

**DANISH AVIATION – BRANCHEFORENINGEN DANSK LUFTFART  
DANISH TRANSPORT AUTHORITY**

---

## **SUSTAINABLE FUELS FOR AVIATION**

**AN ANALYSIS OF DANISH ACHIEVEMENTS AND  
OPPORTUNITIES**



---

With financial support from

---

## PROJECT

---

Project No. 215313  
Project No. 1211177157  
Document No. 129972708  
Version 2  
Prepared by CHER, CTA and  
ECW  
Verified by ECW  
Approved by ECW

Sustainable Fuels for Aviation  
An Analysis of Danish Achievements and Opportunities  
Prepared for Danish Aviation (BDL), sponsored by the Danish Transport  
Authority.

Prepared by:

NIRAS A/S  
Sortemosevej 19  
DK-3450 Allerød

---

T +45 48 10 42 00  
F +45 48 10 43 00  
E-mail [niras@niras.dk](mailto:niras@niras.dk)

The following report has been prepared by Erik Wormslev, Camilla Tang and Christian Eriksen from NIRAS A/S, in close co-operation with Martin Porsgaard, NISA - the Nordic Initiative for Sustainable Aviation and dialogue with SBN - Sustainable Biofuels Network. The report is based on the knowledge of the project team, information published by companies and knowledge institutions within sustainable aviation, participation in the World Bio Markets 2014 conference in Amsterdam and interviews with company representatives and experts in Denmark and internationally.

Contact NIRAS A/S

Erik C. Wormslev

E-mail: [ecw@niras.dk](mailto:ecw@niras.dk)

---

---

---

## CONTENTS

FORORD.....	4
EXECUTIVE SUMMARY .....	6
PREFACE .....	11
EXECUTIVE SUMMARY .....	13
<b>1 Background and Scope.....</b>	<b>21</b>
<b>2 Sustainability .....</b>	<b>24</b>
2.1 Greenhouse Gas Emissions .....	24
2.2 Direct and Indirect Land Use Change (LUC and ILUC) .....	25
2.3 Nutrients (P and N) .....	25
2.4 Pesticides.....	25
2.5 Biodiversity.....	26
2.6 Water Usage .....	26
2.7 Generations of Feedstock.....	26
2.8 Social and Economic Sustainability .....	27
<b>3 Sustainable Fuels for Aviation .....</b>	<b>29</b>
3.1 The Aviation Industry .....	29
3.2 EU Renewable Energy Directive (EU RED) .....	30
3.3 International Organization for Standardization (ISO) .....	32
3.4 NGOs and Public Perception.....	32
3.5 Discussion.....	35
<b>4 The Necessity for Jet Fuel Substitution .....</b>	<b>37</b>
4.1 Aviation – A Key to Prosperity and Growth .....	37
4.2 Measures to Reduce Environmental Impact.....	37
4.3 Why Substitute Aviation Fuels? .....	39
<b>5 Jet Fuel Demands in Denmark .....</b>	<b>42</b>
5.1 Current Danish Jet Fuel Consumption .....	42
5.2 Projections for Danish Jet Fuel Consumption .....	42
5.3 The Required Quantities for Substitution.....	44
<b>6 Technical Specifications – Jet Fuel .....</b>	<b>46</b>
6.1 American Society for Testing and Materials (ASTM) – Technical Certification .....	46
6.2 The Commercial Aviation Alternative Fuels Initiative (CAAFI) – Readiness Tools .....	47
6.3 Fuel Inspection and Certification .....	47
<b>7 Technologies and Production .....</b>	<b>49</b>

---

---

## CONTENTS

7.1	Biorefining.....	49
7.2	Sustainable Jet Fuel Production.....	50
7.3	Technology Perspectives.....	60
7.4	Danish Jet Fuel Production – Current Technologies.....	61
7.5	Identification of Potential Danish Pathways.....	71
<b>8</b>	<b>Feedstock and Feedstock Availability.....</b>	<b>77</b>
8.1	Nationally Produced Feedstock.....	77
8.2	Potentials of Import.....	82
8.3	Biomass Balance.....	83
8.4	Future Land Use Strategies in Denmark.....	85
8.5	Scenarios of Future Feedstock Utilization.....	86
8.6	Discussion.....	92
<b>9</b>	<b>Logistics and Supply Chain.....</b>	<b>94</b>
9.1	Danish Airports.....	94
9.2	Aviation Fuels Logistics and Supply Chains in Denmark.....	95
9.3	Challenges Introducing New Fuels.....	96
9.4	Introducing Sustainable Fuels for Aviation in the Danish Supply Chain ..	97
9.5	Developing New Sustainable Aviation Fuel Supply Chains.....	98
9.6	Downstream Participation - Sustainable Aviation Sponsors.....	99
<b>10</b>	<b>Greenhouse Gas Reduction and Other Environmental Effects.....</b>	<b>100</b>
10.1	Climate Effects of Sustainable Fuels for Aviation.....	100
10.2	Non-Climate Effects of Sustainable Fuels for Aviation.....	101
10.3	Discussion.....	101
<b>11</b>	<b>Price Sensitivity and Break-Even.....</b>	<b>102</b>
11.1	Price Sensitivity of Aviation.....	102
11.2	Benefits for Sustainable Fuels for Aviation Producers.....	102
11.3	Pricing Sustainable Fuel for Aviation.....	103
11.4	Break-Even Scenarios.....	104
<b>12</b>	<b>Potential Social Effects.....</b>	<b>106</b>
12.1	Maabjerg Bioenergy Concept Case.....	106
12.2	Job Creation From a Danish Production of Sustainable Fuels for Aviation .....	106
12.3	Discussion.....	109
<b>13</b>	<b>Conclusions and Recommendations.....</b>	<b>110</b>
13.1	Sustainability.....	110
13.2	Technologies.....	110
13.3	Strategic Collaborations.....	112
13.4	Political Framework.....	112

---

---

**CONTENTS**

<b>14</b>	<b>References.....</b>	<b>114</b>
14.1	Companies.....	118
<b>1</b>	<b>Appendix – Technical Specifications and Certification.....</b>	<b>121</b>
1.1	Technical Specifications .....	121
1.2	Blend-in ratios and certification.....	122
1.3	Technical Certification - ASTM.....	122
1.4	CAAFI – Readiness Tools .....	124
1.5	Fuel inspection and certification .....	126
<b>2</b>	<b>Appendix – The Danish Biomass Balance .....</b>	<b>127</b>
2.1	Data .....	127
2.2	Results .....	128
<b>3</b>	<b>Appendix – Future Feedstock Scenarios .....</b>	<b>133</b>
<b>4</b>	<b>Appendix – scenarios for aviation fuel consumption and sustainable aviation fuel requirements .....</b>	<b>136</b>
4.1	Alternative scenarios for jet fuel consumption .....	136
4.2	Required quantities for substitution .....	136
<b>5</b>	<b>Appendix - Aviation Fuels Logistics and Supply Chains in Denmark.....</b>	<b>139</b>
<b>6</b>	<b>Appendix - Greenhouse Gas reduction and Other Environmental Effects .....</b>	<b>142</b>
6.1	Greenhouse Gas Reduction – A Lifecycle Assessment Approach .....	142
6.2	Non-Climate Effects of sustainable fuels for aviation .....	146
6.3	Discussion.....	147

---

## FORORD

Hvad vil der ske, hvis vi ikke kan flyve? De fleste tænker aldrig over dette spørgsmål, men i 2010 fik Danmark, og det meste af Europa, en mulighed for at se hvad en lammelse af luftfarten betyder, da askeskyen fra en islandsk vulkan gjorde det umuligt at flyve. Forretningsrejser måtte aflyses, folk kunne ikke komme på arbejde og mange kunne ikke komme hjem fra ferier.

Mange vil forbinde flyet med ferier, og ser derfor luftfarten som et luksusgode, som ikke har en vigtig betydning for det danske samfund. Det er en misforståelse af både luftfartens betydning samt Danmarks rolle i verdensøkonomien. De fleste vil huske askeskyen for strandede passagerer eller bekendte, der ikke kunne komme på en længe ventet ferie. Men i virkeligheden er det største problem for Danmark, hvis luftfarten lammes, at vi har en lille åben økonomi, der er helt afhængig af eksport og udenlandske investeringer. Luftfart, handel og eksport er tre ting, der hænger sammen, og derfor er det specielt vigtigt for et lille land som Danmark, at have en effektiv luftfart, der binder os til verdensmarkedet.

Luftfarten har to kontante udfordringer, hvis dette fortsat skal lykkes. Dels skal erhvervet bidrage markant til klimamålenes opfyldelse, og dels skal der være noget at komme i tanken. Og hvad sidstnævnte angår, er luftfarten speciel, fordi flydende brændstof er en nødvendighed mange år frem.

Men måske kan vi slå to fluer med et smæk gennem udvikling og anvendelse af bæredygtige biobrændstoffer. Brancheforeningen Dansk Luftfart (BDL) har derfor prioriteret at få etableret et grundlag for at fremme udviklingen af bæredygtige brændstoffer. Med udgangspunkt i nationale, internationale samt erhvervets egne klimamålsætninger, har vi søgt at etablere et overblik over muligheder og perspektiver ved en dansk satsning på udvikling af bæredygtigt brændstof.

Med økonomisk støtte fra Trafikstyrelsens "Forsøgsordning med energieffektive transportløsninger" har BDL fået udarbejdet en analyse af mulighederne for at udvikle, fremstille og, på sigt, kommercialisere bæredygtigt flybrændstof i Danmark. Projektets succeskriterium har været at frembringe en afrapportering, der kan understøtte perspektiverne i de vækst- og udviklingsmuligheder, som ligger i etableringen af en forsyningskæde for bæredygtige brændstoffer til fly. Samtidig er det målet, at problemstillingen belyses på en måde så udfordringerne også kan få prioritet på den politiske dagsorden.

Den danske luftfartssektor investerer store ressourcer i at blive mere miljø- og klimavenlig. Det vil vi fortsætte med at gøre i fremtiden, og især nye teknologier og biobrændstof vil gøre luftfarten mere miljøvenlig. Luftfarten er så vigtig for dansk økonomi, at løsningen på udfordringerne ikke er at begrænse luftfarten, men derimod at fremme nye og innovative tiltag, der gør luftfarten renere.

---

Vi håber, at vi med denne rapport kan være med til at skubbe udviklingen i en retning, der understøtter udvikling og vækst.

A handwritten signature in black ink, consisting of several overlapping loops and lines, positioned centrally on the page.

Maj, 2014.

Lars Wigelstorp Andersen,

Formand, Brancheforeningen Dansk Luftfart

---

## EXECUTIVE SUMMARY

### DANSK

Luftfartsindustrien har bidraget med en lang række fordele til Danmark og resten af verden i forhold til jobskabelse og økonomisk vækst. Luftfarten giver i EU alene anledning til 7,8 millioner jobs, og bidrager til næsten 4 % af Unionens bruttonationalprodukt, samt transport af passagerer og gods til kulturelle og forretningsmæssige formål. I en dansk kontekst er luftfarten ligeledes essentiel for den danske eksport af højværdiprodukter, let forgængeligt og temperaturfølsomt gods. På den anden side står luftfarten, ligesom de andre transportformer, overfor store udfordringer for at reducere de negative påvirkninger af miljø og klima. Dog er det en præmis for denne rapport, at luftfarten er et afgørende bidrag til vækst og velstand. Som konsekvens af dette skal luftfartens negative påvirkninger reduceres med andre metoder end ved at udfase denne.

Teknologisk udvikling er med til at øge effektiviteten af flymotorer og på anden måde reducere de negative påvirkninger. Det er imidlertid ikke muligt for industrien at nå sine mål om en 50 % netto-reduktion af CO<sub>2</sub>-emissioner i forhold til 2005 på andre bæredygtige måder, end ved også at substituere fossile brændstoffer med bæredygtige alternativer.

**Formålet med denne undersøgelse er at kortlægge potentielle teknologier og råvarer, med henblik på at identificere muligheder for en produktion og forsyningskæde af bæredygtige flybrændstoffer til kommerciel (og potentielt militær) luftfart i Danmark.**

På nuværende tidspunkt er der veldefinerede og globalt accepterede standarder for *alternative flybrændstoffer*, men ikke for *bæredygtigheden af flybrændstoffer*. Der er mange forskellige miljømæssige, sociale og økonomiske bæredygtighedsindikatorer, hvilket komplicerer en entydig definition af bæredygtighed. Der er forskellige internationale certificeringsordninger, hvor en af de mest ambitiøse er fra the Roundtable of Sustainable Biomaterials (RSB). Der er dog stadig visse miljøindikatorer, der ikke er veldefinerede og globalt accepterede. Disse udfordringer må løses for at sikre, at alternative flybrændstoffer, der bliver produceret, i sandhed er bæredygtige.

Det danske behov for bæredygtige flybrændstoffer er beregnet ud fra det af Energistyrelsen fremskrevne behov. Det er estimeret, at behovet for bæredygtige flybrændstoffer vil være omkring 0,6 mio. tonnes og 1 mio. tonnes i henholdsvis 2035 og 2050, hvis målsætningen om en fossilfri energiforsyning i 2050 skal opnås. Faktisk svarer udledningerne fra fly, både flyvninger nationalt og internationalt, tanket i danske lufthavne til ca. 6 % af de totale danske CO<sub>2</sub> udledninger.



---

Bæredygtige flybrændstoffer kan groft opdelt blive produceret af sukre, lipider og gasser. Danmark har flere globalt førende virksomheder inden for bioteknologi og der er stærke forskningsmiljøer på de danske universiteter.

Der er blevet identificeret forskellige potentielle teknologispør fra råvare til brændstof. De mest lovende spor inkluderer teknologierne Alcohol to Jet (AtJ), Hydrotreated Esters and Fatty Acids (HEFA) og Fischer-Tropsch syntese.

Co-processing af bæredygtige olieprodukter i allerede etablerede råolieraffinaderier er en lovende måde at udnytte eksisterende infrastruktur og reducere omkostningerne ved at etablere et komplet teknologispør.

De identificerede teknologispør illustrerer desuden, at de danske styrker især er inden for forbehandlingsteknologier, hvilket resulterer i stor fleksibilitet i valget af råvare.

Biomasse forventes at blive en begrænset ressource i takt med, at fossile reserver reduceres og verdens befolkningstal stiger. Det anbefales, at biomassen udnyttes i de sektorer, der ikke har andre alternativer for at reducere sin miljøpåvirkning i en overskuelig fremtid. Dette gælder skibe (bunker fuel), fly (kerosene) og tunge lastbiler (diesel).

Den danske biomassebalance domineres især af kød- og mælkeproduktion, da ca. 50 % af det totale landareal anvendes til produktion af foder. Der er opstillet to scenarier baseret på biomassebalancen og en "business-as-usual" og "miljøoptimeret" fremtidscase. Da produktionen af bæredygtige flybrændstoffer gør det muligt samtidig at producere højværdikemikalier, andre brændstoffer og energi, antages det at al biomasse produceret til energi kan udnyttes i bioraffinaderier, hvor der produceres flybrændstof, og samtidig dække det danske behov for energi og dyrefoder. Resultaterne viser, at omkring henholdsvis 100 og 150 % af behovet for råvarer kan være dækket til produktion af bæredygtige flybrændstoffer i 2035 i de to scenarier. For at dække et endnu større behov i 2050 må mængden af biomasse øges yderligere ved at ændre udnyttelsen af landareal enten politisk eller gennem konjunktursvingninger, ved at importere biomasse og / eller ved at øge udbytte ved at modificere forskellige afgrøder.

En bekymring ved at introducere bæredygtige flybrændstoffer er, at der vil ske en stigning i brændstofpriser, da bæredygtige brændstoffer er mere omkostningskrævende at producere end de konventionelle. Prisen for bæredygtige flybrændstoffer forventes dog på sigt at falde som følge af produktionsmæssig opskalering og teknologiforbedringer.

En anden udfordring er logistikken forbundet med indsamling og behandling af råvarer og introduktionen af et nyt brændstof i en allerede eksisterende forsyningskæde. Hvor logistikken af flybrændstoffer er relativt simpel i forhold til eksempelvis vejtransport, er logistikken opstrøms det endelige produkt (f.eks. pro-

---

duktion og indsamling af råvarer) mere kompliceret end for traditionel råolieraffinering.

Et vigtigt aspekt i at reducere prisen på brændstoffet er, at bæredygtige flybrændstoffer skal produceres som en del af et bioraffineringskompleks. I et bioraffinaderi er flybrændstof ikke den eneste produktstrøm, da der samtidig produceres højværdikemikalier, diesel, bunker fuel, energi med mere. Dette er vigtigt at overveje, når der skal vælges produktionsteknologi.

Der er mange positive effekter forbundet med en fremtidig produktion af bæredygtige brændstoffer til fly. Der kan opnås reduktioner i drivhusgasemissioner i omegnen 65-80 % ved 100 % substitution og hvis der tages passende hensyn til bæredygtigheden af råvaren. Udover de miljømæssige fordele ved at substituere fossile brændstoffer med bæredygtige alternativer, giver en produktion af bæredygtige flybrændstoffer blandt andet muligheder for jobskabelse. Et konservativt estimat baseret på beregningerne fra Maabjerg Energy Concept indikerer mindst 10.000 permanente, grønne jobs fra en dansk produktion af flybrændstoffer, der dækker behovet i 2035.

### **Hovedkonklusioner og anbefalinger**

Denne analyse identificerer et særskilt behov for bæredygtige flybrændstoffer både nationalt og internationalt for såvel at reducere de negative påvirkninger af miljøet som for at øge forsyningsikkerhed osv.

Udviklingen af en national produktion af bæredygtige flybrændstoffer har potentielle for miljøforbedringer, udvikling af nye teknologier, økonomisk vækst og jobskabelse. En række anbefalede handlinger for at fremme introduktionen af bæredygtige flybrændstoffer præsenteres nedenfor.

#### **Skab incitament for handling**

Flyindustrien ser mulighederne ved at substituere fossile brændstoffer med bæredygtige brændstoffer, men der er et behov for yderligere incitament.

***Anbefaling 1: Beslutningstagere må skabe yderligere incitament for at introducere bæredygtige flybrændstoffer. Dette kan eksempelvis være ved at øremærke dele af provenuet fra det europæiske Emissions Trading System til formålet.***

---

### **Styrket samarbejde mellem interessenter**

Denne rapport identificerer en række særlige danske kompetencer og anerkender en række særlige kompetencer og muligheder i hele den nordiske region, men også behovet for stærkere og mere organiserede samarbejder mellem de forskellige interessenter i regionen. Der er stort potentiale for synergier indenfor teknologiudvikling og beskæftigelse samt udnyttelse af tilgængelige ressourcer.

***Anbefaling 2:** Organiser de individuelle teknologier og deres udviklere i samarbejder omkring specifikke teknologispor gennem hele værdikæden og med en stærk ledende partner til at facilitere og drive udviklingen.*

### **Etabler tværfaglig arbejdsgruppe**

For yderligere at styrke samarbejder og drive udviklingen, særlig på tværs af teknologispor og organisationer, vil en arbejdsgruppe bestående af repræsentanter blandt råvareproducenter, teknologiudviklere, lufthavne, NGO'er, centrale beslutningstagere og luftfartsselskaber kunne facilitere og motivere forskellige samarbejder, særligt gennem hele den nordiske region.

***Anbefaling 3:** Etablér en arbejdsgruppe med repræsentanter blandt de centrale interessenter identificeret i denne rapport, der fokuserer på at fremme udviklingen af potentielle dansk / nordiske teknologispor.*

### **Yderligere analyser**

Beregningerne og konklusionerne i denne rapport er illustrative og yderligere arbejde er nødvendigt for en fuldstændig kortlægning af forskellige scenarier for en fremtidig udvikling af luftfarten mod en anvendelse af bæredygtige brændstoffer og denne udviklings konsekvenser. Dette gælder særligt i forhold til de samfundsøkonomiske konsekvenser.

***Anbefaling 4:** Analysér de forskellige scenarier for en bæredygtig udvikling af luftfartsindustrien, der er resultatet af en implementering af de forskellige teknologier og teknologispor, der er identificeret i denne rapport, især med fokus på de samfundsøkonomiske konsekvenser.*

### **Prioritering**

Denne analyse indikerer, at det fremtidige danske behov for bæredygtige flybrændstoffer helt eller delvist kan dækkes af tilgængelige, nationale biomasse-ressourcer, hvis disse ressourcer dedikeres til sektorer, der ikke har andre alternativer i en overskuelig fremtid. Dette understreges yderligere af diverse scenarier fra Energistyrelsen samt fra flere andre interessenter. Derfor er det vigtigt, at disse ressourcer bliver korrekt prioriteret.

---

**Anbefaling 5:** *Diskutér de politiske prioriteter i fordelingen af den begrænsede biomasseressource med tilstrækkelig inddragelse af de relevante ministerier, hvor der tages hensyn til, at luftfarten ikke har andre alternativer end brugen af (bæredygtige) biobrændstoffer for væsentligt at reducere de negative miljømæssige konsekvenser.*

Endelig er det en konstatering i denne analyse, at der ved at producere bæredygtige flybrændstoffer som en del af et bioraffineringskompleks opnås det største potentiale for at beskytte, forny og udnytte begrænsede ressourcer på den mest bæredygtige måde.

Denne rapport er udarbejdet af NIRAS og tæt fulgt af styregruppen, der havde deltagelse af : Martin Porsgaard, projektleder (NISA), Per Henriksen (BDL), Robert Arendal (Sustainable Biofuels Network, SBN) – i tæt samarbejde med Jens Erik Ditlevsen (Trafikstyrelsen).

---

## PREFACE

What would happen if we were not able to fly? Most of us never give this question any thought. However, in 2010 Denmark and most of Europe was given the opportunity to see what a total shut down of all aviation was like, due to an Icelandic volcano which made it impossible to fly. Business trips had to be cancelled, people were prevented from going to work, and many were not able to return home from their holidays.

Many of us associate flying with holidays, and therefore consider aviation extravagant, and not as something that actually has a significant meaning to the Danish society. It is a misunderstanding of both the meaning of aviation, but also of Denmark's role in the global economy. Most of us remember the ash cloud for stranded passengers, or friends who were not able to go on holiday. In reality, the greatest problem for Denmark if aviation shuts down is that we have a small and open economy being completely dependent on export and foreign investments. Aviation, trade and export, are interconnected matters, and it is therefore crucial to a small country like Denmark to have an efficient aviation industry, that connects us with the world market.

Aviation has two direct challenges in order for this to succeed. On one hand, the industry has to contribute significantly to the realization of climate goals, and on the other hand there has to be enough fuel to fill the tanks. In regard to the last issue, aviation stands out, because liquid fuel will be a necessity for many years to come.

But maybe it is possible to kill two birds with one stone by the use of sustainable biofuel. Danish Aviation (BDL) has therefore prioritized the creation of a knowledge base from which to promote the development of sustainable fuel. With focus directed towards national, international, as well as the aviation industry's own climate ambitions, we have attempted to establish an overview over the possibilities and perspectives in a Danish venture into the development of sustainable fuels for aviation.

With financial support from the Danish Transport Authority, under the programme "Energy Efficient Transport Solutions", Danish Aviation (BDL) has had an overview produced of the possibilities to develop, manufacture and – in the long term - commercialize sustainable fuels for aviation in Denmark.

The key success factor for the project is to deliver a report that can address the perspectives for growth and development opportunities that lay within the establishment of a supply chain for sustainable fuels for aircraft. At the same time, the objective is also to provide input for political prioritization.

The Danish aviation sector is investing great resources in order to become more environmentally and climate friendly. We will continue to do so in the future, and

---

especially new technologies and biofuel will help to contribute and thus make aviation more environmentally friendly. Aviation is so important to the Danish economy that the solution to the challenges that exist, is not to limit aviation, but contrary to compose new and innovative initiatives that makes aviation cleaner.

We hope that this report will facilitate a positive development for growth.

A handwritten signature in black ink, consisting of several overlapping loops and lines, positioned centrally on the page.

May, 2014.

Lars Wigelstorp Andersen, Chairman of the Board, Danish Aviation.

---

## EXECUTIVE SUMMARY

### ENGLISH

The aviation industry has provided many benefits to Denmark and the rest of the world in terms of job creation and contribution to economic growth. Aviation supports 7.8 million jobs in the EU alone and contributes to almost 4 % of the Union's gross domestic product (GDP), in addition to transport of passengers and cargo for cultural, business and leisure purposes. In a Danish context, aviation is likewise essential to the Danish export of high-value goods, as well as perishables and temperature sensitive products. However, like other modes of transport, aviation is facing great challenges in reducing its negative impacts on the environment and climate. It is, however, a premise in this report that aviation is key for growth and prosperity. Consequently, the negative environmental impacts of aviation must be reduced by other means, rather than being phased out.

Technological development constantly increases the efficiency of aircraft engines and by other means reduce the negative impacts. However, in order to reach the industry's goals of a 50 % net reduction in CO<sub>2</sub> emissions by 2050 compared to 2005, aviation has no other sustainable alternatives than substituting conventional fossil fuels with sustainable alternatives.

**The scope of this study is to screen potential technologies and feedstocks, with the aim of identifying opportunities for a production and supply chain for sustainable fuels for commercial (and potentially military) aviation in Denmark.**

Currently there are well-defined and globally accepted standards for *alternative jet fuels*, but not for the *sustainability of jet fuels*. There are many different environmental, social and economic indicators complicating clear definitions of sustainability. There are several sustainability certification schemes available, some being quite ambitious as the scheme from the Roundtable of Sustainable Biomaterials (RSB), but still some environmental indicators are not clearly defined and globally agreed upon. These issues must be addressed in order to ensure that the alternative fuels produced are truly sustainable.

The Danish demand for sustainable fuels for aviation is calculated from the projected jet fuel demands published by the Danish Energy Agency. It is estimated that the demand for sustainable fuel for aviation will be about 0.6 mill. tonnes and 1 mill. tonnes in 2035 and 2050 respectively, if the goal of a fossil free energy system in 2050 is to be reached. In fact, emissions from aircraft having fueled in Danish airports flying both domestic and international routes correspond to approx. 6 % of the total Danish CO<sub>2</sub> emissions.

---

Sustainable fuels for aviation can roughly be produced from sugars, lipids or gas. Denmark has several global industry leaders within biotechnology and significant research environments established at the Danish universities.

Different potential pathways from feedstock to fuel have been identified. The most promising pathways include the technologies Alcohol to Jet (AtJ), Hydrotreated Esters and Fatty Acids (HEFA) and Fischer-Tropsch (FT) synthesis.

Co-processing of sustainable oil products in existing crude oil refineries is a promising path to utilize the current infrastructure and reduce the costs of establishing complete production pathways.

The identified pathways furthermore illustrate how the Danish strengths especially are concentrated within pre-treatment technologies resulting in great flexibility in the choice of feedstock.

Biomass is expected to be a limited resource as fossil fuels reserves decrease and the world's population keeps increasing. It is recommended that the available biomass is used to produce fuel for those sectors who currently have no other alternatives of significantly reducing their environmental impact in the foreseeable future – this is the case with shipping (bunker fuel), aviation (jet fuel) and heavy trucks (diesel).

The Danish biomass balance is heavily dominated by the meat and dairy industries, as about 50 % of the total land area is used for feed production. Two scenarios were calculated based on the biomass balance for a “business-as-usual” and “environment optimized” case. Since the production of sustainable fuels for aviation enables a simultaneous production of high value chemicals, other fuels and energy, it is assumed that all the biomass produced for energy can be utilized in refineries producing jet fuel and still cover the additional Danish demand for energy and animal feed. The results show that about 100 % and 150 % of the demand for feedstock for the production of sustainable fuels for aviation in 2035 is met in the two scenarios respectively. In order to meet a higher demand in the future, the amount of feedstock available must be increased by either changing the current utilization of land by political or cyclical changes, importing feedstock and / or increasing the biomass yields by modifying the different crops.

A concern of introducing sustainable fuels for aviation in the existing fuel supply is an increase in fuel costs as alternative fuels currently are more expensive to produce than conventional fuels. The costs of alternative fuels are expected to decrease due to economy of scale and technology improvements.

Another challenge is the logistics associated with feedstock collection and processing and the introduction of an alternative fuel to the existing supply chain. Where the logistics of aviation fuels are relatively simple compared to those of e.g. road transportation, the upstream processes of the final fuel product (e.g.



---

feedstock production and collection) are more complicated than those of conventional crude oil refining.

A key aspect of lowering fuel costs is that sustainable fuels for aviation must be produced as a part of a biorefinery complex. In a biorefinery jet fuel is not the only product stream, but is produced simultaneously with high value chemicals, diesel fuel, bunker fuel and energy. This is important to keep in mind when choosing the production technology.

There are many positive effects associated with a future production of sustainable fuels for aviation. Reductions of greenhouse gas emissions in the range 65-80 % are achievable with a 100 % substitution and the appropriate attention given to the sustainability of the feedstock. In addition to the environmental benefits of substituting fossil fuels with sustainable alternatives, the production of fuels offers a potential of job creation. A conservative estimate based on the calculation from Maabjerg Energy Concept indicate a job creation of at least 10,000 permanent green jobs resulting from the establishment of a Danish production of sustainable fuels for aviation that meets the projected demand in 2035.

### **Main conclusions and recommended actions**

The analysis identifies a distinct need for sustainable fuels for aviation, nationally as well as internationally, both to reduce the negative environmental impact of aviation and to increase supply security etc.

The development of a national production of sustainable fuels for aviation has the potential for benefits from environmental gains, new technology development, economic growth and job creation. A series of recommended actions are listed below to further the introduction of sustainable fuels for aviation.

#### **Create incentives for actions**

The aviation industry recognizes the opportunities for substituting fossil fuels with sustainable fuels for aviation, but also that there is a need for further incentives.

***Recommendation 1:** Policy makers must create further incentives for the introduction of sustainable fuels for aviation. For example, it could be considered to earmark revenue streams from the European Emission Trading System for this purpose, among others.*

#### **Enforce collaboration between stakeholders**

This report identifies a series of special Danish competences and recognizes a range of special competences and opportunities across the Nordic region, but also the necessity for a stronger and more organized collaboration between the different stakeholders throughout the region. There exists a great potential for

---

strong synergies in technology development and employment as well as utilization of available resources.

***Recommendation 2:*** *Organize the individual technologies and their developers in collaboration around specific production pathways throughout the value chain and with a strong lead partner to facilitate and drive the development.*

#### **Establish inter-disciplinary working group**

To further strengthen the collaboration and drive the development, especially across different pathways and organizations, a group with representatives from both feedstock suppliers, technology developers, airports, NGO's, important decision makers and airlines would be able to facilitate and motivate the different collaborations, in particular across the Nordic region.

***Recommendation 3:*** *Establish a working group, with representatives from the central stakeholders identified in this report, focusing on the further development of potential Danish and / or Nordic production pathways.*

#### **Further analysis needed**

The calculations and analyses of this report are meant to be illustrative and further work is needed to fully explore the different scenarios for the future development of the aviation industry towards the use of sustainable fuels for aviation, especially with respect to the socio-economic consequences.

***Recommendation 4:*** *Analyze the different scenarios for a sustainable development of the aviation industry resulting from the implementation of different technologies and production pathways identified in this report, further exploring especially the socio-economic consequences.*

#### **Prioritization**

This analysis indicates that the future Danish demand for sustainable fuels for aviation could be fully or partially covered by available national biomass resources, if these resources are dedicated to sectors that have no other alternatives in a foreseeable future. This is further underlined by the different scenarios projected by the Danish Energy Agency as well as several other stakeholders. Hence it is important that these resources are properly prioritized.

***Recommendation 5:*** *Discuss the political priorities for allocating the limited biomass resources with the proper involvement of all relevant ministries and other stakeholders, taking into account that aviation has no other options than the use of (sustainable) biofuels in order to reduce the negative environmental impact substantially.*

---

Finally, it is the findings of this analysis that, as with utilizing biomass resources in general, producing sustainable fuels for aviation as part of a biorefining complex shows the greatest potential for protecting, replenishing and utilizing limited resources in the most sustainable way.

This report is written by NIRAS and closely followed by the Steering Group within Danish Aviation: Martin Porsgaard, Project Manager (NISA), Per Henriksen (BDL), Robert Arendal (Sustainable Biofuels Network, SBN), - in co-operation with Jens Erik Ditlevsen (Danish Transport Authority).

---

## **GLOSSARY**

**ADAM** - Annual Danish Aggregate Model

**ASTM** - American Society for Testing and Materials

**ATAG** - The Air Transport Action Group

**ATM** - Air Traffic Management

**AtJ** - Alcohol to Jet

**BDL** - Brancheforeningen Dansk Luftfart (Danish Aviation)

**CAAFI** - Commercial Aviation Alternative Fuels

**CH** - Catalytic Hydrothermolysis

**DCA** - Danish Centre for Food and Agriculture

**DSHC** - Direct Sugar to Hydrocarbons

**EOF** - Energi- og Olieforum

**EPA** - Environmental Protection Agency

**ETS** - Emissions Trading System

**EU RED** - European Union Renewable Energy Directive

**FAME** – Fatty Acid Methyl Esters

**FAO** - Food and Agriculture Organization of the United Nations

**FCC** - Fluid Catalytic Cracking

**FRL** - Fuel Readiness Level

**FSC** - Forest Stewardship Council

**FSRL** - Feedstock Readiness Level

**FT**- Fischer-Tropsch

**FTE** - Full Time Equivalents

**GHG** - Greenhouse Gas

**GFAAF** - Global Framework for Aviation Alternative Fuels

---

**GWP** - Global Warming Potential

**HDCJ** - Hydrotreated Depolymerized Cellulosic Jet

**HEFA** - Hydrotreated Esters and Fatty Acids

**HTL** - Hydrothermal Liquefaction

**IATA** - The International Air Transport Association

**ICAO** - International Civil Aviation Organization

**ILUC** - Indirect Land Use Change

**IPCC** - Intergovernmental Panel on Climate Change

**ISO** - The International Organization for Standardization

**LCA** - Lifecycle Assessment

**LUC** - Land Use Change

**LULUCF** - Land Use, Land Use Change and Forestry

**MASBI** - Midwest Aviation Sustainable Biofuels Initiative

**MEC** - Maabjerg Energy Concept

**NISA** - Nordic Initiative for Sustainable Aviation

**NREL** - National Renewable Energy Laboratory

**OECD** - Organization for Economic Co-operation and Development

**PEFC** - Programme for the Endorsement of Forest Certification schemes

**PJ** - Petajoule (equivalent to  $10^{15}$  Joule or  $2.78 \cdot 10^5$  MWh)

**RSB** - Roundtable of Sustainable Biomaterials

**SAFUG** - Sustainable Aviation Fuel Users Group

**SARPs** – Standards and Recommended Practices

**SAK** - Synthetic Aromatic Kerosene

**SES** - Single European Sky

**SESAR** - Single European Sky ATM Research

---

**SK** - Synthetic Kerosene

**SKA** - Synthetic Paraffinic Kerosene with Aromatics

**SMEs** - small and medium sized enterprises

**SPK** - Synthetic Paraffinic Kerosene

**TJ** - Terajoule (equivalent to  $10^{12}$  Joule or 278 MWh)

**USGS** - United States Geological Survey

**WWF** - World Wildlife Fund

---

## 1 BACKGROUND AND SCOPE

The commercial aviation industry continues to show increasing activity and the demand for energy for aviation is likely to increase significantly over the coming decades. The energy supplied to commercial aviation is currently almost exclusively based on fossil fuels and the contribution to global CO<sub>2</sub>-emissions of civil aircrafts alone has been estimated to be around 2 % (ATAG, 2012).

According to the Danish Energy Agency's annual statistics aviation (fueling in Danish airports) accounts for 6 % of the total Danish emissions of CO<sub>2</sub> in 2012, rising from approximately 5 % in 2009. Domestic aviation only accounts for 0.2 % of the total Danish CO<sub>2</sub>-emissions. This is a result of Denmark, and especially Copenhagen Airport, being a major international hub.

Even though the aviation industry has negative environmental impacts, the industry makes large contributions to economic growth and has been a main driver of globalization. In addition, air transportation of high-value products, perishables and temperature sensitive products is an important component in the Danish export strategy. Thus, a premise of this report is that aviation is not phased out. This means that aviation must reduce its negative environmental impacts rather than being replaced by other means of transportation.

The substitution of conventional fossil fuels with sustainable alternatives correlates well with the national climate goals of Denmark where 100 % of all energy must be renewable in 2050. To reach this goal a 25 % reduction in consumption of fossil fuels must be reached in 2020 compared to 2005. This calls for rapid actions within the area of renewable alternatives.

For airlines and other aviation operators another concern is the dwindling fossil fuels resources available at affordable prices. As global fossil fuel reserves are being consumed, the remaining resources increasingly become a matter of contention with significant increases in cost and possible security concerns as the consequences. If these, and other, negative consequences are to be avoided the dependency of commercial and military aviation on fossil based fuels must be broken.

Although several strategies have been proposed to increase fuel efficiency in aircraft (see Section 4 for further details), these strategies only partially mitigate the negative impact of aviation on the environment. The only viable and complete solution is currently (and in the foreseeable future) to substitute fossil fuels with sustainable fuels for aviation. These fuels are often referred to as *synthetic fuels* because they do not originate from a fossil (crude oil) source. Rather they are *synthesized* from a host of other raw materials.

Sustainable fuels for aviation are produced from renewable resources (waste or biomass) rather than traditional fossils like coal, oil and natural gas. Most path-

---

ways to sustainable fuels for aviation are based on a biological feedstock, i.e. are considered biofuels. The aviation industry has pointed out the development of biofuels as a major way to reduce its greenhouse gas emissions (ATAG, 2009).

The Air Transport Action Group (ATAG) mentions three main advantages of using sustainable biofuels for aviation. First, the reduction in CO<sub>2</sub> emissions related to using biofuels compared to conventional fossil based fuels. Secondly, being dependent on fossil fuels makes it difficult to plan and budget for long-term expenses as the crude oil price is changing. Using biofuels will make the aviation industry independent on site specific drilling locations and instead provide more geographically diverse suppliers. Finally, there are social and economic benefits as growing biomass for aviation biofuel can create a market in developing countries (ATAG, 2009).

The first sustainable jet fuel certified as a drop-in fuel by the American Society for Testing and Materials (ASTM) was produced by Fischer-Tropsch synthesis in 2009. A drop-in fuel is fully compatible with the existing systems and can be used just as it is a conventional jet fuel. In 2011 another process, Hydrotreated Esters and Fatty Acids (HEFA), was certified. Since then commercial use of sustainable fuels for aviation is a fast growing area. By June 2012 more than 1,500 commercial flights had been made using HEFA fuel. Yet, there is still much progress to be made before sustainable fuel for aviation is fully commercially available and can compete with conventional jet fuel in terms of cost.

The development and production of sustainable fuels for aviation has a large potential for regional economic development and growth, and any nation or region gaining a strong market position will be able to harvest great benefits directly and indirectly from this position. Developing processes and technology for sustainable fuels for aviation also promises to yield a large range of spin-off products, solutions and research-areas, which in themselves can lead to further growth and development.

According to the Biorefining Alliance (a Danish consortium) Denmark as a nation must choose if it wants to be just Consumers of bio-based fuels and products, or rather be a Supplier of research, fuels, technology and knowledge (Biorefining Alliance, 2012). Building on the development and know-how of universities and industry, Denmark has the opportunity to gain significant headway within several fields pertaining to bio-based fuels and other products.

The scope of this study is to screen potential technologies and feedstocks, with the aim of identifying possibilities for a production and supply chain for sustainable fuels for commercial (and potentially military) aviation in Denmark.

The criteria for what constitutes sustainable fuels, even the concept of sustainability as a whole, are, however, under some debate. This study therefore at-



---

tempts to identify key parameters of sustainability that apply to the production of sustainable fuels for aviation as well as for the feedstock utilized.

From this outset the study seeks to identify specific competencies in Denmark in terms of research and development into sustainable fuels for aviation, as well as Danish technology currently commercially available. The possibilities for procuring sustainable feedstocks in Denmark will also be discussed with the purpose of ensuring a sustainable supply for the described technologies.

Finally the study aims at identifying possible synergies within the Nordic region, as well as in the rest of the world, based on findings in studies conducted in the region as well as findings of this report.

This document should not be viewed as a technical manual or reference, but is rather a strategic analysis and recommendations for actions that may further the introduction of sustainable fuels for aviation in Denmark and globally.

---

## 2 SUSTAINABILITY

Sustainable development was defined in 1987 in the United Nations' report "Our Common Future" (the so called Brundtland report) as: "*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". This definition is a broad definition that includes both environmental, economic and social aspects.

The production of sustainable fuels for aviation should take place within the general framework of environmental protection. Thus, the sustainable fuels should be produced with respect to the surrounding environment by limiting emissions to air, soil and water, but also maintain a healthy working environment etc. The focus of this section is the parameters that pertain specifically to the *sustainability of an alternative fuel* and thus assumes that general environmental protection is taken into account.

How these parameters are applied in schemes for jet fuel sustainability is further treated in Section 3.

### 2.1 Greenhouse Gas Emissions

CO<sub>2</sub> is the most well-known greenhouse gas (GHG). The man made emissions are primarily from combustion of fossil fuels. Combustion of biofuels is traditionally defined as CO<sub>2</sub> neutral because the amount of CO<sub>2</sub> emitted during combustion is assumed to be less than or equivalent to the amount of CO<sub>2</sub> the plant has taken up by photosynthesis during its lifecycle. For annual plants the released CO<sub>2</sub> from combustion is taken up by a new plant the following year. However, for vegetation with a longer lifecycle the carbon will remain in the atmosphere for a longer period contributing to global warming. Moreover, the harvesting of biomass, conversion technologies and other parts of the supply chain consume energy and thus, biofuels are not technically fully CO<sub>2</sub> neutral.

In addition to CO<sub>2</sub> there are other gasses that contribute to the greenhouse effect. Nitrous oxide (N<sub>2</sub>O) is produced naturally in soil, but 40 % of the global emissions are estimated to be caused by human activity. N<sub>2</sub>O is mainly released into the atmosphere when using nitrogen based fertilizers on fields. Other sources are combustion, using nitrogen from the atmosphere (of which 78 % is nitrogen), and industry.

Methane (CH<sub>4</sub>) is another GHG associated with agriculture. Globally, 60 % of all CH<sub>4</sub> emissions originate from human activities. Natural gas consists mainly of CH<sub>4</sub> and there are emissions associated with the processing of this. In addition agriculture is also a major source of CH<sub>4</sub>, as especially ruminants produce CH<sub>4</sub> as a part of their metabolism.

When assessing GHGs the different gasses are converted to CO<sub>2</sub> equivalents (CO<sub>2</sub>-eq). This is done by multiplying the amount of gas with the Global Warming Potential (GWP) of the gas. The GWP depends of the lifetime of the gas in the

---

atmosphere and how much the gas contributes to global warming. CO<sub>2</sub> has a GWP of 1, whereas N<sub>2</sub>O and CH<sub>4</sub> have a GWP of 298 and 21 respectively when considering a 100 year time period.

GHGs are of special concern in the aviation industry as GHGs emitted in flight altitude contribute more to global warming than GHGs emitted by the land surface. Due to this there is consensus to multiply the GWP with an additional factor known as the radiative forcing index. This factor is difficult to define as it varies depending on the composition of the aircraft combustion emissions and other factors.

## **2.2 Direct and Indirect Land Use Change (LUC and ILUC)**

As land area is cultivated there is a net change in the carbon stock stored in the vegetation. Land use change (LUC) most often occurs when changing from a carbon rich vegetation, such as forest, to a less carbon rich vegetation, such as cereals.

Indirect land use change (ILUC) occurs when the direct use of land for biofuel feedstock production occupies land in other regions in order to produce food or other crops suppressed by the feedstock production. ILUC is difficult to quantify as it is difficult to trace and because the emissions occur at another site than the direct emission.

## **2.3 Nutrients (P and N)**

From an environmental perspective phosphorous (P) and nitrogen (N) are the most important nutrients to consider. Many fertilizers, including animal manure, contain high concentrations of P and N.

P and N can cause eutrophication in streams and lakes if washed from fields which causes oxygen depletion. Furthermore, especially P is a valuable and limited resource where the locations of mines are relatively few and should hence not be lost during incineration or similar processes. Thus, the handling of nutrients appropriately is important when choosing the feedstock and technology for sustainable fuel for aviation production.

## **2.4 Pesticides**

Changing how the land is utilized can both increase and reduce the amount of pesticides applied. Rape and sugar beets are crops that require high amounts of pesticides compared to crops such as grass and maize. Generally perennial crops have a lower pesticide requirement than annual crops as they are more competitive towards weeds. Due to this, changing from agriculture to forestry has a positive effect of pesticide usage. On the other hand increasing the production of high energy crops such as willow can introduce new pests and diseases and hence increase the pesticide demand (DCA, 2013).

---

## 2.5 Biodiversity

Exploiting uncultivated areas such as forests and meadows can affect the biodiversity in these areas. In forests a large part of the biodiversity is biodegrading organisms such as fungi, beetles, bacteria and soil organisms. Damaged trees that are unsuitable as timber can house many endangered species. Due to this, utilizing damaged trees as feedstock for biofuel production contain a risk for affecting the biodiversity.

Biomass production can, on the other hand, be planned to facilitate an improved biodiversity. Meadows require maintenance by cutting off vegetation. If carefully removing the cut off vegetation, which can be used as feedstock, more vulnerable species have better growth conditions.

## 2.6 Water Usage

Water usage includes both the amounts of water used in the production and the quality of water resources as feedstock production can pollute existing water supply resources.

The Organization for Economic Co-operation and Development (OECD) estimates that 70 % of all water used in world is for agricultural purposes. In addition, in 2005 44 % of the world's population was living under severe water stress. Thus, feedstock production risks causing depletion of water resources that are needed by local communities. Less than 1 % of all drinking water in the world is desalinated seawater (USGS, 2014) and the desalination process is highly energy consuming. This causes freshwater resources to be almost the sole drinking water resource for most of the world's population.

Denmark is not suffering from water stress to the extent of more arid regions of the world. However, the Danish water supply is based almost exclusively on groundwater resources that are vulnerable towards pollution such as pesticides. In addition Danish surface waters in some parts of the country suffer from eutrophication causing leaching of nutrients to also be a threat towards water quality.

## 2.7 Generations of Feedstock

Dependent on the feedstock used, biofuels can be categorized in different "generations". There is a general consensus that first generation (1G) biofuels are produced from feedstock that is directly competing with food production. This is for instance rapeseed, sugarcane and maize. Second generation (2G) biofuels are produced from non-food crop sources such as straw, wood residuals and waste. Currently 1G biofuels are by far the most common worldwide.

In addition to 1G and 2G, advanced 3G and 4G fuels are also emerging. There are different definitions of these. According to Avinor (2013), 3G biofuels are produced from feedstock not competing with food and that do not require freshwater in the production. This is for instance brown algae (seaweed) known as

---

“blue feedstock”. Finally, 4G biofuels are produced from microorganisms where oils, sugars and even hydrocarbons are produced directly. Thus, all it requires is sun, a growth environment (or a reactor), CO<sub>2</sub> and nutrients. The different generations and the feedstocks relating to them are listed below:

- **1G:** Food crops, cereals, sugar, starch, plant oils and animal fats
- **2G:** Lignocellulosic materials such as woody byproducts
- **3G:** Micro and macroalgae
- **4G:** Algae, microorganisms and microbes

According to another definition, 3G fuels do not compete with food production and are indistinguishable from the conventional fossil fuel that they substitute (Biomass Magazine, 2014).

The division of feedstock into generations can be misleading as there is a lack of completely clear definitions as some crops will contain both materials that are considered 1G and some that are considered 2G. An example would be cereals where the stock and other non-edible materials can be considered 2G whereas the cereal itself is clearly 1G. In addition the technologies to convert the different types of feedstock to aviation fuel vary greatly in maturity and commercial availability. An added concern is the possible effects from LUC or ILUC that the choice of a specific feedstock may have.

Thus, how suitable a feedstock may be, in terms of the environmental impact as well as others factors such as economic feasibility, is not always a straight forward distinction and may have nothing to do with the “generation” of a feedstock.

This illustrates how feedstock generation must clearly not be the only criterion when selecting feedstocks for the production of sustainable fuels for aviation.

## **2.8 Social and Economic Sustainability**

The United Nation’s definition of sustainability also includes social and economic aspects. Social sustainability includes:

- Working rights
- Rights of land and resources
- Food security
- Rights of development

---

When producing biofuels from 1G feedstock the demands for food crops increase which can affect the global food prices. An increase in food prices will typically negatively affect the urban population in developing countries.

Another concern is the so-called “financialization of commodities” wherein financial investors make speculative investments in agricultural commodities. This can amplify uncertainties regarding commodity prices caused by external factors such as a low harvest or political actions (export bans, prohibitive taxes etc.) and significantly drive up prices.

In 2006 – 2008 commodity prices suddenly spiked and concerns arose that the increase in biomass for energy production could be a main driver of this increase in prices. However, financialization of commodities has been argued to be a leading cause. Several authors also argue that the increased production of biofuels may have played a significantly smaller role in the critical price development of agricultural commodities during the spike than the actual impact by the increase in energy production from biomass (Baffes *et al.*, 2011).

Economic sustainability can be evaluated in different scales. A technology for biofuel production is not economic sustainable if the price cannot compete with conventional fossil fuel unless some other value is created that “offsets” the increase in price with respect to the conventional fuel.

Economic sustainability also includes valuation of the environment and social effects. The United Nations has defined green economy as an economy that: *“Improves human well-being and social equity, while significantly reducing environmental risks and ecological scarcities”* and *“does not favor one political perspective over another but works to minimize excessive depletion of natural capital”*.

According to the United Nations, initiatives that have positive economic impacts on local communities and improves social equity, without negatively impacting the environment, may be said to further economic and social sustainability. Thus, criteria for sustainability must also take local and regional economic and social factors into account.

---

### 3 SUSTAINABLE FUELS FOR AVIATION

In order to classify an alternative aviation fuel as sustainable it is necessary to identify which parameters from Section 2, and possibly additional parameters, to evaluate and determine the criteria to meet. This, however, is not straightforward as there are many different stakeholders to accommodate. Currently there is no consensus on a single internationally recognized specification for sustainable biofuels.

The prioritization of biomass, and especially advanced biofuels, for either aviation or other uses is a political issue and there are different views as well as policies worldwide. As an example the European Commission has a roadmap for sustainable fuels for road transportation but no concrete, decided plans for aviation.

This section presents the views on sustainable aviation by different stakeholders. In addition different sustainability specifications are described. The different specifications are combined into recommended specifications for sustainable fuels for aviation within a Danish context.

#### 3.1 The Aviation Industry

The International Air Transport Association (IATA) is a trade association with members representing 84 % of total air traffic. IATA has defined the following goals for sustainable aviation:

- Fuel efficiency improvement of 1.5 % p.a. on average between 2009 and 2020
- Carbon-neutral *growth* from 2020
- 50 % net emissions reduction in 2050 compared to 2005

IATA recognizes that sustainable fuels are essential in achieving these goals. Due to this the organization is working towards commercializing sustainable fuels in order for them to be cost-competitive with conventional fuels.

The goals of IATA have been in parallel with a number of different independent initiatives within the aviation industry, including, but not limited to, the following:

- **Sustainable Aviation Fuels User Group (SAFUG):** Currently accounting for 32 % of the annual global civil aviation fuel demand and aiming to accelerate the development of sustainable fuels
- **Commercial Aviation Alternative Fuels Initiative (CAAFI):** A North American initiative facilitating the development of environmental sustainability in aviation

- 
- **Nordic Initiative for Sustainable Aviation (NISA):** An association of Nordic stakeholders aiming to promote and develop sustainable aviation focusing on sustainable fuels

SAFUG and CAAFI have developed methods to evaluate the sustainability of a biofuel.

### 3.1.1 *SAFUG and NISA*

SAFUG lists the following criteria for sustainable fuels for aviation:

- Exhibit minimal impact on biodiversity
- Meet a sustainability standard with respect to land, water, and energy use
- Do not displace or compete with food crops
- Provide a positive socioeconomic impact
- Do not require any special fuel handling equipment, distribution systems, or changes to engine design (“drop in compatibility”)

In addition SAFUG follows the specifications by the Roundtable of Sustainable Biomaterials (RSB) which will be further described in Section 3.2.1.

NISA agrees with SAFUG in the sustainability specifications, but also includes impact on local air quality, including ultrafine particles, as a parameter to be assessed.

### 3.1.2 *International Civil Aviation Organization (ICAO)*

International Civil Aviation Organization (ICAO) is a UN specialized agency. ICAO works with the industry to develop international Standards and Recommended Practices (SARPs) which are adapted into legally-binding national civil aviation regulations in the member states.

ICAO works within multiple aspects of civil aviation. The Global Framework for Aviation Alternative Fuels (GFAAF) was launched in 2009. GFAAF provides a continuously updated database about the developments in the field of alternatives for aviation, documentation of technologies and links to relevant webpages. The purpose is to support information sharing for the benefit of the aviation fuels community.

## 3.2 **EU Renewable Energy Directive (EU RED)**

The EU Renewable Energy Directive (EU RED) from 2009 defines criteria for all sustainable biofuels for transportation. The directive has been fully implemented in Danish legislation in 2012 and is valid for both biofuels produced in the EU and biofuels that are imported.



---

The directive contains specifications concerning CO<sub>2</sub> reduction and chain of custody in order for a fuel to be considered sustainable. The feedstock must not be grown in vulnerable areas such as areas with a high biodiversity or rare ecosystems, and certain types of forest. In addition the area must not be storing great amounts of carbon, which is the case of certain types of wetlands and forests. Biofuels made from waste and byproducts (except from agriculture, aquaculture, fishing and forestry) are exempted from this legislation.

The chain of custody from feedstock to biofuel supplier must be accounted for in order to ensure consistency between the sustainability of the feedstock and the claimed sustainability of the finished product.

From 2010 all biofuels for transportation purposes must meet criteria concerning the CO<sub>2</sub> reduction compared to conventional fossil fuels:

- Until January 1<sup>st</sup> 2017 the reduction must be at least 35 %
- From January 1<sup>st</sup> 2017 the reduction must be at least 50 %, and finally
- As from January 1<sup>st</sup> 2018 the reduction must be at least 60 % regarding biofuels from facilities built after January 1<sup>st</sup> 2017

The reduction is calculated from standard reductions from the relevant processes.

EU has initiated studies regarding LUC and ILUC of 1G biofuels from palm oil, soy, sunflower and rape. Based on the studies fuels produced from these feedstocks are not compliant to the EU RED criteria of sustainability (Avinor, 2013). Thus, using 1G biofuels are currently not relevant in sustainable biofuels for aviation.

In 2012 changes to the Directive were suggested to include the term LULUCF as a subject of reporting requirements. LULUCF is short of land use, land use change and forestry, and aims to strengthen the capacity of forests and agricultural soils and to capture CO<sub>2</sub> in a sustainable manner.

By 2013 13 different certification schemes of controlling and certifying sustainable biofuels have been approved by the European Commission. Some schemes apply to a fixed geography and a specific feedstock, whereas others are global and cover all types of feedstock.

### 3.2.1 *Roundtable of Sustainable Biomaterials (RSB)*

The Roundtable of Sustainable Biomaterials (RSB) is a multi-stakeholder initiative from 2007 and has been approved by the European Commission. The initiative has members that are both producers and consumers of biomaterials. The members include IATA and SAFUG, and several aircraft manufacturers such as Airbus and Boeing.

---

A sustainability certification scheme for biofuels was published in 2010 and only includes criteria for direct effects due to the difficulty of assessing indirect effects (RSB, 2011). The scheme divides operators into four different groups and defines which criteria each group must fulfill. The groups are:

- Feedstock producers
- Feedstock processors
- Biofuel producers
- Biofuel blenders

The criteria is grouped in 12 different principles including social aspects (human and labor rights, rural and social development, local food security and land rights), environmental impacts (GHGs, conservation, soil, water, air and waste) and aspects of planning and monitoring. The criterion for GHGs emission reduction is stated specifically for biofuel blends as: “*Biofuel blends shall have on average 50 % lower lifecycle greenhouse gas emissions relative to the fossil fuel baseline*” and that “*each biofuel in the blend shall have lower lifecycle GHG emissions than the fossil fuel baseline*”. This criterion is more ambitious than the current EU RED criterion of a 35 % reduction.

In addition to the criteria, RSB also provide guidelines to evaluate the different principles.

### **3.3 International Organization for Standardization (ISO)**

The International Organization for Standardization (ISO) is currently completing an international standard (under technical committee TC248) of sustainable bioenergy (ISO, 2014). The target publication date is currently April 30<sup>th</sup> 2015.

The scope of the standard is to specify sustainability principles, criteria and measurable indicators. The standard will contain social, economic and environmental indicators similarly to the schemes mentioned in the previous sections. The standard will apply to either the entire supply chain, parts of a supply chain or a single process. The standard is intended to facilitate comparison between bioenergy processes or products. Thus, compliance with the standard does not determine if a given process or product is sustainable, but rather serves as a common frame of reference to compare a process or product to other products or processes in terms of their individual sustainability.

### **3.4 NGOs and Public Perception**

In addition to the industry and governmental organizations, several NGOs are working in the field of sustainable aviation or sustainability in general. This section will provide an overview of NGO and public opinions on sustainable aviation.

---

### 3.4.1 *World Wildlife Fund (WWF) – Evaluation of EU RED*

The World Wildlife Fund (WWF) is especially focusing on the environmental impacts from renewable fuel production. When choosing a suitable technology for production of sustainable fuels for aviation WWF emphasizes the following parameters to be evaluated: Greenhouse gasses, biodiversity and conversion, land use and water use, pesticides, waste management and social labor.

In addition WWF emphasizes that the process of implementing sustainable fuels should be a multi-stakeholder activity. This will ensure a general consensus for specifications on sustainability instead of multiple individual certification schemes.

Finally, WWF states that the *“exploitation of biomass must be prioritized for those sectors that cannot replace fossil fuels with other renewable sources, as high temperature industry processes, aviation, shipping and heavy trucks”* (WWF, 2012). This illustrates how the limited biomass resource must be prioritized between sectors in order to ensure a sustainable exploitation.

WWF has evaluated and rated the 13 existing certification schemes approved by the European Commission (WWF, 2013). RSB is the certification scheme with the overall best rating in the WWF. This indicates that it is an ambitious scheme including many environmental and social parameters.

### 3.4.2 *Woody Biomass – FSC and PEFC Certification*

There are certification schemes focusing specifically on woody biomass, as the production of this can be associated with great LUC effects if the forest cannot grow new wood in the same pace as wood is harvested. In addition wood is a part of many everyday products such as paper and furniture. Consequently, labelling addresses households as well as industries.

Among the most applied certification schemes are Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification schemes (PEFC). Both schemes ensure that the forest resource is not reduced and also contain elements of environmental and social sustainability.

### 3.4.3 *The Danish Council of Ethics (Det Etiske Råd)*

The Danish Council of Ethics (Det Etiske Råd) published the report *“Bioenergi, fødevarer og etik i en globaliseret verden”* in 2012. The report discusses common assumptions regarding bioenergy especially focusing on the concerns that bioenergy competes with food production and that biomass production harms the existing nature.

The council points out four global crises currently being the largest threats towards to the global welfare:

- The food crisis

- 
- The climate crisis
  - The energy crisis
  - The nature and environment crises

The four crises are cohesive as helping one might enhance another. For example the production of biofuels for aviation can help the climate and energy crises, however, it can enhance the food and environment crises if not managed properly.

The council stresses that choosing a technology for bioenergy production cannot be based solely on its economic feasibility. A sustainable bioenergy technology helps the energy crises without damaging, and hopefully helping, the three other areas. In addition the Danish Council of Ethics finds that regulating the prices on sustainable and fossil fuels is a legitimate method of enhancing the production of sustainable bioenergy.

#### 3.4.4 *Concito*

Concito is a Danish green think tank formed in 2008. The about 100 members include companies, researchers and private individuals. Concito works with analyses and political proposals pursuing to reduce the emissions of greenhouse gasses. Concito points out fossil fuels, but also agriculture and land use change, to be the major contributors of climate change.

Especially relevant to this project Concito has published the report “*Klimapåvirkningen fra biomasse og andre energikilder*” which calculates the CO<sub>2</sub>-eq emissions from different biofuels using a lifecycle assessment approach. The results from this report will be further discussed in Section 10 and Appendix 5.

#### 3.4.5 *Public Perception*

The public perception is important in terms of marketing and communication of sustainable fuels for aviation. Air travel has been called “the biggest carbon sin” (Rosenthal, 2013) and generally aviation has a reputation of being a large consumer of energy and bad for the environment.

NGOs and media play an important part in shaping public perception of various subjects, and especially with regards to environmental concerns. The Danish Society for Nature Conservation (Danmarks Naturfredningsforening) has called for a ban on the use of 1G biofuels, on account of their perceived negative impact on environmental and social sustainability (Danmarks Naturfredningsforening, 2007).

Also, being accused of green washing, with the resulting negative publicity and image, should be a real concern for the aviation industry given that the public

---

perception already seems biased against the industry in terms of their environmental impact.

Thus, for airlines to reap the full benefits from their move towards sustainable aviation fuels it is vitally important that they not only address the issue from scientific and economic perspectives, but also address the public perception through a structured and strategic communications effort. The effort should focus not only on the climate and environmental benefits of the employment of sustainable fuels for aviation, but also on the benefits of the fuel in terms of social and economic sustainability. This of course presumes that these concerns have been addressed in the choice of technology and feedstock.

### 3.5 Discussion

The previous sections illustrate the complexity in evaluating the sustainability of aviation biofuels. Based on the different point of views described above, it is concluded that sustainability of fuels is highly dependent on the feedstock chosen for the production - although the entire supply chain should be considered.

The definitions of feedstock generations are more or less historical and based on the technical abilities of conversion. For hundreds of years it has been technically possible to extract sugars from canes and beets. Now it is possible to convert pine, straw and other lignocellulosic materials into edible sugars. The definition of feedstock generation and the competition with food and feed will hence change over time due to the technological progress.

The sustainability criteria in this report are based on the criteria from RSB, as the aviation industry leans towards these and they are considered ambitious and comprehensive. However, some of the principles of RSB are more relevant in a Danish context than others. As mentioned water scarcity is not a major issue in Denmark, although potable water resources should always be used with care and wherever possible secondary water resources should be used. Instead water quality is of high priority both in terms of groundwater protection and reduction of nutrients leaching to streams and lakes.

Many of the sustainability criteria can be reduced to a matter of how the total land area is managed as the crops planted, or generally if anything is planted, affects the nutrient cycles, pesticides usage, LUC/ILUC etc. Based on these considerations the following parameters are found to be the most important to consider when evaluating the sustainability of fuels for aviation in a **Danish context**:

- Land management<sup>1</sup>

---

<sup>1</sup> Land management is heavily regulated in the Danish legislation, which creates both opportunities and possible barriers for the management and utilization of the available Danish land area.

- 
- Greenhouse gasses (GHGs) and other air pollutants
  - Cycling of nutrients
  - Groundwater and environmental protection in general
  - The potential effects of “green growth”
  - Impact on local air quality, including emissions of ultrafine particles, covering both environmental protection and health and safety at work.

For the context of this report we consider managing the total land area, both nationally and globally, in the best possible way a key aspect of sustainability. This, for instance, means not exploiting vulnerable land areas in compliance with the EU RED, and choosing feedstocks that do not compete with food and especially feed. The selection of feedstock will be further discussed in Section 8.

It will be a major benefit for the sustainable fuel for aviation producers and consumers that the coming ISO standard will set an international standard of which indicators to include when evaluating the sustainability of a fuel and methods of how to do this. Even though the ISO standard is intended for comparison between different bioenergies, it can be the base of setting threshold values of the different parameters allowing actual sustainability certifications of biofuels and setting a common terminology of sustainability.

---

## 4 THE NECESSITY FOR JET FUEL SUBSTITUTION

This section contains a discussion on the necessity for substituting conventional fuels for aviation with sustainable fuels. It contains a discussion on the positive impacts of aviation as well as the negative, environmental impacts. It concludes with a brief review of other measures that can help make aviation sustainable. Finally this section contains a detailed argumentation for the need to prioritize aviation because the lack of alternative solutions, as well as the possible benefits to the aviation industry resulting from a substitution with sustainable fuels for aviation.

### 4.1 Aviation – A Key to Prosperity and Growth

When discussing the negative environmental impacts of aviation it is important to keep in mind the major benefits aviation provides to modern society. Aviation is clearly a new industry, barely a century old, but has already become one of the main drivers for increased prosperity, economic growth and globalization.

In the EU alone the air transport industry supports 7.8 million jobs and contributes 475 billion € to the union's gross domestic product (GDP) – which is equivalent to almost 4 % of the union's total GDP. Globally the aviation industry accounts for 3.5 % of the global GDP and supports 56.6 million jobs (ATAG, 2012).

In a Danish context aviation is also a very important component in continued economic growth and prosperity. Aviation can help in pushing the range of export activities further away from Denmark. Especially air transportation of high-value products, perishables and temperature sensitive products is an important component in relation to Denmark's export strategies that to a high degree focus on export of food, knowledge based solutions and advanced technologies. In Denmark Aviation supports more than 45,000 jobs (BDL, 2012).

### 4.2 Measures to Reduce Environmental Impact

Aviation has a very large carbon footprint, a footprint, which under a "business as usual / no mitigation-scenario", is expected to increase significantly (IPCC 1999, Sustainable Aviation 2012, *et al.*).

In spite of the recession and the terrorist attacks of 9/11 2001 the last decade has seen a steady increase in passenger kilometers. This increase is expected to continue in the foreseeable future (IATA 2013b).

As demands on commercial aviation increase the necessity for reducing the environmental impact is becoming more and more urgent. Consequently a number of initiatives have started to research and develop measures to achieve a more sustainable commercial aviation industry. Whereas many initiatives focus on the development of sustainable fuels for aviation, a number also include other measures for sustainable aviation.

---

Measures to *reduce* the negative environmental impact of aviation are listed in the following:

- Efficiency by performance improvements in commercial and military aircrafts
  - Improvements in engine efficiency and aerodynamics of aircrafts, as well as lightweight advanced materials
- Fuel efficiency by Air Traffic Management (ATM) enhancements, such as
  - European Union – Single European Sky (SES) and Single European Sky ATM Research (SESAR), etc.
- Airline operational improvements
- Airports' operational and infrastructure improvements
- Use of sustainable manufacturing processes and materials
- Progressive recycling and reuse of materials and products
- Lighter-than-air cargo transportation for non-time critical demands and super-heavy lifts (e.g. the German "CargoLifter", Department of Defense / NASA initiatives and others)<sup>2</sup>
- Electrification of niche aviation demands
  - Surveillance, mapping and other applications by drones and other electrically powered devices

Improvements in the efficiency of aircraft as well as airline and airport operations have already lead to a 70 % reduction in fuel consumption per passenger kilometer since the introduction of jet aircraft (ATAG, 2012).

In addition to these measures a range of technological and other developments will lead to a decrease (or slower increase) in certain types of commercial aviation demands. Among these are:

- Increase in use of high-speed rail transportation for medium and short distance travel

---

<sup>2</sup> Lighter-than-air transport essentially means aircraft that rely on being lighter than air, such as hot air balloons and airships, and not aero foils (wings) to achieve flight. Some of the advantages to these types of aircraft are an extremely high cargo carrying capacity, low fuel consumption and low costs. Some of the downsides are that these aircraft are very slow and that dedicated infrastructure may be necessary to accommodate them at airports.



- 
- Increase in use of telepresence to replace business travel

Finally a range of economic (political) measures may be employed to reduce the impact of aviation:

- Taxes and levies
- Market based measures such as emission trading systems
- Subsidies, incentives and other economic support measures for sustainable aviation

Emissions trading systems, such as the European ETS, have been heavily discussed as a possible economic tool to cap and decrease the GHG emissions from aviation. There has, however, not developed an international consensus regarding their use as a tool, and the issue is still heavily debated. An advantage to this approach is that it is technology agnostic and would allow the market and the aviation industry to “pick the winners” with respect to the most efficient means for reducing their environmental impact. It is, however, clear that an employment of such a system should as far as possible be done on a global level so as not to introduce unbalanced competitive environments for different airlines.

There is also the possibility of a technology shift wherein the invention of a new technology negates some, or all, of the negative environmental impact of aviation as well as the concerns with regard to fuel scarcity and price developments. But, as such developments are practically impossible to foresee, and may not occur for a very long time (if at all), they can hardly be counted as a contingency against these concerns.

### **4.3 Why Substitute Aviation Fuels?**

Even though the described measures, if fully employed, may serve to decouple the rising demand for commercial aviation from a rising environmental impact, they are unlikely to yield significant absolute reductions in the impact, especially concerning the contribution to anthropic climate change.

Thus, there is a clear need for further measures to be taken. Since electrically powered commercial aviation shows very limited promises for substituting any significant part of the demand, substituting the fuel combusted in aircraft engines is the only viable way of further reducing the environmental impact both in the long and short term.

Figure 1 illustrates ATAG’s view on the necessary measures (and their individual contribution to reducing emissions) to achieve industry goals. Also illustrated is the projected rise in emissions resulting from a “no-action” (business as usual) scenario.

An incremental introduction of sustainable fuels into the fuel streams of commercial aviation is currently the only possible path towards low or zero CO<sub>2</sub> commercial aviation.

This conclusion is supported by a number of organization working for sustainable aviation, among others BDL, NISA, IATA, SAFUG and ATAG.

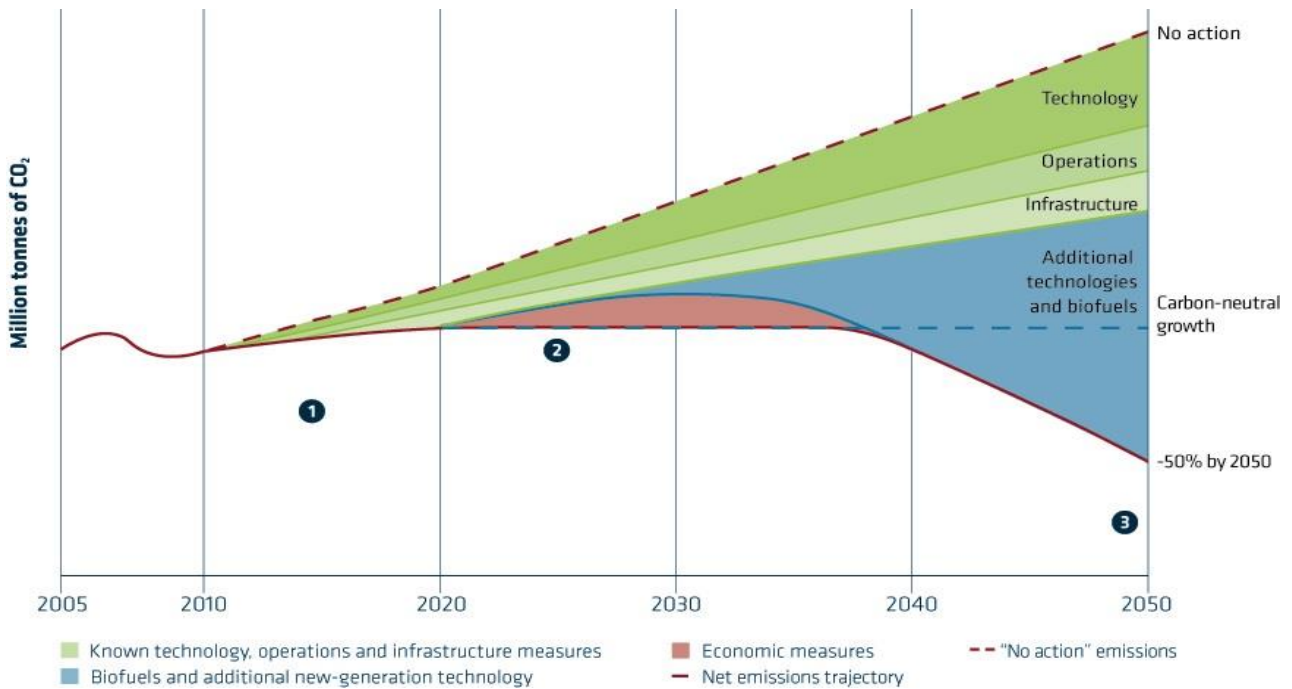


Figure 1: The Air Transportation Action Group (ATAG) emissions reduction roadmap from 2010 (as a schematic indicative diagram). Source: (ATAG, 2010). Non-Environmental Benefits

A number of other benefits can motivate a substitution of fossil based aviation fuels (IATA 2013c). Among these are:

- Supply diversification
- Operational reliability
- Regional economic development and expansion

#### 4.3.1 Supply diversification

Alternatives to fossil based aviation fuels offer operators a chance to diversify supply sources for greater stability and independence. They also offer the opportunity to reinvent aspects of fuel supply chains with economic and environmental benefits as a consequence.

---

#### 4.3.2 *Operational reliability*

Because of the increase in the demand for fossil based products and the non-renewable nature of these resources aviation fuels may become scarce in the future with possible disruptions to the operational reliability of aviation operators. Alternatives to the fossil based products can serve as an extra source of operational reliability for civil as well as military aviation operators.

#### 4.3.3 *Regional economic development and expansion*

The research into, development of and, eventually, commercial scale production of sustainable fuels for aviation has the potential for generating many new (green) jobs across a number of sectors and industry. This aspect is treated further in Section 12.

---

## 5 JET FUEL DEMANDS IN DENMARK

This section describes the current Danish jet fuel consumption and the projected future demand. The quantities of fossil fuels to be substituted by sustainable alternatives are estimated based on the national goal of a fossil free energy system in 2050.

### 5.1 Current Danish Jet Fuel Consumption

There are basically two types of aviation fuels consumed in Denmark: Avgas (for piston engines) and Jet A-1 (for jet and turboprop, which constitutes the majority of all commercial flights). The consumption of Avgas is less than 2 % of the consumption of Jet A-1 and consequently this report will primarily focus on the consumption of Jet A-1 fuel<sup>3</sup>.

The total consumption of Jet A-1 in Denmark from all consumers was approx. 37.3 PJ, equivalent to 860,000 tonnes, in 2012 (Table 1). Out of this about 87 % was consumed by aircraft fueling at Copenhagen Airport.

Table 1: The total consumption of aviation fuels in Denmark for domestic and outbound flights. Source: Danish Energy Agency.

	2010	2011	2012
Total consumption [1000 tonnes]	843	879	860
Avgas [1000 tonnes]	2	1	2
JP1 / Jet A-1 [1000 tonnes]	841	878	858

### 5.2 Projections for Danish Jet Fuel Consumption

We have explored a range of scenarios for the development in the Danish consumption of fuels for aviation, ranging from the standard projections from the Danish Energy Agency to scenarios wherein the consumption increases or decreases significantly due to changes in the Danish and Scandinavian airline industry. The resulting consumption in these different scenarios are described in Appendix 4. In the following sections we have chosen to use the standard projection from the Danish Energy Agency for comparability with the national projections for the development in the energy system.

---

<sup>3</sup> The specification for jet fuel for military aviation is different from Jet A-1 which is the commercial / civil specification for jet fuel, for instance it is labeled JP1 for Jet propellant 1 by several militaries around the globe, but also has other names. For purposes of clarity this report will treat all jet fuels as Jet A-1.

### 5.2.1 The Danish Energy Agency

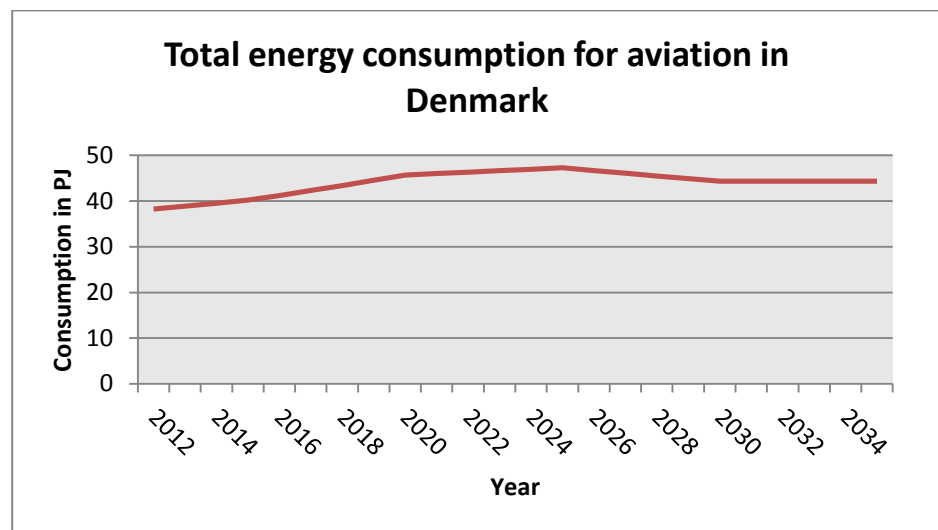
The Danish Energy Agency projects a rise in the energy consumption for outbound aviation until 2025 where they project a decrease for the next five years until the consumption reaches a steady state by the end of 2030. The consumption for domestic aviation is projected to remain at approx. 1.5 PJ, or 35,000 tonnes, until 2035.

This figure is the total quantity of jet fuel consumed by aircraft fueling in Denmark, including the aircraft that, for instance, use Copenhagen Airport as a hub but also service other airports as well as long distance flights. This means that the total consumption of aviation fuels in Denmark is significantly higher than that consumed for domestic flights only.

From 2013 to the end of 2015 the Danish total consumption of energy for aviation (domestic and outbound) is projected to increase by 2 % annually. From 2016 to the end of 2020 the consumption is projected to increase by 3 % annually and from 2012 to the end of 2025 to increase by 1 % annually.

From 2026 to the end of 2030 the consumption is projected to decrease by 1 % annually and reach a steady state from 2030 and onwards (no significant change). Figure 2 shows the projected development in Danish jet fuel demands.

Figure 2: The projected development in Danish energy consumption for aviation, data from the Danish Energy Agency.



In absolute numbers the energy consumption for commercial (civil) aviation is projected to be as shown in Table 2.

Table 2: The projected demand for energy for commercial aviation in Denmark<sup>4</sup>.

Energy consumption for transportation	2012	2015	2020	2025	2030	2035
Domestic flights - consumption [1000 tonnes]	35	35	35	35	35	35
Outbound (international) flights - consumption [1000 tonnes]	860	904	1,033	1,070	1,002	1,002
Aviation (civil) total - consumption [1000 tonnes]	895	939	1,068	1,105	1,037	1,037

The peak demand, projected to be in 2025, is 45.8 PJ or 1.1 mill. tonnes.

### 5.3 The Required Quantities for Substitution

Appendix 4 details a range of different scenarios for the future Danish jet fuel demand as well as a range of scenarios resulting from different strategies for introducing sustainable fuels for aviation.

The scenario highlighted in this section follows the Danish Energy Agency's projection for the future aviation fuel demand and further follows the Danish nation goal for a fossil free energy system by 2050. The scenario assumes a linear introduction of sustainable fuels for aviation from 2015 to complete substitution by 2050.

Table 3: The required quantities of fossil aviation fuel to substitute following a linear introduction of sustainable fuels to meet the national goal of a fossil free energy system in 2050.

Year	2015	2020	2025	2030	2035	2040	2045	2050
Quantity needed for substitution [1000 tonnes]	0	148	296	445	593	741	889	1,037

<sup>4</sup> The figures also contain the consumption of Avgas which makes up about 2 % of the total consumption. Also the method for projecting the energy consumption for transport differs slightly from the method used for counting the energy consumption historically, hence the difference in the listed consumption for 2012.

---

The results clearly show that there is a very large demand for sustainable fuels for aviation in the near future. Currently we have found no concrete plans for a Danish production that could cover any significant percentage of this demand.

---

## 6 TECHNICAL SPECIFICATIONS – JET FUEL

Aviation fuels are, for obvious reasons, very regulated and must meet strict specifications for use in commercial as well as military applications.

It should be noted that there currently are globally accepted standards for *alternative jet fuels*, but not specifically for *sustainable jet fuels nor the sustainability of jet fuels*<sup>5</sup>. The criteria for the sustainability of a given alternative aviation fuel are treated in Section 3.

### 6.1 American Society for Testing and Materials (ASTM) – Technical Certification

The responsible body for evaluating and approving new aviation fuels is the American Society for Testing and Materials (ASTM) International Committee D.02 Petroleum and Lubricants, Subcommittee J.

Developers of sustainable fuels for aviation must participate in this committee and engage other members to acquire and evaluate data, and address questions and concerns raised by subcommittee members. Upon approval the new fuel will be added as an annex to the ASTM D7566 standard. The certification process is further described in Appendix 1. In the following the certification status of different pathways are summarized. The technologies are treated further in Section 7.

The two alternative aviation fuels, Fischer-Tropsch synthesized and Hydrotreated Esters and Fatty Acids (HEFA), have passed the approval process and were added to the standard as annex 1 and 2, respectively.

Two task forces in ASTM are currently working to certify Alcohol to Jet (AtJ-SPK and AtJ-SKA), one is focused on synthetic paraffinic kerosene (SPK) and one focused on synthetic paraffinic kerosene with aromatics (SKA). The SPK task force expects to have completed certification in 2014 and the SKA task force in 2015 (SkyNRG, 2014).

Two other pathways to sustainable fuels for aviation are also in process for certification by ASTM task forces, Direct Sugar to Hydro Carbons (DSHC) and Hydrotreated Depolymerized Cellulosic Jet (HDCJ), but are early in the process and the specific blend-in requirements are, as of yet, unclear due to the nature of these to fuel components.

The ASTM SAK task force focusses on certifying Synthetic Aromatic Kerosene (SAK), a product that is produced by a catalytic process that converts soluble sugars to aromatics in the kerosene range. The ASTM SK task force focusses on

---

<sup>5</sup> The general term “alternative jet fuel” describes any alternative to crude oil-based fuels, including liquid fuel produced from natural gas, liquid fuel from coal and biofuels (ATAG, 2009). A sustainable jet fuel is an alternative jet fuel produced in a way and from resources that meet a set of sustainability criteria.



---

a process similar to the SAK task force, but the product is a pure Synthetic Kerosene stream (no aromatics).

Another task force is working on Catalytic Hydrothermolysis (the ASTM CH task force). The process is similar to the HEFA process but uses water based catalysis to plant and animal fat to a hydrocarbon fuel that contains both paraffins and aromatics.

Finally, a task force focused on co-processing is currently established. The idea is blend oils derived from both crude oil and biological (i.e. synthetic) sources upstream in the production processes. This means that the crude oil and bio-based components undergo hydrotreatment (and eventually distillation) together, improving efficiency and allowing for the utilization of existing infrastructure and process knowhow. It would also result in reduced expenses for certification as the blended fuel could be certified together after refining under ASTM D7566, instead of a separate certification under the ASTM D1655 and D7566 respectively and additional certification of the blended fuel product<sup>6</sup>.

## **6.2 The Commercial Aviation Alternative Fuels Initiative (CAAFI) – Readiness Tools**

The Commercial Aviation Alternative Fuels Initiative (CAAFI) has developed a number of “readiness tools” to create a common language and understanding of the development stages of sustainable fuels for aviation production pathways. Among these are the Fuel Readiness Level (FRL), Feedstock Readiness Level (FSRL) and Environmental Progression. The readiness tools are further described in Appendix 1. The three terms may be used to determine the readiness of a given biofuel for commercial use and take parameters of feedstock sustainability as well as level of commercialization into account (CAAFI / A4A, 2013). However, social and economic aspects are not considered and the definition of feedstock sustainability is also debatable in relation to the considerations mentioned in Section 3.5.

The tools are developed by CAAFI for use by developers of sustainable fuels for aviation and it is the recommendation of this report that potential developers make use of these tools and the assistance and support afforded by international as well as national initiatives for sustainable aviation. For developers in the Nordic region one of the important first steps would thus be to contact the Nordic Initiative for Sustainable Aviation (NISA) and make full use of the initiatives competencies and network.

## **6.3 Fuel Inspection and Certification**

There are very strict demands on the traceability of aviation fuels.

---

<sup>6</sup> Provided that a co-processing annex is made to the ASTM D7566 standard following the task force’s work.

---

The requirements for aviation fuels specify that fuels must be inspected and certified every time it is transferred from one system or container to another. The fuel must be tested for adherence to the specific standard (ASTM in the US and DefStan in Europe), for contamination and to verify its origins.

---

## 7 TECHNOLOGIES AND PRODUCTION

This section will first describe general processes to convert feedstock to jet fuel and how the technologies are applied in different international companies. Different developing and available technologies in Denmark and potential pathways for a Danish production of sustainable fuels for aviation are identified.

### 7.1 Biorefining

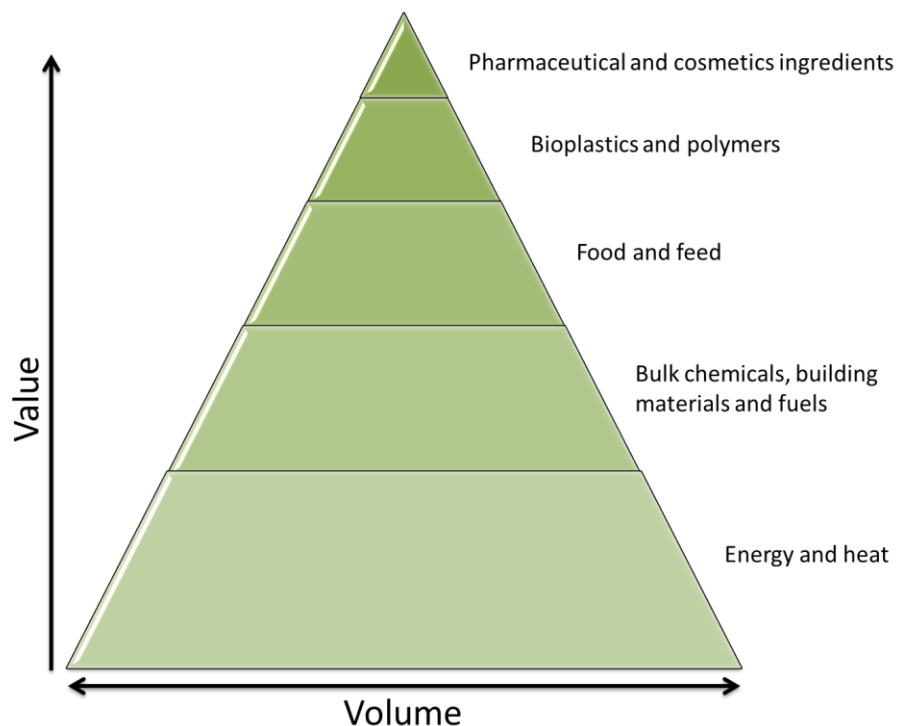
In the context of this report, the production of biofuels is seen as part of a bio refining complex. The principle of biorefining is to extract products and materials in cascading orders of value from an organic feedstock. This means that from the feedstock several products are produced by different levels of refinement, yielding smaller and smaller volumes at higher orders of refinement.

This principle is also referred to as “biomass cascading” by several authors, i.e. the maximum extraction of value from a given biomass by the cascaded use of the different quantities and qualities of products and materials the biomass can yield through fractioning and (bio)refining.

The extraction, refinement and sale of higher order products, for instance pharmaceutical ingredients, can thus help finance the extraction and production of lower order products, such as bulk chemicals or energy and heat from the feedstock.

---

Figure 3: The “biorefining pyramid” showing the relationship between volume and value of different products extracted from biomass in a biorefinery.



---

Another key element in biorefining is that valuable nutrients, such as phosphorus, are returned into their natural cycle. An example of this is when degasified substrate (digestate) from a biogas plant, being the “last link in the chain” after a biorefinery has extracted high value products, is returned to farmers’ fields to help fertilize next year’s crops (of sustainable biomass). Thus phosphorus, nitrogen and other nutrients are reintroduced into their natural cycle.

## 7.2 Sustainable Jet Fuel Production

Biomass mainly consists of proteins, fatty acids, carbohydrates and lignin. Carbohydrates, which can be divided into cellulose, hemicellulose, starch and sugars, and fatty acids are currently suitable for product of aviation fuels. Developments are also underway to utilize lignin for fuel production, but so far only aimed at producing heavier fuels such as marine bunker. In the future, as technologies develop, it may be possible to convert all components of the biomass into useable fuels. It is, however, unlikely that proteins are used for fuel as they are a valuable resource for feed and other high-value purposes.

Jet A-1 consists of kerosene. Kerosene is a fraction of crude oil (petroleum) consisting of a complex mixture of different hydrocarbons (paraffins, cycloparaffins, aromatics and olefins) with a typical number of carbon atoms in each molecule of 9-16. Thus, the purpose is to convert carbohydrates, lignin and fatty acids to hydrocarbon chains with a minimum of oxygen content. This can be done either physically (thermally and/or by pressure), chemically or biologically.

### 7.2.1 *Feedstock groups for sustainable aviation fuel production*

Depending on the specific process different components of the feedstock are used. Thus, based on the feedstock, biofuel production can roughly be divided into three major groups, corresponding to what intermediary product is needed for the process:

#### **Lipids**

- Palm oil
- Rapeseed oil
- Used cooking oil
- Jatropha
- Camelina
- Tall oil
- Micro algae

---

## Gas

- Animal manure
- Municipal waste
- Most organic compounds (all feedstocks suitable for gasification)

## Sugars (carbohydrates)

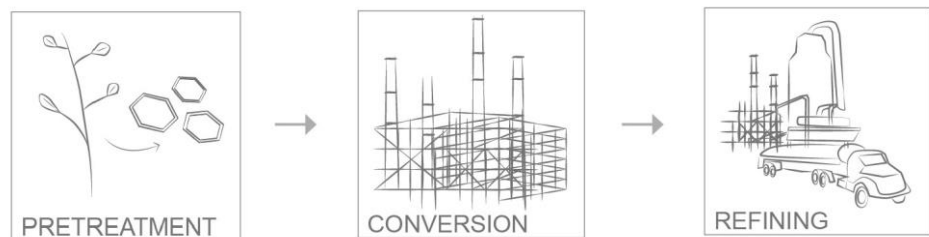
- Sugar cane
- Wheat
- Maize
- Sugar beet
- Straw
- Wood and wood residuals
- Willow
- Macroalgae (seaweed)

### 7.2.2 Basic process from feedstock to aviation fuel

The basic process for producing sustainable fuels for aviation can roughly be broken into three overall process phases as illustrated in Figure 4.

---

Figure 4: Basic process from feedstock to aviation fuel.



Prior to these steps is the generation of knowledge and development of the different processes.

#### 7.2.2.1 Pre-treatment

In the pre-treatment phase the biomass is treated to separate or “release” the individual components so they can be used further on in the process. Depending on the technology, or the desired intermediary product, different approaches exist for pre-treatment.

---

Enzymatic hydrolysis, where chemical bonds are cleaved under the addition of water and facilitated by enzymes, is often used to produce fermentable sugars from lignocellulosic materials.

For producing lipids / bio-oils a range of processes exist that either use the raw feedstock or use sugars extracted from biomass as a feedstock. An example of these processes is hydrothermal liquefaction (HTL) wherein heated, super critical water (under very high pressures) is used to separate the components and a catalyst is used for synthesizing bio-oil. Another alternative is to use the lipids / fatty acids already existing in some feedstock and in these cases the pre-treatment may be as simple as physically pressing oilseeds to gain a bio-oil intermediary product.

Finally, if a gaseous intermediary (syngas) is needed, a range of technologies exist for gasifying biomass feedstock. Today, three methods of gasification are currently available:

- **Fluidized bed:** Operates below the melting point of biomass ashes. The technology is suitable for large-scale production. However, the technology produces syngas of a poor quality that requires further treatment in order to remove impurities.
- **Entrained flow gasification:** A promising technology for large-scale production. Operates just above the melting point of the biomass. Produces a syngas of better quality than the fluidized bed technology, however, currently has higher investment costs.
- **High temperature gasification using plasma torch:** A new technology. Globally, several facilities using the technology are planned.

#### 7.2.2.2 *Processing / Conversion*

Depending on the intermediate product the next phase employs a host of different technologies to produce another intermediary product that can in turn be refined into sustainable fuel for aviation.

Sugars are, in most approaches, fermented into bio-alcohols that are then treated through various processes to obtain a hydrocarbon product suitable for refinement into aviation fuel (see the following section). Another alternative is to use microbial processes to convert the sugars into a bio-oil.

Lipids / Bio-oils are often hydrotreated to either crack long chained molecules and / or remove excess oxygen and aromatics from the product.

Using syngas a catalytic conversion is often employed to produce a liquid hydrocarbon fuel that can be refined into aviation fuel.

---

### 7.2.2.3 *Refining*

The final phase is refining, wherein the hydrocarbon fuel is separated into different fragments, called distillates, for use in different applications. During the refining phase impurities, such as sulphur, are also removed. Other process steps may be needed to ensure the proper characteristics of the final product, among these the addition of special additives.

The main process of this phase is distillation where the fuel is heated until it evaporates. Depending on the specific characteristics of the individual components of the fuel it will condense at different temperatures (lighter products will condense at lower temperatures). This means that several different fractions, called distillates, can be obtained from the same “crude bio fuel”.

Figure 5 on the next page provides a schematic overview of the different pathways based on the ASTM task forces.

The following technologies will be further described in the sections below:

- Fischer-Tropsch synthesis (gas based)
- Hydrotreated esters and fatty acids (lipid based)
- Alcohol to jet (sugar based)
- Direct sugar to hydrocarbons (sugar based)
- Hydrotreated Depolymerized Cellulosic Jet (sugar based)

# ASTM D7566 TASK FORCES

Adapted from Brown, Iowa State, 2012 and Tim Edwards, USAF/AFRL

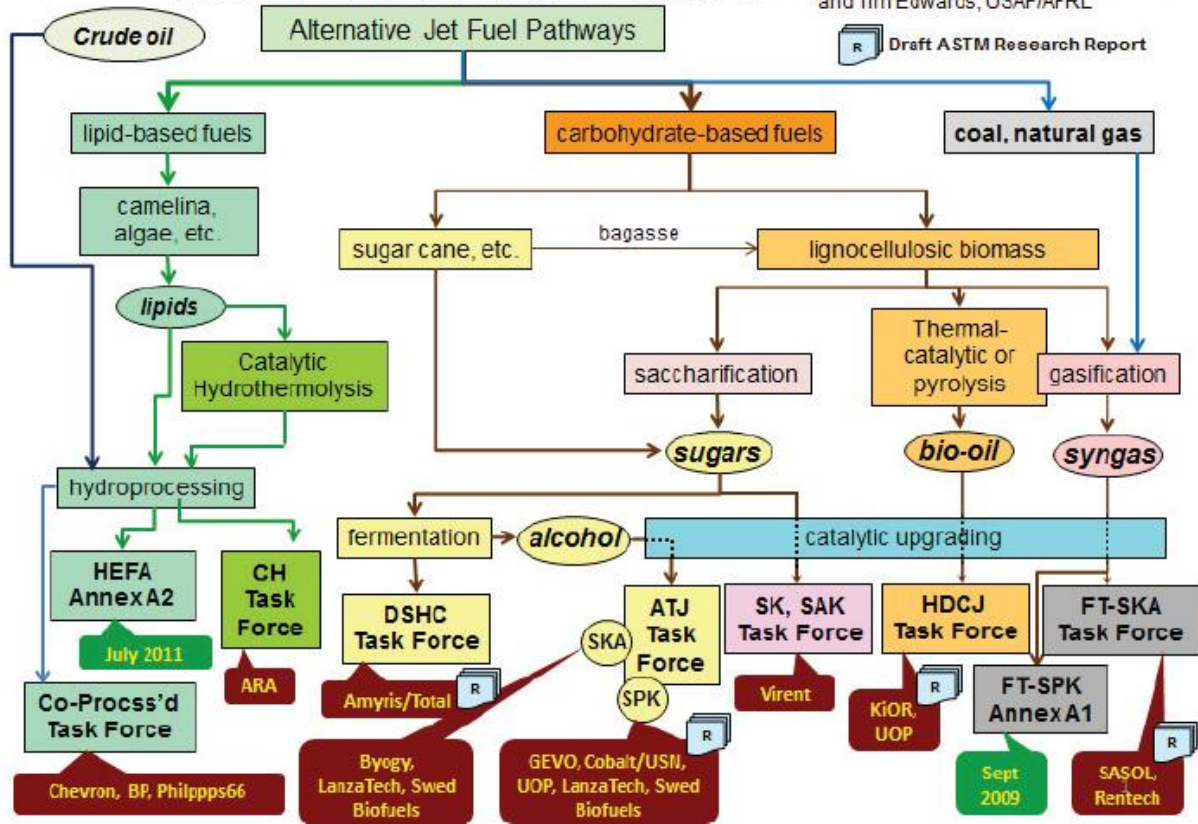


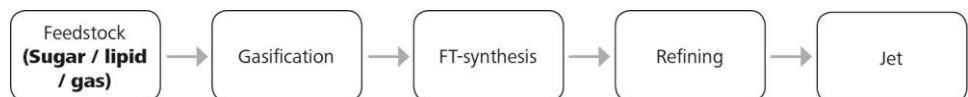
Figure 5: Overview of all current and developing pathways of jet fuel production. The individual pathways will be illustrated in the following section. Source: (IATA, 2013c)

### 7.2.3 Fischer-Tropsch Synthesis

The Fischer-Tropsch synthesis (FT-SPK) was certified for jet fuel production by ASTM in 2009, however, the process was pioneered already in 1920 by Franz Fischer and Hans Tropsch. In the process a syngas is prepared by gasification of feedstock.

Any carbon source can potentially be used as feedstock for the syngas which consists of carbon monoxide (CO) and hydrogen (H). Thus, all the different types of feedstock can be used (wood, straw, organic waste etc.).

Figure 6: Different steps from feedstock to finished product using the Fischer-Tropsch-synthesis. Adapted from: (Avinor, 2013).



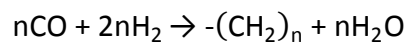


---

First, the biomass undergo gasification in order to break down large molecules into CO and H. This is typically the most energy-intensive and expensive step in the production.

After gasification the syngas still contains impurities such as tar, methane, carbon dioxide and acidic gasses which must be removed prior to the FT-synthesis. This is done catalytically, thermally and / or by scrubbing using different chemicals.

The pure syngas is ready for the actual FT-synthesis where CO and H are converted to long hydrocarbon chains using a catalyst, typically made from iron (Fe) or cobalt (Co). The equation below describes the process:



The FT-synthesis is exothermic meaning that heat is produced. This heat must be rapidly removed in order to avoid overheating of the reactor. Furthermore, too high temperatures favor the formation of methane and not the desired long hydrocarbon chains.

A FT-synthesis and following refining can produce a variety of different products. One facility can adjust the process and make different products. In addition excess heat, electricity and byproducts can be sold in order to make the process more economically feasible.

### **International Applications**

The FT-synthesis is applied in commercial fuel production processes of several international companies. Syntroleum, an American company, uses the FT-synthesis to produce both sustainable and fossil fuels for transport including aviation. The first facility for the production of sustainable fuels uses fats and oils from a meat processing company located in Louisiana. The plant can produce nearly 300 mill. liter synthetic fuels per year.

Velocys is a British company specializing in gas-to-liquid and biomass-to-liquid production using the FT-synthesis. Velocys has been selected for the GreenSky project in London, which is a commercial jet fuel facility designed to convert 500,000 tonnes of solid waste destined to landfill into 50,000 tonnes of jet fuel. The facility will use plasma torch gasification of the solid waste supplied by the American company Solena.

Another supplier of the plasma gasification technology is the American company Westinghouse Plasma Corp. The technology is currently installed in three commercial plants in India and Japan, where municipal and hazardous waste is gasified, and an additional four plants are under construction.

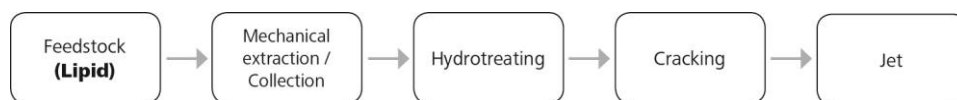
---

### 7.2.4 Hydrotreated Esters and Fatty Acids

Hydrotreated esters and fatty acids (HEFA-SPK) was certified by ASTM in 2011. The process is an example of lipids conversion using triglycerides and fatty acids from bio-oils. The purpose of the process is to remove nearly all oxygen and impurities from the oil leaving only hydrocarbon chains.

---

Figure 7: Different steps in the production of Hydrotreated Esters and Fatty Acids-SPK. Adapted from: (Avinor, 2013).



Oil is produced by the pre-treatment processes described in Section 7.2.2.1. and impurities such as oxygen, sulfur and nitrogen are removed using a catalyst. The oil is then refined under the addition of hydrogen, however, the hydrocarbon chains are at this step too long for the oil to meet the physical and chemical specifications of Jet A-1. Thus, by cracking the oil the chains are broken down to chains of 9 to 16 carbon atoms. 50-70 % of the initial HEFA oil is used in the final jet fuel product. The remaining consists of biodiesel, bio naphtha and biogas. Cracking is a well-known process from conventional crude oil refineries and thus, co-processing is a possibility. At the current stage of development, HEFA-SPK can be mixed in a 50:50 ratio with conventional jet fuel.

#### International Applications

SkyNRG is a Dutch based company and the largest supplier of sustainable jet fuel in the world and so far primarily uses HEFA technology with used cooking oil as the feedstock. SkyNRG is feedstock and technology agnostic and has gained experience in the assessment and development of sustainable jet fuel markets. In March 2014 SkyNRG and Statoil Aviation announced a long term co-operation with the goal to accelerate the demand for and supply of sustainable jet fuel for the Nordic region. Next to supplying sustainable jet fuel, the co-operation will focus on the development of "BioPorts" - regional supply chains turning sustainable feedstock into sustainable jet fuel that are price competitive with fossil jet fuel.

Neste Oil (Finland) and Honeywell UOP have produced jet fuel by the HEFA-process used in several commercial flights in a 50:50 blend with conventional jet fuel. The feedstock has been used cooking oil and vegetable oils. Neste Oil has started a co-operation with the Danish DONG Energy / Inbicon. In this co-operation the Inbicon technology of DONG Energy, that will be described more detailed in Section 7.4, will extract cellulosic sugars from straw. After this Neste

---

Oil converts the sugars to lipids by microbial processes, and finally convert the lipids to fuels using the HEFA process.

#### 7.2.4.1 *Green Diesel*

Green diesel for aviation, also known as renewable diesel, is produced very similarly to HEFA-SPK using vegetable oils and animal fats as feedstock. Although using the same feedstock, green diesel should not to be mistaken with “bio-diesel” that is made by a process of trans-esterification of oils and fatty acids, whereas biodiesel consists almost exclusively of fatty acid methyl esters (FAME). Chemically diesel and Jet A-1 are very similar. In addition green diesel can be blended with conventional fossil fuels for e.g. heavy trucks and trains.

Green diesel has recently been attracting a lot of attention from the sustainable aviation community as a blend-in sustainable aviation fuel. If approved by ASTM green diesel will be added as an annex to the HEFA process (Advanced Biofuels USA, 2014).

#### 7.2.5 *Alcohol to Jet*

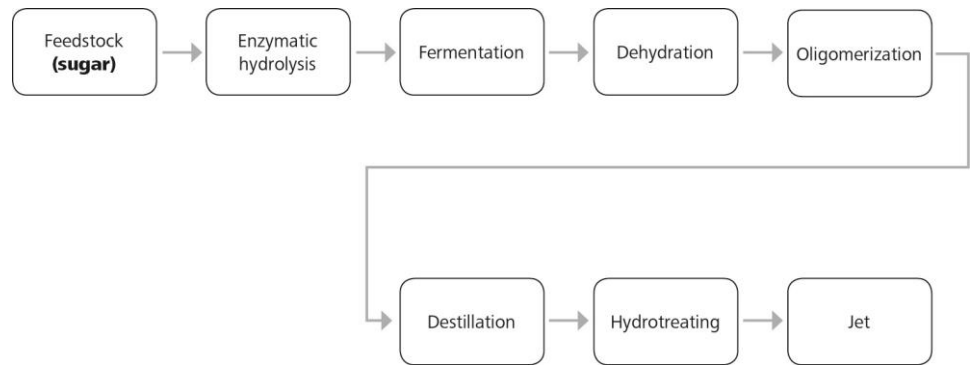
Alcohol to jet (AtJ-SPK) is a process converting alcohols into paraffins and hence jet fuel. The process is currently in the approval phase by ASTM. Bio alcohols can be produced from both starch, sugars, algae and lignocellulose from wood and plants, and can follow many different pathways. Usually the biomass is either gasified or hydrolyzed prior to fermentation. Lignocellulose is for instance thermally treated with acid or enzymes in order to break open fibers to sugars. The most important alcohols in the AtJ-process are:

- Bio ethanol
- Bio butanol (including n-butanol and isobutanol)
- More complex alcohols such as hexanol (alcohol containing six carbon atoms).

Especially during the gasification and hydrolysis of biomass a number of by-products that cannot be fermented into alcohols are formed. These byproducts include lignin from lignocellulose and other chemicals. The fermentation process is a typical fermentation process under anaerobic conditions.

Figure 8 illustrates the different steps in producing jet fuel using the AtJ-process. First the alcohols are dehydrated using a catalyst at 300-500 °C. This forms olefins, which are the building blocks of the desired paraffins, and ethers as byproduct. Through a number of rather complex steps SPK is produced from the olefins.

Figure 8: Steps in producing Jet A-1 from bio alcohol (Adapted from Avinor, 2013).



### International Applications

As mentioned the AtJ-process has not yet been certified by ATSM, however, several companies have succeeded in producing jet fuel by the AtJ-process and the process is expected to be certified in 2014.

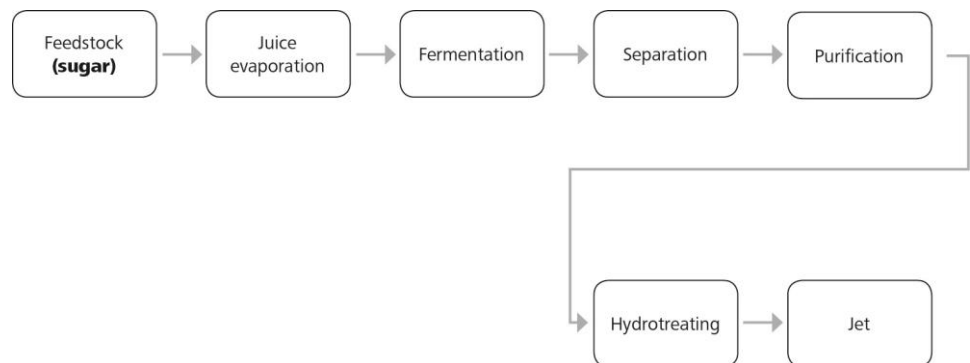
The American company Gevo specializes in biofuels from isobutanol. In addition, Swedish Biofuels produces different alcohols from cellulose from wood.

Cobalt Technologies and the US Navy are cooperating to develop sustainable jet fuel from butanol using cellulose and hemicellulose as feedstock.

#### 7.2.6 Direct Sugar to Hydrocarbons

The Direct Sugar to Hydrocarbons (DSHC), also referred to as direct sugar to jet, process is a biological conversion of sugars to hydrocarbons using microorganisms. The process is currently under an ASTM task force with research reports under preliminary review (IATA, 2013c). Where the classic fermentation of sugars to alcohol is under anaerobic conditions, the biological conversion of sugars into jet is aerobic. The process is illustrated in Figure 9.

Figure 9: Direct sugar to hydrocarbons pathway



---

The feedstock can be any cellulosic material such as maize stalks or wood. The feedstock is pre-treated using enzymatic hydrolysis. After hydrolysis the resulting juice/syrup is filtered in order to remove lignin-rich solids and to purify it.

Subsequent to solids removal the sugar stream may be sent directly to the biological conversion or further processed to concentrate the sugars by evaporation or other means (NREL, 2013). After the biological conversion the end-product must be separated from the water phase. Here the paraffin production has an advantage over ethanol fermentation, as the solubility of long hydrocarbon chains in water is low and the two phases relatively easily separate.

The biological conversion is, as mentioned, carried out under aerobic conditions unlike traditional fermentation of sugars.

Microbial processes are very complex and due to this difficult to optimize. The current process has its base in traditional ethanol fermentation as the processes are similar. This means that it is the same pre-treatment and enzymes that are applied as in ethanol fermentation. However, the microorganisms are different and hence the processes are not identical. Thus, research must be conducted in order to optimize the process. Fortunately, microorganisms can be genetically engineered to produce the desired products with high yields and value (NREL, 2013).

### International Applications

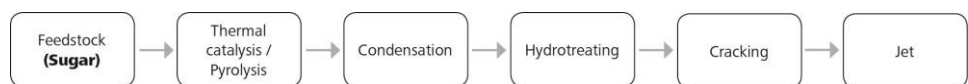
Amyris, Inc. is an American company and is partnering with the French company Total to produce jet fuel. Test flights have been performed with jet fuel from sugar canes.

#### 7.2.7 Hydrotreated Depolymerized Cellulosic Jet

Hydrotreated depolymerized cellulosic jet (HDCJ) is a pathways using lignocellulose, mainly wood, as feedstock. The process is currently under an ASTM task force with research reports under preliminary review (IATA, 2013c).

---

Figure 10: Hydrotreated Depolymerized Cellulosic Jet pathway



The feedstock is initially converted to bio-oil. This can be either by a thermal-catalytic or pyrolysis process. The thermal-catalytic process is similar to Fluid Catalytic Cracking (FCC) which is a well-known process in conventional crude oil refinement. In the pyrolysis process the lignocellulose is heated in the absence of oxygen. The bio-oil is then condensed and can be further treated.

---

In addition to bio-oil, light gasses and water are formed. These are removed by subsequent separation. The light gasses can be used to produce electricity. The bio-oil is refined under the addition of hydrogen, as in the HEFA-process, to produce jet fuel.

The American Kior has successfully produced jet fuel from wood using the HDCJ pathway. A commercial facility has been constructed in Mississippi, US, processing a daily amount of 500 tonnes of wood into different fuels. Kior is planning a new facility three times the size of the current.

### **7.3 Technology Perspectives**

The different pathways described in the previous sections are all ASTM certified or expected to be certified within a reasonable time frame. Considering how extensive the certification process is, it is these technologies that must be the initial technologies in a Danish production of sustainable fuel for aviation. However, in a perspective of 15 to 20 years there are technologies that can prove more sustainable and efficient than the current. In the following a few promising new technologies are introduced. This sub-section briefly discusses two perspective advancements in technology that could significantly decrease the cost of producing sustainable fuels for aviation to illustrate the impact new technologies may have.

#### **7.3.1 Separation Technologies**

Currently, a hurdle in converting feedstock to sustainable fuels for aviation is in extracting sugars from lignocellulose molecules.

At Eindhoven University of Technology a new type of deep eutectic solvents has been developed to dissolve lignocellulose into cellulose and lignin. Using the new solvent the paper industry is estimated to achieve a 40 % energy reduction and thus the energy consumption in biofuel production is also expected to be reduced significantly. After the separation the dissolved lignin, cellulose and solvent can be recovered. Large scale applications are expected to be possible in around 15 years.

A team of Danish and Iraqi researches have synthesized an organic acid from rice husks that can break down cellulose to sugars (Hello *et al.*, 2014). Rice husks are a byproduct in most of the world. The acid can replace enzymes that currently are an expensive part of the extraction of sugars.

#### **7.3.2 Hydrogen Production**

Hydrogen is an important component in many pathways to produce sustainable fuels for aviation. It is, however, energy intensive and expensive to produce.

---

An advantage in a Danish context is that renewable electricity from e.g. wind turbines can be used to produce hydrogen by electrolysis, although still at relatively high energy expenses.

Haldor Topsøe (a Danish leading producer of catalytic technology, see section 7.4.2.2) recently announced their work on an alternative to conventional electrolysis for hydrogen production. Essentially a reversed Solid Oxide Fuel Cell (SOFC), the Solid Oxide Electrolysis Cell (SOEC) is planned to produce hydrogen at significantly lower costs than traditional processes. This is a major potential benefit for several of the sustainable aviation fuel pathways currently employed or under development as hydrogen is a significant component in their processes.

#### **7.4 Danish Jet Fuel Production – Current Technologies**

The previous sections show that international companies already have initiated sustainable fuel for aviation production, even on an industrial scale, with several pathways en route to becoming ASTM certified.

In Denmark several emerging technologies show great potential with respect to establishing a sustainable aviation fuel production. However, as of yet only laboratory or small scale production have been established in Denmark. No technology for aviation fuel production is currently commercialized, but several technologies for biofuel production for other purposes have already been developed and commercialized.

This section describes technologies that are currently available in Denmark, as well as those under development, and attempts to highlight where these technologies in combination with each other or technologies from international partners may lead to feasible production pathways to sustainable fuels for aviation in Denmark. The content of this section is a synthesis of information published by the companies and organizations behind the technologies and information gathered by the authors in direct dialogue with representatives and researchers from the various organizations.

The companies and organizations are relevant in the context of the entire biorefining concept introduced in Section 7.1, however, the main focus is the production of sustainable fuels.

We refer to the following section for a discussion on the feedstocks available and suitable for the technologies described in this section.

##### **7.4.1 *The Danish Bio Technological Tradition***

Denmark has a long tradition for developing bio technology, which has led to the growth of a series of industries and research environments that are among the

---

global leaders within their respective fields. The formation and growth of these environments can be traced back to the Danish tradition for upgrading and refining agricultural products and production.

A pioneering name in this field is the Danish brewery giant Carlsberg. In 1883 the Carlsberg Laboratory isolated the yeast culture *Saccharomyces Carlsbergensis*, which is still the basis for the production of all lagers globally (Carlsberg Group, 2014a). In addition, the concept of pH was invented in the Carlsberg Laboratory, where several advances within protein science were also made (Carlsberg Group, 2014b).

This tradition has given rise to a number of Danish companies that have been highly successful within their respective fields. Among these are Chr. Hansen, a global producer of starters, rennet and food additives, Novo Nordisk, the global leader in insulin production and Novozymes, a global leader in enzyme production.

Also, several research environments have been established in response to the needs of industry and to further the field from an academic point of view. Most notably are the environments at the Danish universities where research and development activities within biotechnologies have contributed significantly to the global know-how and status of the field. Among these lines of inquiry several have been focused on the development of new biofuels. Together with the research environments at the Danish universities, the companies and the tradition for bio technology in Denmark have created several fields of special competencies in Denmark and a body of know-how, that gains Denmark a strategic advantage within the field of biotechnology and consequently within the development and manufacture of biofuels.

Also, know-how and technology developed in the Danish agricultural sector is highly sought after and the sector is widely considered among the best and most efficient in the world, while simultaneously being very environmentally responsible. Denmark, as seen in the mass balance illustrated in Section 8.3, is also a large producer of crops as well as an exporter of a range of agricultural products. This means that Denmark also hosts a wide selection of special competencies within farming and agriculture, as well as an established infrastructure for trading biomass and agricultural products in general.

#### *7.4.2 Danish Technologies for Aviation Fuel or Aviation Fuel Component Production*

The following sections is based on the report “*DENMARK IN A GLOBAL BIO-BASED SOCIETY – do we want to be customers or producers?*” published by Biorefining Alliance in 2012. As the area of biofuels is rapidly evolving the rele-



---

vant companies and stakeholders described in this section have been contacted and information updated for use in this report.

#### 7.4.2.1 *Novozymes*



The Danish company Novozymes is a world leader in the production of enzymes for biofuels. The enzymes produced by Novozymes are used in the pretreatment of lignocellulosic biomass to split it into fractions of lignin, C<sub>5</sub> and C<sub>6</sub> sugars. These sugars are then fermented into ethanol or used in other biorefining processes. The sugars can also be used to produce lipids that can in turn be used to produce aviation fuels (Sugar to Lipids to Jet pathway). Novozymes' enzymes are used in the Inbicon plant in Kalundborg and Novozymes has been heavily involved in the development of the Inbicon technology portfolio.

In October 2013 the world's first commercial scale 2G biofuel plant opened in Crescentino in Northern Italy. Designed to produce 75 mill. liters of biofuels yearly from agricultural waste the plant is a partnership between Beta Renewables and Novozymes. The Novozymes Cellic® enzymes are the base of the pretreatment technology employed.

Novozymes' technology and know-how is essential to several sustainable fuel pathways wherein lignocellulosic materials are converted to a sugar platform that forms the basis for the further process, for example the Alcohol to Jet (AtJ) or Direct Sugar to Hydrocarbons (DSHC) pathways.

#### 7.4.2.2 *Haldor Topsøe*



Within catalytic technology the Danish company Haldor Topsøe has also established a global presence. Much of their experience comes through working with oil refineries and other large scale industrial and chemical processing applications (fertilizers etc.). Today Haldor Topsøe is among the world leader in heterogeneous catalysis and about half of the fertilizer used globally is produced using Topsøe's technology. Haldor Topsøe has a series of special competencies that have been employed in the development of novel technologies for alternative as well as sustainable fuels production.

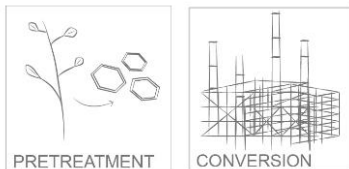
Haldor Topsøe's catalytic technology is used in oil refineries to remove impurities, produce hydrogen for hydrotreating and refining the different products.

The company's catalysts for hydrocracking is also an important component in producing aviation fuels from, for example fat and plant oils, a process central to the production of Green Diesel. Green Diesel is currently attracting a lot attention from the aviation community as a candidate for a blend-in fuel.

---

The company's competencies and products are relevant to a large amount of the current pathways to sustainable fuels for aviation and they are a central stakeholder in the possible development of a Danish industry within this area.

#### 7.4.2.3 *Inbicon / DONG*



Inbicon is a research and technology development company owned by the Danish national energy company DONG. Inbicon develops and markets technologies for the production of industrial sugars as well as cellulosic ethanol.

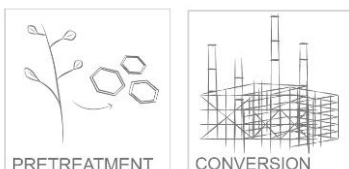
The first pilot plant was established in Fredericia where DONG has its headquarters. Later, leading up to the United Nations COP 15 conference in Copenhagen, it was decided to build a full scale biorefinery in the Danish city of Kalundborg. The Inbicon plant in Kalundborg was the world's first 2G biorefinery using straw and wood residuals to produce bioethanol through fermentation of C<sub>6</sub> sugars recovered from lignocellulosic materials using enzymatic fractioning. In recent years Inbicon has made further advancements, first with the successful industrial scale simultaneous C<sub>6</sub> and C<sub>5</sub> fermentation and later by including the development of a so called "sugar platform" producing a platform for further industrial refinement and production from the C<sub>6</sub> and C<sub>5</sub> sugars.

The latest development is the announcement of a co-operation between DONG (the owners of Inbicon) and Neste Oil focused on the development of a cost-effective technology for producing renewable diesel and aviation fuels from agricultural byproducts.

Technology from Inbicon is to be used in the pre-treatment of biomass to produce cellulosic sugars. These sugars are then planned to be converted into microbial oil using Neste Oil's technology. The microbial oil is then used as the feedstock for producing renewable diesel and aviation fuels from the HEFA process.

The DONG and Neste Oil co-operation could form the backbone for the first complete and full scale Danish (Scandinavian) sustainable aviation fuel pathway.

#### 7.4.2.4 *DAKA*



DAKA Denmark A/S, part of the German SARIA Group, is a Danish biotechnology company producing a variety of products from animal by-products such as fat and waste from slaughter houses. One of the business areas is the production of Biodiesel (FAME, Fatty Acid Methyl Esters). The production is fully commercialized and produces biodiesel for blending into regular diesel in European gas stations.

---

DAKA has initiated collection of food waste and used cooking oil from for instance super markets and hotels, however, DAKA is currently not focusing on the production of jet fuel.

#### 7.4.2.5 *Emmelev A/S*



Emmelev A/S is a Danish biooil and biodiesel producer basing their production on oil from rapeseeds. The biodiesel produced at Emmelev is exported and used in a large number of countries across Europe.

The production capacity and know-how of Emmelev can potentially be a part of a sustainable aviation fuel pathway involving hydrotreating vegetable oils (Green Diesel production) and further refinement to jet fuel standards.

Emmelev has achieved an EU REDcert certification.

#### 7.4.2.6 *Maabjerg Energy concept*



Maabjerg Energy Concept is a concept for a large, commercial scale integrated biorefinery that will act in symbiosis with other energy producers such as a biogas plant, a cogeneration plant and a district heating company. The concept utilizes 2G feedstock in the shape of straw, animal manure and other agricultural residuals.

The concept is to utilize different product and by-product streams for different purposes and thus extract all the value from the feedstock. Enzymes from Novozymes will break down the lignocellulosic biomass and C<sub>5</sub> and C<sub>6</sub> sugars will be released. Both the C<sub>5</sub> and C<sub>6</sub> sugars are fermented into ethanol using a special yeast capable of co-fermentation of the two sugar types.

Besides producing “traditional” biorefinery products from the C<sub>5</sub> and C<sub>6</sub> sugar platform, the concept utilizes the vinasse (byproduct) produced in the process to produce biogas in an adjacent plant and the lignin that is separated is used in a cogeneration plant to produce electricity and heat. Other initiatives for optimizing the process and gaining high yields in terms of quantity, quality or by-product streams are planned or under development.

The integrated approach in the Maabjerg Energy concept and the know-how gained in the planning and development of the concept can be useful in establishing a solid business case for future sustainable fuels for aviation production in Denmark or abroad. Also, the technologies employed are obvious candidates for components in an Alcohol to Jet (AtJ) pathway.

#### 7.4.2.7 *DTU – The Technical University of Denmark*



The Technical University of Denmark (DTU) have two departments working with in fields very relevant to developing a production of sustainable fuels for aviation.

---

They are the DTU departments of DTU Food, Systems Biotechnology & Biorefining and Chemical Engineering (DTU-KT).

At DTU Food research is being made into different pathways towards biofuels made from sugars.

Using lactic bacteria to convert sugars into alcohols, either bioethanol or biobutanol is one avenue of approach. Another is to use yeasts to convert sugars into free fatty acids and then on to biodiesel.

At DTU-KT research is conducted into the fields of pyrolysis, gasification-technologies and using lignin for liquid fuels. The research at DTU-KT is done in close co-operation with Topsøe, DONG and other industry stakeholders.

Both fields of research are interesting with respect to establishing a sustainable aviation jet fuels production.

#### 7.4.2.8 *AaU – Aalborg University*



At Aalborg University research is conducted into hydrothermal liquefaction (HTL) of biomass, a technology potentially interesting as a component for a sustainable aviation fuel pathway based on the oil generated from the process.

The HTL technology uses water at super critical pressures and a catalyst to convert biomass into biooils that can again be upgraded.

Some of the advantages of the HTL technology is that it is very efficient (consuming only about 10 to 15 % of the energy in the biomass), it can use a very large range of feedstock (including the “wet biomasses” such as sewage sludge, manure etc.) and produces bio-oil of a very high quality with a low content of oxygen, sulphur and water. This means that the oil is a good candidate for further refinement into, for instance, jet fuel.

Aalborg University has test facilities for testing jet fuels and other high value products in a rig test set up using a small scale jet engine.

#### 7.4.2.9 *KU – the University of Copenhagen*



The University of Copenhagen, KU, has research areas that can be highly relevant for a future Danish production of sustainable fuels for aviation. Among these are special competencies within biomass production, as well as competencies within alternative fuels production. Among other things the university's KU-Science faculty is involved in a national research project that aims at utilizing lignin to produce marine bunker fuel.

---

#### 7.4.2.10 AU - Aarhus University



Aarhus University, AU, is also involved in a range of relevant research areas for the development of a Danish production of sustainable fuels for aviation. Among these are strong competencies in environmental sciences, bioinformatics, an international center for organic food production and national research centers for Environment and Energy as well as Food and Agriculture.

#### 7.4.2.11 TOMO Liquid

TOMO liquid collaborates with DTU Food and KU Science, on a full pathway to sustainable aviation fuel. This pathway includes microbial fermentation of lignocellulosic C<sub>5</sub> and C<sub>6</sub> sugars to intermedium length alcohols, and further processing into aliphatic ethers, compatible with jet-engine technology. The company expects to have ASTM certificated products and a full pathway optimized for demo-scale production in 5-10 years.

#### 7.4.2.12 Steeper Energy



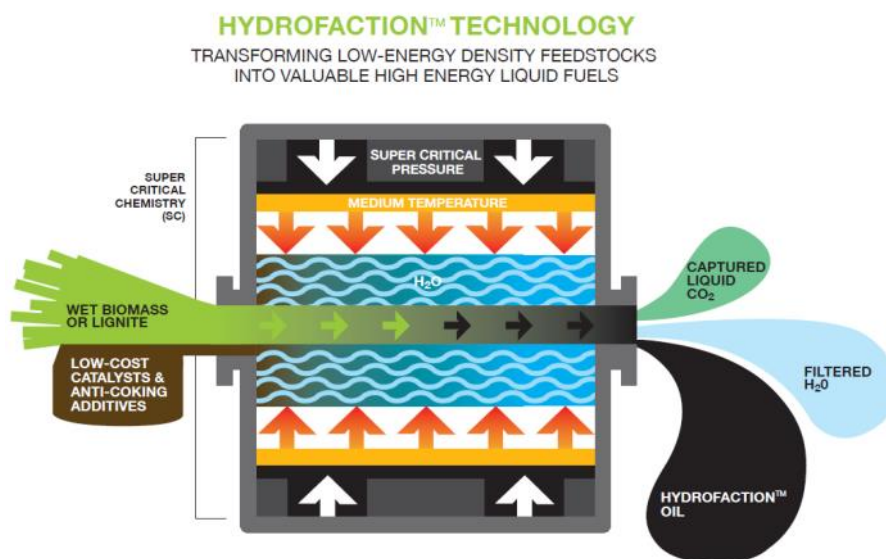
The company Steeper Energy, in close collaboration with Aalborg University, is working to commercialize Hydrofaction™, a supercritical hydrothermal technology which converts biomass to hydrocarbon oil (Figure 11). Steeper Energy is currently running a test facility producing 1 barrel of renewable oil per day and is working to establish a larger, 100 barrel per day pre-commercial facility. The oil contains more than 80% of the energy in the feedstock, less than 5 wt% oxygen and it can be upgraded to jet and diesel fuels in a crude oil refinery.

The technology, can utilize a range of feedstocks, including organic waste, biomass, manure and peat. It can also utilize fossil based feedstocks such as lignite. Another feature is the ability to use wet feedstock, slurries etc.

Feedstocks can be directly fed to the process without the need for drying or pre-heating. All water is conserved within the system and cleaned to irrigation or potable standards. Excess CO<sub>2</sub> produced from the pressurized reaction can be captured and sold as a liquid.

In addition Steeper Energy reports that their technology at present is competitive with unconventional petroleum options, such as Shale oil, Heavy Oil and Oil sands.

Figure 11: Illustration of the Hydrofaction technology, courtesy of Steeper Energy



#### 7.4.2.13 Biogasol



Biogasol is a Danish pre-treatment technology provider that researches and develops technologies for cellulosic biofuels and the biochemical industry. The company was established in 2006 as a spinoff from DTU and is specialized in technologies and equipment for continuous biomass pretreatment, the so-called Carbofrac® system (often through enzymatic hydrolysis). Biogasol, through its sister company Estibio, also provides a co-fermentation of C<sub>5</sub> and C<sub>6</sub> sugars into ethanol.

The pre-treatment technology of Biogasol can be used in the early stages of several jet fuel pathways.

#### 7.4.2.14 Pyroneer / DONG



The Pyroneer technology is a Low Temperature, Circulating Fluid Bed pyrolysis reactor that is capable of generating pyrolysis gas from a range of biomass feedstocks. The technology is under development and is currently employed to produce gas for incineration at cogeneration plants. The perspectives of the technology, however, can be to produce syngas for more advanced applications, among these liquid transportation fuels.

An advantage to the Pyroneer technology, compared to other pyrolysis technologies, is that the nutrients in the biomass can be reclaimed and recirculated through use of the ash from the process due to the low operational temperature. This means that the technology can help in conserving and recirculating nutrients by using the ash as fertilizer in farming.

---

The Pyroneer technology is a good candidate for a component in (syn)gas based jet fuel pathways, with the obvious advantage that nutrients are not “lost in the process”, increasing the sustainability of these gasification based pathways.

#### 7.4.2.15 *Terranol*



Building on the Danish tradition for developing yeast cultures Terranol has developed robust yeast capable of co-fermentation of C<sub>5</sub> and C<sub>6</sub> sugars. The Terranol yeast strain achieves high ethanol concentrations and yields with a low production of the by-product xylytol.

#### 7.4.2.16 *REnescience / DONG*



REnescience is a technology development and marketing company owned by DONG that researches, develops and markets pre-treatment technologies for separating municipal solid waste (MSW) in to useable fractions. The main product is a “bio-pulp” that can be used to generate biogas or other biofuels. The technology uses enzymatic hydrolysis to separate the organic components from the MSW to produce a high energy organic sludge that is easily used in biogas plant or other applications. The technology also generates other by-product streams for recycling.

#### 7.4.2.17 *Avista Oil*



Avista Oil (formerly Dansk Olie Genbrug / Danish Oil Recycling) collects, processes and refines fossil waste oil products from auto shops, industry, harbors and shipping companies. The oil is treated and converted into a base oil that is then refined into a variety of distillates and re-used, for instance as lubricants, fuel and other applications. Avista oil could be relevant in collecting used cooking oils for aviation fuel production.

#### 7.4.2.18 *Organic Fuel Technology (OFT)*



Using microwaves and a proprietary catalyst to generate bio-oil from a variety of feedstocks, Organic Fuel Technologies is pioneering a new approach to generating sustainable fuels with a flexible choice of feedstock. The process gasifies the biomass using a reactor heated by microwaves and uses a proprietary catalyst to crack the product into useable biodiesel.

#### 7.4.2.19 *Separation of organic waste from e.g. MSW*



Denmark has a long tradition for sorting and recycling waste. More than 90 % of the waste produced in Denmark is currently recycled or used for waste-to-energy, with only a small fraction going to landfills or hazardous materials processing. This tradition means that a large number of public and private companies have a wealth of experience developing and running waste management and sorting facilities, experience that could be put to use securing alternative feedstocks for sustainable aviation fuel production.

---

#### 7.4.2.20 IBUS



IBUS Innovation A/S works with technology development within sustainable biomass utilization in food and fuel biorefineries. IBUS envisions refineries that offer full flexibility from fuel to food, uses multiple feedstocks, produces biofuels without the use of fossil fuels or an external water supply and additionally recycles nutrients.

To pursue these targets IBUS innovation focus on the following developments:

1. **Horizontal diabetic distillation/evaporation** technology using sequential mechanical vapor recompression (MVR) as energy input, saving up to 75% of the energy consumption compared with the conventional vertical adiabatic systems driven by steam.
2. **Drying of non-fermentable residues** for animal feed using pressurized superheated steam as the drying media, which means that about 90% of the input energy can be recovered as pressurized steam at 3-5 bar to be exploited elsewhere in the biorefinery
3. **Separation of Municipal Solid Waste (MSW)** with a biodegradable fraction (BMW) with food waste, paper, cardboard etc. in 3-7 fractions using a "Water Sorter" The biodegradable fraction will be pressed to 35-40% dm and delivered to the biorefineries in the region.

#### 7.4.3 *Perspective organizations and facilities*

A number of organization and companies are currently developing projects that could result in a significant Danish production of sustainable fuels for aviation.

##### 7.4.3.1 *DBH technology*

Hveiti, named after the old-Norse word for wheat, is the name chosen by a Danish company, DBH Technology, for their developing concept for a biorefinery based on wheat. The concept is planned to generate four product streams; proteins for animal feed, bioethanol, fibers for food production and pure CO<sub>2</sub>.

Even though the plant plans to use wheat, a clear 1G feedstock, the company considers the production sustainable because it produces a large quantity of animal feed besides the production of bioethanol, thus "preserving the feed value of the wheat" in the form of proteins.

##### 7.4.3.2 *Clean World Capital*

Clean World Capital (CWC) is a London based advisor and investor with offices in Copenhagen. CWC is focused on the global transition to a sustainable economy. Reportedly CWC is working on a project that aims at establishing a produc-



---

tion of sustainable fuels for aviation based on Honeywell / UOP's technology. It has not been possible to confirm this information with CWC nor has it been possible to obtain further information regarding the project.

#### 7.4.3.3 *Bioenergi Tønder*

The organization Bioenergi Tønder is working on the development of business plans for two full production plants placed in the municipalities of Tønder and Thisted. The organization states that the plants will produce 300,000 tonnes of synthetic fuels for aviation based on technologies supplied by companies from the United States and hydrocracking technology from Haldor Topsøe. The production will reportedly be based on the Fischer-Tropsch pathway. The feedstock is reported to be both waste and biomass gasified through a plasma gasifier.

### 7.5 Identification of Potential Danish Pathways

This report finds that of the stakeholders introduced in the previous sections, some are more relevant in a Danish-based sustainable fuel for aviation production than others. The AtJ and HEFA process are found to be the most interesting and promising pathways in a Danish context and in the short and medium terms. Another promising pathway is a gas pathway using gas either from gasification or biogas to prepare a syngas for a FT-synthesis. However, there are currently no Danish suppliers of the FT technology.

In the following the three pathways are illustrated including the companies / universities that can supply technologies and / or components, as well as which feedstocks can be utilized.

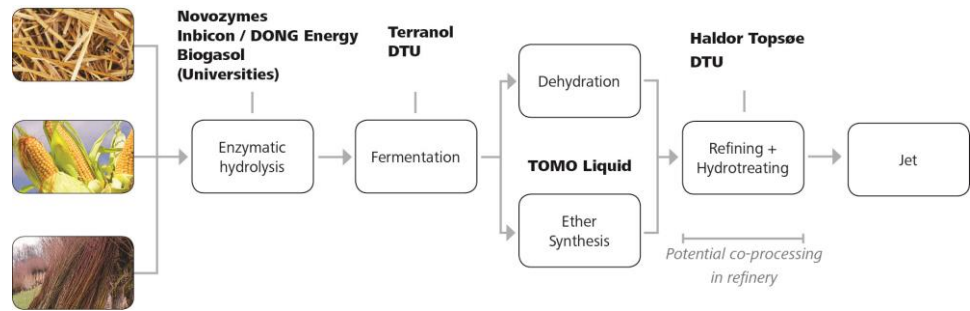
The three pathways all include the potential of co-processing at the two existing crude oil refineries.

#### 7.5.1 *Alcohol to Jet*

A strength of a Danish AtJ pathway (Figure 12) is within the pre-treatment process, where the technologies of Novozymes, Inbicon (DONG Energy), Biogasol, as well as Terranol, can produce the alcohols from a number of different cellulosic feedstocks. In addition Haldor Topsøe can provide the technologies for the refining and hydrotreating of the intermediate products. DTU is working with both fermentation and refinement and can thus be a key knowledge provider in an establishment of this pathway.

TOMO Liquid is developing an alternative pathway to the traditional AtJ pathway wherein the intermediary product is not ethanol but other alcohols and a process of ether synthesis rather than dehydration is used before the final steps in the process. It should also be noticed that hydrotreating is not a necessary step in this alternative pathway which goes directly to their own process of distillation.

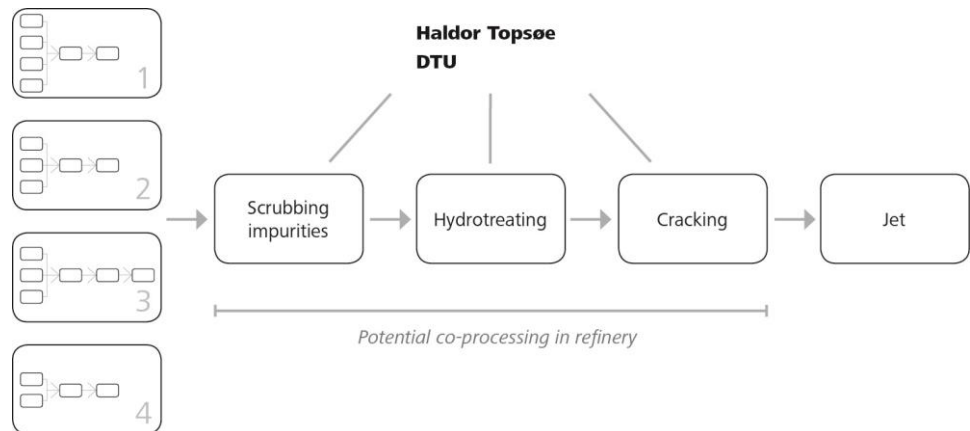
Figure 12: Potential Danish alcohol-to-jet pathway.



### 7.5.2 Hydrotreated Esters and Fatty Acids (HEFA)

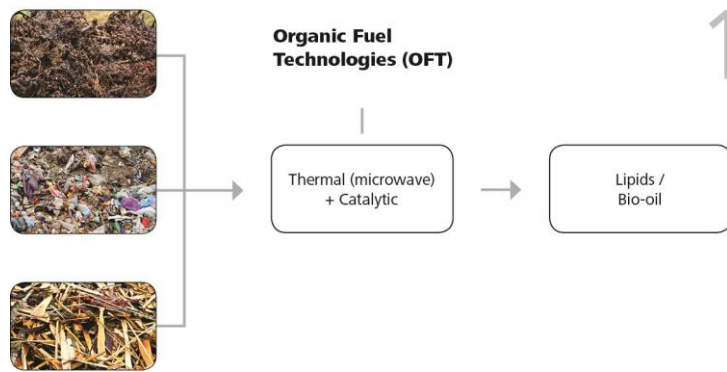
The HEFA process requires a lipid product and afterwards further hydrotreating and refining (Figure 13). In a Danish context four different pathways to produce lipids are pointed out, which are presented individually in the following. Haldor Topsøe and DTU are essential technology and knowledge providers in all of the remaining steps from lipid to the final jet fuel product. As mentioned in Section 7.2.4, the HEFA process requires an input of hydrogen which is energy consuming to produce. As Denmark has a strong tradition in wind energy this is a potential source of energy for hydrogen production as a way to consume spare energy on windy days.

Figure 13: Potential Danish Hydrotreated Esters and Fatty Acids (HEFA) pathway.



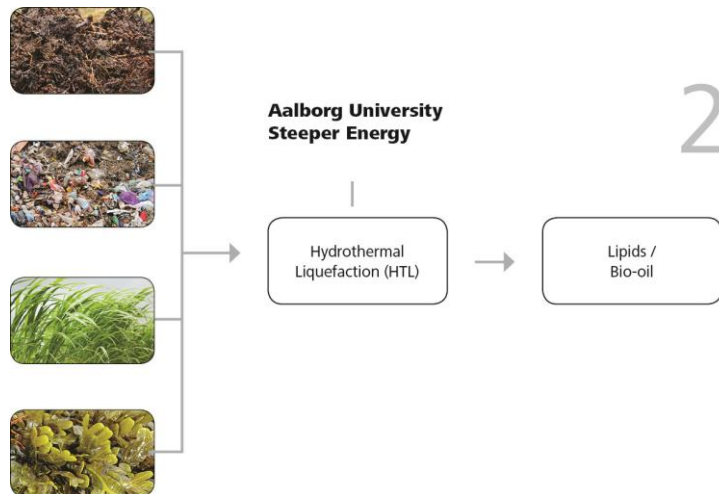
A potential provider of technology for the production of lipids is Organic Fuel Technologies (OFT). The advantage of this technology is the great flexibility in feedstocks including animal manure, municipal waste and other waste products (Figure 14).

Figure 14: Production of lipids for the HEFA process based on the technology from Organic Fuel Technologies (OFT)



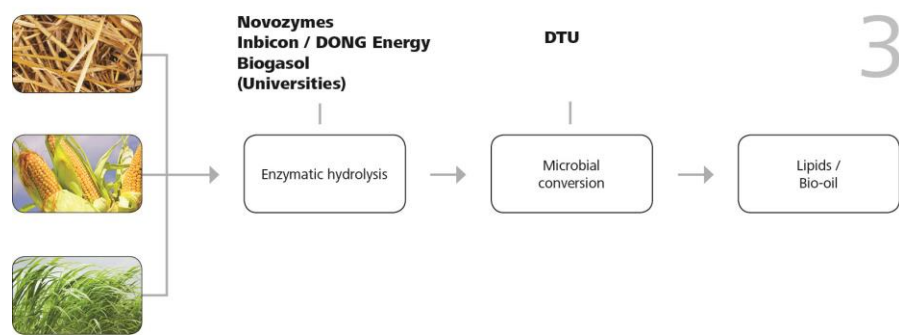
The hydrothermal liquefaction technology from Steeper Energy / Aalborg University is another technology for lipids production (Figure 15). As the technology from OFT, this technology also offers great flexibility in feedstocks including wet materials that are difficult to utilize with the most other technologies.

Figure 15: Production of lipids for the HEFA process based on the technology from Steeper Energy / Aalborg University using hydrothermal liquefaction.



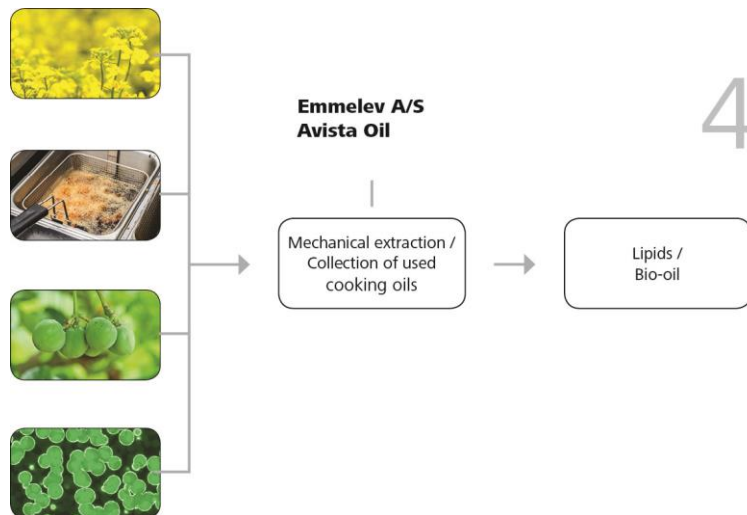
The announced cooperation between Inbicon and Neste Oil is based on a microbial conversion of sugars from cellulosic materials to lipids. This technology is thus also suitable in a Danish HEFA pathway (Figure 16). DTU is working within the microbial conversion technologies.

Figure 16: Microbial conversion of cellulosic material to lipids for a Danish HEFA pathway.



Finally, the HEFA process can be based on lipid rich crops as feedstock (Figure 17). The lipids can be mechanically extracted from for instance rape, imported jatropha or algae. Another option is the collection of used cooking oil where Avis-ta Oil potentially could collect the oil.

Figure 17: Mechanical extraction of oil or collection of used cooking oil for a Danish HEFA pathway.



The general strength of the Danish pathways is the high flexibility in feedstock including both cellulosic material and lipids. This is due to the many technology providers within pre-treatment. Which feedstocks are available will be discussed in Section 8.

From the potential pathways it is obvious that a single company cannot provide the technology for an entire supply chain. Co-operations between feedstock producers and different technology suppliers are essential if a Danish production of sustainable fuels for aviation is to be established.

From the pathways it is also noted that there are gaps in the supply chain. This calls for synergies within the Nordic region and the rest of the world.

### 7.5.3 Fischer-Tropsch Synthesis - Biogas

Another option for a Danish production of sustainable fuels for aviation is using a gaseous feedstock, such as biogas produced from manure or sludge from wastewater treatment plants. The gas can also be produced by gasification of nearly all different carbon containing feedstocks. The gas must be reformed to syngas and converted to aviation fuel using the FT-synthesis (Figure 18)

As of yet there are no Danish suppliers of the FT-technology. However, as mentioned in Section 7.2.3 there are international suppliers of this technology.

Figure 18: Pathway from syngas to jet using the Fischer –Tropsch synthesis

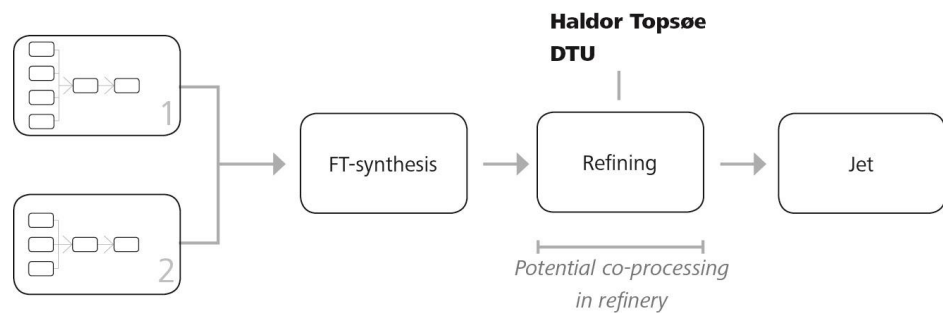
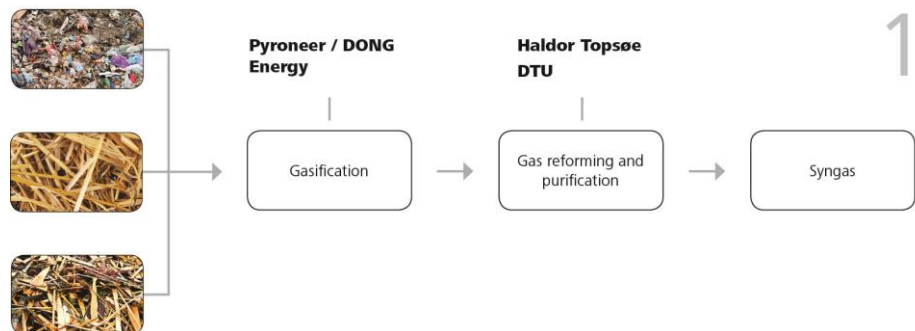


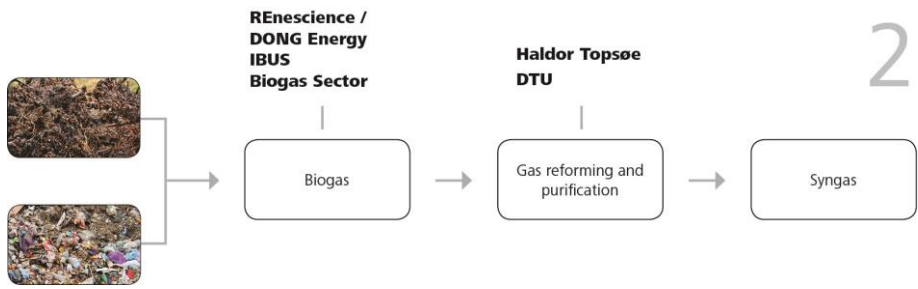
Figure 19 illustrates a pathway of syngas production were feedstock is gasified. There are many different international suppliers of gasification technologies. From a biorefining perspective it is essential when choosing the gasification technology that high value chemicals and nutrients can be reclaimed. The technology from Danish Pyroneer / DONG Energy has the advantage that nutrients are preserved.

Figure 19: Syngas pathway from the gasification of feedstock



Denmark already has a tradition in producing biogas from e.g. animal manure and sludge from wastewater treatment plants. Thus, biogas is a research area at the Danish universities and different technologies are available. The REnescience and IBUS technologies are also interesting with respect to producing biogas from solid waste.

Figure 20: Syngas pathway from reforming biogas



---

## 8 FEEDSTOCK AND FEEDSTOCK AVAILABILITY

There are numerous types of feedstock that can be converted to biofuels, and as technologies develop and mature, more and more feedstocks become feasible to convert. However, which type of feedstock to choose is not straightforward. Biomass in Denmark is used for different purposes such as food, animal feed, energy production etc. Due to this the chosen feedstock must fit into the current biomass balance of Denmark to ensure there is enough biomass available to supply the different sectors. Alternatively the current biomass production might have to be reorganized if Denmark decides to be a producer and not just a consumer of biofuels.

The production of biomass is vulnerable towards for instance weather conditions that can greatly affect the harvest. If basing the supply of sustainable fuels for aviation, or any type of energy, on biomass it is important that the supply of feedstock is consistent in order to ensure security of supply.

This section provides an overview of feedstocks produced in Denmark and the potentials of import. A simple biomass balance is set up in order to identify favorable feedstocks in Denmark and assess if the current biomass production should be altered in order to accommodate the biofuel demands of the future.

### 8.1 Nationally Produced Feedstock

One of the main challenges in producing sustainable fuels for aviation in Denmark is that there is no single feedstock that seems to be able to cover the entire demand from aviation fuels. For instance, in Norway and Sweden biofuel can be produced from forest and / or residuals from the wood industry. In addition Sweden has a feedstock in black liquor from pulp mills as Sweden has a significant paper industry. Denmark, on the other hand, has a limited geographical area and thus not the amounts of wood available as in the other Nordic countries.

On the other hand the potential Danish pathways identified in Section 7.5 show that the Danish pre-treatment technologies can process virtually any type of feedstock. Different types of feedstock that can be produced in Denmark are presented in the following.

#### 8.1.1 *Straw*

Straw (Figure 21) is traditionally considered a byproduct in Danish agriculture. In 2012, 37 % of all straw was left to compost on the fields and not utilized (Danmarks Statistik). Of the gathered straw approx. 50 % is used for heat production and the remaining 50 % is used for animal feed and bedding. As a byproduct straw does not compete with food production and does not cause ILUC effects.

---

However, by removing the composting straw from the field, nutrients are removed and must be recovered and cycled back. In addition the composting straw has positive effects on the microbial activity in the soil.

### 8.1.2 *Wood and Wood Residues*

13 % of the Danish land area is forest. Both wood and wood residues can be used in the production of sustainable fuels for aviation (Figure 21). However, compared to the other Nordic countries the Danish wood production is limited and nationally produced wood cannot be the sole feedstock for biofuel production in Denmark.

---

Figure 21: Left: Straw.  
Right: Wood



### 8.1.3 *Organic Waste*

In Denmark 9.1 mill. tonnes of waste (Figure 22) was produced in 2011. More than 90 % of this is currently recycled or used for waste-to-energy. The recycled biological waste fraction is used to produce cardboard and paper (cardboard and paper), compost (branches, leaves and grass), chipboard (wood) and biogas (sludge). Of the total waste 29 % was incinerated to produce electricity and heat, and 6 % was sent to landfills. Since most of the waste is utilized, waste must be considered an unlikely feedstock for the biofuel production unless a transition to a new utilization occurs. Also, the organic fraction must be sorted from the rest of the municipal waste for it to be utilized. Finally there are ethical concerns that producing biogas from household organic waste will legitimize waste of food (Det Etske Råd, 2013). It is also conceivable that the separation of food waste can lead to an increased awareness of the wasted amounts and hence have the effect of reducing food waste.

### 8.1.4 *Used Cooking Oil*

Internationally used cooking oil (Figure 22) is, as mentioned in Section 7.2.4, widely applied in the HEFA process. In Denmark used cooking oil so far unexploited and is hence a potential feedstock for a sustainable fuels for aviation production.

Experiments have been made collecting used cooking oil and fats from households during a two months period. The results indicate an annual potential of about 17,500 tonnes. An advantage of collecting household used cooking oil is



---

that the oil is not flushed in the sink reducing pressure on the wastewater treatment plants.

The Danish company Avista Oil (formerly Dansk Olie Genbrug) currently collects an annual amount of 30,000 tonnes of fossil waste oils from the industry and refines it back to oils for industrial purposes. As indicated in Section 7.5 used cooking oil collection might be initiated in cooperation with a company such as Avista Oil.

### 8.1.5 *Animal Manure*

Denmark has the fourth largest pig production (quantity wise) in Europe (Landbrug og fødevarer, 2013) and hence animal manure (Figure 22) is produced in large quantities.

The total resource of animal manure is around 3.9 mill. tonnes (dry weight) where nearly 7 % are utilized in energy production (Gylling *et al.*, 2012). Animal manure can be used in biogas production and can still be used as fertilizer afterwards. The challenges in utilizing animal manure are mainly logistics. As for organic waste there are also ethical considerations since Denmark could be dependent on having an extensive meat production (Det Etske Råd, 2013).

---

Figure 22: Left: Municipal waste. Middle: Used cooking oil. Right: Animal manure.



### 8.1.6 *Energy Crops*

There are different high energy crops that can be grown in Denmark:

- Elephant grass
- Willow and poplar
- Maize

Maize (Figure 23) is already grown extensively in Denmark with an annual production of 6.8 mill. tonnes for animal feed. Maize has a yield of around 10-15 tonnes/ha (dry weight). Maize can be used to optimize biogas production from animal manure and as a sugar source.

Willow (Figure 23) and poplar are perennial, fast growing crops making them suitable as energy crops for biofuel production. It is estimated that production of

---

willow can yield 8-14 tonnes/ha (dry weight). If the production of willow is economic feasible depends greatly on the prices on cereals and wood chips.

C<sub>4</sub>-photosynthesis requires more heat, but has a higher biomass yield than C<sub>3</sub>-photosynthesis. Maize is the only currently produced crop that uses C<sub>4</sub>-photosynthesis. Miscanthus (elephant grass, Figure 23) is grown in Great Britain, but only sparsely in Denmark. This crop also uses C<sub>4</sub>-photosynthesis and has an approx. 60 % larger biomass yield than maize. Elephant grass is fast growing and can yield 16 ton/ha or 9 ton/ha (dry weight) is harvested in the fall and spring respectively.

Elephant grass and willow reduce the wash out of nutrients and pesticide consumption compared to cereals.

---

Figure 23: Left: Maize.  
Middle: Willow. Right: Elephant grass.



#### 8.1.7 Rape seeds and sugar beets

500,000 tonnes of rape was harvested in 2011. The rape seeds can be used to produce oil that can be converted to jet fuel via a lipids pathway.

2.7 mill. tonnes of sugar beets were harvested in 2011. 95 % of these were utilized in sugar production. The remaining 5 % was used as feed.

Both sugar beets and rape seeds currently used for food (primarily) and feed.

---

Figure 24: Left: Rape.  
Right: Sugar beet.



---

### 8.1.8 *Cover crops*

Cover crops are planted after harvesting the main crops. Thus, cover crops grow in the time period of July / August until February / March. The purpose of cover crops is prevent nutrients washing out to nearby streams. The cover crops are plowed into the soil before planting new crops and are due to this not used as biomass.

By harvesting 75 % of all cover crops will increase the biomass production by approx. 390-490 tonnes per year (DCA, 2013). However, it is important to be aware of the loss of nutrients that will occur as a consequence. The nutrients must be recovered and cycled back to the fields.

### 8.1.9 *Biomass from land management, parks etc.*

An alternative, and as of yet mostly unexploited, resource may be biomass from, among other things, gardening, landscaping, land and nature management, up-keep of parks and weed clearance in streams.

DCA (2013) reports that about 0.7 mill. tonnes (dry weight) of this resource is currently being utilized, exclusively for firewood, but notes that this is as highly uncertain estimate (presumably because there is no direct way of counting or measuring how much is produced or consumed). Without further research it is hard to quantify this potential resource, but it could help boost the available biomass for aviation fuel production, however to what degree is uncertain.

A challenge in utilizing this resource is the nature in which it is produced. Whereas agriculture and forestry are evolved industries with well-established logistics and supply chains, the sources for this “extra biomass” are highly fragmented and unorganized. In addition, meadows, that benefit positively from the removal of cut off grasses, are vulnerable areas where heavy machinery cannot be used in gathering biomass. In various municipalities attempts have been made to utilize some of this material, but as of yet no coordinated effort has been made to account for or utilize this resource.

### 8.1.10 *Macroalgae (seaweed)*

Blue feedstock has the great advantage that it does not occupy land area. In a Danish context brown macroalgae (seaweed, Figure 25) and especially sugar kelp and finger kelp are the most common species. The naturally occurring algae cannot be harvested as they grow in protected areas, however, they can grow on lines using the same principles as growing mussels.

Brown algae is currently not grown in industrial scale in either Denmark or Europe. Due to this the growth potential is yet to be determined. There are two producers of seaweed in Denmark.

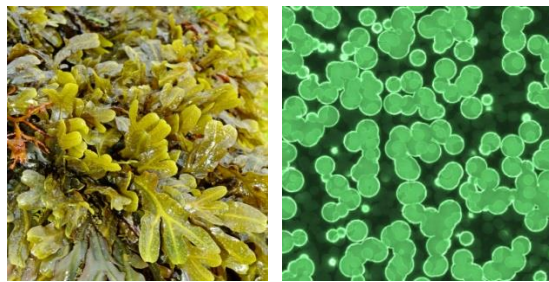
---

There is 72,000 km<sup>2</sup> Danish territorial sea available for brown algae production, however, suitable areas must meet water quality requirements to optimize the production of brown algae. It has been estimated that brown algae can yield 5-15 tonnes/ha (dry weight).

By harvesting 1 tonnes of brown algae from the sea approx. 20 kg of N and 5 kg of P is also removed from the sea (DCA, 2013). This is a benefit in Danish seas and the nutrients can potentially be utilized in agriculture. In addition brown algae contain relatively high amounts of protein which can be used in feed. In order to make brown algae a financially feasible feedstock biorefining removing for instance nutrients and protein is essential.

---

Figure 25: Left: Seaweed.  
Right: Microalgae.



## 8.2 Potentials of Import

There are types of feedstock that cannot be grown in Denmark as they favor a different climate. It might be necessary to import these if the efficiency of producing biofuel from these is higher than for the locally grown feedstocks. The feedstocks presented in the following are not typical food crops and capable of growing in areas with difficult soil conditions or can grow in saline conditions. This creates possibilities for creating a market in developing countries and thus creates possibilities of social development.

### 8.2.1 *Jatropha*

*Jatropha* (Figure 26) is a plant that produces oil rich seeds. Each seed produces 30 to 40 % of its own mass in oil. A benefit of *jatropha* is that it can grow in a range of difficult soil conditions that are otherwise non-arable areas.

### 8.2.2 *Camelina*

*Camelina* (Figure 26) has a high lipids content of 32 to 40 %. After the oil extraction the byproduct can be used as a chicken feed. *Camelina* can be planted as a part of crop rotation programs with cereals in periods where the soil would otherwise be left fallow (unplanted). Thus, mono-cropping is reduced which is known to reduce yields.

---

Figure 26: Left: Jatropha. Middle: Camelina. Right: Halophyte.



### 8.2.3 *Microalgae*

Microalgae (Figure 25) are the potentially most promising feedstock as they do not compete with land area. Algae are estimated to produce up to 15 times more oil per square kilometer compared to other feedstock (ATAG, 2009). However, algae require large amounts of sunlight and hence growing them in Denmark is challenging. In addition nutrients must be supplied from e.g. wastewater.

### 8.2.4 *Halophytes*

Halophytes (Figure 26) are plants that prefer saline growth conditions such as salt marsh grasses. Thus, they can grow in areas where it is not possible to grow conventional food crops.

## 8.3 Biomass Balance

A biomass balance has been made to illustrate the current biomass streams in Denmark (Figure 27). The mass balance includes both food and other bio based products such as wood and animal manure. It should be noted that the purpose of the mass balance is to provide an overview of biomass quantities and is thus a rough estimate of the most significant biomass streams.

The production is the total amount produced and thus not necessarily the amount that is technically available. This is the case for straw, where not all straw produced is utilized. The amount utilized can be seen in the consumption and / or export.

All data is from Danmarks Statistik (Statistics Denmark), Danish governmental authorities such as the Danish Environmental Protection Agency (EPA), and the Danish Agriculture & Food Council (Landbrug & Fødevarer). All data is from 2011 unless otherwise stated. See Appendix 1 for more details concerning the mass balance.



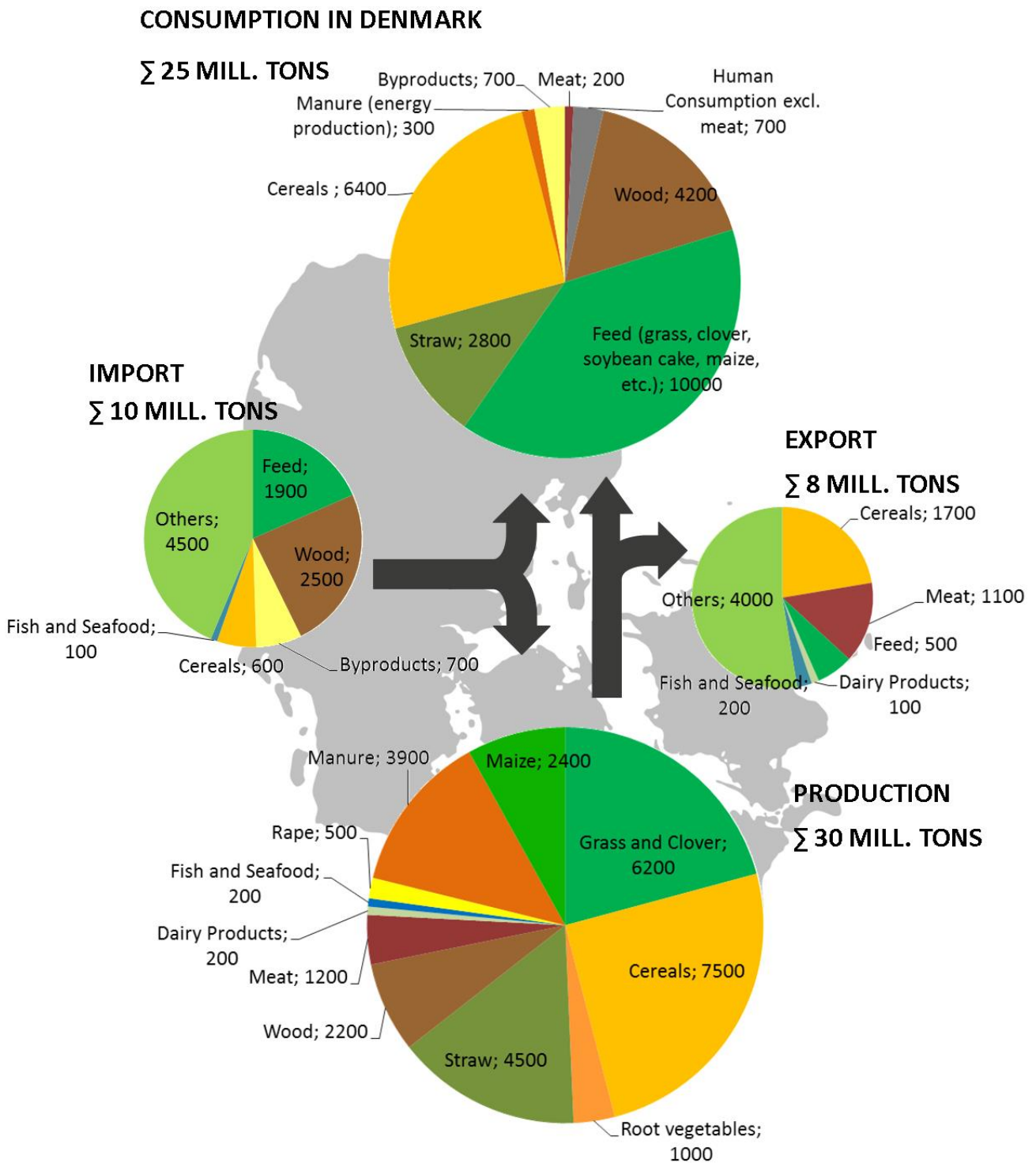


Figure 27: Biomass balance of Denmark based on data from 2011 [1000 tonnes dry weight unless otherwise stated]. The areas of the circle diagrams represent the ratios between the total mass imported, exported, produced and consumed.

---

From Figure 27 it is seen that the Danish biomass balance is dominated by the extensive meat production. The largest import commodities are feed for meat production and wood mainly for energy production. The biomass production is mainly cereals, grass, clover and maize. 70 % of the cereals produced are used for feed. The feed (which is in the amount of about 16 mill. tonnes) consumed produces around 1.2 mill. tonnes meat which is mainly pork, but also bovine and poultry meats. Cereals and meat are the largest export commodities.

## 8.4 Future Land Use Strategies in Denmark

The limiting factor in feedstock production in Denmark is mainly land area. Thus, planning the future biomass production is a matter of dividing and utilizing a limited land area in the most optimum manner. However, deciding if the area should be used to grow feed, produce food or grow energy crops is not straightforward and thus Denmark must prioritize which products are needed, including those the nation wishes to export. In addition to economic considerations, production of crops should aim to be sustainable and environmental considerations must be taken into account.

The following section will provide different scenarios if sustainable fuels for aviation are to be produced in Denmark. The scenarios are all developed on the basis of data from the report “*The +10 million tonnes study*” by Gylling *et al.* (2012) and the biomass balance (Figure 27).

### 8.4.1 “*The +10 million tonnes study*”

The report “*The +10 million tonnes study*” by Gylling *et al.* (2012) describes the possibilities of increasing the Danish biomass production through three different scenarios:

- A business-as-usual scenario increasing the utilization of the current production
- A biomass optimized scenario where the biomass production is maximized
- An environment optimized scenario increasing biomass production but reducing nitrate leaching and increasing biodiversity.

The report concludes that the Danish biomass production can be increased by 10 mill. tonnes by 2020 compared to 2009 in the biomass optimized scenario. The environment optimized scenario can yield an extra 8 mill. tonnes, whereas the business-as-usual scenario can provide around an additional 4 mill. tonnes.

The environment optimized scenario is chosen over the biomass optimized scenario as a Danish production of aviation fuels should meet the sustainability crite-

---

ria listed in Section 3. The business-as-usual scenario is also included as it is relatively simple to implement as it requires no change in crop species and technologies applied.

#### 8.4.2 *Optimizing protein production – Concito*

There are other points of view on the future land use in Denmark than increasing the production of biomass for energy production. Concito (Section 3.4.4) published the report “*Klimagevinster ved øget protein production*” in 2014. The report draws attention to the high protein demand of the Danish pig industry. For instance, the annual import of cake of soybeans for feed causes emissions of about 6 mill. tonnes of CO<sub>2</sub>-eq, which is equivalent to 80 % of the emissions from cars in Denmark or nearly 50 % of the national emissions from agriculture. Thus, alternatives to imported protein crops are desired in order to achieve a more sustainable animal production in Denmark.

Producing protein rich crops suitable for pig production is difficult in Denmark. This is due to pigs not being able to metabolize protein rich crops such as grass and clover that ruminants can digest. One option to produce more protein rich crops in Denmark, suitable as feed for pigs, is fermenting protein rich crops, however, a much higher protein yield can be achieved by extracting the protein in either a mechanical or aqueous process. Concito argues that the CO<sub>2</sub>-eq emissions caused by the Danish meat production are so significant that biorefineries should focus on extracting protein from crops and biofuels should be a byproduct rather than the opposite.

### 8.5 Scenarios of Future Feedstock Utilization

In the following all calculations are based on the assumed demand of sustainable fuel for aviation of 0.6 mill. tonnes in 2035 (see Section 5.3). Two different scenarios are presented to illustrate the possibilities of a feedstock supply to a Danish production of sustainable fuel for aviation. In the first scenario the current food and feed production will not be affected by the production of sustainable fuels for aviation. The second scenario includes changes in the crops grown in Denmark and might affect the feed production.

The scenarios both include a sustainable fuel for aviation production based on multiple types of feedstock and thus different technologies. A mass conversion rate of 0.08 from feedstock to fuel is chosen based on numbers from Avinor (2012) and the already existing Inbicon plant<sup>7</sup>. There is great uncertainty associated with this conversion rate as technology constantly develops and because the same conversion rate most likely does not apply to all types of feedstock and technologies. With a mass conversion rate of 0.08 an amount of **7-8 mill. tonnes**

---

<sup>7</sup> The factor has been chosen in “the high end of the scale” anticipating a positive development in conversion technologies in the decades to come



---

**of feedstock** is required to meet the Danish demand for sustainable fuel for aviation in 2035.

Currently around 4 mill. tonnes of the nationally produced biomass is utilized for the production of energy (Gylling *et al.*, 2012). These feedstocks are mainly straw, wood and manure.

It is assumed that biomass produced for energy should primarily be used to produce fuels for the sectors that currently does not have other options for a sustainable energy supply. This being the shipping (bunker fuel), heavy cargo (diesel) and aviation (jet fuel) industries.

In a biorefinery jet fuel is not the only product stream as also high value chemicals, diesel bunker fuel and excess energy (in the form of heat) can be produced. The different feedstocks contain an amount of lignin in the range of 15-25 % (Biorefining Alliance, 2012). The lignin can be incinerated to produce energy or be converted to bunker fuel as new developing technologies show. It is assumed that a single biomass stream into a refinery will be able to cover the demand from all the mentioned industries. This would be the case if the distribution of products from a given amount of feedstock is the following:

- High value chemicals and materials: 10 %
- Jet fuel: 30 %
- Diesel: 30 %
- Bunker fuel and energy: 30 %

This assumption is justified by the fact that the energy consumption for aviation in 2035 by the Danish Energy Authority is projected to make up approx. 17 % of the total projected energy consumption for transportation. This includes a large percentage from light road transportation as well as rail transportation (gasoline powered road transportation plus rail transportation accounts for a further 26 % of the total projected consumption). These modes of transportation have other (sustainable) alternatives, for instance electricity, and thus do not require liquid biofuels. Additionally the production of sustainable fuels can be adjusted to match a desired outcome, typically referred to as yield optimization.

In addition to the different streams coming directly from the jet fuel production there is a potential of producing biogas as an additional stream by utilizing for instance the vinasse byproducts from fermentation of straw as the Maabjerg Energy Concept is planning to do. Given the amounts of jet fuel and, consequently, feedstock necessary to cover the Danish demand a very high simulta-

---

neous production of biogas will be made possible. This gas is very well suited for storage as well as for balancing the electricity grid.

The production of sustainable fuels also produces excess heat that can contribute to the district heating system or be utilized as process energy. It would also be possible to extract valuable proteins from the feedstock before or during processing and thus building a protein factory adjacent to the bio-refinery would increase the total utilization and value extraction of the feedstock even more.

Furthering such symbiotic relationships between the production of sustainable fuels for aviation and other industries (including the production of other forms of liquid fuels) will be a cornerstone in achieving sustainability, not only environmentally but economically as well.

The following scenarios will thus include the already produced 4 mill. tonnes of biomass used for energy production, but exclude the other streams from the biomass balance, especially animal feed, and the imported biomass used for energy production. This is mainly wood pellets. The amount of a certain type of biomass used for energy production can potentially be significantly different in the future as for instance blue biomass and new conversion technologies emerge.

Thus it is assumed that 100 % of all the biomass produced for energy can be utilized in refineries producing jet fuel and simultaneously that the Danish demand for energy from biomass, for instance for regulating the electricity grid, is still covered<sup>8</sup>. The results from the different scenarios are presented in the following sections and summarized in Table 4 on page 90.

#### 8.5.1 Scenario 1 – Business-As-Usual

The first scenario is based on the current biomass production where so far unexploited biomass is used for energy production. Thus, there are no changes in the crop species or technologies for harvesting. The calculations are based on the business-as-usual scenario from “*The +10 million tonnes study*” (Gylling *et al.*, 2012). This includes:

- Increase yields and energy crops produced based on projections of the current production
- Increasing the harvest of straw otherwise left to compost in fields

---

<sup>8</sup> According to information supplied by the Danish Energy Agency this would be the case in at least one of the scenarios being discussed for 2050, in which wind will be the dominant energy producer and electricity the dominant energy carrier. .

- 
- Utilizing all of the manure produced<sup>9</sup>

The results show that the business-as-usual scenario will be able to meet about 100 % of the demand as an additional 4 mill. tonnes of biomass can be produced. In this scenario the dominating feedstocks are manure and straw both representing a third of the total biomass respectively. In addition wood, contributing with 12 %, is a significant resource.

#### 8.5.2 Scenario 2 – Environment Optimized

This scenario includes the implementation of the “environment optimized” scenario from “*The +10 million tonnes study*” (Gylling *et al.*, 2012) in order to increase the production of biomass for energy production.

Denmark has a strict legislation concerning the use of pesticides and the use of animal manure on fields in order to protect the groundwater resources and prevent eutrophication. In addition it is not allowed to cultivate the land within a zone proximate to streams. Due to this it is difficult to intensify the biomass production using these means. According to Gylling *et al.* (2012) it is possible to increase the biomass yield by extensifying vulnerable areas and intensify more rugged areas.

Cereal crops do not fully utilize the limited solar radiation there is in Denmark as they from July to September ripen, are harvested, are ploughed and replanted. Crops that are green and productive throughout the entire summer season has a higher potential yield. By harvesting cereals before they ripe and storing them in siloes it is possible to replant crops in the mid of the summer.

Straw has traditionally been considered a byproduct in Denmark. Due to this the species of cereals developed are not yielding much straw. By changing to more straw producing species it is possible to increase the biomass production. The scenario includes a change to cereals species producing 15 % more straw and an increased straw gathering of 15 % - however, no straw is removed from soils with a critically low carbon content.

The Danish forests mainly consists of wood that is not the result of varietal selection. Varietal selection of wood is a long process but research indicates that a biomass increase of 25-35 % can be achieved.

Finally, changing from cereals and rape to energy crops has positive environmental effects such as reduced leaching of nitrate to the surrounding environ-

---

<sup>9</sup> Based on an annual production of animal manure of around 34 mill. tons (wet weight) it seems that the “*The +10 million tonnes study*” assumes a dry matter content of amount 10-12 % which might be an overestimation, however, the dry matter content of manure changes over time and thus estimates of future dry matter contents are uncertain.

ment (Gylling *et al.*, 2012). By implementing the environment optimized scenario 0.2 mill. ha of rape and cereals production are replaced with perennial energy crops. However, it is estimated that the feed production in biorefineries will be able to compensate for the lost feed production from these areas.

The scenario also includes:

- Utilization of roadsides, water weeds and cover crops
- No use of fertilizers in wetland areas
- 4,500 ha annual afforestation and significantly lower harvest than growth
- The gains achieved from genetic improvements of trees are utilized

This scenario will provide 13-14 mill. tonnes of feedstock for energy production which is about 1.5 times the amount required to meet the demand for sustainable fuel for aviation in 2035. In this scenario straw and manure are still important, but energy crops are also important contributing around 30 % of the total biomass produced.

Table 4 summarizes and compares the two different scenarios. Both scenarios succeed in meeting the feedstock demand in 2035.

Table 4: Two different scenarios of feedstock supply for a Danish production of sustainable fuel for aviation. The table includes the nationally produced feedstock, the imported and the % of the feedstock demand covered to meet the sustainable fuel for aviation demand in 2030.

	Scenario 1	Scenario 2
	Business-as-usual	Environment optimized
Nationally produced feedstock [1000 tonnes]	7,800	11,400
Feedstock demand covered [%]	100 %	150 %

### 8.5.3 Perspectives on Future Biomass Production

The calculations are based on the demand in 2035 – however, in 2050 the demand will increase to around 1 mill. tonnes of fossil fuels for commercial aviation being completely substituted with sustainable alternatives. Furthermore, the calculations are based on aviation, shipping and heavy trucks being the only con-

---

sumers of biofuels. It is expected that other sectors also will demand biomass in the future. Finally, it is important to explore the possibility of alternative sources of feedstock in order to secure the supply in case of harvest failure.

The increase in demand will make the additional biomass production from the “+10 million tonnes study” insufficient. Thus, alternatives to increase the amount of available feedstock must be found. This could be:

- Import of feedstock
- Changing current utilization of land
- Varietal selection (potentially with new technologies)

The biomass balance (Figure 23) illustrates how large amounts of biomass already are imported to Denmark. For instance 1.7 mill tonnes of wood pellets were imported for energy production in 2012.

The import of feedstock causes potentials of Danish know-how being implemented in developing countries. This would be a benefit to Denmark as a remote production of feedstock can help in meeting the future demands for biomass. There are also potentials of ensuring social sustainability where developing countries can gain a new market

Another option for increasing the amount of feedstock available for the production of sustainable fuels for aviation is changing the current utilization of land area in Denmark. For instance, changing about 43,000 ha of grass and clover, and 75,000 ha of cereals (which are equivalent to 4 % of the total land area for agriculture) to for instance 65 % sugar beets, 10 % willow and 25 % elephant grass can yield an additional 2 mill. tonnes of feedstock based on the potential yields from Gylling *et al.* (2012).

This will cause an additional 120,000 ha of land used for food and feed production to be occupied and thus risks affecting the current meat production. However, as mentioned feed can be produced (by extracting proteins) in biorefineries, so the consequences are expected to be minimal.

The technologies for harvesting and utilizing blue feedstock are not yet feasible. However, blue feedstock should not be ignored in future biomass scenarios. Growing brown algae in an area of 260,000 ha (which is equal to 10 % of the Danish agricultural area) could potentially produce 1-4 mill. tonnes of biomass depending on the brown algae yield per ha.

As the world's population increase the global stress on water resources are expected to increase. New technologies of genetically enhancing for instance the

---

yield of crops can prove important in a future both supporting the world's population and demand for biomass for energy production, materials etc.

An example of this is genetically modified poplar where the lignin molecule has been modified in order to make the extraction of sugars less resource demanding. This can potentially double the amount of sugar extracted from the tree without affecting the stability of the tree which is the function of lignin (Wilkerson *et al.*, 2014). However, it is important to point out that any development within genetic modification of crops and, potentially, animals should meet strict environmental criteria in the broadest sense to mitigate any negative consequences to the environment, and especially biodiversity.

## 8.6 Discussion

As mentioned in Section 3.5, many sustainability criteria of biofuels can be reduced to a matter of how the total land area is managed. The biomass balance shows that the current utilization of Danish land area prioritizes meat, and especially pork, production.

The two scenarios for future feedstock production for energy indicate that it is possible to provide feedstock to meet the Danish demands for sustainable fuel for aviation in 2035 by implementing the environment optimized scenario or following the business-as-usual scenario from the “+10 million tonnes study” (Gylling *et al.*, 2012).

The most important feedstocks in a Danish production of sustainable fuels for aviation, based on nationally produced feedstocks, are:

- Straw
- Manure
- Energy crops
- Wood

These four types of feedstocks are suitable for many different conversion processes and correlate well with the Danish strengths within especially pre-treatment technologies that result in great feedstock versatility. In addition, choosing a wider selection of feedstock will make the supply more secure in case of harvest failure of a specific type of feedstock.

In the future it is expected that even larger amounts of biomass is required due to the demand from sectors other than shipping, aviation and heavy trucks, and also that the demand for sustainable fuels for aviation as blend-in ratios increase, culminating in a 100 % substitution. Thus, it will not be possible to meet

---

the future demand without actions being taken either politically or by cyclical changes.

Regardless of the feedstock being nationally produced or imported it is key that the production is sustainable and meets the criteria mentioned in Section 3. Where an import of feedstock can be difficult to monitor there is also potential of social development with a production in developing countries using Danish agricultural know-how.

Proteins can, as mentioned, be produced as a byproduct in biorefineries. This means that a Danish prioritization of sustainable fuels does not necessarily conflict with the report from Concito focusing on a more sustainable meat production. Extracting protein efficiently from feedstock can reduce the import of cake of soybeans from Argentina and Brazil and hence reduce the large GHG emissions associated with this.

---

## 9 LOGISTICS AND SUPPLY CHAIN

This section describes that current logistics of aviation fuel supply in Denmark. It furthermore describes which challenges must be overcome in order to introduce sustainable fuels for aviation and how this can be done gradually as the new fuels gain a larger market share. Finally the importance of strategic co-operations is highlighted.

### 9.1 Danish Airports

Given the number of commercial airports (in relation to, for example, gas stations for cars) a lower number of facilities will have to be updated (if necessary) to accommodate a new type of fuel.

As of May 30<sup>th</sup> 2013 the Danish Transport Authority lists 87 airports in Denmark. Of these 51 are smaller, private airports or helipads (for instance at hospitals, oil rigs in the North Sea and so forth).

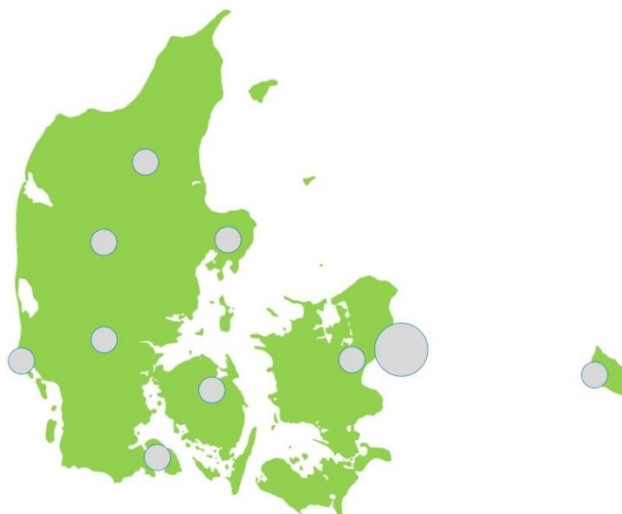
The Royal Danish Air Force is located at four airbases across Denmark and 14 airports are listed as large, commercial airports. Also, a number of smaller airports exist that are not listed as commercial airports.

The largest commercial airports in Denmark are Copenhagen Airport (CPH), Billund Airport (BLL), Aalborg Airport (AAL), Esbjerg Airport (EBJ), Odense / Hans Christian Andersen Airport (ODE), Tirstrup Airport (AAR), Roskilde Airport (RKE), Bornholm Airport (RNN), Karup Airport (KRP) and Sønderborg Airport (SGD), with Copenhagen Airport being by far the largest (see Section 5).

Copenhagen Airport is also the largest airport in Scandinavia and a major international hub.

---

Figure 28: Location of the largest commercial Danish airports.





---

## 9.2 Aviation Fuels Logistics and Supply Chains in Denmark

The logistics and supply chains involved in covering the transportation demand for aviation in Denmark are relatively simple, compared to e.g. the complex infrastructure and supply chains involved in supplying energy for road transportation. With the exception of military in-flight refueling, aircrafts only refuel at a relatively low number of places compared to the approx. 2,000 publicly accessible service / gas stations in Denmark.

This sub-section provides a brief overview of the production sites and supply structure for aviation fuels in Denmark with the aim of highlighting the relatively small need for new and expensive infrastructure that arises when substituting fossil aviation fuels with sustainable fuels. A more detailed description is provided in Appendix 5.

### 9.2.1 *Danish Oil Refineries*

There are two oil refineries located in Denmark, a Shell refinery in Fredericia and a Statoil refinery in Kalundborg. Both refineries have previously produced aviation jet fuel and continue to produce other fuel products.

Medio March 2014 Shell announced their intentions to sell the refinery in Fredericia.

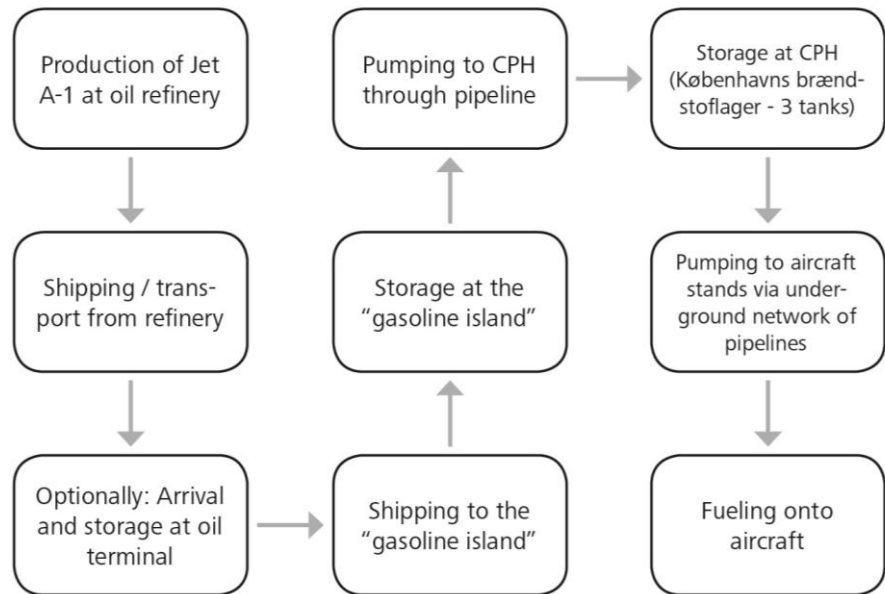
During the latter years Danish production of jet fuels has decreased with Statoil reporting zero production at the Kalundborg refinery in 2012. The refineries still have the know-how and can potentially start producing jet fuel again if market conditions are more favorable.

The process infrastructure set up at these two locations, as well as the know-how represented in the companies, may prove very valuable for refining lower order biofuels into aircraft grade fuels, such as Jet A-1. Also, the supply structure, if found usable for sustainable fuels for aviation, may prove to be a valuable asset in supplying the new fuels to airports nationally as well as internationally.

### 9.2.2 *Supply Chain to Copenhagen Airport*

Copenhagen Airport is, by far, the largest consumption point for aviation fuels in Denmark. The airport is supplied with aviation fuels from the near-by “Benzinøen” (“the gasoline island”) located off the coast of Amager (the island of the east coast of Zealand, on which the airport is located). Figure 29 illustrates the supply chain from the refinery to the aircraft.

Figure 29: The elements in supplying Jet A-1 to aircraft at Copenhagen Airport.



### 9.2.3 Other Danish Airports

Most commercial airports store both Jet A-1 and Avgas for aircraft serviced at the site. The common supply chain involves transport of the fuel by truck or rail for the last leg of the journey to the airport, but some airports are supplied by a pipeline (especially the military airports in Jutland).

Even though the last leg of the journey is by truck or rail transportation, the relative scarcity of consumption sites makes the supply chain relatively simple and easy to convert or augment with biofuels for aviation.

## 9.3 Challenges Introducing New Fuels

While the relative simplicity of the supply chain affords a good platform for introducing biofuels into the aircraft serviced at Danish airports, for instance at Copenhagen Airport, a few challenges may arise.

Suppliers of sustainable fuels for aviation may encounter some resistance from distributors, airlines or other stakeholders to the introduction of the new fuel. There have already, however, been completed a large (and still growing) number of commercial flights on sustainable fuels and as further experience is gathered the use of sustainable fuels for aviation will become an everyday thing and probably not give rise to any objections and rather be taken as a given.

---

#### 9.3.1.1 *Challenges of Traceability and Auditability With Respect to Sustainability*

There exists a further challenge in introducing new *sustainable* fuels for aviation. The reason is that both conventional crude oil products and the feedstocks for sustainable fuels for aviation are freely traded, often residing in storage depots, material exchanges or oil terminals. This means that there exists a possibility of co-mingle storage (or “contamination” by non-sustainable products), which could make the final product un-certifiable as a sustainable fuel for aviation.

Producers must ensure that the products and feedstocks are traceable and auditable in order to document and certify the sustainability of the end-product (the aviation fuel). Because the possibility of co-mingled storage exist, it is necessary to put in place mechanisms that ensure traceability and auditability of the products. Alternatively separate supply chains for feedstock (biomass) and bio fuel must be established at an additional cost.

### 9.4 **Introducing Sustainable Fuels for Aviation in the Danish Supply Chain**

Given the factors described above an introduction of sustainable fuels into the Danish supply chain for aviation fuels would be feasible to do starting in Copenhagen Airport.

A three step introduction is suggested so that larger and larger quantities can be introduced gradually at different points in the supply chain.

The amount of airlines and flights requiring the fuel, and the relative percentage to the overall consumption in the airport will determine the point in the supply chain the fuel is introduced. The three levels are: small scale testing by one (or a few) airlines on a limited number of flights, medium scale testing or commercial use by a larger percentage of airlines on either all flights or a larger number of flights and, finally, large or full scale use on a large percentage of the airlines serviced and a large amount of the total flights from the airport.

The three steps / points in the supply chain are:

1. Blended fuels supplied directly to the aircraft by (dedicated) truck (smallest scale)
2. Blended fuels stored at one of the tanks at Copenhagen Airport and supplied to the aircraft through the on-site pipeline system (medium scale)
3. Full blend-in of fuels at the large storage facilities at “the gasoline island” (large to full scale)

---

Generally the two first step may of course also be implemented at any other airport in Denmark than Copenhagen.

Ideally the sustainable fuel for aviation is blended in at a stage as early as possible in the supply chain, either at the refinery or at an oil terminal. This would decrease the amount of additional testing and certification as well as the need for dedicated equipment and storage facilities, which could be a limiting factor at airports with restricted capacity for storage or distribution.

## **9.5 Developing New Sustainable Aviation Fuel Supply Chains**

Whereas traditional transportation fuel supply lines are very complicated downstream from the refineries (because of the many sites of purchase), the value chain upstream from the refineries are in general relatively simple. In this respect sustainable fuels for aviation may be seen as having a disadvantage since a large number of producers are likely to be needed for the required amounts of feedstock and consequently the supply chain will be equally complicated.

It is beneficial for prospective producers of sustainable fuels for aviation to develop strong relations to, and partnerships with, biomass producers and distributors. Building on their competencies and knowledge the partners can collaborate on developing an economically, as well as environmentally, sustainable supply of feedstock for the production of sustainable fuels for aviation.

Internationally initiatives have been taken by several key players in the market seeking to integrate up-, middle- and downstream components of the value chain for supplying sustainable fuels for aviation. Notable coalitions include Boeing partnering with Brazilian GOL Linhas Aereas Inteligentes to supply sustainable fuels for flights at the world cup finals in 2014 and for the Rio Olympics in 2016. Virgin Atlantic is partnering with LanzaTech and GE Aviation has recently made agreements to buy synthetic biofuels from D'Arcinoff Group (Forbes, 2013).

One of the more ambitious partnerships is the announced partnership between Statoil Aviation and supply chain integrator company SkyNRG. The partnership aims to develop so-called Bioports that are local complete supply chains for the production of sustainable fuels for aviation. Based on local / regional feedstocks the coalition will employ suitable conversion technologies and team up with airports, airlines, biomass producers and other relevant partners to complete the Bioport supply chain (SkyNRG, 2014b). In 2013 SkyNRG announced that they were the first aviation biofuel provider worldwide to have their entire supply chain from "feedstock to flight" certified as sustainable by the RSB (ClimateSolutions, 2013).

In a Danish context such partnerships could help further the development and introduction of new sustainable fuels for aviation immensely. There is also a very

---

large potential for developing such partnerships. Denmark, as seen in Section 7.5, has very strong special competencies within several relevant areas as well as several possible production pathways if some of these competencies are combined. Especially co-processing based pathways utilizing the infrastructure in place at either the Fredericia or Kalundborg refineries and including one or more of the potential pathways illustrated in earlier sections could be viable routes to a Danish sustainable fuels for aviation production. Building on existing infrastructure and strong special competencies to accelerate the development, such partnerships are to significantly increase the speed with which sustainable fuels for aviation are introduced. Also, existing infrastructure and know-how within Danish Agrotech could be important contributions in developing these new supply chains.

### **9.6 Downstream Participation - Sustainable Aviation Sponsors**

A recent development could help further the development of sustainable fuels for aviation supply chains, namely downstream participation in the value chain by corporate sponsors.

SkyNRG, the aforementioned developer of sustainable fuel for aviation supply chains, has introduced a corporate travel partnerships program wherein companies like Nike, Accenture, Heineken, DSM, Philips and Schiphol Group have been the first to sign up to pre-order and pre-purchase sustainable fuels for aviation. The companies thus gain significant carbon reductions resulting from their business travels as well as a green profile and other CSR related gains (ClimateSolutions, 2013).

Denmark has a large international profile as a pioneer in sustainability as well as a strong commercial sector within environment, energy and climate solutions and a large number of high profile companies supplying energy and climate solutions. Thus the potential should exist for demand aggregation through an intermediary company (as with SkyNRG's business model) and consequently an accelerated introduction of sustainable fuels for aviation.

---

## 10 GREENHOUSE GAS REDUCTION AND OTHER ENVIRONMENTAL EFFECTS

This section qualitatively discusses the possible effects on the environment and climate if substituting conventional fossil fuels with sustainable alternatives.

A more detailed overview is provided in Appendix 5.

### 10.1 Climate Effects of Sustainable Fuels for Aviation

As mentioned in Section 2.1, greenhouse gasses (GHGs) such as CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> all contribute to global warming.

Sustainable fuels for aviation and conventional fuels are produced very differently except during the final steps in the process. The emissions vary in extent except for the combustion in the aircraft engine that is similar due to the technical specifications applying to both types of fuels (Stratton *et al.*, 2011).

Prior to the refining process, the emissions associated with the production of alternative fuels roughly originate from the following sources:

- Collection of feedstock
- Transportation of feedstock to pre-treatment / conversion
- The pre-treatment / conversion processes

The process energy for pretreatment / conversion should be produced from a fraction of the biomass, e.g. lignin, in order to avoid the use of fossil fuels. This will cause a loss of feedstock that can be used for fuel product, but will significantly reduce GHG emissions from the process energy.

Different studies examining the GHG emissions from biofuels using a lifecycle assessment (LCA) approach have been performed (Sgouridis *et al.*, 2011, Concito, 2013, *et al.*).

There is consensus that biofuels are not CO<sub>2</sub> neutral as the processing of feedstocks require energy and the biomass can cause LUC and ILUC effects. In addition bio-based fuels currently have higher emissions associated with conversion and processing compared to conventional fossil fuels (Avinor, 2013). However, the GHG emissions calculated vary greatly from study to study depending on the boundary conditions.

If feedstock is produced without LUC and ILUC effects, potential CO<sub>2</sub>-eq reductions of 65 to 80 % are achievable (Avinor, 2013). For the case of straw the reduction might even be a removal of CO<sub>2</sub> from the atmosphere (Concito, 2013).

---

On the other hand when including ILUC effects, these results can change dramatically. Thus, ILUC effects should not be ignored as the emissions can be greatly underestimated. This is currently challenging as ILUC effects are difficult to assess. Thus, these methods must be improved and standardized to ensure consistent results for the different technologies and feedstocks. In addition transparency in the entire chain of custody is key when assessing if an alternative fuel truly is sustainable.

## **10.2 Non-Climate Effects of Sustainable Fuels for Aviation**

As for the GHG emissions estimating non-climate effects of sustainable fuels for aviation is complex.

The non-climate effects include several relevant parameters, as described in Section 2. DCA (2013) has qualitatively assessed the non-climate effects by an increased production of different crops. The results show that there are no crops that have only positive effects on nutrients leaching, the carbon stock in soil, pesticide usage, biodiversity and ILUC. The results are further discussed in Appendix 5.

## **10.3 Discussion**

The previous two sections illustrate the importance of not only well-defined sustainability criteria, but also standardized methods to evaluate these. The GHG reductions of biofuels can potentially be 65 – 80 %, but biofuels can also have higher CO<sub>2</sub> emissions than conventional fossil fuels, if the production of feedstock does not take for instance ILUC effects into account.

## 11 PRICE SENSITIVITY AND BREAK-EVEN

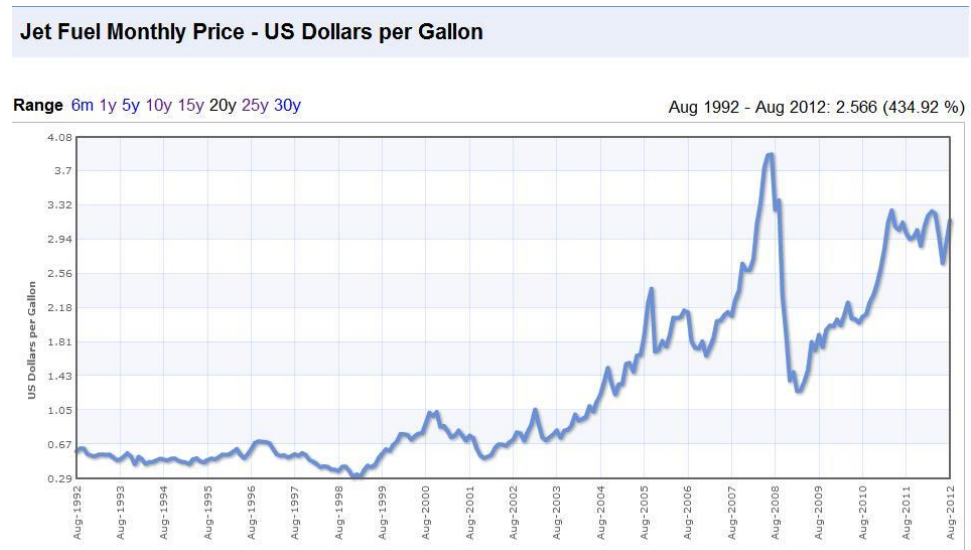
In substituting fuels for aviation the additional cost is the main barrier, but there are a range of scenarios for the introduction of sustainable fuels and some factors that may offset the additional cost of sustainable fuels for aviation. This section discusses the price sensitivity of aviation, describes benefits that may offset the additional cost of sustainable fuels and examines the additional cost of different scenarios for substitution.

### 11.1 Price Sensitivity of Aviation

The price sensitivity of aviation is debated in many publications, but overall there seems to be a consensus that aviation is indeed very price sensitive. Also there seems to be a consensus that this sensitivity is most present in the lower priced markets, especially in the fast growing discount airline industry where fuel costs make up a very large percentage of the operating cost of the airlines.

Fuel costs have grown from about 14 % of operating expenses in 2003 to an estimated 31 % in 2013 (IATA, 2013a). This sensitivity is amplified by the highly unstable market and large fluctuations in the cost of aviation fuels as seen in Figure 30.

Figure 30: The price development for a gallon of jet fuel over 20 years. A high degree of fluctuation and price volatility can be seen, especially over the last decade illustrated where prices have also more than tripled. Source: (AirportWatch, 2014).



### 11.2 Benefits for Sustainable Fuels for Aviation Producers

An important aspect to jet fuel pricing is the nature of jet fuel purchasers. They are typically a concentrated and coordinated group who may willingly enter into long-term purchasing agreements offering a very stable consumer base for jet fuel producers (CAAFI, 2013).



---

If an alternative jet fuel, such as one of the sustainable fuels described in this report, can achieve certification by proper authorities, as well as acceptance from the airline community, these benefits may help to strengthen the business case for a biofuels producer significantly. The “other side of the equation” is that purchasers of sustainable fuels for aviation, by entering into long term contracts, are ensured a stable supply at foreseeable prices, consequently freeing them from some of the concerns posed by their dependencies on the fluctuating jet fuel market.

The diversification of supply gained by having access to several sources of fuels for aviation is in itself a benefit to the airlines that can offset some of the additional costs. Also local suppliers that are more independent from influences from e.g. conflicts and other risks increase the security of supply for the airlines and decrease price volatility, which can also be considered offsetting factors for the additional cost of the sustainable fuels.

### **11.3 Pricing Sustainable Fuel for Aviation**

There are three key factors in making the price of biofuels competitive to fossil fuels:

- Feedstock costs
- Economy of scale
- Technology development

Feedstock costs are dependent on a range of factors, including the year to year variations in the yield of different crops and general supply and demand. It is vital for a prospective producer of sustainable fuel for aviation to ensure a steady flow of feedstock for the planned facility (or facilities) and preferably secure long time purchase agreements with suppliers. The downsides of such agreements could arguably be offset by the upside of a stable supply of feedstocks and the fact that aviation fuel customers, as mentioned in Section 11.2, often are willing to engage in long term agreements for purchase of the products. It is important to remember that advanced sustainable fuels must be produced from feedstocks that are neither edible nor replace the production of food or feed to ensure a decoupling of the price of feedstock for energy and food prices as far as possible. See Sections 3 and 8 for a further discussion on feedstock and food security.

Economy of scale is a very important factor, as it has been seen with several bioenergy projects, and is generally well documented in the conventional fuel industry. Thus prospective producers of sustainable fuels for aviation should either plan for an initial large scale production or, if possible, work towards co-

---

processing of the sustainable fuels in conventional fuel refineries to harvest the economy of scale benefits without the capital investment intensity of large “green field investments”.

As technologies for pre-treatment, conversion and refining develop more and more feedstocks become feasible to use for sustainable fuel production and the cost is decreased. Additional development and innovation within the production of sustainable fuel for aviation promises to yield significant cost savings and, consequently, competitive prices.

An incentive for substituting conventional aviation fuel with sustainable fuels could be market based measures or an emissions trading system including aviation. Alternatively incentives (subsidies) could be placed on the use of sustainable fuels for aviation, which of course would affect the cost for aircraft operators. This will be discussed further in Section 13.

The EU has custom duties on ethanol imported from outside the EU. These help promote the production of sustainable ethanol in the EU as this production is not price competitive with for instance the production of ethanol from sugar canes from Brazil.

Jet fuel is current exempted from custom duties with a proposal of continuing this from 2014 as well (European Union, 2013). As the production of sustainable jet fuels increases it could not be ruled out that custom duties equivalent to those on ethanol are implemented in order to promote a production and protect the market within the EU.

#### **11.4 Break-Even Scenarios**

Several different publications have calculated the incentive currently needed to make sustainable fuels for aviation (based on biomass) cost competitive with conventional fuels. Most fall within an interval of 39.6 to 53.5 eurocent per liter of jet fuel (see e.g. MASBI, 2013, SQ Consult, 2014).

Choosing an average of 47 eurocent per liter different scenarios for break even for different blend-in ratios are calculated (Table 5).

The increase in tickets prices is also calculated assuming that the fuel costs contribute to 30 % of the total ticket price.

Table 5: Additional cost of fuel and tickets if introducing sustainable fuels for aviation for different blend-in ratios.

Blend in ratio	Additional cost [€ per liter]	% of average price <sup>10</sup>	% ticket price increase
2.5 %	0.01	2 %	0.6 %
5 %	0.02	4 %	1.2 %
10 %	0.05	8 %	2.4 %
20 %	0.09	16 %	4.8 %

At low blend-in ratios the price difference between a blended fuel and the average price for a gallon of conventional jet fuel is negligible.

As there are major uncertainties regarding the future price development for fossil fuels and as the break-even point obviously is closely related to this development it is hard to speculate on the precise duration before we have a situation where fossil and sustainable fuels are equal with respect to their cost. It is, as described in this section, clear that the additional cost for sustainable fuels for aviation is a minor factor a low to medium blend in ratios.

Although there is a lot of debate about when sustainable fuels for aviation will be competitive with conventional fuels in a 100 % drop-in scenario, the stated goals of the industry as well as a range of other factors point towards a gradual introduction. Given the benefits of substitution, both those listed in this section and the direct and indirect benefits discussed in other sections of this report, the limited additional costs at low blend-in ratios should not be a major barrier. Additionally the rapid growth of the sustainable fuels for aviation sector has the potential for positive synergies with the production of other sustainable fuels, bio-based materials and high value products, as discussed in Section 7.1, which is further motivation to advance the field.

These conclusions are supported by a number of publications, see for instance Winchester *et al.* (2013).

<sup>10</sup> Relative to the average price per gallon for jet fuel in 2013, as listed by Airlines for America (2014).

---

## 12 POTENTIAL SOCIAL EFFECTS

In 2012 the production of jet fuels in Denmark had been almost terminated, meaning that the entire demand has to be imported with negative consequences for the Danish national economy as a consequence.

This section evaluates the socio-economic possibilities associated with a Danish production of sustainable fuels for aviation in terms of job creation.

### 12.1 Maabjerg Bioenergy Concept Case

Using published data from Maabjerg Bioenergy Concept (MEC) a case is built illustrating the potential job creation and growth resulting from a Danish production of aviation biofuels.

#### 12.1.1 *Maabjerg Energy Concept (MEC)*

As mentioned in Section 7.4.2.6, MEC is a concept under development for a comprehensive, sustainable energy solution based on local feedstocks and using the newest technology. This technology is pioneered in Denmark by e.g. Novozymes and Inbicon.

The main product of the biorefinery will be bioethanol produced from agricultural residuals (straw etc.). The plant is expected to produce 80 mill. liters of bioethanol p.a.

#### 12.1.2 *Job Creation at MEC*

Using ADAM (Annual Danish Aggregate Model), the Danish national economic model, provided by Danish Statistics MEC has made detailed calculations of the expected job creation from the construction and operation of the plant.

In the construction phase MEC has calculated a job creation of 2,500 full time equivalents (FTEs) for two years. Once in operation MEC has calculated a permanent job creation of approx. 1,000 jobs.

### 12.2 Job Creation From a Danish Production of Sustainable Fuels for Aviation

Extrapolating from the MEC case we can illustrate the growth potentials of a Danish production of sustainable fuels for aviation.

The demand for sustainable aviation fuels in 2035, following the scenario described in section 5.3, is approx. 0.6 mill tonnes, or approx. 735 million liters, of aviation fuel.

Using a very conservative (high) conversion rate of 0.44 liters of aviation fuel from 1 liter of ethanol the demand for ethanol will be 1.66 billion liters of ethanol.

Given the planned production capacity of MEC this would require almost 21 plants of the same scale as MEC<sup>11</sup>.

It is conceivable that certain efficiency gains will be made from both economy of scale and the advancements in technology that will take place over the coming years. If we assume a 50 % efficiency gain we arrive at a job creation a factor of 10 higher than those calculated by MEC. This would mean that from the production of ethanol alone the expected job creation would be approx. 25,000 jobs during the construction phases and approx. 10,000 permanent jobs during the operations of the plants.

The jobs would be divided on different industries as described in Table 6.

Table 6: Expected job creation from a Danish production of bioethanol for sustainable aviation fuels. The job creation is equivalent to ten times the expected job created at the Maabjerg Energy Concept (MEC).

Industry	Jobs created
Agriculture and raw material production	3,000
Manufacturing	600
Electricity, gas and heating	1,800
Construction	1,400
Trade, transportation and communication	1,300
Financial services	1,600
Private and public services	200
<b>Total</b>	<b>9,900</b>

While being an estimate based on an extrapolation from the MEC case, the estimate should be considered a conservative one. The reasons being legion. First-

<sup>11</sup> It is, however, not feasible to construct so many facilities in Denmark, nor would it be optimal with respect to feedstock availability, optimization requirements etc. A good estimate would be that between 6 and 8 (very) large scale biorefineries will be constructed in Denmark.

---

ly, the job creation is only calculated for the ethanol production and everything upstream in the value chain. Secondly, the extrapolation assumes a very significant efficiency gain from economy of scale and technology development as well as a very high conversion rate from ethanol to aviation fuel (the lower the rate the higher the demand for ethanol and consequently more job creation). Thirdly, the calculation does not take the downstream processing into account, nor the significant job creation gained downstream from the production of high value distillates from the refinery process (see Section 7.1 for a discussion on the biorefinery concept and the extraction of high value products). Finally the MEC calculations using the ADAM model have been made assuming full employment at the time of construction and operation and thus assume that some existing jobs are replaced by the new jobs (since skilled laborers are assumed to be already employed). Additionally any public proceeds (through taxes etc.) are assumed not to be reinvested, which also decreases the calculated effect.

### 12.2.1 *Impacted Industries*

The construction of a higher order biorefinery complex would not only impact the aviation fuel production industry, but will have widespread effects on other industries. Innovation and growth will likely happen in all of the following fields and industries:

- Universities / research institutions
- Agriculture / farming / forestry
- Transportation / logistics
- Danish technology developers and suppliers
- Construction and planning (consultants, construction industry, contractors, suppliers)
- Operations (operation managers, facility employees, etc.)
- Maintenance

If it is decided that a Danish biofuel production should be based on imported feedstock, it is important to note that the expected growth will not be as significant compared to a national production of feedstock. However this “remote production” will result in economic growth in the areas where the feedstock is produced and is likely to increase social and economic sustainability in these areas. Also Denmark may export know-how and solutions ensuring a sustainable and efficient production of biomass.

---

### 12.3 Discussion

The growth potentials of sustainable fuels for aviation in a Danish context are very large. Not only will a national production of sustainable fuels for aviation improve the Danish Balance of Payments by substituting imported fossil based aviation fuels with locally produced aviation fuels, it could also create many new (green) jobs that will contribute positively to both local and national economy as well as increase employment locally and regionally across several sectors.

Additionally the promotion of sustainable fuels for aviation in Denmark has the potential to increase the knowledge base and further innovation, as well as lead to spin-off technologies and businesses. A further advantage is the development of small and medium sized enterprises (SMEs) that result from the development of sustainable fuels for aviation. SMEs are a cornerstone of the Danish economy and export market and such a development would, concordantly, be very desirable.

Export of knowledge, consulting, products, solutions and technology also promises to be a major benefit yielded from the emergence of a national sustainable fuels for aviation industry, provided that this emergence can benefit from a “first mover effect”.

---

## 13 CONCLUSIONS AND RECOMMENDATIONS

The previous sections have illustrated how sustainable fuels for aviation are the only possibility the aviation industry has to significantly reduce its negative environmental and climate impacts and meet its climate targets of 2050.

A national production of sustainable fuels has potential benefits gained from the reduction of negative environmental impacts, new technology development, economic growth and job creation.

The following are recommendations for actions that can further the development of a production of sustainable fuels for aviation in Denmark.

### 13.1 Sustainability

In order to ensure a truly sustainable production of alternative aviation fuels it is important that well-defined certification schemes are being developed not only on a NGO level. The schemes must be globally accepted and standardized.

The coming ISO standard of sustainable bioenergy (under technical committee TC248) may serve as a standard method of measuring and reporting different sustainability indicators.

In addition to global standards, sustainability criteria should be adapted to the specific region where the feedstock and fuel is produced. In a Danish context cycling of nutrients, groundwater and environmental protection in general and the potential effects of “green growth” are examples of indicators that are important in terms of sustainability.

In general the aviation industry as well as present and future developers and producers of sustainable fuels for aviation should work for a consensus on appropriate sustainability criteria, both within the industry and in a global context.

### 13.2 Technologies

It is evident from section 7 and 8 that the available Danish technologies provide great flexibility in the choice of feedstock and pre-treatment technology. It is recommended that the biorefining concept is kept in mind when choosing technologies, as for instance some processes prevent a potential recycling of nutrients and recovery of valuable chemicals. The biorefining concept is important both in terms of the sustainability, but also price competitiveness, of the final fuel product.

Based on the identified technologies in Section 7.5, the following pathways are the most promising in a Danish production of sustainable fuels for aviation:

- Alcohol to jet (AtJ)



- 
- Hydrotreated Fatty Acids and Esters (HEFA)
  - Fischer-Tropsch synthesis (FT)

There is currently no production of jet fuel in Denmark, however, there are two existing crude oil refineries and hence, there is a great potential of co-processing sustainable oils together with crude oil when this has achieved an ASTM certification.

From the discussions in sections 2, 3, 7 and 8 it should be clear that the concrete choice of pathway, the components in the pathway and the utilized feedstock has major impacts on the overall sustainability of the produced fuel. Of the possible Danish choices on pathway there are significant consequences of giving priority to one pathway over another.

It is the clear recommendation of this report that all relevant sustainability criteria are taken into account when making these choices. This report finds that priority should be given to pathways that are compatible with the bio-refining concept. Hereafter priority should be given to pathways based on FT synthesis of biogas to liquid fuels as this pathway makes it possible to recirculate vital resources, such as scarce nutrients, back into their natural cycles. Some types of low temperature gasification may also include this desirable feature.

The least priority should be given to high temperature gasification as this in many respect negates the option of recirculating and conserving vital resources, for instance by making phosphorous biologically unavailable to crops.

Denmark also has the world's largest share of renewable electricity in the energy grid, mainly from a large portion of wind turbines installed in Denmark with even more to come. This means that at times there is a surplus of renewable electricity, electricity that may be used to generate hydrogen that in turn may be used for hydrotreating and upgrading of sustainable fuels for aviation.

### 13.2.1 *Future Analysis*

As mentioned, the scope of this analysis was to provide a general overview of Danish competences and strengths in a national production of sustainable fuels for aviation and is thus not a technical manual or reference.

Further work is needed to fully explore the different scenarios for the future implementation of different technologies and production pathways identified in Section 7.5 in this report. This especially with respect to the socio-economic as well as environmental consequences of the different choices.

---

### 13.3 Strategic Collaborations

As there are no companies in Denmark capable of supplying a complete pathway from feedstock to jet fuel, it is essential that stakeholders collaborate if sustainable fuels for aviation are to be produced in Denmark.

The collaborations are first of all technological in order to supply the feedstocks and technologies required for a complete pathway from feedstock to final jet fuel product.

It is recommended in this report that stakeholders are mobilized through workshops and / or conferences with the aim to further the development of a full production pathway of sustainable fuels for aviation in Denmark. These stakeholders include not only technology providers, but also feedstock suppliers, fuel suppliers, refineries, researchers, investors, airports, airlines and authorities. The purpose of this is to identify new potential technology collaborations, but also to form a working group with some of the key stakeholders identified in this report. This working group should focus on facilitating, and being a strong lead on, the development of complete production pathways.

In the future it is expected that many benefits can be gained by expanding collaborations to also include stakeholders in other Nordic countries, or countries in the rest of the world, as these countries have different strategic advantages than Denmark.

### 13.4 Political Framework

The strategy of how to achieve the national goal of a fossil free energy system in 2050 must be defined.

Politically it is possible to create further incentives for the aviation industry to not only recognize the opportunities of substituting fossil-based fuels, but also work actively towards this. This analysis indicates that the future Danish demand for sustainable fuels for aviation could be fully or partially covered by available national biomass resources, if these resources are dedicated to sectors that have no other alternatives in a foreseeable future. This is further underlined by the different scenarios projected by the Danish Energy Agency as well as several other stakeholders. Hence it is important that these resources are properly prioritized.

It is therefore recommended that a discussion of the political priorities for allocating the limited biomass resources is initiated with the proper involvement of all relevant ministries and other stakeholders, taking into account that aviation has no other options than the use of (sustainable) biofuels in order to reduce the negative environmental impact substantially.

---

A clear strategic goal of biomass playing a substantial and dedicated role in the future energy supply in Denmark will help facilitating the necessary investments in a production of sustainable fuels for aviation. It is equally important that the optimal use of biomass is decided on a strategic level so that the available biomass is used where it yields the highest value with the least environmental impact.

---

## 14 REFERENCES

Advanced Biofuels USA (2014). *Boeing Seeks Approval for Green Diesel as New Aviation Biofuel*. <http://advancedbiofuelsusa.info/boeing-seeks-approval-for-green-diesel-as-new-aviation-biofuel> [Accessed April 10<sup>th</sup> 2014]

Airlines for America (2014). *Annual Crude Oil and Jet Fuel Prices*. <http://www.airlines.org/Pages/Annual-Crude-Oil-and-Jet-Fuel-Prices.aspx> [Accessed April 16<sup>th</sup> 2014]

AirportWatch (2014). Homepage: <http://www.airportwatch.org.uk/> [Accessed April 16<sup>th</sup> 2014]

ATAG, The Air Transport Action Group (2009). *Beginner's Guide to Aviation Biofuels*. ATAG Geneva.

ATAG, The Air Transport Action Group (2010). *Beginner's Guide to Aviation Efficiency, reference version*, June 2010, ATAG Geneva.

ATAG, The Air Transport Action Group (2012). *Aviation – Benefits beyond borders*, October 2012, ATAG Geneva.

Avinor, (2013). *Utredning: Bærekraftig Biodrivstoff for Luftfart*. Report. Rambøll, Killingland, M.; Aga, P.; Grinde, M.; Saunes, I.; Melbye, A.M.; Vevatne, J.; Christophersen, E.B.

Baffes , John (The World Bank) (2011) : *The long-term implications of the 2007 – 08 commodity-price boom* . Development in Practice , Vol . 21 , Issue 4-5 , pp 517-525

Biomass Magazine (2014). *Sustainability of biofuels: Future generations*. <http://biomassmagazine.com/articles/2070/sustainability-of-biofuels-future-generations> [Accessed March 7<sup>th</sup> 2014].

Biorefining Alliance (2012). *DENMARK IN A GLOBAL BIO-BASED SOCIETY – do we want to be customers or producers?*, Biorefining Alliance, Frederiksberg.

Boeing (2011). *Impact of Alternative Jet Fuel and Fuel Blends on Non-Metallic Materials Used in Commercial Aircraft Fuel Systems*, Final report for the Continuous Lower Energy, Emissions and Noise (CLEEN) Program of the Federal Aviation Administration, June, 2011.

BDL – Brancheforeningen Dansk Luftfart (2012), *Luftfart – en forudsætning for vækst og velstand*, BDL Copenhagen.

---

ClimateSolutions (2013), *New milestones move aviation biofuels forward*, <http://climatesolutions.org/cs-journal/new-milestones-move-aviation-biofuels-forward> [Accessed March 31<sup>st</sup>, 2014].

Commercial Aviation Alternative Fuels Initiative (CAAFI) (2013). *Path to Alternative Jet Fuel Readiness*, CAAFI.

Commercial Aviation Alternative Fuels Initiative (CAAFI) and Airlines for America (A4A) (2013). *Guidance for Selling Alternative Fuels to Airlines*.

Concito (2014). *Klimagevinster ved øget proteinproduktion i Danmark*. Chrintz, T.

Danmarks Naturfredningsforening (2007), *Biobrændstof med hovedet under armen*, october 2007, <http://www.dn.dk/Default.aspx?ID=1339&PID=16675&NewsID=232>, [Accessed March 6th 2014].

DCA, Nationalt Center for Fødevarer og Jordbrug (2013). *Biomasseudnyttelse i Danmark – potentielle ressourcer og bæredygtighed*. Jørgensen, U.; Elsgaard, L.; Sørensen, P.; Vinther, F.P.; Kristensen, E.F.; Ejrnæs, R.; Nygaard, B.; Krogh, P.H.; Bruhn, A.; Rasmussen, M.B.; Johansen, A.; Jensen, S.K.; Gylling, M.; Bojesen, M., Aarhus Universitet.

Det Etske Råd (2012). *Redegørelse om bioenergi, fødevarer og etik i en globaliseret verden*. Det Etske Råd.

Dufferwiel, S. (2011), *Alternative Aviation Fuels – Aromatics & Thermal Stability*, The University of Sheffield, June 2011.

Energi- og olieforum, EOF (2013). *Energinoter og statistik 12/13*. <http://ipaper.ipapercms.dk/eof/energinoter/Energinoter2013/>

European Union (2013). *Customs proposals (legislation)*. [http://ec.europa.eu/taxation\\_customs/common/legislation/proposals/customs/index\\_en.htm](http://ec.europa.eu/taxation_customs/common/legislation/proposals/customs/index_en.htm) [Accessed May 8<sup>th</sup> 2014]

Food and Agriculture Organization of the United Nations, FAO (2013). *FAOSTAT*. <http://faostat.fao.org/>

Forbes (2013), *Next step for Green Aviation: Bioports*, <http://www.forbes.com/sites/pikerresearch/2013/12/12/next-step-for-green-aviation-bioports/> [Accessed 31. March 2014]

Green Air (2014). *Growing confidence in understanding the climate impact of aviation non-CO2 effects, says leading scientist*. Online:

---

<http://www.greenaironline.com/news.php?viewStory=1818> [Accessed Feb 3<sup>rd</sup> 2014].

Gylling, M.; Jørgensen, U.; Bentsen, N.S. (2012). *+ 10 mio. tons planen – muligheder for en øget dansk produktion af bæredygtig biomasse til bioraffinaderier*. Københavns Universitet, Frederiksberg.

Hello, K.M.; Hasan, H.R.; Sauodi, M.H.; Morgen, P. (2014), *Cellulose hydrolysis over silica modified with chlorosulphonic acid in one pot synthesis*. *Applied Catalysis A: General*(475), pp 226-234.

IBUS Innovation A/S, Integrated Biomass Utilization Systems (2014). *Personal correspondence*. Homepage: <http://www.ibusinnovation.dk/>

IPCC (1999), *Aviation and the Global Atmosphere: A Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press.

International Air Transport Association, IATA (2013a). *Fact sheet : Fuel*, december 2013, Montreal.

International Air Transport Association, IATA (2013b). *IATA Air Transport Market Analysis*, Montreal.

International Air Transport Association, IATA (2013c). *IATA 2013 Report on Alternative Fuels*. 8<sup>th</sup> Edition, Montreal.

ISO, (2014). *ISO/PC 248 Sustainability criteria for bioenergy*. International Organization of Standardization. Available at: [www.iso.org](http://www.iso.org) [Accessed February 2<sup>nd</sup> 2014].

Landbrug og Fødevarer (2013). *Fakta om erhvervet 2013*. Landbrug og Fødevarer, København.

Landbrug & Fødevarer (2013b). *Udenrigshandel 2008-2012 – fødevarer til hele verden*. Landbrug & Fødevarer, København.

National Renewable Energy Laboratory, NREL (2013). *Biological Conversion of Sugars to Hydrocarbons Technology Pathway*. Technical Report. U.S. Department of Energy, Colorado.

Rosenthal, E. (2013). *Your biggest carbon sin may be air travel*, New York Times, January 26<sup>th</sup>, New York.

RSB, Roundtable of Sustainable Biomaterials (2010). *RSB Principles & Criteria for Sustainable Biofuel Production*. RSB, Geneva.

---

Sgouridis, S.; Warshay, B.; Pan, J. (2011). *Aviation industry's quest for a sustainable fuel: considerations of scale and modal opportunity carbon benefit*. *Biofuels* 2(1), pp 33-58.

SQ Consult (2014), *Bringing biojetfuels to the market*, [http://www.sqconsult.com/content/newsletter\\_html/mrt\\_14\\_SQ\\_Consult\\_Bringing\\_biojet\\_fuels\\_to\\_the\\_market.html](http://www.sqconsult.com/content/newsletter_html/mrt_14_SQ_Consult_Bringing_biojet_fuels_to_the_market.html) [Accessed March 27<sup>th</sup> 2014].

Stratton, R.W.; Wolfe, P.J.; Hileman, J.I. (2011). *Impact of Aviation Non-CO<sub>2</sub> Combustion Effects on the Environmental Feasibility of Alternative Jet Fuels*. Environmental Science & Technology

Sustainable Aviation (2012) – *CO<sub>2</sub> Road-Map*, Sustainable Aviation, Great Britain - <http://www.sustainableaviation.co.uk>.

USGS (2014). *Saline Water: Desalination*. U. S. Geological Survey homepage. <http://www.usgs.gov/> [Accessed March 7<sup>th</sup> 2014].

Wilkerson, C.G.; Mansfield, S.D.; Lu, F.; Withers, S.; Park, J.-Y.; Karlen, S.D.; Gonzales-Vigil, E.; Padmakshan, D.; Unda, F.; Rencoret, J.; Ralph, J. (2014). *Monolignol Ferulate Transferase Introduces Chemically Labile Linkages into the Lignin Backbone*. *Science* 344(90), pp. 90-93

WWF (2012). *WWF's recommendations for sustainability criteria for biomass used in electricity, heating and cooling in Europe*. Position paper.

WWF (2013). *Searching for sustainability: Comparative Analysis of Certification Schemes for Biomass used for the Production of Biofuels*. Report, WWF Deutschland, Germany.

---

## 14.1 Companies

The following list is a selection of relevant companies and include all stakeholders mentioned in this report

AaU, Aalborg University (2014). *Personal correspondence*. Homepage: [www.aau.dk](http://www.aau.dk) [Accessed April 4<sup>th</sup> 2014]

Amyris (2014). Homepage : <http://www.amyris.com/> [Accessed April 4<sup>th</sup> 2014]

AU, Aarhus University (2014). Homepage: [www.au.dk](http://www.au.dk) [Accessed April 4<sup>th</sup> 2014]

Avista Oil (2014). Homepage: <http://www.oliegenbrug.dk/> [Accessed April 4<sup>th</sup> 2014]

Bio Energi Tønder (2014). *Personal correspondence*. Homepage: <http://www.be-t.dk/> [Accessed April 4<sup>th</sup> 2014]

BioGasol (2014). *Personal correspondence*. Homepage: <http://www.biogasol.com/Home-3.aspx> [Accessed April 4<sup>th</sup> 2014]

Carlsberg Group (2014a), *Louis Pasteur and Carlsberg Cure the 'Beer Disease'*, Carlsberg Group homepage, <http://www.carlsberggroup.com/Company/heritage/Research/Pages/Pasteur.aspx> [Accessed march 5<sup>th</sup> 2014].

Carlsberg Group (2014b), *Sørensen Invents the pH Scale*, Carlsberg Group homepage, <http://www.carlsberggroup.com/Company/heritage/Research/Pages/pHValue.aspx> [Accessed march 5<sup>th</sup> 2014].

Cobalt technologies (2014). Homepage: <http://www.cobalttech.com/cobalt-innovations.html> [Accessed April 4<sup>th</sup> 2014]

CWC, Clean World Capital (2014). Homepage: <http://www.cleanworldcapital.com/> [Accessed April 4<sup>th</sup> 2014]

D'Arcinoff Group (2014). Homepage: <http://www.darcinoff.com/> [Accessed April 9<sup>th</sup> 2014]

DAKA Denmark A/S (2014). *Personal correspondence*. Homepage: [www.daka.dk](http://www.daka.dk) [Accessed April 4<sup>th</sup> 2014]

DBH Technology A/S (2014). Homepage: <http://hveiti.dk/da/dbh-technology> [Accessed April 4<sup>th</sup> 2014]



---

DTU, Technical University of Denmark (2014). *Personal correspondence*.  
Homepages: DTU Chemical Engineering: <http://www.kt.dtu.dk/english>, DTU  
Food, Systems Biology & Biorefining: <http://www.bio.dtu.dk/english> [Accessed  
April 4<sup>th</sup> 2014]

Emmelev A/S (2014). *Personal correspondence*. Homepage:  
<http://www.emmelev.dk/> [Accessed April 4<sup>th</sup> 2014]

GE Aviation (2014) Homepage: <http://www.geaviation.com/> [Accessed April 9<sup>th</sup>  
2014]

Gevo (2014). Homepage: <http://www.gevo.com/> [Accessed April 4<sup>th</sup> 2014]

Haldor Topsøe (2014). *Personal correspondence*. Homepage:  
<http://www.topsoe.com/> [Accessed April 4<sup>th</sup> 2014]

Hveiti (2014). *Personal correspondence*. Homepage: <http://hveiti.dk/> [Accessed  
April 7<sup>th</sup> 2014]

IBUS Innovation A/S (2014). *Personal correspondence*. Homepage:  
<http://www.ibusinnovation.dk/> [Accessed April 4<sup>th</sup> 2014].

Inbicon / DONG Energy (2014). *Personal correspondence*. Homepage:  
<http://www.inbicon.com/Pages/index.aspx> [Accessed April 4<sup>th</sup> 2014]

Kior (2014). Homepage: <http://www.kior.com/> [Accessed April 4<sup>th</sup> 2014]

KU, University of Copenhagen (2014). Homepage: <http://www.ku.dk/english> [Ac-  
cessed April 4<sup>th</sup> 2014]

LanzaTech (2014). Homepage: <http://www.lanzatech.com/> [Accessed April 9<sup>th</sup>  
2014]

Maabjerg Energy Concept (2014). Homepage: <http://maabjerg-bioenergy.dk/>  
[Accessed April 4<sup>th</sup> 2014]

Midwest Aviation Sustainable Biofuels Initiative – MASBI (2013), *Fueling a Sus-  
tainable Future for Aviation*, MASBI.

Neste Oil (2014). Homepage: [www.nesteoil.com](http://www.nesteoil.com) [Accessed April 4<sup>th</sup> 2014]

Novozymes (2014). *Personal correspondence*. Homepage:  
[www.novozymes.com](http://www.novozymes.com) [Accessed April 4<sup>th</sup> 2014]

OFT, Organic Fuel Technology (2014). Homepage:  
<http://organicfueltechnology.com/> [Accessed April 4<sup>th</sup> 2014]

---

Pyroneer / DONG Energy (2014). *Personal correspondence*. Homepage: <http://www.dongenergy.com/pyroneer/Pages/index.aspx> [Accessed April 4<sup>th</sup> 2014]

REnescience / DONG Energy. Homepage: <http://www.dongenergy.com/renescience/Pages/index.aspx> [Accessed April 4<sup>th</sup> 2014]

SkyNRG (2014b). *Bioport Development*, <http://skynrg.com/our-services/bioport-development/> [Accessed March 31<sup>st</sup> 2014].

SkyNRG (2014). *Technology section, SkyNRG homepage*, <http://skynrg.com/technology-section/> . [Accessed March 6<sup>th</sup>, 2014]

Solena Fuels (2014). Homepage: <http://www.solenafuels.com/index.php/our-solution> [Accessed April 4<sup>th</sup> 2014]

Statoil Aviation (2014). *Personal correspondence*. Homepage: <http://www.statoilaviation.com/> [Accessed April 4<sup>th</sup> 2014]

Steeper Energy (2014). *Personal correspondence*. Homepage: <http://steeperenergy.com/> [Accessed April 4<sup>th</sup> 2014]

Swedish Biofuels (2014). Homepage: <http://www.swedishbiofuels.se> [Accessed April 4<sup>th</sup> 2014]

Syntroleum. Homepage: <http://www.syntroleum.com/profiles/investor/fullpage.asp?BzID=2029&to=cp&Nav=0&LangID=1&s=0&ID=11912> [Accessed February 13<sup>th</sup> 2014]

Terranol A/S (2014). *Personal correspondence*. Homepage: <http://www.terranol.dk/> [Accessed April 4<sup>th</sup> 2014]

UOP - A Honeywell Company (2014). Homepage: [www.uop.com](http://www.uop.com) [Accessed April 4<sup>th</sup> 2014]

Velocys (2014). Homepage: <http://www.velocys.com/> [Accessed April 4<sup>th</sup> 2014]

Westinghouse Plasma Corp (2014). Homepage: <http://www.westinghouse-plasma.com/> [Accessed April 4<sup>th</sup> 2014]

---

# 1 APPENDIX – TECHNICAL SPECIFICATIONS AND CERTIFICATION

## 1.1 Technical Specifications

The global technical certification of jet fuels is defined by the American Society for Testing and Materials International (ASTM) and specified in the ASTM D1655 standard. The certification process is described in the following sections. This section summarizes the key physical and chemical specifications defining Jet A-1 which is the global standard aviation fuel with the exception of the United States.

Jet A-1 consists of kerosene. Kerosene is a fraction of crude oil (petroleum) consisting of a complex mixture of different hydrocarbons (paraffins, cycloparaffins, aromatics and olefins) which a typical number of carbon atoms in each molecule of 9-16. Jet A-1 must meet the physical and chemical specifications listed in Table 7. Aromatic hydrocarbons are hydrocarbons with alternating double and single bonds between carbon atoms, giving a ring shape.

Table 7: Technical specifications for Jet A-1 (ATAG, 2009).

Criteria	Explanation	Jet A-1 specification
Flash point	The temperature at which the fuel ignites in the engine to cause combustion to occur	38 °C (minimum)
Freezing point	The temperature at which the fuel would freeze	- 47 °C
Combustion heat	The amount of energy that is released during combustion, per kilo of fuel	42.8 MJ/kg (minimum)
Viscosity	The thickness of the fluid or ability to flow	8.000 mm <sup>2</sup> /s (maximum)
Sulphur content	The amount of sulphur in the fuel (parts per million)	0.30 ppm
Density	How heavy the fuel is per liter	775-840 kg/m <sup>3</sup>

### 1.1.1 IATA

IATA has, in addition to the specifications on sustainability, set up technological requirements for sustainable alternative jet fuels:

- 
- Can be mixed with conventional jet fuel, can use the same infrastructure and do not require adaptations of aircrafts or engines (“drop in” fuel)
  - Must meet the specifications listed in Table 7
  - Automotive bioethanol and biodiesel are not suitable

## 1.2 Blend-in ratios and certification

Aromatic hydrocarbons at high levels are generally undesirable in aviation fuels, but aviation fuels with zero aromatic contents are also potentially problematic. The presence of aromatic hydrocarbons have been shown to have certain effects on non-metallic compounds used in aviation systems (Boeing, 2011). For instance nitrile rubber O-rings swell in the presence of aromatic hydrocarbons. This has given rise to concerns that using (synthetic) fuels containing zero or very low amounts of aromatic hydrocarbons may lead to undesirable effects in aviation systems, even to component failure due to leaks etc. Consequently the ASTM approved synthetic paraffinic kerosene (SPK) fuels produced by Fischer-Tropsch (FT) or Hydrotreated Esters and Fatty Acids (HEFA) processes, that will be described in Section 7, are only certified up to a 50 % blend with conventional aviation fuels.

These concerns have led to research into aromatic additives as well as synthetic aromatic aviation fuels.

Questions have, however, been raised with regard to the thermal stability of alternative aviation fuels with aromatic additives and research is still needed to avoid negative consequences arising from their use (Dufferweil, 2011).

## 1.3 Technical Certification - ASTM

Certifying fuels for aviation is a complex and also resource-demanding process. Robust and dependable certification schemes are, however, one of the cornerstones of modern aviation safety and as such a necessity.

This, of course, also means that bio-based aviation fuels must be certified to be used in commercial or military aviation.

There are several institutions certifying aviation fuels, but the most commonly referred standard for Jet A-1 is ASTM D1655 (civil) in the US and Defense Standard (DEFSTAN) 91-91 in Europe.

The ASTM D1655 standard does not, however, apply to synthetic or alternative fuels. The D1655 standard specifically states that jet fuel is refined from mineral oil. This means that a new standard must specify alternative fuels not derived from mineral oil. This standard is the ASTM D7566 – “Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons”. The process by

---

which this approval must be granted is also standardized in the ASTM standard D4054 – 09: Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives.

The first two annexes to the D7566 standard, for Fischer-Tropsch and HEFA, were added in 2009 and 2011 respectively.

### 1.3.1 *The ASTM certification and approval process*

The responsible body for evaluating and approving new aviation fuels is the American Society for Testing and Materials (ASTM) International Committee D.02 Petroleum and Lubricants, Subcommittee J. Developers of aviation biofuels must participate in this committee and engage other members to acquire and evaluate data, and address questions and concerns raised by subcommittee members. Upon approval the new fuel will be added as an annex to the ASTM D7566 standard.

The two new alternative aviation fuels, Fischer-Tropsch synthesized and HEFA, passed the approval process and were added to the standard as annex 1 and 2 respectively.

#### 1.3.1.1 *Steps to ASTM approval*

There are generally seven steps to an ASTM approval:

- I. Establish ASTM Task Force (by subcommittee)
- II. Data and research through fuel, engine, component and rig testing (process defined in ASTM D4054-09 Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives)
- III. Initial balloting at subcommittee level
- IV. Comments and review period
- V. Discussion and voting on specific concerns in semiannual ASTM meeting
- VI. Final balloting at committee level
- VII. Fuel passes balloting and ASTM adds the new fuel as an annex to the ASTM D7566 Standard (provided that all concerns by sub-committee or committee members have been addressed or dismissed)

There are currently a number of task forces working toward ASTM approval with several new aviation fuel types and fuel components. Depending on the specific

---

composition of kerosene ASTM differs between paraffinic and aromatic kerosene.

Two task forces in ASTM are currently working to certify Alcohol to Jet (AtJ-SPK and AtJ-SKA), one is focused on synthetic paraffinic kerosene (SPK) and one focused on synthetic paraffinic kerosene with aromatics (SKA). The SPK task force expects to have completed certification in 2014 and the SKA task force in 2015 (SkyNRG, 2014).

Two other pathways to sustainable fuels for aviation are also in process for certification by ASTM task forces, Direct Sugar to Hydrocarbons (DSHC) and Hydrotreated Depolymerized Cellulosic Jet (HDCJ), but are early in the process and the specific blend-in requirements are, as of yet, unclear due to the nature of these to fuel components.

The ASTM SAK task force focusses on certifying Synthetic Aromatic Kerosene (SAK), a product that is produced by a catalytic process that converts soluble sugars to aromatics in the kerosene range. The ASTM SK task force focusses on a process similar to the SAK task force, but the product is a pure Synthetic Kerosene stream (no aromatics).

Another task force is working on Catalytic Hydrothermolysis (the ASTM CH task force). The process is similar to the HEFA process but uses water based catalysis to plant and animal fat to a hydrocarbon fuel that contains both paraffins and aromatics.

Finally, a task force focused on co-processing is currently established. The idea is blend oils derived from both crude oil and biological (i.e. synthetic) sources upstream in the production processes. This means that the crude oil and bio-based components undergo hydroprocessing (and eventually distillation) together, improving efficiency and allowing for the utilization of existing infrastructure and process knowhow. It would also result in reduced expenses for certification as the blended fuel could be certified together after refining under ASTM D7566, instead of a separate certification under the ASTM D1655 and D7566 respectively and additional certification of the blended fuel product.<sup>12</sup>

See Section 7 - Technologies and Production for more details on the different technologies and sustainable fuel pathways.

#### **1.4 CAAFI – Readiness Tools**

The Commercial Aviation Alternative Fuels Initiative (CAAFI) has developed a number of “readiness tools” to create a common language and understanding of

---

<sup>12</sup> Provided that a Co-processing annex is made to the ASTM D7566 standard following the task force’s work.

---

the development stages of aviation biofuels production pathways. Among these are the Fuel Readiness Level (FRL), Feedstock Readiness Level (FSRL) and Environmental Progression. The three terms may be used to determine the readiness of a given biofuel for commercial use and take parameters of feedstock sustainability as well as level of commercialization into account (CAAFI / A4A, 2013). However, social and economic aspects are not considered and the definition of feedstock sustainability is also debatable in relation to the considerations mentioned in Section 3.5.

#### 1.4.1 *Fuel Readiness Level (FRL)*

Fuel Readiness Level (FRL) is a communicative tool developed by CAAFI with the aim of classifying and tracking progress within the phases of research, development, certification and commercialization of alternative aviation fuels. Ranging from Fuel Readiness Level 1 (FRL1), where observation and documentation of basic principles is completed, to Fuel Readiness Level 9 (FRL9), where commercial production capacity is established, the tool provides a common frame of reference for developers, certification and standardization organizations, OEM's and airlines. The tool can also help guide the development of alternative aviation fuels by clarifying the technical development stages and the associated testing and activities.

The FRL tool is augmented with a series of FRL *exit criteria* that helps link the process covered by the Fuel Readiness Levels to the process of ASTM certification of a new fuel. The FRL exit criteria serve as a checklist of specific actions required to advance from one level to the next and include components of ASTM testing as well as other aspects of fuel development (CAAFI, 2013).

#### 1.4.2 *Feedstock Readiness Level (FSRL)*

Responding to their members' concerns with regard to feedstock availability and viability CAAFI has also developed a tool named Feedstock Readiness Level (FSRL) in close cooperation with the US Department of Agriculture. The tool details steps necessary in order to introduce or expand the production of a novel, dedicated energy crop for aviation biofuels production. The tool may be used by technology developers and feedstock producers to evaluate potential barriers for full scale feedstock production and utilization.

#### 1.4.3 *Environmental Progression*

The Environmental Progression tool was developed by CAAFI to help developers determine the timing of specific environmental impact analysis in relation to the development process. This tool is provided to help ensure that analysis are carried out in due time to mitigate long term negative impacts of the various steps in the process, for instance introduction of specific feedstocks or invasive species into an ecosystem.

---

These tools are developed by CAAFI for use by developers of sustainable fuels for aviation and it is the recommendation of this report that potential developers make use of these tools and the assistance and support afforded by international as well as national initiatives for sustainable aviation. For developers in the Nordic region one of the important first steps would thus be to contact the Nordic Initiative for Sustainable Aviation (NISA) and make full use of the initiatives competencies and network.

## **1.5 Fuel inspection and certification**

There are very strict demands on the traceability of aviation fuels.

The requirements for aviation fuels specify that fuels must be inspected and certified every time it is transferred from one system or container to another. The fuel must be tested for adherence to the specific standard (ASTM in the US and DefStan in Europe), for contamination and to verify its origins.



---

## 2 APPENDIX – THE DANISH BIOMASS BALANCE

This appendix contains details of the calculations of the Danish biomass balance.

### 2.1 Data

The biomass balance has been prepared from data from the following sources:

#### 2.1.1 Data from Danmarks Statistik

- HST77: Høstresultat efter område, afgrøde og enhed (2006-2012)
- HALM1: Halmudbytte og halmanvendelse efter område, afgrøde, enhed og anvendelse (2006-2012)
- SKOV55: Hugsten i skove og plantager i Danmark efter område og træsort
- GARTN1: Produktion af frugt og grønt efter område, enhed og afgrøde
- FISK2: Danske fartøjers landing af fisk efter fangstområde, landingsplads, enhed og fiskeart
- ANI7: Mælkeproduktion og anvendelse efter enhed (1990-2013)
- KORN: Anvendelsen af korn efter afgrøde, periode, oprindelse og type (1995-2012)
- FODER1: Foderforbruget efter fodermiddel, oprindelse og enhed (1990/1991-2012/2013)
- FVF1: Fødevarerforbrug efter type og enhed (år) (1990-2011)
- AFG07: Det dyrkede areal efter område, enhed og afgrøde (2006-2013)
- SKOV11: Skovarealet efter område og bevoksning (1990-2011)

#### 2.1.2 Other data sources

DCA, Nationalt Center for Fødevarer og Jordbrug (2013). *Biomasseudnyttelse i Danmark – potentielle ressourcer og bæredygtighed*. Jørgensen, U.; Elsgaard, L.; Sørensen, P.; Vinther, F.P.; Kristensen, E.F.; Ejrnæs, R.; Nygaard, B.; Krogh, P.H.; Bruhn, A.; Rasmussen, M.B.; Johansen, A.; Jensen, S.K.; Gylling, M.; Bojesen, M., Aarhus Universitet.

Gylling, M.; Jørgensen, U.; Bentsen, N.S. (2012). *+ 10 mio. tons planen – muligheder for en øget dansk produktion af bæredygtig biomasse til bioraffinaderier*. Københavns Universitet, Frederiksberg.

---

Landbrug & Fødevarer (2013b). *Udenrigshandel 2008-2012 – fødevarer til hele verden*. Landbrug & Fødevarer, København.

SimaPro 8. *LCA Software*. <http://www.simapro.co.uk/>

## 2.2 Results

### 2.2.1 Danish Production

Denmark has an area of 43,100 km<sup>2</sup> where 26,000 km<sup>2</sup> are cultivated. Forrest covers 5,800 km<sup>2</sup>. In addition to these areas there are so far unexploited areas near railways, roads, airports, military installations etc.

Table 8 presents the amounts of food and bio based products produced in Denmark in 2011. All masses have been converted to dryweight .

Table 8: The major commodities within biomass production in Denmark, 2011

Commodity	Amount [1000 tonnes dryweight]
Grass and Clover	6,200
Cereals	7,500
Root vegetables	1,000
Straw	4,500
Wood	2,200
Meat	1,200
Dairy Products	200
Fish and Seafood	200
Rape	500
Manure	3,900
Maize	2,400

In Denmark, agriculture is an important sector with 66,000 employees. An addition there are 53,000 employees in the food processing industry and 56,000 employed in supply, transportation and other services. As mentioned, Denmark

---

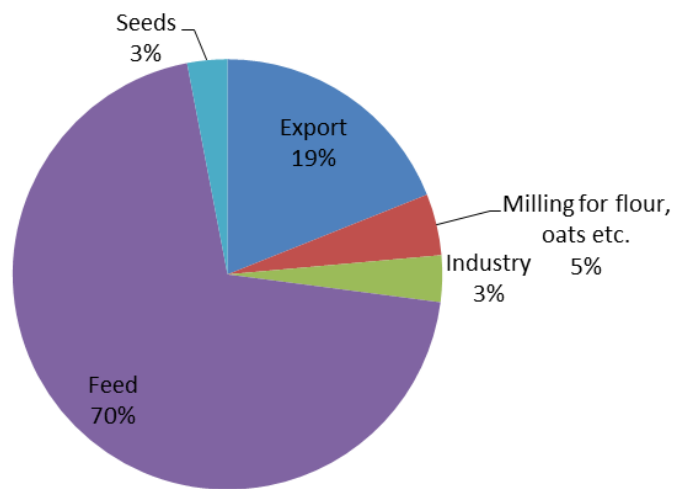
has the fourth largest pig production (quantity wise) in Europe (Landbrug og fødevarer, 2013). The large numbers of animals yield an annual amount of 3.9 mill. tonnes animal manure of which around 7 % are used for energy production (Gylling *et al.*, 2012).

The grass and green feed produced in Denmark is primarily feed for cows since pigs cannot digest large amounts of this. The root vegetables include sugar beets for sugar production, potatoes for potato flour production and potatoes for consumption.

The cereals harvested are mainly wheat and barley. The following figure presents how produced and imported cereals were utilized in Denmark in 2011.

---

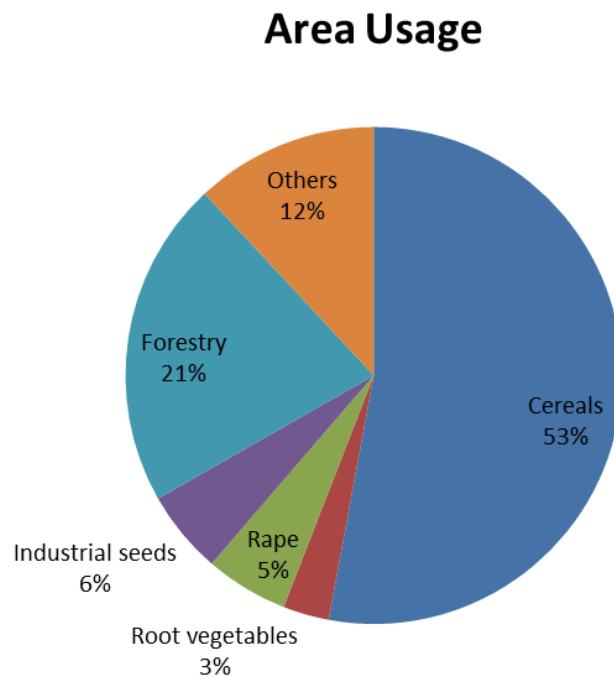
Figure 31: Distribution of how imported and produced cereals are utilized in Denmark in 2011 (Danmarks Statistik)



70 % of all cereals are used for the production of animals feeds, however, for wheat the fraction is 80 %. Only 5 % of the cereals harvested are milled and used for food production (Danmarks Statistik).

Figure 32 shows how the cultivated land is divided between different crops and forestry. Cereals include mainly wheat and barley, takes up the largest fraction of land.

Figure 32: Usage of land area for agriculture and forestry in 2011 (Danmarks Statistik)



According to the Danish Council of Ethics, feed production currently occupies 50 % of the total land area of Denmark (Det Ethiske Råd, 2013) .

### 2.2.2 Danish Consumption

It was not possible to find consumption data for wood, fruits and vegetables, and fish and seafood. The amount imported and produced that is not exported has been estimated to be the amount consumed (includes losses and waste):

$$\text{Consumed} = \text{Produced} + \text{imported} - \text{exported}$$

Table 9: Production of food and bio based products in Denmark 2011 (Danmarks statistik)

Commodity	Amount [1000 tonnes dry weight]
Meat	200
Human Consumption excl. Meat*	700
Wood*	4,200
Feed (grass, clover, soybean cake, maize, etc.)	10,000

Straw	2,800
Cereals	6,400
Manure (energy production) <sup>13</sup>	300
Byproducts	700

\*Estimated from the equation above

### 2.2.3 Import and Export

Import and export data has been found in Landbrug & Fødevarer (2013b) and is data from 2012.

Table 10 presents some of the largest import commodities in Denmark and the quantities in which they were imported in 2012. The commodity “others” is not converted to dry weight as it consists of many different products.

Table 10: The five largest import commodities (in terms of fresh weight) in 2012. The amounts in the table is dry weight (Landbrug & Fødevarer, 2013b).

Commodity	Amount [1000 tonnes dry weight]
Feed	1,900
Wood	2,500
Byproducts	700
Cereals	600
Fish and Seafood	100
Others	4,500*

\*Not dry weight

Feed and wood are the by far largest import commodities in Denmark. Feed is estimated include mainly cake of soybean and waste from sugar beet processing. Of the cake of soybean imported 80% is used in the pig production, where the remaining is used for feed in the rest of the meat production.

The import of wood for energy production is rapidly increasing. 1.4 mill. tonnes of wood pellets were imported for energy production in 2011. In addition to wood

<sup>13</sup> It is assumed that 7 % of the produced manure is utilized in the production of energy.

---

pellets, about 600,000 tonnes of firewood and wood chips were imported for energy production (DCA, 2013).

Non-edible byproducts are for instance fishmeal and fish waste that are used in the Danish feed production. In 2011 300,000 tonnes of fishmeal and fish waste were imported to Denmark (Danmarks Statistik).

The cereals imported are mainly wheat and barley, whereas the fish and seafood imported is both fresh and processed.

Table 11 presents the five largest export commodities in Denmark. Meat includes pork, bovine and poultry meats.

Table 11: The five largest export commodities (in terms of fresh weight) in 2012. The amounts in the table is dry weight (Landbrug & Fødevarer, 2013b).

Commodity	Amount [1000 tonnes dry weight]
Cereals	1,700
Meat	1,100
Feed	500
Dairy Products	100
Fish and Seafood	200
Others	4,000

\* Not dry weight

Barley and wheat are, as for import, the cereals exported in the largest quantities. Pork is the second largest export commodity in Denmark.

In addition to importing feed, Denmark also export feed. The same is the case for fish and seafood.

### 3 APPENDIX – FUTURE FEEDSTOCK SCENARIOS

The following table presents the results from the two scenarios for future biomass utilization. The results are based on the biomass balance and the report “The +10 million tonnes study” by Gylling *et al.* (2012).

#### 3.1.1 Production yields

The mentioned crops have different yields as listed in Table 12. For some crops the yield depend on the season that they are harvested. The composition of seaweed changes with the season and thus the yield that can be utilized in bio-fuel production depends if the focus is protein or sugar rich seaweed.

#### 3.1.2 Scenarios

Table 12 presents the current and potential yields per ha of a selection of relevant crops.

Table 12: Yield from different crops

Crop	Potential Production yield [tonnes dry weight / ha]
Wheat (including straw)	9 <sup>1,2</sup> 10 <sup>3</sup>
Sugar beets	19 <sup>3</sup>
Maize	12 <sup>3</sup>
Soy	2 <sup>1</sup>
Rape	5 <sup>1</sup> 1 (oil) <sup>2</sup>
Clover	12 <sup>1</sup>
Clover grass	13 <sup>1</sup> 7 (organic) <sup>2</sup> 15 <sup>3</sup>
Meadow grass	3 <sup>1</sup>
Willow	11 <sup>2</sup> 12 <sup>3</sup>
Elephant grass	16 (fall) <sup>2</sup> 9 (spring) <sup>2</sup>
Afforestation	4 <sup>2,3</sup>
Seaweed	5-15 <sup>2</sup>

<sup>1</sup>Concito (2014)

<sup>2</sup>DCA (2013)

<sup>3</sup>Potential from Gylling *et al.*(2012)

The two scenarios are based on the “business-as-usual” and “environment optimized” scenarios from Gylling *et al.* (2012) and the biomass balance (Table 8-Table 11).

Table 13 presents the results from the two scenarios including the potential mass of each feedstock and the percentage contribution to the total available biomass.

Table 13: The available biomass [1000 tonnes] based on the biomass balance and Gylling *et al.*(2012). The table also includes the percentage distribution of feedstock in the two different scenarios.

	Business-as-usual [1000 tonnes]	Business-as-usual [%-wise distribution]	Environment Optimized [1000 tonnes]	Environment Optimized [%-wise distribution]
Straw	2,500	32.3	2,850	24.9
Seed grass	420	5.4	420	3.7
Energy crops replacing rape	0	0.0	1110	9.7
Energy crops replacing cereals	0	0.0	2,240	19.6
Energi forrest (willow and poplar)	140	1.8	140	1.2
Grass from wetlands	280	3.6	210	1.8
Cover crops	0	0.0	390	3.4
Manure	2,570	33.2	2,440	21.3
Land management, parks etc.	700	9.0	700	6.1
Rapeseed oil	210	2.7	20	0.2
Existing forrest	930	12.0	890	7.8
Weed cutting	0	0.0	10	0.1



---

Harvest from roadsides	0	0.0	10	0.1
Maize	0	0.0	0	0.0
<b>TOTAL</b>	<b>7,750</b>		<b>11,430</b>	

The potential of feedstock from feed crops being replaced with energy crops is calculated using the potential yields from Table 12.

---

## **4 APPENDIX – SCENARIOS FOR AVIATION FUEL CONSUMPTION AND SUSTAINABLE AVIATION FUEL REQUIREMENTS**

The following appendix describes a range of alternative scenarios for jet fuel consumption and necessary quantities for substitution that result from different approaches to introducing sustainable fuels for aviation.

### **4.1 Alternative scenarios for jet fuel consumption**

#### *4.1.1 Expanding CPH – Copenhagen Airport’s plans for expansion*

In January 2014 CPH - Copenhagen Airports announced ambitious plans to expand the airports activities and the number of passengers traveling from CPH. The plans entail a rise in the total number of passengers to 40 mill. p.a. from the current approx. 24 mill. p.a. Such an expansion could mean a significant rise in the Danish total consumption of aviation fuels (given that CPH accounts for a very large percentage of the total Danish aviation fuels consumption).

#### *4.1.2 Decreasing CPH – weakened Scandinavian aviation sector*

Another alternative scenario for the development in the Danish aviation fuel consumption is a weakened Scandinavian aviation sector wherein the number of passengers traveling from CPH is reduced to a level around the number of passengers a decade and a half ago. This could for instance be the result of CPH ceasing to be one of the major northern hubs and primarily servicing Danish costumers. Such a development would clearly result in a decrease in the total consumption of fuels for aviation.

### **4.2 Required quantities for substitution**

The quantities of fuel to be substituted depends both on how aggressively sustainable fuels for aviation are introduced and on the development in the Danish consumption of aviation fuels, which again depends heavily on the development at Copenhagen Airport (and generally on the strength of the Scandinavian aviation sector).

Following the industry goal of carbon neutral growth from 2020 (see section 3.1 - The Aviation Industry), any projected increase in fuel consumption must be covered by an increased use of sustainable fuels for aviation to such a degree that it cancels out the increased consumption (including the possible GHG emissions from the sustainable fuel).

The RSB criteria that states that a blend-in fuel must achieve at least a 50 % reduction relative to conventional fuels is used as a baseline. This means that for every unit of energy from conventional aviation fuels that is needed in addition to a baseline set by the consumption in 2020 two units of energy from sustainable fuels for aviation must be substituted into the consumption of the aviation sector to meet the industry goal of Carbon neutral growth.

A number of other scenarios are also proposed. The scenario's different premises are described in Table 14.

Table 14: Different scenarios affecting the demand of sustainable fuel for aviation.

Scenario	Scenario premises
CO <sub>2</sub> -neutral growth 1	Carbon neutral growth from 2020, DEA consumption scenario, peak consumption in 2020
CO <sub>2</sub> -neutral growth 2	Carbon neutral growth from 2020, Expanding CPH consumption scenario
2,5 % absolute 1	2,5 % of consumption from 2020, Decreasing CPH consumption scenario
2,5 % absolute 2	2,5 % of consumption from 2020, DEA consumption scenario
2,5 % absolute 3	2,5 % of consumption from 2020, Expanding CPH consumption scenario
5 % absolute 1	5 % of consumption from 2020, Decreasing CPH consumption scenario
5 % absolute 2	5 % of consumption from 2020, DEA consumption scenario
5 % absolute 3	5 % of consumption from 2020, Expanding CPH consumption scenario
Progressive 1	5 % of consumption from 2020, increasing 1 % p.a., Decreasing CPH consumption scenario
Progressive 2	5 % of consumption from 2020, increasing 1 % p.a., DEA consumption scenario
Progressive 3	5 % of consumption from 2020, increasing 1 % p.a., Expanding CPH consumption scenario

The required quantities for substitution under the different scenarios are given in Table 15.

Clearly the progressive scenarios in general yield the highest quantities to be substituted, with one, in a Danish perspective, very interesting exception.

If Copenhagen Airports are to achieve their ambition of a total 40 mill. passengers p.a. and also keep in line with industry goals (as well as CPH's own vision) of Carbon neutral growth from 2020 there is a very high demand for sustainable

fuels for aviation within 10 years, growing to more than half a million tonnes by 2035.<sup>14</sup>

Table 15: Required quantity of fossil jet fuel to substitute in the different scenarios.

Scenario	Required quantity to substitute 2020 [1000 ton]	Required quantity to substitute 2025 [1000 ton]	Required quantity to substitute 2030 [1000 ton]	Required quantity to substitute 2035 [1000 ton]
CO <sub>2</sub> -neutral growth 1	0	75	0	0
CO <sub>2</sub> -neutral growth 2 <sup>15</sup>	0	269	336	547
2,5 % absolute 1	23	23	21	16
2,5 % absolute 2	27	28	26	26
2,5 % absolute 3	29	32	33	36
5 % absolute 1	47	47	42	33
5 % absolute 2	53	55	52	52
5 % absolute 3	58	65	66	72
Progressive 1	47	84	98	107
Progressive 2	53	111	156	207
Progressive 3	58	130	199	287

<sup>14</sup> Assuming that a large portion of the airport's growth takes place from 2020 and onwards.

<sup>15</sup> Both "Carbon neutral growth" scenarios assume that the RSB criteria is met, but is not exceeded. If sustainable fuels for aviation are developed with emissions reduced by more than 50 % relative to conventional fuels the quantities for substitution decrease respectively.

---

## 5 APPENDIX - AVIATION FUELS LOGISTICS AND SUPPLY CHAINS IN DENMARK

The logistics and supply chains involved in covering the transportation demand for aviation in Denmark are relatively simple, compared to e.g. the complex infrastructure and supply chains involved in supplying energy for road transportation. With the exception of military in-flight refueling, aircrafts only refuel at a relatively low number of places compared to the approx. 2,000 publicly accessible service / gas stations in Denmark.

This appendix details the production sites and supply structure for aviation fuels in Denmark with the aim of highlighting the relatively small need for new and expensive infrastructure that arises when substituting fossil aviation fuels with sustainable fuels.

### 5.1.1 *Danish Oil Refineries*

There are two oil refineries located in Denmark, a Shell refinery in Fredericia and a Statoil refinery in Kalundborg. Both refineries have previously produced aviation jet fuel and continue to produce other fuel products.

Medio March 2014 Shell announced their intentions to sell the refinery in Fredericia.

The Shell refinery receives all of the crude oil it refines from a 320 km pipeline from the North Sea oil fields. The pipeline terminates at DONG Energy's crude oil terminal at Fredericia where approx. 15 mill. tonnes of crude oil is received each year. About a third of this is refined at the Shell refinery and the rest is shipped to other refineries internationally through the oil terminal in Fredericia. The products from the refinery are either shipped to customers by sea from the terminal or delivered by truck or rail.

The Statoil refinery receives all of its crude oil by ship and ships most to customers as well. The refinery in Kalundborg is listed as the largest in Denmark, refining approx. 5 mill. tonnes of crude oil and condensate each year. The refinery is part of the Kalundborg Industrial Symbiosis wherein a number of industrial companies in Kalundborg exchange energy and other material streams.

The process infrastructure set up at these two locations, as well as the know-how represented in the companies, may prove very valuable for refining lower order biofuels into aircraft grade fuels, such as Jet A-1. Also, the supply structure, if found usable for sustainable fuels for aviation, may prove to be a valuable asset in supplying the new fuels to airports nationally as well as internationally.

#### 5.1.1.1 *Danish Jet Fuel Production*

During the latter years Danish production of jet fuels has decreased with Statoil reporting zero production at the Kalundborg refinery in 2012. Statoil reports that this is due to process optimization and prioritization, meaning that is more eco-

---

nomically attractive for them to prioritize other products in the current market and with their current raw material supply and operational configuration.

We have been unable to obtain official statements from Shell regarding the specific status of their aviation fuels production at the Fredericia refinery. Representatives from Shell have, however, commented that generally the same factors apply as reported by Statoil and any change in the production portfolio at a specific refinery is mainly due to optimization of the product spread vis-a-vis the specific content of the input and current market conditions.

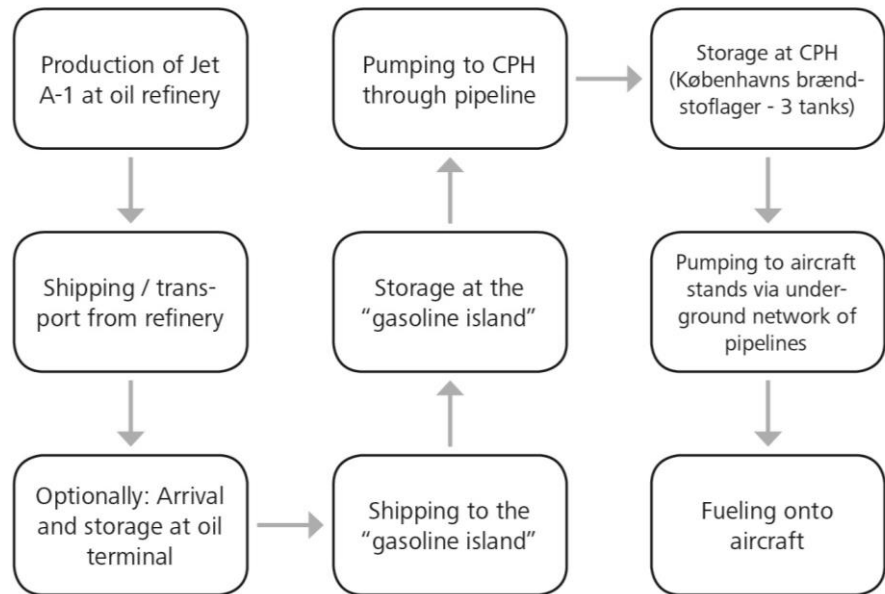
### *5.1.2 Supply Chain to Copenhagen Airport*

Copenhagen Airport is, by far, the largest consumption point for aviation fuels in Denmark. The airport is supplied with aviation fuels from the near-by “Benzinøen” (“the gasoline island”) located off the coast of Amager (the island of the east coast of Zealand, on which the airport is located). From this island aviation fuels are piped to the airport for storage in three buffer tanks. The storage capacity at the airport is about 4.5 million liters and is reported to cover only 24 hours of operation and thus the continuous supply of fuels from the storage facilities on the “gasoline island” is essential to airport operations.

“The gasoline island” is accessible by sea and has a large oil terminal with docking and unloading facilities for oil tankers and thus constitutes a supply infrastructure that could relatively easily be converted or adapted to also include sustainable fuels for aviation.

At Copenhagen Airport the fuel is stored in nine buffer tanks before it is pumped via an underground network of pipelines to the aircraft stands around the airport. From here it is fueled directly into the aircraft by a specialized relay vehicle. The fuel is pressurized in the transmission system and thus no pumps are required in the relay vehicles.

Figure 33: The elements in supplying Jet A-1 to aircraft at Copenhagen Airport.



### 5.1.3 Other Danish Airports

Most commercial airports store both Jet A-1 and Avgas for aircraft serviced at the site. The common supply chain involves transport of the fuel by truck or rail for the last leg of the journey to the airport, but some airports are supplied by a pipeline (especially the military airports in Jutland).

Even though the last leg of the journey is by truck or rail transportation, the relative scarcity of consumption sites makes the supply chain relatively simple and easy to convert or augment with biofuels for aviation.

---

## 6 APPENDIX - GREENHOUSE GAS REDUCTION AND OTHER ENVIRONMENTAL EFFECTS

This section qualitatively discusses the possible effects to the environment and climate from substituting conventional fossil fuels with sustainable alternatives.

Concito lists the following as sources of emissions from bioenergy, and thus biofuels for aviation, production:

- Change in the carbon stock in soil and trees
- Changes in crops
- Use of machinery, pesticides and fertilizers
- N<sub>2</sub>O emissions from soil and leaching of nitrate
- ILUC effects
- Processing of the crops to energy, and construction of production facilities.

The following sections provide an overview of potential climate and non-climate effects of a Danish production of sustainable fuels for aviation.

### 6.1 Greenhouse Gas Reduction – A Lifecycle Assessment Approach

As mentioned in Section 2.1, greenhouse gasses (GHGs) such as CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> all contribute to global warming. This section will focus mainly on these emissions as the national and industry reduction goals often are expressed by these.

Sustainable fuels for aviation and conventional fuels are produced very differently except during the final steps in the process. Thus, sustainable fuels for aviation and conventional fuels both have emissions from the refinement process, the distribution of fuel and the combustion in the aircraft engine. The emissions vary in extent except for the combustion in the aircraft engine that are similar due to the technical specifications applying to both types of fuels. The combustion CO<sub>2</sub> of synthetic paraffinic kerosene (SPK) is 0.98 relative to conventional jet fuel (Stratton *et al.*, 2011)

The production of fossil fuels have emissions from:

- The exploration of crude oil / natural gas / coal
- The establishment of infrastructure / oil rigs etc.



- 
- From the production (flaring, energy consumption etc.)

Prior to the refining process, the emissions associated with the production of alternative fuels can roughly be divided into the following sources:

- Collection of feedstock
- Transportation of feedstock to pre-treatment / conversion
- The pre-treatment / conversion processes

The emissions associated with the processes vary according to the feedstock and technology chosen. It is key in achieving reductions in CO<sub>2</sub> emissions that new biomass can take up the emitted CO<sub>2</sub> in order to avoid LUC and ILUC effects.

The process energy should be produced from a fraction of the biomass, e.g. lignin, in order to avoid the use of fossil fuels. This will cause a loss of feedstock that can be used for fuel product, but will significantly reduce GHG emissions from the process energy.

The following three sections include different studies assessing the GHG reduction potentials from a LCA approach, however, with different boundary conditions. The list is not comprehensive but provides examples of different assessment methods and the resulting GHG reduction potentials.

#### 6.1.1 *Sgouridis et al.*

*Sgouridis et al.* (2011) published a paper reviewing different feedstocks and pathways in order to assess the energy and carbon yields. The study includes fuels for car transportation as well as for aviation since many technologies produce several products in addition to jet fuel.

*Sgouridis et al.* (2011) assume that all the process energy is from the biomass itself, thereby reducing the net fuel product output, but incurring no fossil energy or emission particles. The paper does not include ILUC effects, however, it stresses how including these could drastically change the results if for instance palm oil is grown on the cost of rain forest.

The GHG reductions are calculated as the reduction per pax-km<sup>16</sup>. The results show that reductions in the range of 100 to 150 g CO<sub>2</sub>-eq/pax-km can be

---

<sup>16</sup> Pax-km is passenger kilometer, which is representing the transport of one passenger by a given mean of transportation (in this case car and aircraft) one kilometer.

achieved using sugarcane, switch grass (a crop similar to elephant grass that can grow in saline conditions) and palm oil.

Sgouridis *et al.*(2011) highlights how energy efficient algae are, however, at this current stage the process energy demands are too high and there are too many other technological and economic issues to be resolved before it is a relevant feedstock in biofuel production.

The paper emphasizes that the mass yield per area is not a sufficient basis for decision as the carbon and energy yields should also be considered.

### 6.1.2 Avinor

In the feasibility study from Avinor (2013) LCA calculations were performed from “well-to-wing”. That includes, for the fossil fuels, the exploitation of crude oil, transportation of crude oil, refining, transport of jet fuel and finally the combustion in the aircraft engine.

The calculations assume that the combustion of biofuels is CO<sub>2</sub> neutral and thus emissions originate only from growing the feedstock to producing the jet fuel. Thus, the calculations do not include LUC and ILUC effects.

The calculations are based on wood as the sole feedstock and the chosen conversion technologies are Fischer-Tropsch and alcohol-to-jet.

Table 16: Avinor’s findings in potential GHG reduction of two types of biofuels: Fischer-Tropsch synthesis and alcohol-to-jet processing of wood residues, compared to the fossil Jet A-1.

	GHG emission [g CO <sub>2</sub> -eq/MJ liquid fuel]	Reduction compared to conventional fuel [%]
Jet A-1	84	-
FT-SPK	16	81
Bioethanol + AtJ	29	65

Table 16 shows that reductions in the range 65 to 81 % can be achieved under the assumption that the combustion is CO<sub>2</sub> neutral.

The calculations in Avinor (2013) furthermore show that 90 % of the emissions from fossil jet A-1 are from combustion, whereas the majority of emissions (60-80 %) from alternative fuels are from pre-treatment and conversion process.

### 6.1.3 Concito

Concito has published the report “*Klimapåvirkningen fra biomasse og andre energikilder*” (2013) calculating the GHG emissions associated with an increased production of different biofuels such as biodiesel and bioethanol (both 1G and 2G) and hence not emissions with the entire chain of custody in aviation fuel production. The LCA-model includes ILUC and capital goods such as the construction of machines etc. The model does not include services such as research.

The results show that the GHG emissions can be equal to or higher for biofuels than fossil fuels dependent on the chosen time scale.

Table 17: Selection of results from Concito (2013). The numbers are based on the GWP100<sup>17</sup> and is per MJ liquid fuel produced and combusted.

	GHG emissions [g CO <sub>2</sub> -eq/MJ liquid fuel]
Fossil diesel	86
Fossil petrol	90
Palm oil biodiesel	150
Bio-ethanol (1 <sup>st</sup> generation maize)	49
Bio-ethanol (2 <sup>nd</sup> generation straw)	-69

The emissions from straw is negative, since there is no ILUC effect is included as straw is a byproduct and that C<sub>5</sub> molasses can be used as used as feed resulting in reductions in GHG emissions.

Even though the emissions are not calculated for aviation fuels, the results illustrate the importance of meeting the sustainability criteria from Section 3. The results also show how estimating GHG reductions using a LCA approach is highly dependent on the system boundaries chosen. Where Sgouridis *et al.* (2011) found palm oil to be one of the most climate friendly fuels, the report from Concito shows that palm oil causes higher GHG emissions than conventional fossil fuels.

The previous three sections illustrate that putting exact numbers on the potential GHG reduction is difficult as it is highly feedstock dependent. However, if a feed-

<sup>17</sup> GWP100 is the global warming potential calculated using a 100 year time frame.

stock is meeting the sustainability criteria listed in Section 3, the GHG reduction is maximized.

## 6.2 Non-Climate Effects of sustainable fuels for aviation

As for the CO<sub>2</sub>-eq emissions estimating non-climate effects of sustainable fuels for aviation is complex.

DCA (2013) has assessed the environmental impact of an increased production of different feedstocks. Table 18 summarizes the effect on nitrate leaching (nutrients), the carbon stock in soil, pesticide usage, biodiversity and ILUC. A positive effect, that is a reduction in nitrate leaching, pesticide leaching and ILUC and an increase in carbon in soil and biodiversity are assigned a green checkmark and negative effects are assigned a red cross. An overall assessment is made where a positive effect evens out a negative effect and vice versa. The assessment is a rough simplification as it is assumed that the effects are equally important. In addition, it should be noted that not all the relevant sustainability parameters are included, however, all the parameters are important in a Danish context.

Table 18: Environmental effect by increased production of feedstock compared to a reference. ✓ = positive impact compared to the reference, ✗ = negative impact compared to the reference, 0 = no change compared to the reference. Brackets indicates uncertainty. Adapted from DCA (2013).

Feedstock	Nitrate leaching	Carbon stock in soil	Pesticide usage	Biodiversity	ILUC
Manure <sup>1</sup>	(✓)	✗	0	0	0
Straw <sup>1</sup>	0	✗	(✓)	0	✓/0
Wood residues <sup>1</sup>	0	✗	0	✗	0
Municipal Waste <sup>1</sup>	(✗)	✓	0	0	0
Macroalgae (sea-weed) <sup>1</sup>	(✗)	(✓)	0	(✓)	✓/0
Cover crops <sup>1</sup>	(✓)	✗	0	0	0
Wheat (whole-crop) <sup>2</sup>	0	✗	0	0	0/✗
Maize (whole-crop) <sup>2</sup>	0	(✗)	(✓)	(✗)	✗

Sugar beet <sup>2</sup>	0	(X)	0	0	0/X
Rape oil (non-food) <sup>3</sup>	0	0	0	0	X
Willow <sup>2</sup>	✓	✓	✓	✓	X
Elephant grass <sup>2</sup>	✓	✓	✓	(✓)	0/X
Crop rotation clover grass <sup>2</sup>	(✓)	✓	✓	✓	X
Afforestation <sup>2</sup>	✓	✓	✓	✓	X
Continuous grass <sup>2</sup>	✓	✓	✓	✓	X

<sup>1</sup>Reference scenario: Not utilizing the biomass

<sup>2</sup>Reference scenario: A traditional grain rich rotational crop

<sup>3</sup>Reference scenario: Using the rape seed oil for consumption

Table 18 illustrates how complex choosing a suitable feedstock is as none of the feedstocks have only positive effects on the chosen environmental parameters. Perennial crops (such as willow, afforestation etc.) generally appear to be performing well from an environmental point of view.

### 6.3 Discussion

The results from the three studies on GHG emissions and Table 18 illustrate the importance of well-defined sustainability criteria within both climate and environmental aspects.

It seems clear that biofuels are not CO<sub>2</sub> neutral as the processing of feedstocks require energy. In addition bio-based fuels currently have higher emissions associated with conversion and processing compared to conventional fossil fuels. Nevertheless, if the feedstock is produced without a net change in carbon stock, potential CO<sub>2</sub>-eq reductions of 65 to 80 % are achievable. For the case of straw the reduction might even be a removal of CO<sub>2</sub> from the atmosphere.

This section shows how the reporting method of GHG emissions can significantly change the results. This emphasizes the importance of not only well-defined sustainability criteria, but also well-defined reporting and quantification methods.

When assessing the climate effects of sustainable fuels for aviation, ILUC effects should not be ignored as the effects can be greatly underestimated. This is challenging as ILUC effects currently are difficult to assess. Thus, these methods

---

must be improved and standardized to ensure consistent results for the different technologies and feedstocks. In addition transparency in the entire chain of custody is key when assessing if an alternative fuel truly is sustainable.