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Innovations in Nordic value chains for cellulosic ethanol: Denmark case study

Desk top report + interviews

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1 Value chain characteristics

1.1 Background

The core concepts for this biorefinery were developed in the late 1990s. Between 2002 and 2006, a Danish energy company Elsam was a leader of an EU R&D project "Co-production biofuels", allowing building prototypes of the plant, followed by opening their first pilot plant in 2003, and scaling up ten times in 2005. A year later, Elsam merged with six other energy companies in Denmark to form DONG Energy. Inbicon is thus a fully owned subsidiary of DONG Energy, and the technology is based on the IBUS process, in which wheat straw bales are used to produce second generation (2G) ethanol, lignin pellets and C5 molasses.

The first Inbicon Biomass Refinery was opened in Kalundborg, Denmark and integrated with the Asnæs Power Station, in 2009. In 2010, Inbicon began the licensing process of their technology for commercial scale in North America and elsewhere around the world. In the meantime, the Kalundborg plant has become fully operational, and as of now it has been commissioned and progressed into production phase, while still continuing testing and optimizing its systems. (Larsen, Østergaard Haven, & Thirup, 2012)

1.2 Main activities/segments of the value chain

1.2.1 Overview

The figure below depicts the integration of various technologies within the Inbicon concept. The process consists of a few steps, with various products and by-products, out of which: solid and liquefied fibres, bioethanol, C5 molasses and solid biofuel.

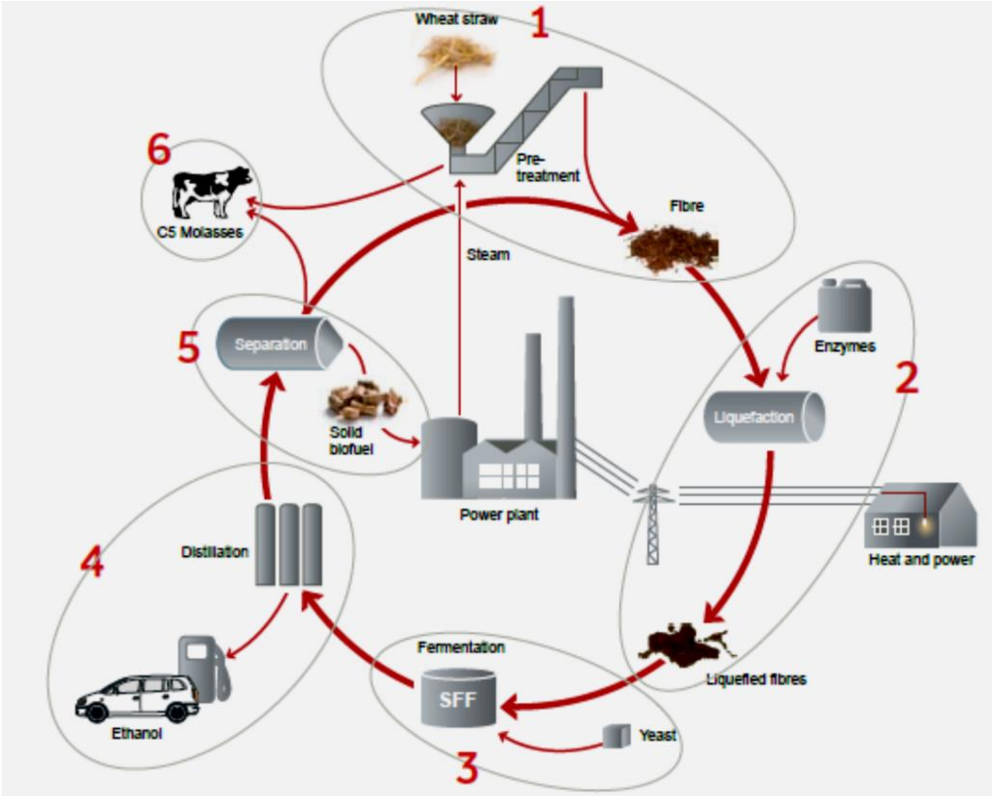

Figure 1 Inbicon technology (Inbicon)

1.2.2 Feedstock provisioning and mechanical pre-treatment

Currently, the feedstock used in Inbicon is wheat straw. Harvested straw is bound into so-called Heston bales and remains on the fields until being transported by truck to the plant. It contains on average 14% mass fraction water. At the plant site, there is a biomass storage area gathering biomass for maximum three days of operation, from where the bales are moved to the string removal, debaling, stone trap and cutting to a length of approx. 5 cm. After this mechanical pre-treatment, the cut straw is pneumatically transported to the hydration area. (Larsen, Østergaard Haven, & Thirup, 2012)

1.2.3 Processing (primary and secondary)

The Inbicon technology was first proven on a pilot plant stage in the beginning of 2003. It is a three-stage process, consisting of: hydrothermal pre-treatment, releasing lignin-cellulose in solid form; enzymatic hydrolysis, separating cellulose from lignin and hemicellulose; and fermentation converting cellulose to ethanol.

The figure below shows the Inbicon process:

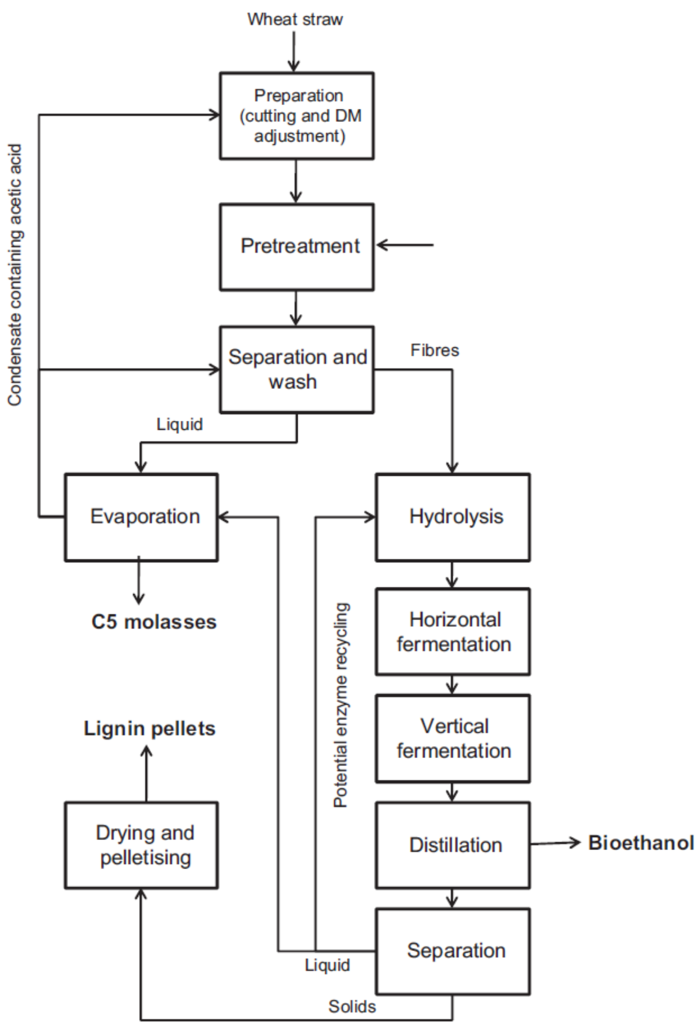

Figure 2 Overview of the process streams in the demonstration plants (Larsen et al. 2012)

Hydrothermal pre-treatment, a standard method applied for bioethanol feedstocks such as straw or sugarcane bagasse, is run at 180-190°C, for 10-15 minutes. The steam applied and acid released from the material itself make it easier to open up the structure. As a result, the cellulose, together with lignin, stays in the solid fraction, while the mix of C5 molasses, inhibitors and acid is sorted out in liquid fraction. Variation in the process affects the final chemicals to be produced. (Kadar, 2013)

The Inbicon type of pre-treatment allows to yield a much higher concentration of sugar in the fermentation liquid than other types of pre-treatment, therefore the resulting alcohol concentration is at least double the normal percentage expected in cellulosic ethanol processing. Each batch has a lot less water and a lot more ethanol, further increasing yield and efficiency, translating to a lower cost. (Larsen, Østergaard Haven, & Thirup, 2012)

After pre-treatment, the solid phase (cellulose and lignin) undergoes enzymatic hydrolysis and fermentation, either in one reactor (SSF process) or separately (Inbicon is aiming at switching to this method). In the process, specific enzymes (cellulases) are added, converting cellulose into liquid glucose, then yeast are added, facilitating fermentation of glucose into ethanol. (Kadar, 2013)

The lignin part, still in the solid state, does not seriously intervene with fermentation, therefore it can either reside with ethanol until distillation (Inbicon method) or be separated just after the hydrolysis with additional separation step (method used by IOGEN firm, reduces the overall liquid volume in the following process stages). (Kadar, 2013)

After fermentation, distillation follows, after which a solid material (lignin cake) and a liquid (thin stillage) remain. The lignin cake is recycled to the process, dried in a tube bundle dryer and pelletized to form a solid biofuel (lignin, residual cellulose and yeast). (Larsen, Østergaard Haven, & Thirup, 2012)

Molasses (containing the main part of the recovered C5 sugars and salts) form the third product produced in the Inbicon process. They originate from the liquid fraction separated from the fibre fraction after hydrothermal pre-treatment (80%) and part of the thin stillage separated from the lignin cake (20%). The main sugar type in C5 molasses is xylose, used as cattle feed (cattle are perfectly capable of converting C5 sugars), can also be blended up to 5% as feed pellet "glue" in pig feed, used as a booster in biogas production or for sweetener production, like xylitol (Larsen, Østergaard Haven, & Thirup, 2012) (Kadar, 2013)

Using the C5 molasses as feed requires a stable quality, therefore the ones produced during the first year of operation in Kalundborg were used as a biogas feedstock in a nearby manure-based biogas plant. (Larsen, Østergaard Haven, & Thirup, 2012)

In 2010 the plant produced 162,500 litres of bioethanol. The table below shows an overview of theoretical mass and energy balance for the demonstration plant per hour, in case that 4 tonnes of straw are used.

	Mass balance		Energy balance	
	In [kg h^{-1}]	Out [kg h^{-1}]	In [GJ h^{-1}]	Out [GJ h^{-1}]
Straw	4000 (86% dry matter)		57.6	
2G ethanol		576 (99.5%)		16.0
C5 molasses		1484 (65% dry matter)		15.0
Lignin pellets		1740 (90% dry matter)		10.1[a]

a Surplus of lignin pellets not used to fuel the process.

Figure 1 Overview of mass and energy balance for the demonstration plant (Larsen, Østergaard Haven, & Thirup, 2012)

It can be calculated that 1 t of straw results in 144 kg of bioethanol - assumed 789 k/m^3 ethanol density, this amounts to 182 l of bioethanol.
As observed, the actual technical yield per tonne of straw was slightly lower for bioethanol, but higher for molasses and lignin. (Ingeniøren)

Currently, Inbicon is not running continuously, but in periodical campaigns. (Kadar, 2013)

1.2.4 End use and distribution

The produced ethanol is sold to the oil company Statoil and distributed in 100 filling stations all over Denmark as Bio95 petrol (5% of ethanol). (Larsen, Østergaard Haven, & Thirup, 2012)

Lignin pellets are sold to DONG Energy and used as a high-quality solid biofuel in power plants. The C5 molasses are sold as biogas production booster in local biogas plants. (Larsen, Østergaard Haven, & Thirup, 2012)

1.2.5 Marketing and sales

Inbicon's bioethanol comply with the CEN - European Committee for Standardization standard specification for blend-in ethanol (EN15376:2007). (Larsen, Østergaard Haven, & Thirup, 2012)

1.3 Main supporting activities

1.3.1 RD&D undertaken in companies

1.3.2 RD&D undertaken by public research organisations

1.3.3 RD&D funding support by public agencies

1.3.4 Transport and processing equipment?

1.4 Lead actors involved in each segment of the value chain

What type of a company is it (global or domestic; state-owned or private; size; core business etc) How do those firms influence/determine the conditions under which firms participate in the value chain (e.g. by setting quality standards) including the functional division of labour along the chain (who does what). What market share do they have? Where in the value chain – upstream or downstream – are these firms typically located?

1.4.1 Feedstock provisioning

The feedstock used at Kalundborg plant is straw. It is not clear whether it is entirely supplied from local farmers.

The idea of importing bagasse-based biomass pellets to Denmark was considered by some, but has not been realized in any way. (Holm Christensen, 2013)

1.4.2 Processing (biorefinery)

Inbicon's unit in Kalundborg is so far the only 2 G biofuel refinery in Denmark, but its owner, DONG Energy participates in several initiatives concerning biorefineries.

DONG Energy is a State-owned (79.96% ownership) public limited company, has 7,000 employees and is headquartered in Denmark. Its business is based on procuring, producing, distributing and trading of energy and related products in Northern Europe. (DONG Energy)

DONG Energy is a member of various alliances and organisations acting at the bioenergy scene. One of them, started in 2011, is called Biorefining Alliance and consists of: DONG Energy, Novozymes, Haldor Topsøe and Danish Agriculture and Food Council (Landbrug & Fødevarer). Their work was supported by the Green Development and Demonstration Programme (Grønt Udviklings- og Demonstrationsprogram, GUDP) of the Danish Ministry of Food, Agriculture and Fisheries. The Biorefining Alliance focuses on issues such as: lobbying for guaranteed minimal price for 2G ethanol and supporting export of the technology for integrated production of biogas, electricity and ethanol. (Biorefining Alliance) (Falholt, 2012)

Another initiative (described further in a separate case study) is Maabjerg Energy Concept, a consortium consisting of Vestforsyning, Struer Forsyning, Nomi (50%) and 50% shared between DONG Energy and Novozymes. Their plan is to integrate a 2nd generation bioethanol plant, with a hydrogen production plant and a waste treatment plant in Måbjerg, between Holstebro and Struer in Denmark. Moreover, the biogas production of the existing plant Maabjerg BioEnergy will be increased and the biomass-fired cogeneration plant Måbjergværket will be refurbished. (Maabjerg Energy Concept)

1.4.3 Enzymes

The companies specializing in the development and production of enzymes for cellulosic ethanol are Novozymes, Danisco (acquired in 2011 by DuPont; its Accelerase® enzyme is used by Inbicon among others)[1] and BioGasol in Denmark.

Genencor/Danisco produces enzymes, sugar from beet, food ingredients. Biogasol (Maxifuel process) develops technologies for 2G biofuel, biogas, hydrogen, anaerobic thermophilic bacteria, pilot plant for Maxifuel process, planning demonstration plant

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1.4.4 Distribution, marketing and sales

Inbicon delivers 2G bioethanol to Statoil, which sells 2G biogasoline at 98 stations around the country. Statoil is an oil producer and refinery in Denmark, only distributor of ethanol containing gasoline in Denmark.

There is a stated amount of bioethanol that has to be blended in the regular fuel.

1.4.5 End use

Car users?

1.4.6 International lead actors

As bioethanol production in Denmark so far is only represented by Inbicon, it seems worthwhile to discuss what international companies are leading the way in this sector. The international actors can be divided into:

- Biorefinery operators:

PRAJ Industries (India) builds ethanol factories and operates some of them, e.g. in Colombia. The feedstock used is molasses.

IOGEN was the first to propose production of enzymes on-site instead of buying. ,http://www.iogen.ca/company/about/index.html

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[1] The Genencor division of Danisco, based in California, develops enzymes for biofuels: "Genencor's Accellerase® enzyme platform is using non-food agricultural residue, such as wheat straw, wood chips and switchgrass, to help producers develop the route to cellulosic ethanol. Considered the next generation of biofuels, Accellerase® technology can help ethanol producers reduce carbon emissions by greater than 50 percent over previous processes, which makes it an important tool to break industry dependence on petroleum." Source: http://www.genencor.com/industries/biofuels/fuel_ethanol_from_biomass_cellulosic_biofuels/, http://www.accellerase.com/

- Large oil companies

In Brazil, large oil firms (such as BP, Shell, Exxon) buy biorefineries and operate them alone, or in joint ventures with others, contracting supplies from large land areas. In this way they are a power factor, which has significant funds. What interests them is to treat ethanol as a long-term investment that may pay off in relation after oil extraction becomes less profitable. They are also aiming at improving their CSR image. (Holm Christensen, 2013)

- Large engineering companies

Those are: Abengoa, Chemtex, ICM (USA) and Delta (USA). Very active in Brazil, they often go into partnership with existing biorefineries, in order to get experience in full scale.

- Enzyme producers

Their products are necessary in the biofuel production, but the competition is very high.

- Feedstock producers (farmers)

They are especially important in Brazil

2 Assessment of the technological development stage of key technologies

2.1 Main activities

In order to increase the versatility of the biorefining process, using a mix of feedstocks would seem reasonable – this is not done today. Most facilities use only one feedstock at a time, but may shift between feedstock over the year, depending on the season. In terms of technology required for utilising new resources, for example wood, development of efficient pre-treatment phase is the most important factor. So far, Lund University has conducted experiments on lab-scale, with steam explosion for wood. (Kadar, 2013)

The most well researched to date method for straw, the hydrothermal pre-treatment is not only used in Inbicon plant, but also e.g. in Chemtex plant in Italy. (Kadar, 2013)

Another interesting issue is use of C5 molasses. At Inbicon, they are utilised as cattle feed. In biogas plants, it can be used as booster in biogas production. C5 can also be made into xylitol (used as sweetener). Some researchers claim that it is not feasible to use C5 for ethanol,because the bacteria strains used are genetically modified and that presents a risk. The C5 fermenting strains are very fragile, as opposed to "regular" ones.

Two methods are used for hydrolysis and fermentation: either both in the same reactor, when the strains convert the cellulose as soon as it is produced by the enzymes, avoiding inhibition by glucose or separately – is when you combine hydrolysis and fermentation in the same. Inbicon used this method. The problem is that the optimal temperature of the two processes are 30 and 50°C, so that a 32-40°C temperature needs to be used. Inbicon is shifting to a new process, where they separate the fermentation from the hydrolysis process. Research issues: the cost of enzymes used to be a key issue, but Novozymes claim that the price of enzymes now is not an issue. The enzymes used for wheat; research on how to recyle enzymes, and where to recycle the enzymes, and make enzymes that can stand high temperature ("termo stable", ask Børge, and research at VTT has been done on this, plus the company ROAL). Inbicon does not recycle the enzymes at the moment. Recycling enzymes is difficult because they get attached to the material.

Enzyme technology is considerably less developed than the pre-treatment (less than 'in the middle)' in terms of both efficiency of conversion, cost and recycling. (Non-recycled enzymes just go out with the lignin.) Also research on enzymes suited for different feed resources. Commercial enzymes are used today, i.e. enzymes sold by specialist producers such as Novozymes, IOGEN. Novozymes is doing research in Denmark on Enzyme technology. Zsofia has a contact in Novozymes, Katja Johanson, with whom they have a project. Henrik Bangsø works at Novozymes (on biogas)

2.2 Assessment of the development stage of the technologies Is the technology dominant design, disruptive or path-following/incremental?

The biorefinery process, although still being developed, is generally viewed as gradually improving with experience.

As reported in Ingeniøren in December 2011, the activities in Inbicon plant could be slowing down, due to not receiving a governments' subsidy of 6.1 million DKK. However, such a delay was denied by the CEO Thomas Dalsgaard, while also proposing two solutions: improving the economy through synergy between a full-scale ethanol plant and the world's largest biogas plant Maabjerg Bioenergy in Holstebro, due to their interest in C5 molasses. Additionally, the process of ethanol production may be changed to can utilize all the starch in the straw, either to manufacture bioethanol or - eventually - raw materials in the form of sugar for various industries. (Ingeniøren)

Nonetheless, according to some researchers like Professor Henrik Wenzel from the University of Southern Denmark, the metabolism of microorganisms that conduct the process cannot be changed enough to significantly increase a yield of ethanol.) (Ingeniøren)

2.3 Technologies for further use of the aforementioned products (esp.C5 molasses and lignin pellets)

Currently, C5 molasses can be used as cattle feed and biogas booster and this technology is dominant and developed. It is claimed by some that the technology for by-products use could be improved, so that they are fermented to alcohol instead.

3 Market characteristics

The bioethanol market in Denmark is a nursing market due to lack of other producers than Inbicon. It is even claimed by some that the prices 2G are artificially set up at a high level by producers in order to get financial support. (Holm Christensen, 2013)

As of 2013, the US is the world's largest ethanol producer of ethanol, followed by Brazil (RFA, 2013). In the latter, the market is a mass market and constantly further developed, for example by securing discounts and/or payment grace periods for upfront investors, in order to finance prototypes to experiment with new technology. Moreover, the dominant state-owned oil firm, Petrobras, prefers to produce bioethanol and export oil. (Holm Christensen, 2013)

4 Geographical scope

Activities are ongoing to export Inbicon technology to other countries through certification of companies to build Inbicon Biorefineries). Two examples are: the US, where Pöyry, a Finland-based engineering firm in USA was chosen, (Bevill, 2011) and Harris in Canada (?)

The company has so far only one biorefinery in Denmark, operating since 2009, but is also involved in the development of a project a construct a unit in North Dakota (USA), where a hybrid corn/cellulosic ethanol plant is to be co-located with a coal-fired power generation plant operated by Great River Energy. (Bevill, 2011)

5 Institutional context and governance

After the pilot plant, the demonstration plant was inaugurated in 2009 and financed by Inbicon's own equity and funding from the Danish Energy Agency (the sum originated from the Danish EUDP program) , with the first four years of operation granted by EU in the project KACELLE (Kalundborg Cellulosic Ethanol) (Larsen, Østergaard Haven, & Thirup, 2012)

The KACELLE project will, among others, assess the energy consumption of the biorefinery process, including drying and pressing of the lignin.

Design and construction was supported by the Danish EUDP program with 76.7 million DKK, demonstration unit – by the European 7th Framework Programme with 67.7 million DKK and the development of the technology in an earlier stage previously granted from the European 5th Framework Programme. (Inbicon b)

From 2002 – 2006 Elsam (later a part of DONG Energy) was coordinator of the FP5 Project (IBUS), that also included Sicco K/S (DK), TMO Biotech (UK), Research Centre Risoe (DK), and The University of Copenhagen, Faculty of Life Sciences (DK). The project aimed to develop cost- and energy-effective production systems for co-production of bioethanol and electricity (Larsen et al., 2008).

Projects/Fundings

List of European projects that Inbicon has taken part in:
http://www.inbicon.com/Projects/Pages/Project%20frontpage.aspx

In terms of funding, it seems that the IBUs process was not appreciated enough to get support from Danish funds (Holm Christensen, 2013).

6 Path dependencies and innovation

The development of the bioethanol sector has been shaped by several factors, among them capital investments, policy and legislation, political interests and dominant technical design.

Due to the fact that capital investment costs are very high, the design applied in a specific refinery will probably continue throughout the lifetime of the plant, allowing only minor adjustments and innovation.

With regards to the (partly political) issue in the EU of whether biomass for energy purposes contributes to the indirect land use change, this causes a significant image problem for cellulosic bioethanol branch, while some (Holm Christensen, 2013) claim that biomass resources for 2G bioethanol production are causing the beneficial indirect land-use change (BILUC), as it yields both energy and fodder (C5 molasses). Misconceptions in terms of the crop yields and how the agriculture works has driven path dependencies within use of biomass in energy and only changing of the political ambiance around biofuels would allow increased development of 2G bioethanol.

Another political issue –specifically in Denmark, according to (Holm Christensen, 2013), is the use of straw for firing in heating plants, historically path-dependent for the last 30 years. Due to political decisions, straw incineration gets a subsidy of DKK 700 /t biomass, while use of it for ethanol production is not supported. What seems to be forgotten is that bioethanol helps to solve the problems of fossil-based area of transportation, where not many effective solutions are used.

In Brazil hydrous ethanol (94-95% alcohol) is used directly in flex-fuel cars. In the EU, in is required that bioethanol is mixed with the fossil fuel, therefore it has to be anhydrous (99% alcohol), which is a more expensive practice due to more post-treatment required. It is considered by some that this requirement is pressed by oil firms and car manufacturers to avoid use of 100% bioethanol in the EU. (Holm Christensen, 2013). Thus, it can be classified as path-dependency caused by large market shares of this biofuel system being captured by lead oil- and car manufacturing firms.

Concerning the dominant technological design types, the flexibility of the biorefining technologies is important, as it allows various feedstocks to be used and various end-products to be produced, which also improves the probability of innovation happening. As noted by (Holm Christensen, 2013), although there are firms experimenting with genetically modified yeast capable to conduct C5 molasses fermentation, such a use is not necessarily most optimal solution, as the existing uses for fodder and biogas booster allow broadening the portfolio of products. Moreover, the C5 use flexibility can be increased by producing so-called single-cell proteins (SCPs). For example, in the Inbicon's process, the yeast used in fermentation is also able to convert waste materials, such as C5 molasses, into various proteins, that can be used further in many sectors. (Holm Christensen, 2013). In order to allow flexibility, it also seems relevant to to start building refineries in a way that allows them to be ready for shifting among those products and feedstocks (straw, whole grains, energy maize). Changes in crop management, for example in the time of harvesting of energy maize, can also contribute to increasing yields. As claimed by (Holm Christensen, 2013), another future innovation area could be distillation. This process is very costly and requires up to 5% of world energy use annually, thus there is a need to make it cheaper and more energy-efficient, for example with diabatic distillation technique.

Among other elements of the value chain, it is understood that innovations in the enzyme technology are a less significant factor, though it is important to decrease their cost in relation to the enzymes used in 1G biofuel production. (Holm Christensen, 2013)

There is also potential in energy savings in pelleting of lignin, although only necessary if the pellets have to be dried and exported. The process of air drying is very energy-intensive. But if lignin can be used for energy purpose locally, in a "zero fossil fuel concept ", a set of other procedure can be used, such as super-stream drying, where lignin is immersed in high-temperature lipid mixture from waste, which saves a lot of energy.

7 Conclusions

TBC

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