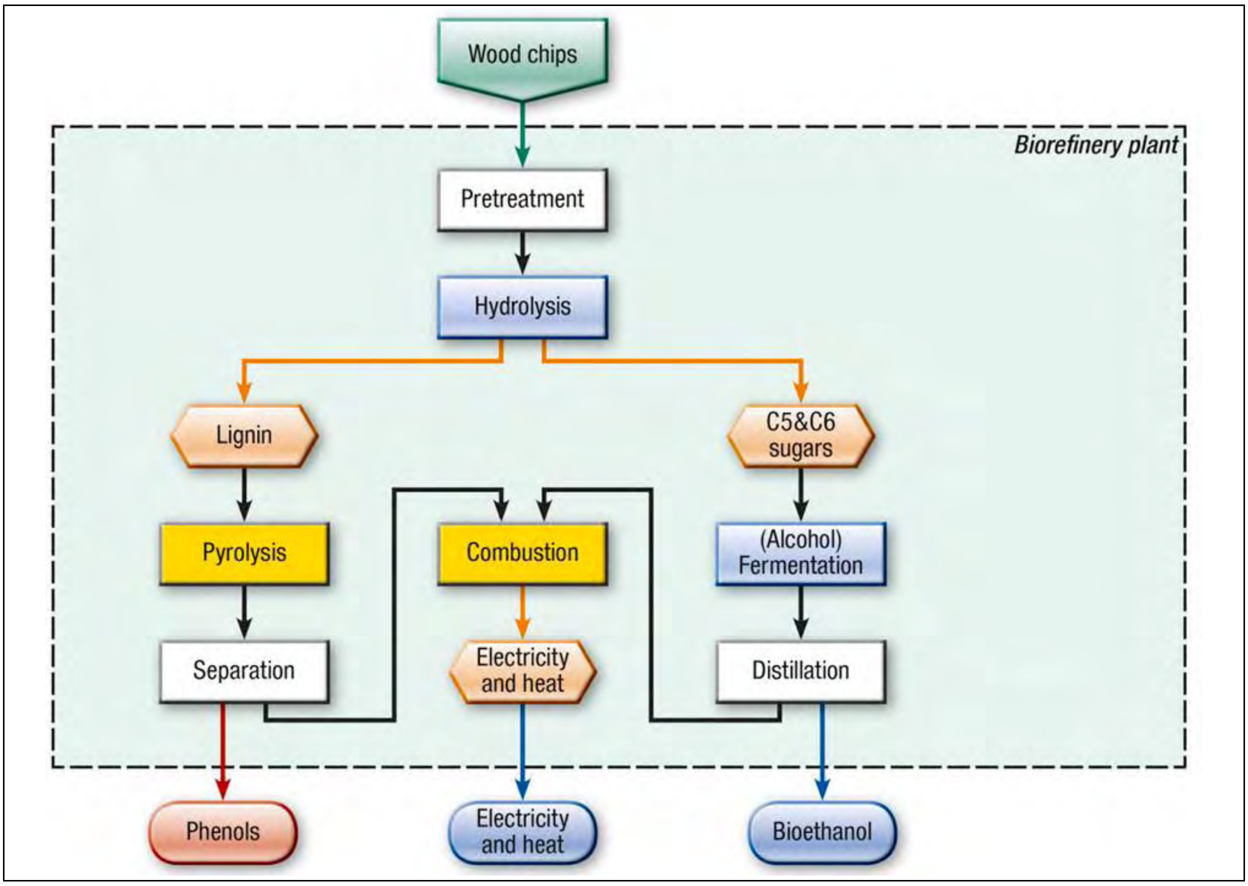

Figure 22: 3-platform (C5&C6 sugars, electricity&heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat and phenols

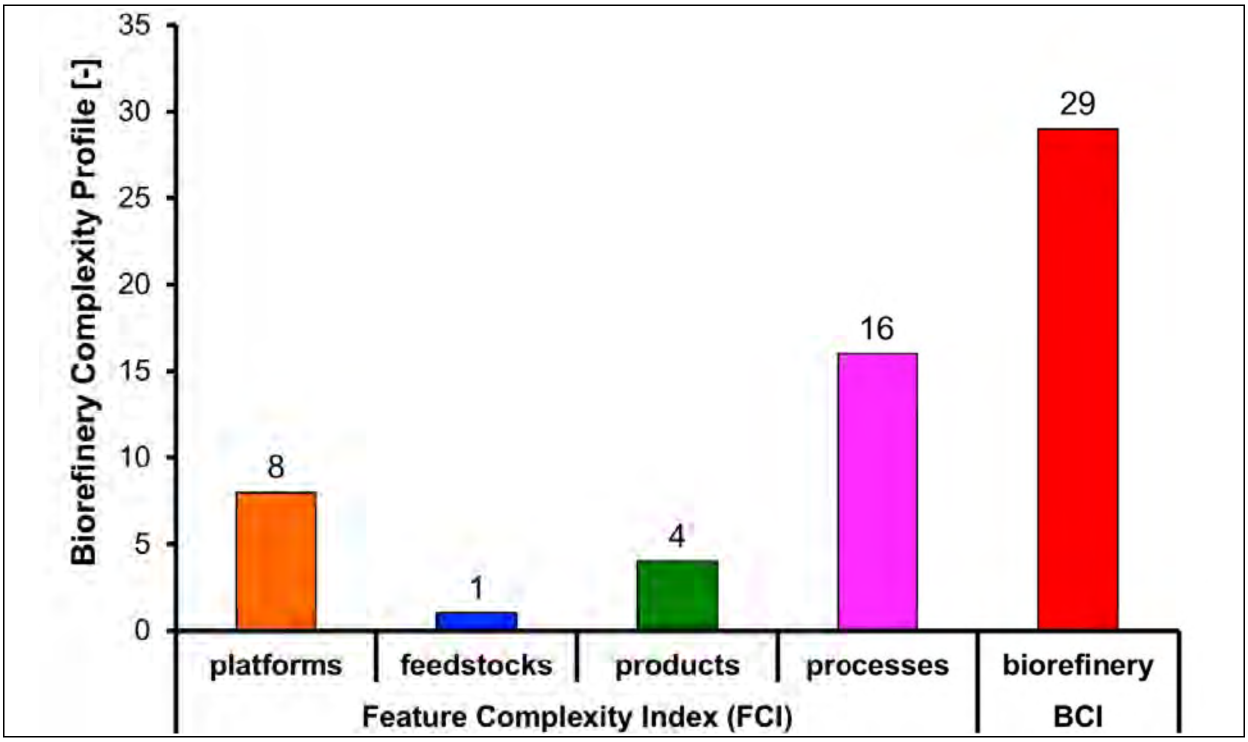

Figure 23: Biorefinery Complexity Profile 29 (8/1/4/16) of "3-platform (C5&C6 sugars, electricity&heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat and phenols"

6.5 "3-platform (pyrolysis oil, syngas, electricity&heat) biorefinery using straw for FT-biofuels and methanol with oxygen gasification"

The scheme of the energy driven "3-platform (pyrolysis oil, syngas, electricity&heat) biorefinery using straw for FT-biofuels and methanol with oxygen gasification" is shown in Figure 24. In the fast pyrolysis the straw is used to produce pyrolysis oil and char in several decentralized locations close to the origin of the straw supply. The oil and the char are mixed together and are transported as a slurry to one central gasification plant. In the gasification a syngas is produced by using oxygen as gasification medium. This syngas is then converted to FT-biofuels in the FT-synthesis and to methanol in the methanol synthesis. The main difference of the FT- and the methanol synthesis is on pressure, temperature, catalyst and the ratio between CO and H_2 in the synthesis gas, (e.g. FT-biofuel: 200 – 250 °C, 20 – 30 bar with Fe and/or Co as a catalyst). The methanol is mainly used as a chemical. Process residues are used to produce electricity and heat.

After the successful development and demonstration of fast pyrolysis of straw in the future further applications and uses for the pyrolysis oil might become interesting, e.g. the direct integration of pyrolysis oil in an existing oil refinery via upgrading to a renewable diesel fuel. In addition, the char from pyrolysis can be used to produce other products for the chemical industry to substitute fossil based products, e.g. activated char.

In Figure 25 the Biorefinery Complexity Profile 25 (8/2/4/11) is shown.

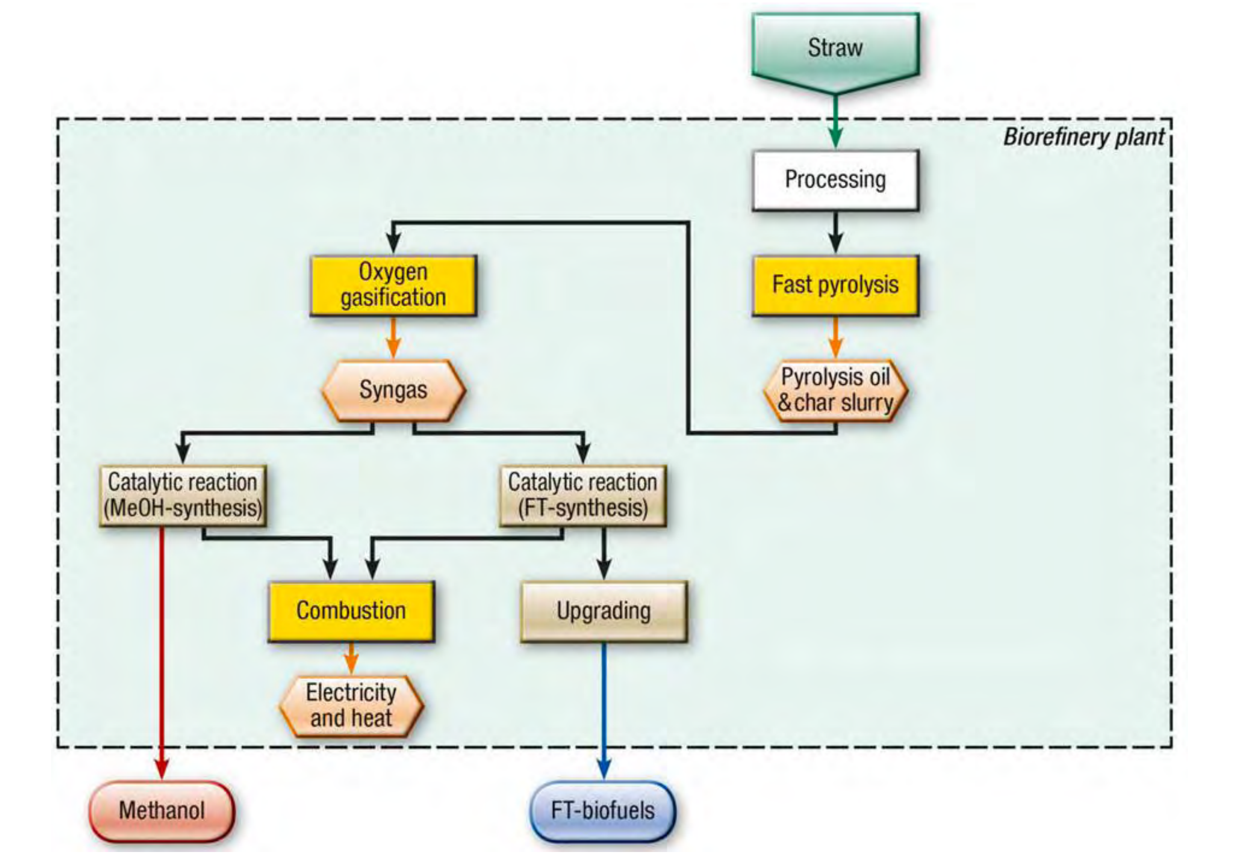

Figure 24: 3-platform (pyrolysis oil, syngas, electricity&heat) biorefinery using straw for FT-biofuels and methanol with oxygen gasification

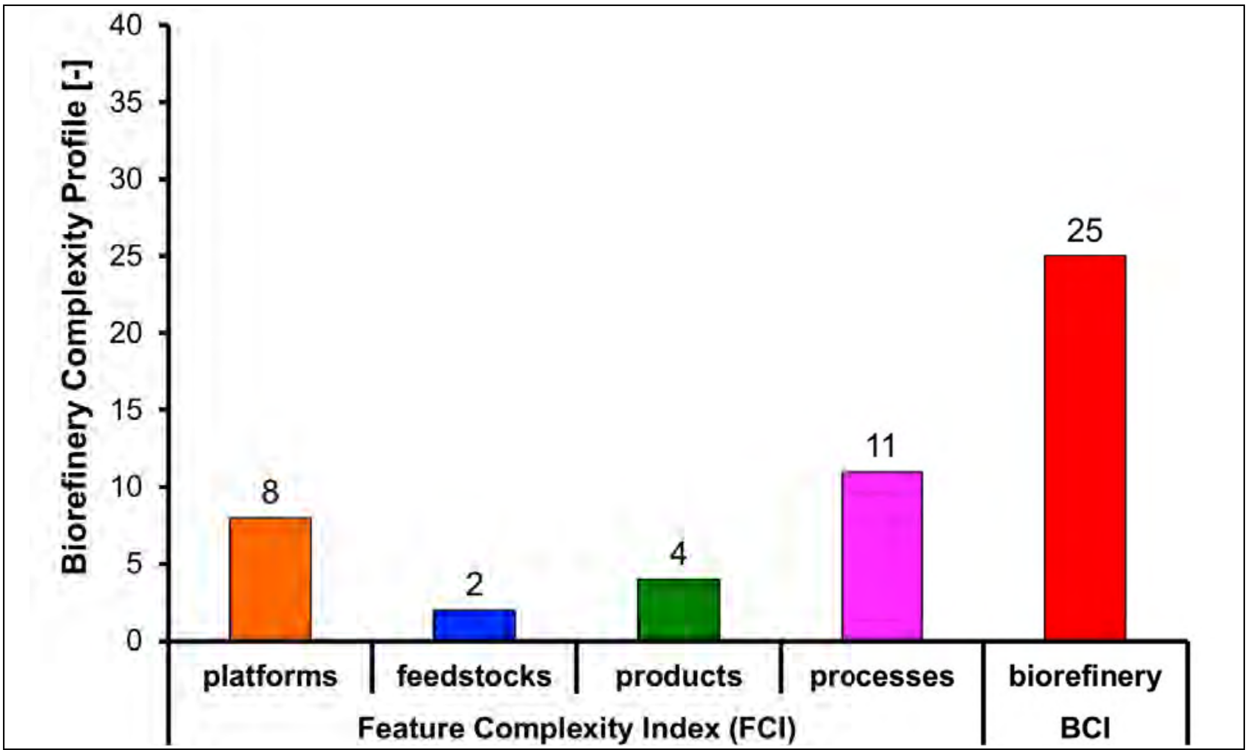

Figure 25: Biorefinery Complexity Profile 25 (8/2/4/11) of "3-platform (pyrolysis oil, syngas, electricity&heat) biorefinery using straw for FT-biofuels and methanol with oxygen gasification"

6.6 "2-platform (electricity&heat, syngas) biorefinery using wood chips for FT-biofuels, electricity, heat and waxes with steam gasification"

The demonstration scale energy driven "2-platform (electricity&heat, syngas) biorefinery using wood chips for FT-biofuels, electricity, heat and waxes with steam gasification" is shown in Figure 26.

Within the "2-platform (electricity&heat, syngas) biorefinery using wood chips for FT-biofuels, electricity, heat and waxes with steam gasification" the wood chips are gasified with steam to produce a synthesis gas (syngas), which is used to produce raw FT-biofuels via a catalytic reaction (FT-synthesis). The final quality of the transportation FT biofuel is reached in the upgrading step, e.g. hydroprocessing. The process residues are combusted to produce electricity and heat. As a further product waxes are produced.

Depending on the further successful development, beside the steam gasification of wood, which is suitable for smaller to medium sized gasifiers, also the gasification with oxygen for large applications (e.g. entrained flow gasification) might become interesting. The large amount of syngas will then be an optimal starting point to produce additional synthetic products depending on the market demand for biomass based chemicals, e.g. methanol.

In Figure 27 the Biorefinery Complexity Profile 16 (2/1/7/6) is shown.

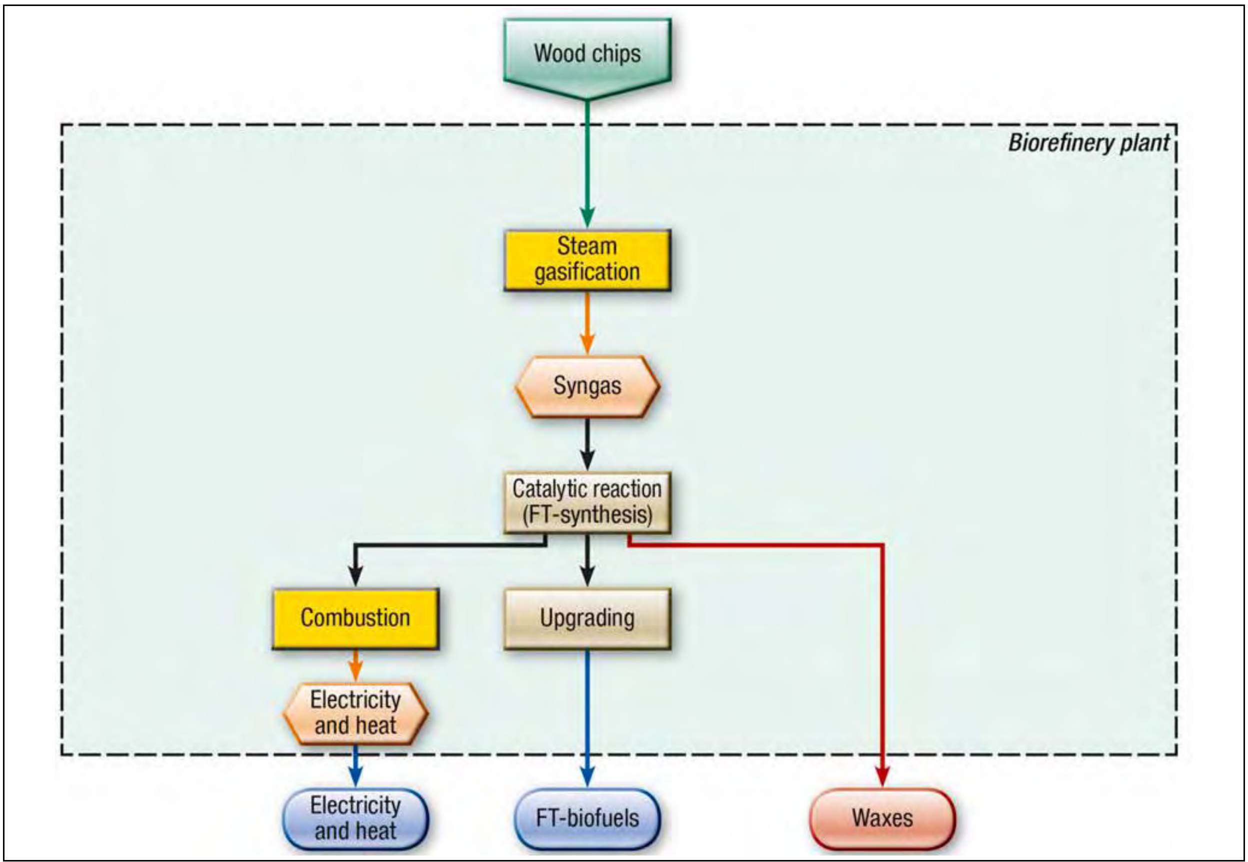

Figure 26: 2-platform (electricity&heat, syngas) biorefinery using wood chips for FT-biofuels, electricity, heat and waxes with steam gasification

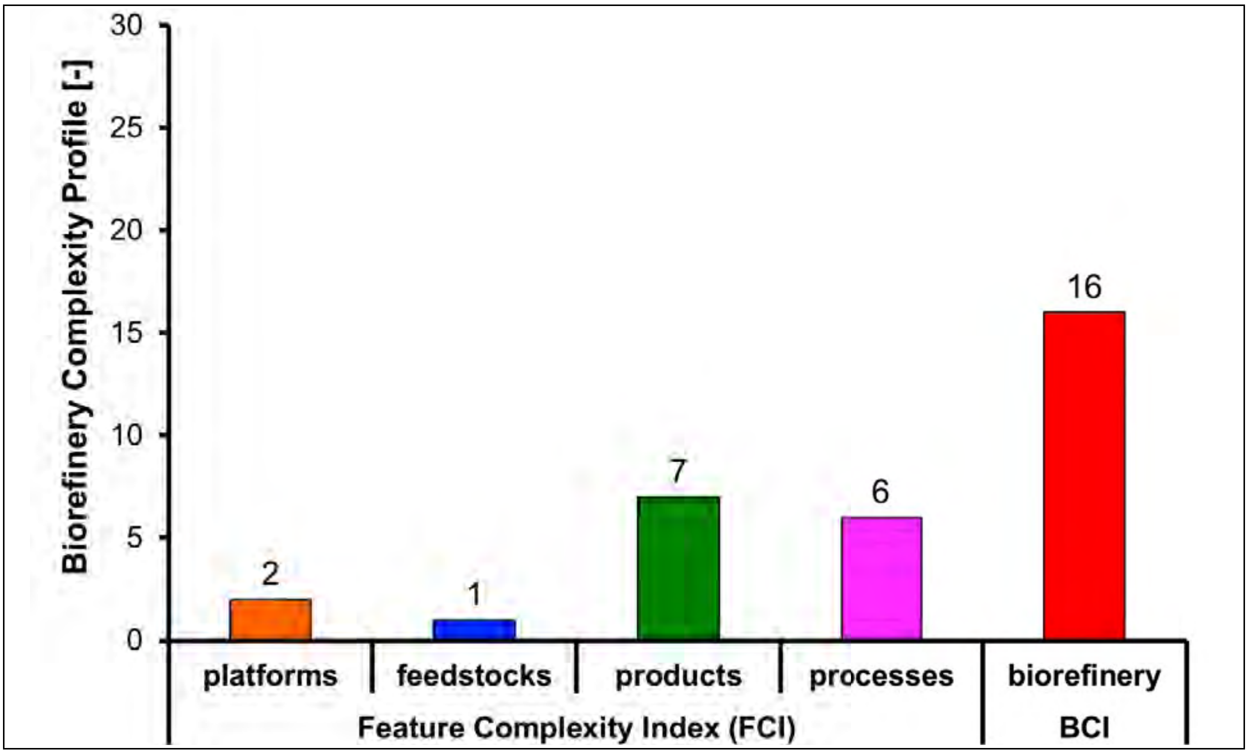

Figure 27: Biorefinery Complexity Profile 16 (2/1/7/6) of “2-platform (electricity&heat, syngas) biorefinery using wood chips for FT-biofuels, electricity, heat and waxes with steam gasification”

6.7 “4-platform (biogas, biomethane, oil, electricity&heat) biorefinery using algae for biodiesel, biomethane, electricity, heat and glycerin, omega 3 and fertilizer”

The conceptual energy driven “4-platform (biogas, biomethane, oil, electricity&heat) biorefinery using algae for biodiesel, biomethane, electricity, heat and glycerin, omega 3 and fertilizer“ is shown in Figure 28.

The algae are harvested and the oil of the algae is extracted. The oil is a platform. Omega 3 fatty acids are separated and the rest of the oil is esterified, producing FAME biodiesel and raw glycerin. To derive pure glycerin for pharmaceutical purposes the glycerin is subsequently distilled. The residues of the oil extraction are fermented in a biogas reactor to produce biogas. The biogas is upgraded to biomethane and partly combusted in a CHP plant to produce electricity and heat. The digestate is used as a fertilizer.

In light of the global efforts in developing algal biomass as a promising raw material for the industry and the energy sector by relevant scientific work, further successes in the development of efficient, low-cost, ecological production from microalgae are expected. For a commercial large-scale implementation further optimization of the cultivation and processing of algal biomass is necessary. A strong effort will be put on the development of further speciality products made from algae.

In Figure 29 the Biorefinery Complexity Profile 35 (5/6/12/12) is shown.

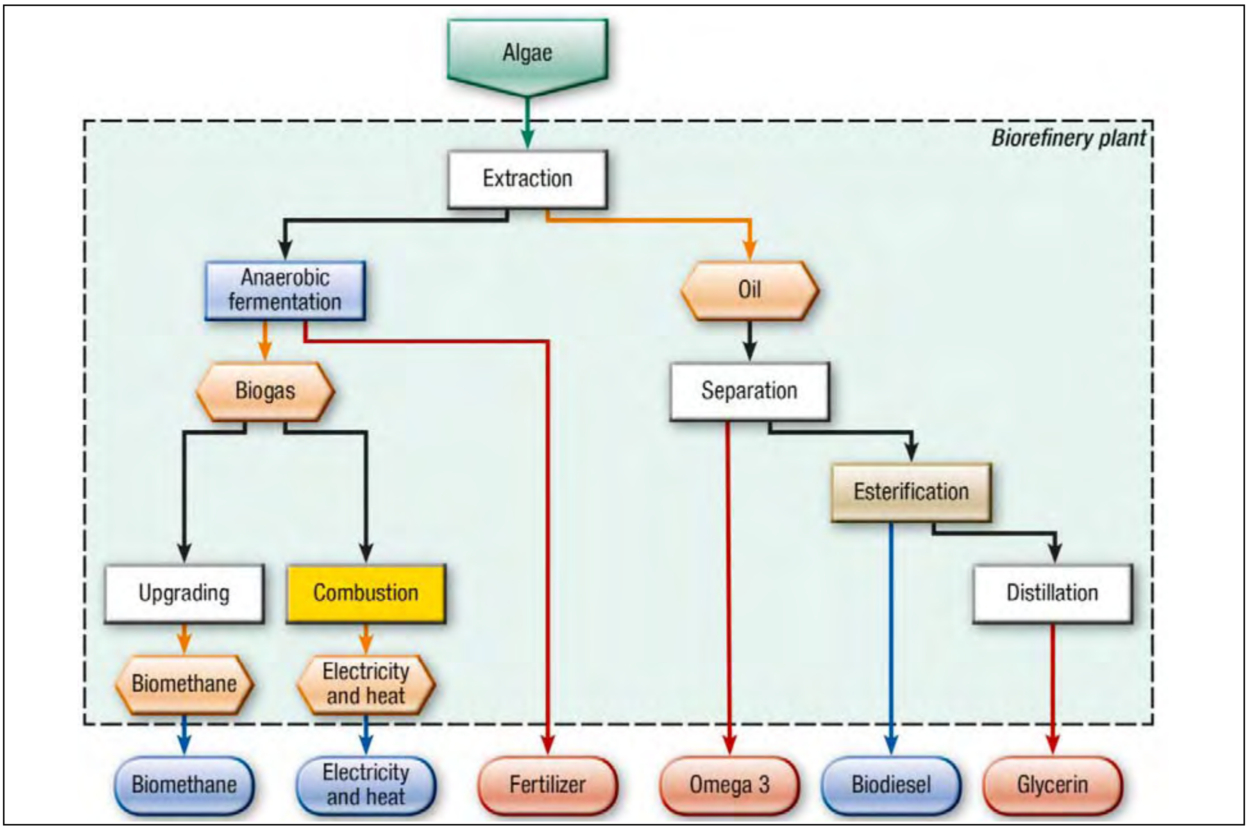

Figure 28: 4-platform (biogas, biomethane, oil, electricity&heat) biorefinery using algae for biodiesel, biomethane, electricity, heat and glycerin, omega 3 and fertilizer

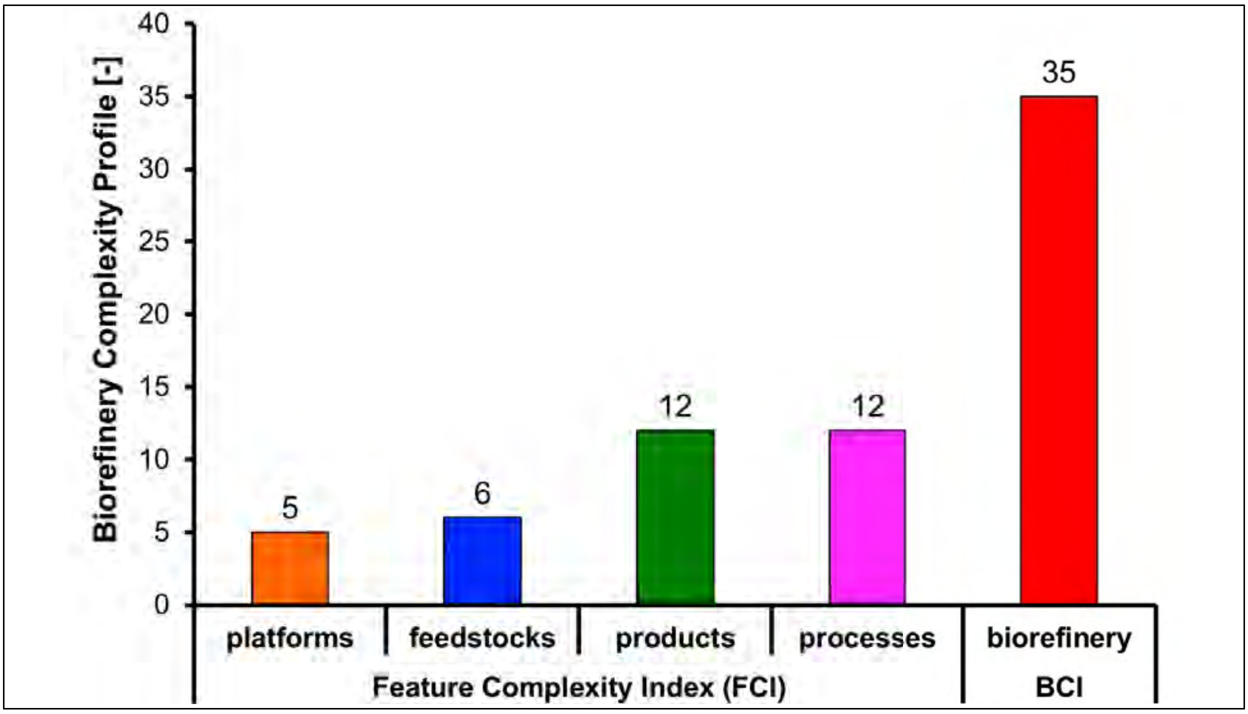

Figure 29: Biorefinery Complexity Profile 35 (5/6/12/12) of “4-platform (biogas, biomethane, oil, electricity&heat) biorefinery using algae for biodiesel, biomethane, electricity, heat and glycerin, omega 3 and fertilizer”

7 Comparison of BCI of selected biorefinery concepts

The Biorefinery Complexity Profile and the Biorefinery Complexity Index of the energy-driven biorefineries described in the previous chapter are compared in Figure 30. It can be seen, that the BCI of 8 – 9 of the three commercial biorefineries producing biodiesel and bioethanol from conventional crops and residues are significant lower compared to the biorefineries under development with a BCI between 16 and 35. In analyzing the BCP it can be seen that the complexity of the processes and the platforms of the biorefineries under development significantly contribute to the BCI. In addition for the algae the complexity of the feedstock also has a strong contribution to the BCI.

As the "1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed" has with 8 the lowest BCI, it can be used as a reference for the complexity of the other biorefineries. Referring to this biorefinery the BCI of (Figure 31)

- "1-platform (oil) biorefinery using oil based residues for biodiesel, glycerin, bio oil and fertilizer" is 12.5% higher
- "1-platform (C6 sugars) biorefinery using starch crops for bioethanol and feed" is 12.5% higher
- "3-platform (C5&C6 sugars, electricity&heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat and phenols" is 362.5% higher
- "3-platform (pyrolysis oil, syngas, electricity&heat) biorefinery using straw for FT-biofuels and methanol with oxygen gasification" is 312.5% higher
- "2-platform (electricity&heat, syngas) biorefinery using wood chips for FT-biofuels, electricity, heat and waxes with steam gasification" is 200% higher
- "4-platform (biogas, biomethane, oil, electricity&heat) biorefinery using algae for biodiesel, biomethane, electricity, heat and glycerin, omega 3 and fertilizer" is 437.5% higher.

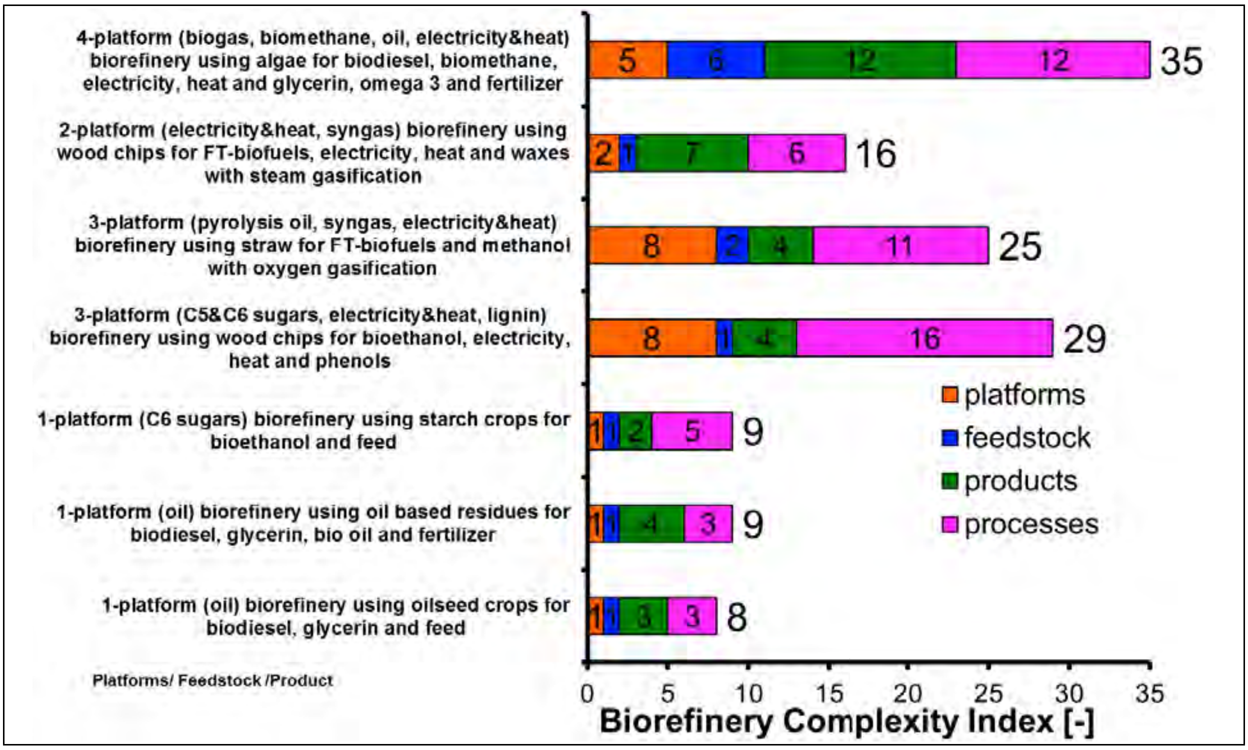

Figure 30: BCI of selected biorefinery concepts

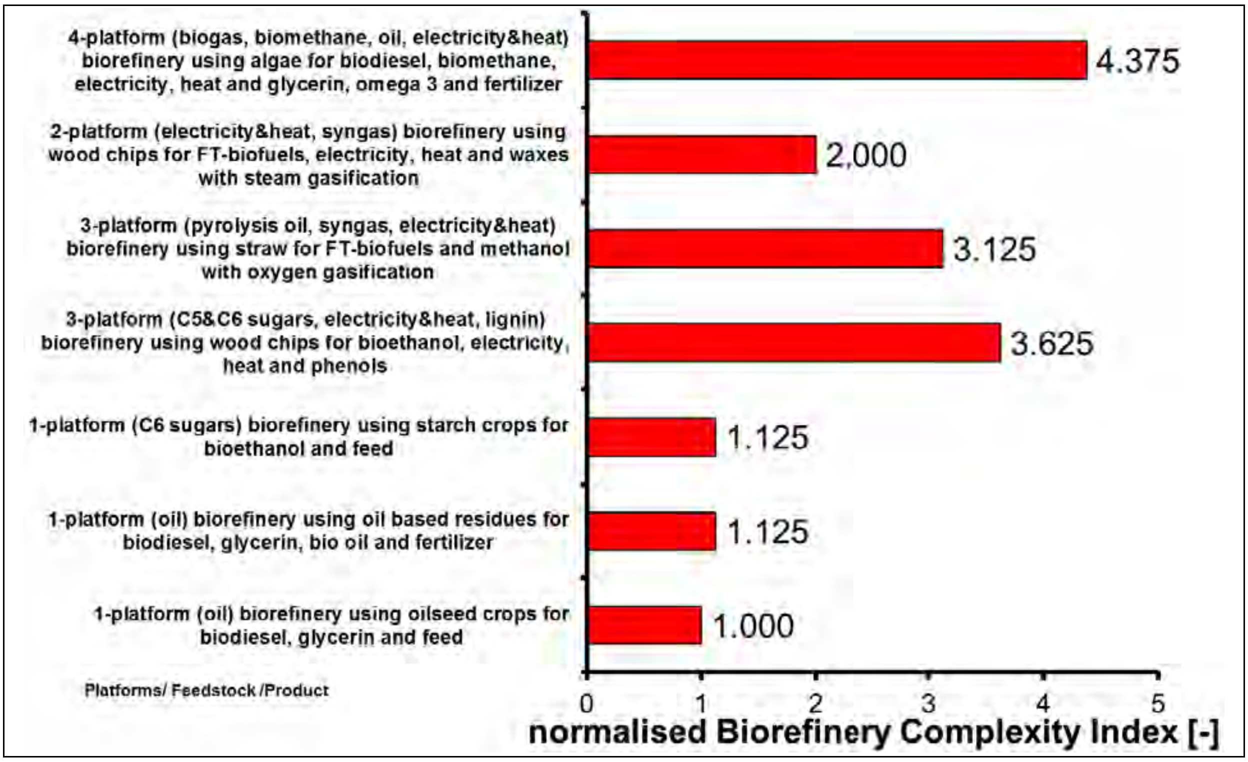

Figure 31: BCI of selected biorefinery concepts referring to the "1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed"

8 Discussion

Based on the classification system of biorefineries and the “Nelson´s complexity index” for oil refineries a Biorefinery Complexity Index (BCI) is developed. For each of the four features of a biorefinery the Technology Readiness Level (TRL) is assessed using level description between 1 (“basic research”) to 9 (“system proven and ready for full commercial deployment”). Based on the TRL the Feature Complexity (FC) for each single feature of a biorefinery is calculated. With the number of features and the FC of each single feature the Feature Complexity Index (FCI) for each of the four features (platforms, feedstocks, products and processes) is calculated. The BCI is the sum of the four FCIs. The Biorefinery Complexity Profile (BCP) is a compact format to present the complexity of a biorefinery by giving the BCI and the four FCIs of each feature.

The BCP, which includes the BCI and the four FCI has the following format:

BCP: BCI ($FCI_{platforms}$/$FCI_{Feedstocks}$/$FCI_{Products}$/$FCI_{Processes}$),

with an example 8 (1/1/3/3).

The calculation method of the BCI is applied to 7 different biofuel-driven biorefineries. For each of these biorefinery concepts the BCP and the BCI are presented and compared to each other. The BCI and BCP of the analysed selected biofuel-driven biorefinery concepts are:

- 8 (1/1/3/3) of “1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin and feed”
- 9 (1/1/4/3) for “1-platform (oil) biorefinery using oil based residues for biodiesel, glycerin, bio oil and fertilizer”
- 9 (1/1/2/5) of “1-platform (C6 sugars) biorefinery using starch crops for bioethanol and feed”
- 29 (8/1/4/16) of “3-platform (C5&C6 sugars, electricity&heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat and phenols”
- 25 (8/2/4/11) of “3-platform (pyrolysis oil, syngas, electricity&heat) biorefinery using straw for FT-biofuels and methanol with oxygen gasification”
- 16 (2/1/7/6) of “2-platform (electricity&heat, syngas) biorefinery using wood chips for FT-biofuels, electricity, heat and waxes with steam gasification”
- 35 (5/6/12/12) of “4-platform (biogas, biomethane, oil, electricity&heat) biorefinery using algae for biodiesel, biomethane, electricity, heat and glycerin, omega 3 and fertilizer”.

So the BCI is closely connected to the TRL of the individual features, as the TRL determines the Feature Complexity (FC). This makes the methodology and the results quite complex. As the FC is given to each feature there might be some kind of duplication of the complexity, as the products derive from processes and platform. So maybe the concept can be further developed towards the application of the TRL to process and platforms only and the Market Readiness Level (MRL) to feedstock and products. The combination of the TRL and the MRL to the BCP and BCI then must be different, e.g. the BCP has two parts, one for the TRL of processes and platforms and the MRL for feedstock and products.

9 Conclusions

The basic assumptions on the complexity of a biorefinery are the following:

- The number of different features of a biorefinery influences the complexity. The complexity increases by the number of features in a biorefinery.
- The state of technology of a single feature influences the complexity. The complexity decreases the closer a technology is to a commercial application. This means a high “Technology Readiness Level” of a feature has lower technical and economic risks and a lower complexity.
- This leads to the basic assumption for the calculation procedure of the Biorefinery Complexity Index that the complexity is directly linked to the number of features and the Technology Readiness Level of each single feature involved.

The following conclusions on the BCI and BCP are drawn:

1. They give an indication for the relative comparison of different biorefinery concepts and their development potential
2. They present a benchmark of the “complexity” of a biorefinery in terms of involved platforms, feedstocks, processes and products, and their specific and overall “Technology Readiness Level”
3. The higher the Biorefinery Complexity Index the more beyond “state of the art” is the biorefinery
4. The BCI of a biorefinery producing biodiesel from vegetable oil which is fully deployed, with 8 (1/1/3/3) is a benchmark to compare the complexity of other current and future biorefinery systems:
    a. The complexity of producing biodiesel from vegetable oil and waste cooking oil is 1.25 more complex than using just vegetable oil
    b. The complexity of producing FT-Biofuel from wood is 3.125 more complex than producing biodiesel from vegetable oil
    c. The complexity of producing bioethanol from wood is 2.0 more complex than producing biodiesel from vegetable oil
    d. The complexity of producing biodiesel from algae is 4.375 more complex than producing biodiesel from vegetable oil.
5. The BCI will change in the future if the Technology Readiness Level has changed, e.g. if a demonstration plant for FT-Biofuels will go in to operation.
6. The Biorefinery Complexity Profile show the most relevant features contributing to the complexity of a biorefinery

7. The BCP of a biorefinery gives an indication on the technological and economic risks.
8. The first results and conclusions of a critical review by the country representatives in IEA Bioenergy Task 42 show that the “Biorefinery Complexity Index” adds additional relevant information on the assessment and comparison of different biorefinery systems
9. In future the BCI and BCP might also become a part of the “Biorefinery Fact Sheet” is developed by IEA Bioenergy Task 42 (Jungmeier et al. 2013, Jungmeier et al. 2014).

The results might become relevant for industry, decision makers and investors as additional information to assist them in their strategies to implement the most promising biorefinery systems by minimising technical and economic risks.

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The Austrian participation in Tasks 42 of IEA Bioenergy is financed by the Federal Ministry for Transport, Innovation and Technology / Department for Energy and Environmental Technologies.