Förstudie för biobaserat flygbränsle för Stockholm-Arlanda Flygplats

Tomas Ekbom, Carl Hjerpe, Martin Hagström, Fredrik Hermann
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Pilot study of Bio-jet A-1 fuel production for Stockholm-Arlanda Airport

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Fredrik Hermann

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Abstract

The air traffic industry faces big changes in the near future, one being how to reduce their share of the CO$_2$-emissions. Therefore LFV set the framework to investigate the pre-conditions for a biorefinery plant in conjunction with Arlanda Airport. The biorefinery is based on advanced gasification technology and Fischer-Tropsch synthesis to a bio-jet fuel product.

Locations at Brista and Igelsta were studied for two different process plant configurations, with each 50 kton bio-jet fuel annual capacity, or 290 and 610 MWth biomass input, respectively. The biomass-to-fuels efficiency was 46 % and total net efficiency was 79 %. The capital investment was calculated as 5.1 and 7.4 billion SEK, and production costs of 8300 SEK (812 EUR/1183 USD) and 5000 SEK (490 EUR/714 USD) per cubic meter bio-jet, respectively, whereas the Jet A-1 fuel today costs some 6000 SEK, at crude oil price of $67 per barrel.

Keywords: Biorefinery, gasification, aviation, bio-jet fuel, biomass
Sammanfattning

Flygindustrin ställs inför stora utmaningar i framtiden. Frånsett dagens ekonomiska situation finns det svårigheter med säkerställande av bränsle, emissionskrav och miljötillstånd. Den kanske tuffaste utmaningen av alla ligger hur industrin kan expandera och samtidigt reducera sin andel av CO₂-emissionerna. LFV har satt ett mål att reducera användningen av fossila bränslen och koldioxidutsläppen med 50 % inom tre år. För nästa steg har LFV initierat detta projekt att utreda de tekniska och ekonomiska möjligheterna för ett bioraffinaderi i anslutning till Arlanda flygplats.


<table>
<thead>
<tr>
<th>Anläggning</th>
<th>Brista</th>
<th>Igelsta</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Typ</strong></td>
<td><strong>Massa</strong></td>
<td><strong>Energi</strong></td>
</tr>
<tr>
<td>Biobränslekonsumtion</td>
<td>108 t/h</td>
<td>289 MW</td>
</tr>
<tr>
<td>Raff.bränsle (som biomassa)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Elimport (som biomassa)</td>
<td>-</td>
<td>4.5 MW</td>
</tr>
<tr>
<td><strong>Total energi in</strong></td>
<td>-</td>
<td>293 MW</td>
</tr>
<tr>
<td>Naftaproduktion</td>
<td>17.9 kton/år</td>
<td>27.9 MW</td>
</tr>
<tr>
<td>Bio-jetproduktion</td>
<td>50.0 kton/år</td>
<td>74.8 MW</td>
</tr>
<tr>
<td>Tung diesel + UCO-produktion</td>
<td>21.4 kton/år</td>
<td>32.2 MW</td>
</tr>
<tr>
<td>Värmeproduktion</td>
<td>-</td>
<td>96.9 MW</td>
</tr>
<tr>
<td><strong>Total energi ut</strong></td>
<td>-</td>
<td>232 MW</td>
</tr>
<tr>
<td>Kylvatten/förluster</td>
<td>&lt;2700 t/h</td>
<td>61 MW</td>
</tr>
<tr>
<td><strong>Bio-jetbränsle, utbyte</strong></td>
<td>-</td>
<td>25 %</td>
</tr>
<tr>
<td><strong>FT-produktverkningsgrad</strong></td>
<td>-</td>
<td>46 %</td>
</tr>
<tr>
<td><strong>Termisk verkningsgrad</strong></td>
<td>-</td>
<td>79 %</td>
</tr>
</tbody>
</table>

Investeringskostnaden har baserats på en omfattande databas med budgetofferten som ha uppdaterats till 2Q 2009 och skalade till studerade storlekar på anläggning. Kapitalkostnaden har beräknats med låneränta om 6 %, avkastning på eget kapital om 15 % (80/20 skuldkvot) och en låneperiod om 20 år, vilket ger en annuitet om 7,80 %. Antalet drifttimmar är antagna till 8000 och med 5000 timmar värmeproduktion per år.
Produktionskostnaden är beräknad med täckningsbidrag från biprodukter nafta, tung diesel och värme, där oljeprodukterna är värderade utifrån ett oljepris om 67 dollar per fat med dagens energi- och koldioxidskatter på bensin och dieselolja, se nedan.

### Produktion Kostnader:

<table>
<thead>
<tr>
<th>Produktion</th>
<th>Enhetspris</th>
<th>Brista</th>
<th>Igelsta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fjärrvärme</td>
<td>450 SEK/MWh</td>
<td>218 MSEK</td>
<td>410 MSEK</td>
</tr>
<tr>
<td>Nafta</td>
<td>940 SEK/MWh</td>
<td>209 MSEK</td>
<td>148 MSEK</td>
</tr>
<tr>
<td>Tung diesel</td>
<td>770 SEK/MWh</td>
<td>198 MSEK</td>
<td>1140 MSEK</td>
</tr>
<tr>
<td><strong>Totala intäkter</strong></td>
<td></td>
<td><strong>489 MSEK</strong></td>
<td><strong>1464 MSEK</strong></td>
</tr>
<tr>
<td>Biomassa</td>
<td>180 SEK/MWh</td>
<td>416 MSEK</td>
<td>880 MSEK</td>
</tr>
<tr>
<td>El</td>
<td>480 SEK/MWh</td>
<td>7 MSEK</td>
<td>7 MSEK</td>
</tr>
<tr>
<td>Raffinering av bio-jet</td>
<td>-</td>
<td>0 MSEK</td>
<td>81 MSEK</td>
</tr>
<tr>
<td>Drift och underhåll</td>
<td>-</td>
<td>197 MSEK</td>
<td>271 MSEK</td>
</tr>
<tr>
<td>Kapitalkostnader</td>
<td>-</td>
<td>510 MSEK</td>
<td>746 MSEK</td>
</tr>
<tr>
<td><strong>Totala kostnader</strong></td>
<td></td>
<td><strong>1140 MSEK</strong></td>
<td><strong>2007 MSEK</strong></td>
</tr>
<tr>
<td>Bio-jetkostnad</td>
<td>-</td>
<td>0.86 SEK/kWh</td>
<td>0.52 SEK/kWh</td>
</tr>
<tr>
<td>Bio-jetkostnad per m³</td>
<td>-</td>
<td>8280 SEK/m³</td>
<td>5000 SEK/m³</td>
</tr>
<tr>
<td><strong>Bio-jetkostnad per m³</strong></td>
<td></td>
<td><strong>812 EUR / 1183 USD</strong></td>
<td><strong>490 EUR / 714 USD</strong></td>
</tr>
</tbody>
</table>


Nyckelord: Bioraffinaderi, förgasning, flyg, jetbränsle, biomassa
Executive Summary

The air traffic industry faces big changes in the near future. Apart from today’s economic situation there are challenges like security of fuel supply, meeting emission requirements and environmental restrictions. Perhaps the biggest challenge of all is how the industry can expand while reducing their share of the CO$_2$-emissions. LFV has a target to reduce their use of fossil fuels and reduce carbon dioxide emissions by 50% within three years. For next step LFV has initiated this project to investigate the technical and economical pre-conditions for a biorefinery plant in conjunction with Arlanda Airport.

Two locations of the plant were studied, with two different plant configurations. One plant alternative is to produce bio-jet fuel on site and another alternative to produce an intermediate product, a synthetic oil crude, which is called a Fischer-Tropsch [synthetic oil] product to be further refined and upgraded at a refinery. A number of locations were identified as possible sites for the bio-jet fuel plant whereof four sites were selected for deeper considerations. The four sites are Gävle, Brista, Lövsta and Igelsta, of which Brista was chosen for a plant with the full production of bio-jet fuel and Igelsta for production of the intermediate FT-product.

The fuel plant is designed for gasification of biomass producing a synthesis gas to be synthesised into a Fischer-Tropsch product with recovery of low-grade heat for industrial and district heat use. The plant will consist of the following process islands:

- Air separation plant: Oxygen and nitrogen production with supply and storage system
- Biomass gasification plant: Feedstock handling, preparation, storage, drying, feed mechanism, gasification, reforming, gas cooling, gas cleanup
- Gas cleaning and conditioning plant: Gas compression, gas clean-up with shift and sulphur and CO$_2$ separation
- Fischer-Tropsch synthesis plant: Compression, Fischer-Tropsch synthesis, ATR, PSA, HPC and distillation, storage and tank station
- Power and steam system plant: Steam turbine and gas/biomass boiler combined heat and power production, BFW, process steam and cooling water system.

Note that the difference between the Brista and the Igelsta plants lay in the Fischer-Tropsch synthesis process islands where the Igelsta plant does not include the PSA, HPC and distillation processes.

The production of bio-jet fuel has been fixed as calculation basis for 50 000 tonnes per year, as this could enable Arlanda Airport as a carbon dioxide neutral airport. Therefore, the plant size is different for the two alternatives, where the Brista plant is of 290 MW and Igelsta plant of 610 MW. The estimated operation is assumed with 8000 hours per year with 5000 hours of heat production. The material balance for streams is then summarised in the Table below.
The energy efficiency from biomass to fuels is 46 % for Brista and 44 % for Igelsta. Finally, the total energy efficiency with heat included is 79 % for Brista and 73 % for Igelsta (main results are shown in below Table).

<table>
<thead>
<tr>
<th>Plant</th>
<th>Brista</th>
<th>Igelsta</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power consumed</td>
<td>-</td>
<td>21.2 MW</td>
</tr>
<tr>
<td>Power production</td>
<td>-</td>
<td>19.4 MW</td>
</tr>
<tr>
<td><strong>Net power balance</strong></td>
<td>-1.8 MW</td>
<td>-1.9 MW</td>
</tr>
<tr>
<td>Biomass consumed</td>
<td>108 t/h</td>
<td>289 MW</td>
</tr>
<tr>
<td>Refinery utilities (as biomass)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Import power (as biomass)</td>
<td>-</td>
<td>4.5 MW</td>
</tr>
<tr>
<td><strong>Total energy in</strong></td>
<td>-</td>
<td>293 MW</td>
</tr>
<tr>
<td>Naphtha production</td>
<td>17.9 kton/yr</td>
<td>27.9 MW</td>
</tr>
<tr>
<td>Bio-jet production</td>
<td>50.0 kton/yr</td>
<td>74.8 MW</td>
</tr>
<tr>
<td>Heavy diesel + UCO production</td>
<td>21.4 kton/yr</td>
<td>32.2 MW</td>
</tr>
<tr>
<td>District heat production</td>
<td>-</td>
<td>96.9 MW</td>
</tr>
<tr>
<td><strong>Total energy out</strong></td>
<td>-</td>
<td>232 MW</td>
</tr>
<tr>
<td>Cooling water/heat losses</td>
<td>&lt;2700 t/h</td>
<td>61 MW</td>
</tr>
<tr>
<td>Bio-jet fuel yield</td>
<td>-</td>
<td>25 %</td>
</tr>
<tr>
<td>FT-product efficiency</td>
<td>-</td>
<td>46 %</td>
</tr>
<tr>
<td><strong>Total thermal efficiency</strong></td>
<td>-</td>
<td>79 %</td>
</tr>
</tbody>
</table>

The investment cost has been based on an extensive in-house data base with budget quotations, which have been updated to 2Q 2009 and scaled to the studied plant size. The investment cost for the parts has thus been assessed by using in-house information and applying accepted factor and index methods for updating.

The capital investment was calculated with an inflation of 2 %, a debt interest of 6 %, equity of 15 % (debt/equity ratio of 80/20) and a loan period of 20 years – a weighted average cost of capital of 7.80 %. The equivalent operating hours is estimated as 8000 per year with a district heat production of 5000 hours per year. The exchanges rates were as of 16 September 2009 1 EUR = 10.20 SEK, 1 USD = 7.00 SEK.
<table>
<thead>
<tr>
<th>Investment cost</th>
<th>Brista</th>
<th>Igelsta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air separation plant</td>
<td>178 MSEK</td>
<td>278 MSEK</td>
</tr>
<tr>
<td>Gasification plant</td>
<td>1103 MSEK</td>
<td>1728 MSEK</td>
</tr>
<tr>
<td>Gas cleaning &amp; conditioning plant</td>
<td>535 MSEK</td>
<td>777 MSEK</td>
</tr>
<tr>
<td>FT-plant</td>
<td>1156 MSEK</td>
<td>1473 MSEK</td>
</tr>
<tr>
<td>Boiler and steam turbine plant</td>
<td>284 MSEK</td>
<td>485 MSEK</td>
</tr>
<tr>
<td>Balance of plant (a)</td>
<td>794 MSEK</td>
<td>1165 MSEK</td>
</tr>
<tr>
<td>Equipment and assembly</td>
<td>4070 MSEK</td>
<td>5926 MSEK</td>
</tr>
<tr>
<td>In-direct costs (b)</td>
<td>1014 MSEK</td>
<td>1513 MSEK</td>
</tr>
<tr>
<td><strong>Total costs</strong></td>
<td><strong>5084 MSEK</strong></td>
<td><strong>7439 MSEK</strong></td>
</tr>
<tr>
<td><strong>Total costs (EUR / USD)</strong></td>
<td><strong>500 MEUR / 726 MUSD</strong></td>
<td><strong>729 MEUR / 1063 MUSD</strong></td>
</tr>
</tbody>
</table>

Notes:

a) In-house estimate which includes utility feedstocks and off-sites comprising land and buildings, roads and pipelines and centrals and lines for electricity, water etc.

b) In-house estimate, which includes site costs, temporary and spare equipment, storage, owner’s cost (project development, permitting and approval, detailed engineering, commissioning and start-up costs etc), working capital, financing and legal fees, interest during construction etc.

The production cost has been calculated with below assumed prices of energy and commodities. Firstly, the revenues are given e.g. district heat which is exported. Then the total yearly costs are given, with the resulting the production costs as 8300 SEK per cubic meter and 5000 SEK per cubic meter bio-jet, respectively. The basis for the costs have been the current Brent oil price which was $67 per barrel as of 16 September, which relates to the revenues of naphtha and diesel with additional energy and carbon dioxide taxes, as per below.

<table>
<thead>
<tr>
<th>Production cost</th>
<th>Unit price</th>
<th>Brista</th>
<th>Igelsta</th>
</tr>
</thead>
<tbody>
<tr>
<td>District heating</td>
<td>450 SEK/MWh</td>
<td>218 MSEK</td>
<td>410 MSEK</td>
</tr>
<tr>
<td>Naphtha (a)</td>
<td>940 SEK/MWh</td>
<td>209 MSEK</td>
<td>148 MSEK</td>
</tr>
<tr>
<td>Heavy diesel (b)</td>
<td>770 SEK/MWh</td>
<td>198 MSEK</td>
<td>1140 MSEK</td>
</tr>
<tr>
<td><strong>Total revenues</strong></td>
<td><strong>489 MSEK</strong></td>
<td><strong>1464 MSEK</strong></td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td>180 SEK/MWh</td>
<td>416 MSEK</td>
<td>880 MSEK</td>
</tr>
<tr>
<td>Electricity</td>
<td>480 SEK/MWh</td>
<td>7 MSEK</td>
<td>7 MSEK</td>
</tr>
<tr>
<td>Refining bio-jet (c)</td>
<td>-</td>
<td>0 MSEK</td>
<td>81 MSEK</td>
</tr>
<tr>
<td>Operation &amp; maintenance</td>
<td>-</td>
<td>197 MSEK</td>
<td>271 MSEK</td>
</tr>
<tr>
<td>Capital costs</td>
<td>-</td>
<td>510 MSEK</td>
<td>746 MSEK</td>
</tr>
<tr>
<td><strong>Total costs</strong></td>
<td><strong>1140 MSEK</strong></td>
<td><strong>2007 MSEK</strong></td>
<td></td>
</tr>
<tr>
<td>Bio-jet cost</td>
<td>-</td>
<td>0.86 SEK/kWh</td>
<td>0.52 SEK/kWh</td>
</tr>
<tr>
<td>Bio-jet cost per m³</td>
<td>-</td>
<td>8280 SEK/m³</td>
<td>5000 SEK/m³</td>
</tr>
<tr>
<td><strong>Bio-jet cost per m³</strong></td>
<td><strong>812 EUR / 1183 USD</strong></td>
<td><strong>490 EUR / 714 USD</strong></td>
<td></td>
</tr>
</tbody>
</table>
Notes:

a) The naphtha sales price has been calculated as current Brent oil price with $2.5 penalty per barrel Brent oil and current petrol carbon dioxide and energy tax of 5520 SEK/m³ as a green fuel for petrol blend, stated by Preem.

b) The heavy diesel sales price has been calculated as current Brent oil price with $8.0 added per barrel Brent oil and current diesel and EO1 heavy fuel oil carbon dioxide and energy tax of 3804 SEK/m³ as a green fuel for diesel and heavy fuel oil blend, stated by Preem.

c) This cost is given by Preem as the cost for refining the bio-jet on an operation cost calculated as 5 % reduction in product value, which is then calculated from the total product value. This cost includes the operation cost including utilities and no regard for the investment cost is taken.

The main results are very promising, showing high efficiency and competitive production costs. There is option for much optimisation as there are several variables and alternatives that have not been calculated in detail. The investment cost is rather steep but there is room for reducing the investment costs, however, the uncertainty of these calculations and results limits on how defined conclusions can be made.

The Brista plant shows production costs that are not competitive with today’s conventional jet fuel at a crude oil price of $67 per barrel. However, with future emission trading included in the price and a slightly larger plant it is likely that this plant would be competitive. Still the Igelsta plant shows several benefits with an FT-product that is shipped to a refinery for upgrading into a jet fuel. Already this is tentatively competitive, albeit at very large scale. And a presumption is that a smaller, e.g. 400 MWth plant would still be competitive. There are thus economical arguments for a biorefinery to be located at a CHP plant as a base with very good biomass logistics and potential that would produce a FT-product.

In conclusion to this report, the bio-jet fuel product would most likely be accepted as jet fuel blend and this report shows two interesting plant configurations where an intermediate FT-product for further upgrade into bio-jet fuel production would be competitive already with today’s prices and costs. It is therefore a summarising recommendation that this work is continued for a detailed feasibility study with supplier contacts and further technical optimisation. The basis for a plant would be the location at a CHP plant for the district heat network but also the most important biomass logistics and option of power production.

Keywords: Biorefinery, gasification, aviation, bio-jet fuel, biomass
Table of contents

1 INTRODUCTION .................................................................................................................. 1
  1.1 BACKGROUND ............................................................................................................... 1
  1.2 RESEARCH AREA AND PROJECT METHODOLOGY .................................................... 2
  1.3 PROJECT OBJECTIVES ............................................................................................... 3
  1.4 GOAL AND AUDIENCE ............................................................................................... 4
  1.5 PROJECT ORGANIZATION ........................................................................................... 4

2 REQUIREMENTS ON ALTERNATIVE AVIATION FUELS ................................................... 6
  2.1 THERE ARE NO PARKING PLACES IN THE SKY .......................................................... 6
      2.1.1 Aviation fuel specifications .................................................................................... 6
      2.1.2 Specification development and certification process ............................................. 9
      2.1.3 Status of jet fuel specification .............................................................................. 11

3 FUEL AND DISTRIBUTORS, AIRPORTS AND AIRCRAFT OPERATORS ....................... 12
  3.1 STAKEHOLDERS IN ALTERNATIVE AVIATION FUELS .............................................. 12
      3.1.1 Organisations and projects .................................................................................... 12
      3.1.2 Aircraft and engine manufacturers ......................................................................... 14
      3.1.3 Aircraft operators .................................................................................................. 14
      3.1.4 Fuel producers ....................................................................................................... 15
      3.2 STOCKHOLM-ARLANDA AIRPORT ......................................................................... 15
      3.2.1 Fuel handling ......................................................................................................... 17
      3.2.2 Handling of alternative fuels ................................................................................ 17
      3.2.3 Fuel handling environmental permit ...................................................................... 18
  3.3 PREEMRAFF ................................................................................................................. 18

4 BASIS FOR DESIGN ........................................................................................................... 20
  4.1 GENERAL PRINCIPLES AND METHODOLOGY ........................................................... 20
  4.2 PRINCIPAL PLANT CONFIGURATION ......................................................................... 20
  4.3 PLANT LOCATION ......................................................................................................... 21
      4.3.1 General .................................................................................................................. 21
      4.3.2 Biomass supply security ......................................................................................... 22
      4.3.3 Supply of regular jet fuel to Arlanda ...................................................................... 23
      4.3.4 Candidate sites ....................................................................................................... 23
      4.3.5 Evaluation of site alternatives .............................................................................. 25

5 PROCESS DESCRIPTION ....................................................................................................... 28
  5.1 INTRODUCTION ............................................................................................................ 28
  5.2 AIR SEPARATION PLANT ............................................................................................ 29
  5.3 BIOMASS GASIFICATION PLANT .................................................................................. 30
      5.3.1 Biomass handling .................................................................................................... 30
      5.3.2 Biomass drying ...................................................................................................... 31
      5.3.3 Gasification process ............................................................................................... 32
      5.3.4 Gas reforming, cooling and cleaning ..................................................................... 33
      5.3.5 Utility gases ........................................................................................................... 34
  5.4 GAS CLEANING AND CONDITIONING PLANT .............................................................. 34
      5.4.1 Overall description .................................................................................................. 34
      5.4.2 Rectisol process, first wash unit .......................................................................... 35
      5.4.3 CO shift conversion ............................................................................................... 36
      5.4.4 Second wash unit and regeneration ...................................................................... 36
  5.5 FISCHER-TROPSCH SYNTHESIS PLANT ....................................................................... 37
      5.5.1 Fischer-Tropsch synthesis .................................................................................... 37
      5.5.2 Auto-Thermal Reforming ...................................................................................... 40
      5.5.3 Brista plant, FT-product upgrading ...................................................................... 40
## 5.5.4 Igelsta plant, FT-product upgrading at refinery ........................................ 42

### 5.6 POWER AND STEAM SYSTEM PLANT ......................................................... 43

#### 5.6.1 Biomass boiler .......................................................... 44

#### 5.6.2 Steam turbine ..................................................... 45

#### 5.7 BALANCE OF PLANT ................................................................. 48

##### 5.7.1 Utilities and off-sites ........................................... 48

### 6 MATERIAL AND ENERGY BALANCES .......................................................... 49

#### 6.1 Study alternatives ...................................................... 49

#### 6.2 Process calculations .................................................. 49

#### 6.3 Plant results ............................................................ 53

#### 6.4 Plant logistics ........................................................... 55

### 7 ECONOMY ................................................................................. 56

#### 7.1 Capital investment .......................................................... 56

#### 7.2 Production costs ........................................................... 57

### 8 ENVIRONMENTAL IMPACT ................................................................. 60

#### 8.1.1 Environmental effects .......................................................... 60

#### 8.1.2 Sustainability, lifecycle and emissions ............................................ 60

#### 8.1.3 Life Cycle Assessment of greenhouse gases ....................................... 61

#### 8.2 Gas clean-up requirements ..................................................... 62

#### 8.3 Emissions to air, land and water .................................................. 62

##### 8.3.1 Air emissions ........................................................... 62

##### 8.3.2 Solid waste ............................................................... 63

##### 8.3.3 Water emissions .......................................................... 63

#### 8.4 Noise pollution ............................................................... 63

### 9 CONCLUSIONS AND DISCUSSION ......................................................... 64

#### 9.1 Economic parameters .......................................................... 64

##### 9.1.1 Historical and future oil prices ............................................... 64

##### 9.1.2 Aviation fuel price ......................................................... 65

##### 9.1.3 Biomass price ......................................................... 65

#### 9.2 Different sources of bio-fuels and production processes ....................... 66

##### 9.2.1 Biomasses, present and future possibilities ....................................... 66

##### 9.2.2 Production processes .................................................... 66

#### 9.3 Selecting the processes ...................................................... 67

#### 9.4 Plant reliability and availability .................................................. 68

#### 9.5 Plant scale analysis ........................................................... 68

#### 9.6 Possible technical improvements .................................................. 69

#### 9.7 Technical and economical results .................................................. 69

### 10 ABBREVIATIONS AND ACRONYMS ......................................................... 71

### 11 REFERENCES ............................................................................. 72

#### 11.1 Internet ........................................................................... 72

#### 11.2 Literature ......................................................................... 72

**Appendices**

A STOCKHOLM-ARLANDA AIRPORT

B FISCHER-TROPSCH RESEARCH AT KTH
1 Introduction

1.1 Background

The air traffic industry faces big changes in the near future. Apart from today's economic situation there are challenges like security of fuel supply, meeting emission requirements and environmental permissions. Perhaps the biggest challenge of all is how the industry can expand while reducing their share of the CO$_2$-emissions.

LFV has a target to reduce their use of fossil fuels and reduce carbon dioxide emissions by 50% within three years, where earlier energy efficiency work has led to a 60% decrease the last five years. Therefore LFV set the framework for this project to investigate the pre-conditions for a biorefinery plant in conjunction with Arlanda Airport.

An initial work gave at hand good possibilities in several aspects for a plant in the vicinity of Arlanda. The nearby Brista combined heat and power plant is connected to the north-western district heating network of Stockholm. There are also good transport opportunities by road and train for biomass in the area, as well as the distribution network for jet fuel. In addition, there is ample interest in the aviation industry with airline companies and other actors to reduce CO$_2$ emissions from aircraft.

The biorefinery is based on advanced gasification technology (e.g. Andritz/Carbona), fuelled by forest fuels, integrated with ultra-efficient gas cleaning and Fischer-Tropsch synthesis processes to produce green aviation fuel products. This technology is deemed by many as the alternative with the highest potential. Several Swedish development projects are underway with gasification pilot plants in Värnamo, Gothenburg and Piteå, which in various degrees demonstrates the technology.

This project group has set out to evaluate locations, integration with the area, biomass and product logistics, necessary process components and plant performance with relevant numbers in the form of biomass to fuel efficiency, conceptual investment and production costs. Part of the work tasks is also to highlight current fuel standards and the possibility for fuel blends.

In next chapter we will firstly describe the requirements on aviation fuels and motivations for the implementation of alternatives to conventional sources as base for fuel production. Two questions are in focus, price and environmental impact with an emphasis on near time implementation, i.e. within a decade. The year 2008 showed how unpredictable fuel prices are but despite the short term variation the general assessment of future oil price is that it will increase continuously, passing $100 per barrel within few years time.
At the same time aviation is predicted to increase, and by that the green house gas emissions from aviation. Although aviation’s contribution to the world’s total green house gas emissions presently is small, about 2 %, it will increase as air traffic increase and other CO\textsubscript{2} sources are reduced as alternative energy technologies are introduced.

The strict requirements on the properties of aviation fuel are a consequence of the high safety standards and a reason why biomass based fuel is not yet commercially available in aviation although it has been since long for land transport systems. There are several ways to produce alternative fuels although the only one certified for aviation fuel today is by Fischer-Tropsch. Further, we look into the requirements on airports’ infrastructure, impacts on aircraft operators and fuel distributors. We also list some alternative ways of producing aviation fuel from biomass and review the benefits and hurdles of the different alternatives.

1.2 Research area and project methodology

The area of this project has not been studied before at VärmeForsk and there have not been any other study related to aviation fuel production. There have been a few studies of bioenergy combine for liquid fuel production which is similar to the current study. In general, the research area is quite new and there has been little published considering biomass gasification and bio-jet fuel production.

Thus, this project is of interest where the host of a combined heat and power plant may serve as host for a fuel production plant with synergies in fuel handling and logistics, heat and power production and off-set of a new product market to reduce fossil fuel use with alternative fuels, in this instance with aviation fuels. This project is mainly relevant to the key areas of System Technology:

- “Sustainable fuel supply – new concept and resources with alternative use of forest fuels for production of alternative fuels, heat and power,
- “Resource management” with new concept of efficient production of heat and power, and more efficient use of fuel over a larger system,
- Energy combine – local and regional energy solutions with a study of energy combine solutions, where the effects of synergy give efficient systems and good management of resources.

Within the area of Plant and combustion technology: “Plant concept” the project is coherent with the goal to create a project which produce technical and economical documentation in order to increase the system integration and the total energy efficiency for plants with maximum power production during most of the year.
Tangible goals in the Base program that are developed are:

- Energy efficient system solutions for profitable production of more than one of energy carriers power, cold and fuels in combination with heat production,
- To within a period of five years produce new applicable concepts for energy combine solutions, where the effects of synergy give efficient systems and good management of resources,
- Development of technical solutions for cost-efficient reduction of emissions in that those national environmental targets can be attained.

This project will identify and evaluate locations, integration possibilities in the vicinity, raw material and fuel logistics, necessary process components within the plant for an energy combine and biorefinery, plant performance with key numbers of efficiency and conceptual investment costs and production costs. Jet fuel issues regarding certification and blends will be high-lighted. The acceptance of airline operators will be described, especially considering the impact of trade of emissions and fluctuating oil prices.

The project is divided into work packages (WP), where the methodology that will be used is the following:

- WP1. Establishing of system conditions, restrictions, limitations, and plant pre-conditions etc.
- WP2. Investigation of location, integration, logistics etc
- WP3. Selection of process design, process alternatives, calculation cases
- WP4. Calculation of heat and material balances for selected cases
- WP5. Estimation of investment costs, establishing fuel prices and parameters for calculation of production costs.
- WP6. Fuel standards, certification, environmental aspects, airline operator price sensitivity etc.

The investment cost estimate will be mainly based on public material and in-house material with limited supplier contacts. A couple of similar studies for the Swedish Energy Agency have been made in the area by Nykomb and therefore much of the material is available for this project.

1.3 Project objectives

The objective with the project is to investigate the overall technical and economical feasibility of a biorefinery with a production of 50 000 tonnes of green bio-aviation fuels per year. This could class Arlanda Airport as carbon-neutral – an achievement which would be world-unique. At the same time, other hydrocarbons and district heat are produced and put together this could reduce the CO₂-emissions of Arlanda by 150 000 tonnes per year with a 10 % blend of bio-jet fuels.
1.4 Goal and audience

The long-term goal of this project is to establish an energy-combine – a biorefinery – for production of biomass based jet fuel, in conjunction with a heating plant. The first brick of such a plant is of course to serve presumed stakeholders with necessary decision material with costs and possibilities and risks for a project development towards a commercial demonstration project.

The concrete goal of this project is to investigate the technical and economical feasibility of a biorefinery plant which produces bio-jet fuels that could replace fossil fuels at Arlanda Airport, while producing other fuels and heat at a combined heat and power plant.

These results are made for an audience in the aviation industry and authorities, as well as actors in the chain from biomass logistics, plant management at combined heat and power industry level to refinery upgrading know-how.

1.5 Project organization

The project group was coordinated by Nykomb Synergetics, project leader and responsible for work packages of WP1. Project identification, WP2. Plant location, WP3. Selection of process design, WP4. Material and energy balances, WP5. Investment and production costs. FOI was responsible for WP6. Fuel standards and certification and environmental impact. Other project group members were Fortum Värme who contributed in WP1-5, Grontmij who contributed in WP1-6, LFV who contributed in WP1-6 and Preem who contributed in WP4-6. The project was part-financed by VärmeForsk and LFV, with in-kind contribution from Fortum Värme and Preem.

Nykomb Synergetics coordinated this project works as a process architect engineering consultant, with experience and special knowledge in integration technologies for gasification, gas cleaning & conditioning, power systems and fuel synthesis for biorefineries. With relevance of this project Nykomb coordinated the BLGMF II (Black Liquor Gasification with Motor Fuels production) study project in 2005 [32] (preceded by the BLGMF study [31]), which was supported by the Swedish Energy Agency. The study detailed black liquor gasification integrated with a pulp and paper mill for the production of Fischer-Tropsch diesel fuels and lubricants.

FOI is a large research agency employing 800 researchers in various fields. At FOI aeronautical research is pursued and the institute has a long experience in the field of aviation and environment. Since 15 years FOI performs the emission calculations for the Swedish transportation agency and the Swedish Air Navigation Provider (LFV group). The calculations are based on detailed models of aircraft performance, engines and navigation procedures and one of the most comprehensive emission models used.
FOI is active in several research networks and EU research projects foremost in collaboration with institutes and universities in Europe. In the project Environmentally Compatible Aviation Transport System, (ECATS) a substantial part of the research is directed towards the analysis and development of alternative fuels. With the support of advanced experimental capabilities several experiments establishing properties and consequences of the use of alternative fuels have been made in the project partners laboratories making valuable information available to FOI.

Grontmij Group is a large international technical consultant with 8000 employees, with headquarters in Europe. In Sweden, the company is active in three market sectors; Energy, Building and Infrastructure. Grontmij’s Energy sector is involved in projects ranging from conventional power plants (bio and fossil), waste incineration plants, biogas and nuclear power plants to improve the energy utilisation at various applications.
2 Requirements on alternative aviation fuels

An alternative fuel, i.e., not from fossil source, for aviation must meet certain basic requirements. It must be a drop-in fuel, completely compatible with the existing fuel supply chain, existing aircraft and engines. Aviation is global and a successful implementation of an alternative fuel must not be limited geographically (e.g. a nation) or technically (e.g. to only a certain aircraft type). A meaningful alternative should also reduce the dependence on crude oil supplies, be sustainable and be environmentally beneficial. To succeed it must also be affordable.

2.1 There are no parking places in the sky

Safety is the first, second and third most important aspect of aircraft systems, closely followed by economy. An aircraft must not fall apart, and the engines must always work as there is no place to pull over in case of engine failure or lack of fuel. Since commercial aviation started the reliability of engines and propulsion systems have continuously increased, and today a modern jet aircraft has engine failure rate less than 0.002/1000 hours [73]. To reach such an extreme reliability, every component in the propulsion system needs to meet very specific requirement, including the fuel.

Aircraft also represent major investments and they need to be carefully maintained and protected. The safety issues and cost aspects impose very strict regulations and requirements on the fuel that is used for aircraft. Therefore standardisation organisations, where all stakeholders as aircraft and engine manufacturers, aircraft operators, fuel producers and subsystem providers take part, develop specifications, e.g. for aviation fuel, which must be followed by all partners in the fuel supply chain. If a new fuel, i.e. biomass based alternative fuel, is to be used, specifications must be developed to guarantee that the fuel is compatible with all existing aircraft systems.

2.1.1 Aviation fuel specifications

In this document we refer to jet engine fuel, AVTUR (Aviation Turbine fuel), when discussing aviation fuel. For piston engines a gasoline fuel is used, and in aviation it is called AVGAS (Aviation Gasoline), also a fuel that meets much more specific and restrictive specifications than gasoline sold to cars.

Jet engine fuel is kerosene, lighter than diesel and heavier than gasoline. Jet fuel comes in different versions, or according to different standards. For commercial aviation the fuel is named Jet A-1, Jet A, or sometimes AVTUR. The standards ASTM D1655 (US) and Def Stan 91-91 (UK) [1], [19], prescribes properties of the fuel such as freezing point, ignition point, boiling point and several other features the fuel must have and comply with.
Jet engines are parts of very sensitive and delicate technical systems. The fuel system contains valves, tubes, pumps and sensors. The engine itself is an advanced machine operating at extreme conditions. The fuels specifications are developed to guarantee that engines always perform equally, that the safety margins are maintained and that the maintenance cost of the engines does not exceed expectations due to unusual wear caused by contamination of the fuel or degraded lubrication.

If the fuel is contaminated the cost for a complete overhaul of the propulsion system could be disastrous for the aircraft operator. If the fuel is too volatile it could be environmentally harmful and a low flash point as well as a high freezing temperature might jeopardise safety, as outdoor temperature is very low at cruising altitude.

Altogether the strict specifications for aviation fuel increase the demands on fuel producers, on the training of the personnel and handling processes for distribution. They substantially raise the bar for what can be used in real flights compared to land transport systems where an unplanned stop is more an inconvenient disturbance than a catastrophe.

Specifications are not a full material definition and have been based on assumptions, like that the fuel source is petroleum based. The high reliability of jet propulsion systems is due to years of experience and engineering knowledge. Combustion is an area still under scientific investigation, from a phenomenal point of view there is still lot to learn. Alternative fuels for aviation are therefore a challenging field with no simple truths.

The existing performance based specifications will not exclude that an alternative fuel, meeting the specifications but stemming from another source than crude oil, might have slightly different distribution of the different hydrocarbon chains and other substances. An illustration of this is seen in below Figure 1 which illustrates how broad spectrum a conventional fuel has compared to a pure FT-product. In the new specification for an FT-based fuel this is cared for with extended and some additional requirements. This strategy is expected to be used for requirements for a general aviation fuel specification.
Figure 1. Depicted in the figures are the abundances of components in FT-kerosene (top) and conventional Jet A-1 (bottom) [75].

The existing performance requirements in ASTM D1655/Def Stan 91-91 are enhanced and some new added. Due to the reduced amount of sulphur lubricity will be more specified, density, viscosity and density are other existing requirements which are more detailed specified. The lack of aromatics in FT fuels introduces a requirement of lowest amount of aromatics, not only a maximum value. Instead of a single boiling point a more detailed boiling curve is required. The storage and bulk modulus properties are extra carefully defined. Further conductivity, electrical and thermal have extended prescriptions. Toxicity is not an issue when it comes to FT-fuel but something that need to be looked at for other production processes.
For comparison, some properties of AVTUR have been listed in the Table below along with the specification of fuel oil (Eldningsolja 1 E32).

<table>
<thead>
<tr>
<th>Name</th>
<th>AVTUR</th>
<th>Eldningsolja 1 E32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15°C</td>
<td>775 - 840 kg/m³</td>
<td>810-840 kg/m³</td>
</tr>
<tr>
<td>Viscosity at minus 20°C</td>
<td>Max 8 mm²/s</td>
<td>N/A</td>
</tr>
<tr>
<td>Viscosity at 40°C</td>
<td>N/A</td>
<td>1,5-3,0 mm²/s</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>Min 42,80 MJ/kg</td>
<td>(43,2 - 43,0 MJ/kg)*</td>
</tr>
<tr>
<td>Stotal sulfur</td>
<td>Max 0,3 % m/m</td>
<td>0,05 % m/m</td>
</tr>
<tr>
<td></td>
<td>Max 26,5 % v/v</td>
<td>N/A</td>
</tr>
<tr>
<td>Distillation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial boiling point</td>
<td>Report</td>
<td>N/A</td>
</tr>
<tr>
<td>10% Recovery</td>
<td>Max 205</td>
<td>Max 230°C</td>
</tr>
<tr>
<td>50% Recovery</td>
<td>Report</td>
<td>N/A</td>
</tr>
<tr>
<td>90 %Recovery</td>
<td>Report</td>
<td>N/A</td>
</tr>
<tr>
<td>95% Recovery</td>
<td>N/A</td>
<td>Max 370°C</td>
</tr>
<tr>
<td>End Point</td>
<td>Max 300</td>
<td>N/A</td>
</tr>
<tr>
<td>Flash Point</td>
<td>N/A</td>
<td>Min 60</td>
</tr>
<tr>
<td>Freezing point</td>
<td>-47°C</td>
<td>N/A</td>
</tr>
<tr>
<td>Lowest filtering temp</td>
<td>N/A</td>
<td>-32°C</td>
</tr>
<tr>
<td>Standard</td>
<td>Def Stan 91-91 Issue 6</td>
<td>Svensk Standard SS 15 54 10</td>
</tr>
<tr>
<td>* Typical test data</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Properties of AVTUR, along with the specification of fuel oil (Eldningsolja 1 E32).

### 2.1.2 Specification development and certification process

The specifications for aviation fuels are developed by certification organisations. ASTM International, originally known as the American Society for Testing and Materials (ASTM), is one of the largest voluntary standards development organizations in the world, and responsible for ASTM D1655 (Jet A-1). UK Defence Standardization (DSTAN) is another important standardisation organisation, and Def Stan 91-91 is equivalent to ASTM D1655.

All interested stakeholders are members of ASTM which is divided in committees and in committee D02 on Petroleum Products and Lubricants the different fuel specifications are developed.

When a new amendment or standard for aviation fuel is to be developed, the candidate fuel is analysed and compared to existing requirements. If no negative findings are made, the testing process is continued with component tests, engine tests and finally flight tests, as depicted in Figure 2 below. After appropriate tests are made and with positive results the new, or extended, standard is formally voted on in subcommittee, main committee, and Society respectively.
**Figure 2.** The process to reach new fuel specifications [51].

**Aviation Alternate Fuels Roadmap**  
*(Level 2 / Scenario 1 - Long Term)*

**Figure 3.** The CAAFI roadmap to certification of alternative aviation fuels [77].
2.1.3 Status of jet fuel specification

On 24 of June 2009 the subcommittee D02.J0 on Aviation Fuels reviewed and discussed return ballots and comments submitted in regard to “Draft Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons” see [61]. The specification was formally voted on and passed on to the top-level Petroleum Products and lubricants committee. There it was formally voted for in August and is now a formal ASTM specification, D-7665-09 [2].

This specification is being structured, via annexes, to accommodate different classes of alternative fuels. To begin with the specification allows up to a 50 % blend of FT fuel with conventional Jet A. FT fuels can be generated from almost anything that contains coal. Biomass to liquid (BTL), natural gas to liquid (GTL), and coal to liquid (CTL) and combinations thereof are all possibilities which are explored today. It is expected that the FT approval will be followed by approvals for hydrotreated renewable Jet (HRJ) blends and other alternatives as data from technical evaluations is obtained. An ASTM required research report on the HRJ fuels is expected by this year’s end.
3 Fuel and distributors, airports and aircraft operators
With a certified alternative fuel there are no technical impacts on existing systems which is one of the key points of the certification process. There might be a need for the introduction of extended handling procedures if batch of FT-fuel is to be blended with petroleum based fuel in the distribution system. The reduction of CO\textsubscript{2} emissions is expected to have benefits for both the airport and the aircraft operators. The reduced levels of sulphur and aromatics will give overall positive environmental effects.

3.1 Stakeholders in alternative aviation fuels
Aviation needs to, as all other energy-consumers, reduce the greenhouse gas (GHG) emissions. Even if aviation’s present part of the world’s total GHG emissions is around 2% it will rapidly increase as other actors reduce their fossil fuel use and aviation grow. The air traffic will increase in all available scenarios [3], [51], and the long term forecast points to a growth on global use of aviation fuel between 170 % and 300 % in 2050 compared to 2006. Many initiatives exist to reduce fuel consumption. Improved engines, airframes, more efficient routing but to meet the requirements set by ACARE with a substantial total reduction in emissions by 2050 and increasing traffic other measures must be taken. A CO\textsubscript{2} neutral fuel is one alternative which is in focus for most of the stakeholders.

3.1.1 Organisations and projects
There are several organisations active in the field of alternative aviation fuel. In US traditional research and funding institutes as NASA, DARPA, NSF runs or funds research programs or projects as PARTNER, coordinated from MIT. In Europe the major research institutes in the aeronautical sector are active, mostly within EU framework programs. ECATS, Alfabird and SWAEFA are examples of these. The airline’s association, IATA, follows the development closely and publishes reports on recent achievements.

Since 2006 the Commercial Aviation Alternative Fuels Initiative (CAAFI) has sought to enhance energy security and environmental sustainability for aviation by exploring the use of alternative jet fuels. CAAFI is a coalition of airlines, aircraft and engine manufacturers, energy producers, researchers, international participants and U.S. government agencies. Together these stakeholders are leading the development and deployment of alternative jet fuels for commercial aviation.

CAAFI’s goal is to promote the development of alternative jet fuel options that offer equivalent levels of safety and compare favourably on cost with petroleum based jet fuel, while also offering environmental improvement and security of energy supply for aviation.
The recent volatility in petroleum prices caused fuel to become the single largest component of U.S. airline operating cost for the first time in history in 2006. And, concern about the environmental impacts of aviation growth is also rising within the international community. While U.S. commercial aviation consumes about 3% of U.S. total energy use, it drives about 6% of the U.S. gross domestic product and just under 9% of national employment. Secure and sustainable fuel sources are essential for its continued prosperity. Aviation is international in scope, highly integrated in its fuel supply chain and, because of a significant ability to align and coordinate within the industry, well positioned to pursue alternative fuels.

IATA recognizes that aircraft are long-lived assets and will be using kerosene or kerosene type fuels for many years to come. It supports research, development and deployment of sustainable bio-fuels that should offer net carbon reductions over their life cycle, not compete with fresh water requirements and food production and without causing deforestation or other environmental impacts such as biodiversity loss. IATA’s goal is for its members to be using 10% alternative fuels by 2017. IATA publishes reports in recent achievements, and the report from last year [51] is a thorough analysis of technical challenges and possibilities.

The Network of Excellence ECATS is an expert group contributing to environmentally compatible air transport. With initial funding from the European Commission ECATS' scope is to contribute to the environmental goals of the Vision 2020 for Aeronautics and the Strategic Research Agenda (SRA). An in-depth integration of the competences and activities available across Europe further improves the competitiveness of European aeronautics industry.

SWAFEA is a study for the European Commission's Directorate General for Transport and Energy to investigate the feasibility and the impact of the use of alternative fuels in aviation. The SWAFEA team involves 20 European and international organisations, representing all players in alternative aviation fuels: aircraft and engine manufacturing, air transport, oil industry, research and consulting organisations covering a large spectrum of expertise in the fields of fuel, combustion, environment as well as agriculture.

ALFA-BIRD aims at developing the use of alternative fuels in aeronautics. In a context where the price of oil is increasing and with impact of fossil fuels on climate change, the sustainable growth of the civil aviation is conditioned by the respect of the environment. In this context, using biofuels and alternative fuels in aeronautics is a great challenge, since the operational constraints (e.g. flight in very cold conditions) are very strict, and due to the long lifetime of current civil aircraft.

PARTNER – the Partnership for AiR Transportation Noise and Emissions Reduction – is a leading aviation cooperative research organization, and an FAA/NASA/Transport Canada-sponsored Centre of Excellence. PARTNER fosters breakthrough technological, operational, policy, and workforce advances for the betterment of mobility, economy, national security, and the environment.
Air Transport Action Group is an independent coalition of organizations and companies throughout the air transport industry that has formed an independent organization striving for sustainable aviation and fuels.

### 3.1.2 Aircraft and engine manufacturers

The two major airframe producers Airbus and Boeing both run programs on alternative fuels. During 2008 and in 2009 there have been several test flights on different kinds of alternative fuels. In February 2008 Airbus flew an A380 with one Rolls-Royce engine on a Shell GTL fuel, performing extensive tests during a three hour flight between Filton, UK and Toulouse, France. The same month Boeing showed the technical possibility of using biofuel in a Virgin Atlantic 747 from London to Amsterdam. However, a mix of coconut oil, not considered to meet all sustainability or reliability requirements where used. Boeing followed with other tests, together with Rolls-Royce, GE Aviation and Pratt & Whitney in different combinations with Air New Zealand, Continental Airlines and Japan Airlines.

Alternative fuels pose a new challenge to engine manufacturers. Reliable and technical complex systems as aviation jet turbines are developed over long time and based on experience and experiments. Despite the advanced state of the technology the theoretical knowledge is limited as it involves fluid mechanics, chemistry, materials and mechanics in a complex setting. Therefore the engine manufacturers have increased their research efforts to understand phenomena that previously were considered well known, but under the assumption conventional fuel was used. A very cautious approach is used when it comes to introducing alternatives in real test flights but the engine manufacturers are very active in research and testing, however the limited supply of FT fuel has been a major bottle neck for efficient research. The manufacturers are active in certification and standard development.

The Sustainable Aviation Fuel Users Group was created in September 2008, to promote sustainable, second-generation biofuels for the aviation industry. The members are the aircraft manufacturer Boeing and several airlines (e.g. Air France, Air New Zealand, ANA (All Nippon Airways), Japan Airlines, KLM, SAS, Virgin Atlantic Airways, Alaska Airlines, British Airways, Cathay Pacific, TUIFly and Virgin Group. Other environment preserving organisations are members or affiliated as well. The group has initiated several projects to judge the viability of different biomass alternatives.

### 3.1.3 Aircraft operators

For aircraft operators, the implementation of bio aviation fuel at Arlanda offers the possibility to reduce the CO₂ emissions from petroleum sources. This has several benefits for the operators. The future Emission Trade System (ETS) for aviation [36] is expected to be introduced by 2012. Aircraft operators will be given free allowances up to a certain level, and forced to by allowances on the market to cover emissions due to increasing traffic. This will add to the fuel cost. A rough estimate is that it may increase the fuel cost for traffic flying in and to Europe with 5-15 %.
As fuel since 2005 is the largest cost for operators this could imply a large economical burden. Bio based fuel is presently free in the ETS and does not consume allowances. Aircraft operators could thus pay more for bio FT aviation fuel and still be cost neutral to conventional fuel. The prediction for oil price is that it will increase and sometimes possibly fluctuate as it did 2008. An alternative source for aviation fuel would be a supplement to conventional fuel and compensate for both increased and fluctuating prices.

The existing certified alternative aviation fuel, i.e. a substitute and drop-in replacement is technically equivalent to what is used today. Since engine and airframe manufacturers are part of the certification process all conditions required to fulfil the maintenance programs are fulfilled.

3.1.4 Fuel producers

The list of fuel producers which are involved in alternative aviation fuel is long. The different projects stretch from near term solutions as FT gas-to-liquid to future applications of genetically designed crops rich in lipids.


Despite the large number of interested fuel producers the lack of fuel for testing is one of the main bottle necks in development and certification of alternative fuels. British Airways and Rolls Royce have invited fuel producers to supply fuel in a large test program but the amount of accessible fuel is still an obstacle for large test campaigns.

3.2 Stockholm-Arlanda Airport

Stockholm-Arlanda is the only airport in the world with a carbon dioxide emission cap in its environmental permit. This stipulation means that emissions from aircraft take-offs and landings, road traffic to and from the airport, internal vehicle traffic and space heating of buildings may be no higher in 2011 than they were in 1990. LFV, which owns, operates and develops the airport, is therefore responsible for organising its operations in such a way as to minimise overall emissions of carbon dioxide from aviation operations as well as ground transport at, to and from the airport.
However, not all of LFV’s actions can be counted within the cap for example purchasing only green electricity, giving preferential treatment to environmentally clean cars at parking facilities, extensively streamlining the airport’s energy use and optimising cargo operations.

In recent years there has been a clear trend towards more passengers per aircraft taking off at Stockholm-Arlanda. Compared to 1990, the number of aviation passengers has increased by 21%. Meanwhile aviation emissions at the airport have declined by 15%. Carbon dioxide emissions from road traffic, however, have increased by 30% and now account for more than half of the emissions within the cape. Emissions from energy use and internal vehicle traffic at the airport have through a series of measures decreased by 68% since 1990. LFV’s share of the airport’s total carbon dioxide emissions is about 2%.

Not all emissions from aviation operations are included in the emission cap. It is the operations during landing and start, i.e. traffic under 915 meters, usually named LTO-cycle, which is considered as part of the airport activities. The LTO-cycle is divided in phases corresponding to different thrust-settings. This is shown in the Figure 4 below.

This corresponds to around 10% of all the fuel filled at Arlanda. With a 10% bio-jet blend in the fuel distributed at Arlanda the reduction of CO₂ emissions from aircraft leaving the airport will be up to 150 000 tonnes per year (compared to 2008), depending on the CO₂ efficiency of the fuel production. To what extent LFV can take credit for this reduction in relation of the emission cape must be established in a discussion with the appropriate authority.

Strong indications for positive environmental effects regarding particle formation as well as reduced emissions containing sulphur, however to what extent is not clear. No negative environmental effects are expected, FT-fuel aimed for Diesel engines is assessed in a series of reports [10], [24], [25], [26] to be less toxic, to reduce the particle formation. However is not obvious that the NOₓ-production is reduced, a cleaner combustion could well lead to a small increase in NOx, although it is an involved question.

Figure 4. Figure of LTO cycle ICAO.
3.2.1 Fuel handling

Several actors are today involved in the distribution of Jet A-1 Fuel at Arlanda. The distribution system is modern, with train and pipeline as the basic transportation components. Handling is to a large extent automated in closed systems. Until a few years ago the fuel was transported on truck, which arrived twice hourly at the depot, a system less favourable from an environmental point of view. However, the truck terminals are still usable and could offer a solution if synthetic paraffin will be delivered for blending.

The distribution can be divided into two stages, first, the transport and storage of fuel, from the harbour of Gävle to the fuel deposit at Arlanda and the hydrant system in the airport and secondly the fuelling of aircraft at the airport. Several quality tests are made during the fuel transport, from ship to aircraft tank. As fuel properties may change during storage and transport these are monitored from the reception at the harbour until the delivery to the aircraft. The first test is a re-certification of the fuel as Jet A-1, with subsequent measurements of some properties as density, clarity, water content and conductivity.

To the harbour of Gävle the different fuel producers deliver Jet A-1 where it is stored and after re-certification loaded onto a train which twice daily transports 1300 m$^3$ fuel on 17 wagons to Brista, south of Arlanda where the fuel after a testing is unloaded into a pipeline and pumped to the Arlanda Fuel deposit in the south part of the airport. At the deposit the fuel is stored in one of four cisterns, each one holding up to 5000 m$^3$ fuel. From the cisterns it is later pumped into the hydrant system at the airport. This phase is essentially run by the fuel management company Arlanda Bränslehantering AB (AFAB) cooperatively owned six fuel producers, i.e. oil companies.

Fuelling of aircraft is then performed by fuelling trucks which connects the hydrant system with the aircraft, filtering and measuring the fuel as it is transferred to the aircraft tanks. In some cases fuel tank trucks are used when aircraft are parked in positions where the hydrant system is unavailable. Fuel trucks are also used when an aircraft need to be unloaded, due to repair or other technical reasons. The fuel can then be stored in special cisterns at AFAB. There are two fuelling companies at Arlanda, with three owners (fuel companies) each. The fuel from the different producers is mixed at AFAB who keeps a deposit balance for each company based on the fuel piped in and reports from the fuelling companies, who bills the aircraft operators on behalf of each fuel company.

3.2.2 Handling of alternative fuels

The new specification of synthetic kerosene requires blending batches of synthetic and conventional fuel components. If a bio-jet fuel is delivered to the harbour in Gävle there is no need for any change of adaption of the present distribution system of processes since it is already certified aviation fuel. However, if a solution is chosen where a synthetic component is delivered, possibly by truck, directly to AFAB, a blending procedure need to be developed and implemented at site.
At the AFAB deposit two 200 m$^3$, one 50 m$^3$ and one 30 m$^3$ cistern are available for different purposes. A proper handling can easily be implemented. If an FT-fuel component is produced in Brista a blending procedure with necessary equipment should be possible to install without problems.

Today all fuel, from the different suppliers, is mixed in the distribution system. It will not be different in the future and thus all aircraft will use the same blend of fuel. As today, the financial transactions between the suppliers and the users will not map directly against the actual fuel (molecules) delivered, but corresponding to volumes of fuel used. The Bio FT-Jet A-1 and conventional Jet A-1 fuel is technically equivalent but the right to account for reduced emissions in the future ETS [36] due to the use of Bio FT-Jet A-1 will be based on the contract with the fuel producer. This is not expected to meet any difficulties.

3.2.3 Fuel handling environmental permit

The fuel distribution consists of cisterns (both in Gävle and at AFAB), the Brista-Arlanda pipeline and the hydrant system. Each part may contain several thousands cubic meter fuel and therefore an environmental permit is needed for each part. The present environmental permits for the fuel distribution system are defined for petroleum products. Since the planned bio-jet fuel is not, an addendum to the permit is likely to be necessary. As such environmental permits sometimes take long handling time it is recommended that the process is started early.

3.3 Preemraff

Preem Petroleum AB is Sweden’s largest oil company with a refining capacity of more than 18 million tonnes crude oil per year. The Preem Group has two-thirds of the Swedish refinery capacity and comprises the whole chain from refining crude oil to distribution of end-products. There are two oil refineries, Preemraff Gothenburg and Preemraff Lysekil. About 65% of the production is exported outside Sweden.

The Preem two refineries are ranked as one of the top refineries in Europe in complexity and energy efficiency. The refinery process plants comprise the following main plants:

- Crude oil distillation
- Plants for desulphurisation of top fraction
- Reformer units for naphtha to petrol
- Plants for isomerisation of naphtha
- Plant for desulphurisation/dearomatisation of diesel and fuel oil
- Hydrocrackers
- Hydrogen plant
- Energy recovery units (for district heating)
- Sulphur recovery unit, and many more units.
Figure 5. Photo of Preemraff in Lysekil on the Swedish west coast. © Preemraff 2008.
4 Basis for Design

4.1 General principles and methodology

This technology documentation is limited to the information acquired within the scope of the study to detail the technical feasibility of a large scale bio-jet fuel plant. The basis have been data from process suppliers, in-house estimates and public information, which have been integrated in a best possible way according to experience gathered from many proprietary and industry studies.

The main technical objectives of the plant are to be biomass based fluidised bed gasification technology integrated with a physical gas cleaning and conditioning process and a slurry based synthesis plant, where the steam and power needs have been balanced with a biomass boiler plant. The design chosen is simple and robust to ensure competitive investment cost and high plant availability and reliability. Except for the biomass gasification technology which has not been demonstrated at large scale for synthesis gas production, only proven and commercially available technology has been incorporated in the chosen plant configuration.

For further background on the state-of-the-art in biomass gasification technology, which details the performance of different gasification concepts see these references [6],[7],[8],[13],[47],[54],[62],[63],[66],[72]. Some system studies of biorefineries have also been made which show the integration concepts and their characteristics and performances, see [14],[30],[31],[32],[33],[59].

The overall integration has been developed and configured by Nykomb Synergetics. Nykomb has calculated heat and material balances, with refinery upgrading balances provided by Preem, and in addition calculated the investment cost and production economics. The calculation basis has been a bio-jet fuel production of a minimum of 50 ktonnes per year, as this could qualify Arlanda Airport as a carbon dioxide neutral airport.

4.2 Principal plant configuration

Two locations of the plant were studied, with two different plant configurations. One plant alternative is to produce bio-jet fuel on site and another alternative to produce an intermediate product, a synthetic oil crude, which is called a Fischer-Tropsch [synthetic oil] product to be further refined and upgraded at a refinery.

Both plant alternatives can be termed a biorefinery as they will incorporate a multitude of products like power & heat and liquid fuels, also with option of process integration for steam export where applicable. Most important when locating the plant are securing fuel logistics and a nearby district heating network. However, the many choices put different constraints and therefore there is large number of variables in integrating the processes and no one best solution or optimum design can be found.
A block flow process scheme for dedicated bio-jet fuel production is shown below in Figure 6. The option to export power & heat is not shown. Several process technologies are available and depending on configuration the other processes need to be integrated to complete the energy balance with steam and electricity.

![Figure 6. Block flow diagram of the process configuration for a dedicated bio-jet fuel plant.](image)

The overall plant configuration comprises the following sections:

- Air separation with oxygen and nitrogen production and storage
- Fuel handling, fuel storage, and feed preparation with crushing, shredding, magnetic separation and drying
- Gasification with oxygen and steam, tar and methane reforming and cooling and gas filtering and wet scrubbing
- Deep gas cleaning, sulphur and carbon dioxide separation, CO shift conversion and gas conditioning
- Bio-jet fuel synthesis, gas compression, ATR, PSA, HPC and fuel distillation
- Power generation, steam raising and boiling feed water production in boiler and a steam turbine cycle.

4.3 Plant location

4.3.1 General

The bio-jet fuel plant is a multi task plant in respect that it is a biomass processing plant, an oil refinery and a plant for producing hot water for district heating. Each three tasks result in different requirements regarding where to locate the plant. The biomass processing plant should be located close to the biomass source as to keep biomass transportation costs low. The oil refinery plant should be located by the coast as refineries are mostly located by the coast to enable transportation of large volume oil products at low cost. The hot water producing plant should be located where it can connect to the district heat network piping.
District heat (DH) technology is a Swedish specialty where networks exist in all major cities. Within the Stockholm region the networks are expanding as the city is growing while outside the Stockholm region the networks are generally not expanding. This is explained by negligible population expansion and that the heat demand in the future is expected to decrease as warmer winters are expected due to global warming and that more energy efficient buildings are being built. Further, new and more efficient municipal waste treatment plants are being built where the heat from the plant is used as district heat.

Biomass is assumed to be purchased wherever costs and quality is favourable. In practical terms this means that both domestic and imported biomass is anticipated. Grot is believed to be most common and preferably chipped at source for a more cost efficient transportation. Logs may also be supplied which would then be chipped at the bio-jet fuel plant. The syncrude and the by-products are assumed to be processed at the Preem refinery close to Lysekil on the Swedish west coast. The refinery has good port facility. The refinery has no railway connection and road transportation is not favoured. For this project transportation by sea only is considered.

In the considerations for plant location, any operation resulting in commodities having to reload from one transportation means to another transportation means is avoided as reloading is strongly detrimental to economics. For the purpose of finding a land lot for the plant, the footprint is assumed to be a square of 500 x 350 meters. This is excluding the biomass storage. The biomass storage has to be viewed separately as supply logistics and storage strategy varies strongly with the site.

4.3.2 Biomass supply security

Biomass to the plant is assumed be purchased and transported to plant according to the lowest cost at plant principle. To maintain a competitive supply situation, biomass should be transported to the plant by two of the three transportation means; truck, railway or ship.

Biomass is preferably chipped at source. Normally chipping at source result in the most cost effective transportation as the material density becomes favourable and e.g. the chipped material is easy to load and dump from a truck. Alternatively non-chipped material such as logs and grot may be supplied and chipped at plant.

The plant gasifiers require chipped and dried biomass with chip size typically 3-5 cm. To secure a continuous feed of biomass to the gasifiers, each gasifier has a silo connected to the gasifier feeder. The silo has a 24 hour capacity. The purpose of the silo is twofold, one to act as buffer, second the silo allows a 24 hour respite for fixing any problem in biomass drying or the biomass conveyer systems.
Further, chipped material is stored in a roofed “pyramid” storage corresponding to one week operation. Further, the plant includes an outdoor storage for grot, logs and chipped material. This storage may serve as a strategic storage for cost for purchasing purpose or simply act as an extra supply security. The capacity and area requirement for the outdoor storage will have to be viewed in terms of the site specific needs. Sharing the storage with other biomass users in the area may bring down costs and a better utilisation of land area. Yet for additional operational security, storage of pellets may be maintained. Pellets can be fed directly into a loading pocket of the 24 h silo by a front loader.

### 4.3.3 Supply of regular jet fuel to Arlanda

For the basis of design it is very important to consider how the regular jet fuel is supplied today at Arlanda to make an easy integration. As described regular jet fuel to Arlanda arrives by ship to the oil harbour (oljehamnen) in Gävle. The fuel is discharged from the ship to tank storages and from there pumped to railway carriages for rail transportation to Brista which is located 6 km south-west of Arlanda airport. Arriving at the Brista terminal the jet fuel is simultaneously discharged from all carriages while pumped via pipeline to the airport where it is put in tank storage. Note there is no tank storage at Brista. However, the present certification requires batch blending of the FT-component and the conventional jet fuel.

### 4.3.4 Candidate sites

A number of locations were identified as possible sites for the bio-jet fuel plant whereof four sites were selected for deeper considerations. The four sites are Gävle, Brista, Lövsta and Igelsta as shown on the map in Figure 7 below and further described below.

![Figure 7. Arlanda and four candidate sites.](image-url)
Gävle has close access to the large forest areas of central and northern Sweden. This allows for low transportation costs of domestic biomass. Gävle has a district heat network of 700 GWh with a possibility to add 250 GWh by connecting the Sandviken city network to the Gävle network. About half of the heat today comes as waste heat from the Korsnäs pulp and paper mill east of Gävle city centre. Gävle has a good harbour with direct access to the Baltic Sea. The harbour has an oil terminal where the regular jet fuel to Arlanda arrives and is reloaded. Gävle is therefore a point for mixing the bio-jet fuel with the regular jet fuel. Land area for the 500 x 350 m plant footprint exists in the area around the oil terminal. The logistics of supply and off-take of commodities can be solved in a reasonable way.

Brista is located about 6 km south-west of the Arlanda airport. Existing key industrial activities at Brista includes the Fortum operated biomass fired CHP (Combined Heat and Power), a proposed waste CHP plant and the AFAB jet fuel terminal where the regular jet fuel arriving by train from Gävle is discharged and pumped by pipeline to Arlanda. All three facilities are within a 1 km radius. The existing Brista CHP plant produces about 730 GWh district heating which is fed to the Stockholm north-west DH network. This network is one of two major networks of Stockholm. The network is growing as the Stockholm city expands towards the north where the expansion of Arlanda airport and Arlanda Stad commercial centre are strong contributors to the growth. This implies that the north-west network will need more heat in the future.

Biomass to Brista CHP is today supplied by truck. But the terminal for jet fuel is also build to receive biomass which is done by discharging the biomass from train carriages to the opposite side of the tracks. The biomass supply to Brista CHP by rail is now under its start-up phase. Biomass supplies by rail will be preferred for the future. Another feature is that Brista is the second preferred place for mixing bio-jet fuel with the regular jet fuel as the fuel is discharged from rail carriages and pumped to the airport. Land area for the 500 x 350 m footprint is available. Brista has no access to harbour. The logistics of supply and off-take of commodities can be solved in a reasonable way although the site is suffering from no harbour so that oil by-products produced at the bio-jet fuel plant must first be loaded to railway carriages and then at Gävle discharged to storage tank and further loaded to ship for transportation to refinery.

At the other end of the Stockholm north-west DH network is the Fortum operated Hässelbyverket CHP plant. The plant is old and has no expansion capability while there is need for additional DH capacity as the Stockholm city is growing. About 3.5 km northwest of Hässelbyverket is a site named Lövsta, which earlier hosted a waste treating plant. This is now demolished and the area is a possible location for the bio-jet fuel plant. Heat produced by the plant would be pipelined to Hässelbyverket through a newly build connection.
The 500 x 350 m footprint is possible although with some constraints. Both Lövsta and Hässelbyverket are located by the shore of Lake Mälaren. Mälaren is connected to the Baltic Sea through the locks at Södertälje. These locks were built in 1920 with the objective to service the vessels sailing the Swedish coasts at that time. Today the locks are considered small, allowing vessels with maximum length of 135 m and 19 m width, which allows ships of about 5 000 DWT or about 10 000 DWT as barges, to pass the locks. This may not be an issue with the volumes of the oil related products but will certainly result in significant ship traffic if biomass would be supplied to Lövsta by ship. Lövsta has no railway connection. Logistics related to the supply and off-take of commodities can be solved but under some constraints.

Igelsta is a biomass fired CHP plant located at the north shore of the Södertälje canal downstream of the Södertälje locks. Igelsta has direct access to the Baltic Sea. The plant is operated by Söderenergi AB. The Igelsta plant is the major producer of district heating to the southern Stockholm DH network which is the second large DH network of Stockholm and with a capacity of about 1800 GWh. A newly build 265 MW (thermal) CHP block is currently under commissioning. Despite the newly built CHP block the heat produced by the bio-jet fuel plant can fit into future heat demand. Igelsta has no railway connection.

Biomass to Igelsta is supplied in two ways. One, biomass is supplied by trucks where the trucks are loaded at a biomass terminal at Nykvarn, 19.4 km west of Igelsta. The Nykvarn terminal receives biomass by railway. The second supply option is to take in biomass by ship. The ships comes from everywhere whenever cost becomes favourable, including occurred shipments from South America. Biomass storage capability at Igelsta is limited which makes it necessary with a sea shore biomass terminal to secure supply logistics. A terminal is in operation at Stora Vika about 20 nautical miles south of Igelsta. The 500 x 350 m land footprint requirement is possible adjacent to the newly built CHP block however with some constraints. Alternative land could be south of Hall prison or on the other side of the canal. All logistics related to supply and off-take of commodities can be solved in a reasonable way.

4.3.5 Evaluation of site alternatives

The evaluation procedure shall result in the selection of a most promising site for the plant producing bio-jet fuel on site (X-plant) and a most promising site for the plant producing the intermediate product (Y-plant). The X plant and the Y plant location shall not be the same. The selection shall be based on the outcome of an evaluation tool together with the subjective understanding of which site is best. A useful evaluation tool is to compute the differential costs for supply and off-take of commodities of each of the four sites. However, at this stage of the project the plant performance is not known. Hence the base for the costs for supply and off-take of commodities will have to be based on provisional performance numbers estimated from a provisional mass and heat balance shown in Figure 8 below.
Figure 8. Provisional mass and heat balance for site evaluation purpose

The definition of supply and off-take of commodities is shown in Figure 9 below.

<table>
<thead>
<tr>
<th>Supply</th>
<th>X-Plant</th>
<th>Y-Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>biomass</td>
<td>biomass</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Off-take</th>
<th>X-Plant</th>
<th>Y-Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>jet fuel</td>
<td>F-T product</td>
<td>district heat</td>
</tr>
<tr>
<td>by-products (*)</td>
<td>district heat</td>
<td></td>
</tr>
<tr>
<td>district heat</td>
<td>(*) naphtha, diesel fuel, waxes to be processed at refinery</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9. Commodity definition

The cost evaluation and a resulting order of precedence are shown respectively Figures show unique costs only, i.e. costs that apply identically to all the sites are not considered. Numbers are in MSEK/year. Note the comments below the Figures.

<table>
<thead>
<tr>
<th>X-PLANT</th>
<th>GÄVLE</th>
<th>BRISTA</th>
<th>LÖVSTA</th>
<th>IGELSTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply biomass</td>
<td>truck</td>
<td>-41.6</td>
<td>-33.8 (50%)</td>
<td>-41.6 (50%)</td>
</tr>
<tr>
<td></td>
<td>railroad</td>
<td>-48.7 (50%)</td>
<td></td>
<td>-48.7 (50%)</td>
</tr>
<tr>
<td></td>
<td>ship</td>
<td>-40.8 (60%)</td>
<td>-26.0 (60%)</td>
<td></td>
</tr>
<tr>
<td>Off-take jet fuel</td>
<td>truck</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>railroad</td>
<td></td>
<td>-2.3</td>
<td>-2.3</td>
</tr>
<tr>
<td></td>
<td>ship</td>
<td></td>
<td>-2.5</td>
<td>-2.5</td>
</tr>
<tr>
<td>byproducts truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>railroad</td>
<td></td>
<td>-3.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ship</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>storage</td>
<td></td>
<td>-0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lake traffic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>district heat (pipeline)</td>
<td>49.5</td>
<td>99.0</td>
<td>99.0</td>
</tr>
<tr>
<td>Net revenues</td>
<td>7.9</td>
<td>13.5</td>
<td>8.1</td>
<td>6.7</td>
</tr>
<tr>
<td>Order of precedence</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 10. X-Plant order of precedence
Comments to Tables above:

- Cost for biomass is assumed to be the same to all cases.
- Biomass pick-up distance by truck is: Gävle 50 km, Brista 100 km, Lövsta 130 km and Igelsta 19.4 km (from Nykvarn).
- “(50 %)” indicates that half of the biomass is assumed to be transported by this means while the other half is by the other means. The railway cost and truck costs are combined as both means are required for supplying biomass to Igelsta.
- Transportation by truck is assumed with a 42 tonne vehicle. Loading and discharging a truck is assumed as a cost of 15 SEK/tonne. Transport cost is assumed as 0.5 SEK/tonne, km.
- Transportation by railway is assumed to be a 17 carriages train set. Loading and discharging is 85 SEK/tonne. Transport is 0.06 SEK/tonne, km. Biomass transportation distance by railway is: Brista 100 km, Igelsta 100 km (to Nykvarn)
- Transportation by ship is 50 SEK/tonne and that nautical mile costs is negligible.
- Cost for ship transportation from the east coast to the refinery at the west coast is assumed to be equal to all cases.
- District heat is assumed as: Gävle 275 GWh, Brista, Lövsta and Igelsta 550 GWh with a credit of 180 SEK/MWh [44] as general contribution cost.

In conclusion, the results of the precedence order comply with the general understanding that Brista and Igelsta respectively are the sites to be considered for continuation work. The X-plant with full production of bio-jet fuel is therefore termed the Brista plant in this study and respectively the Y-plant as the Igelsta plant for production of the intermediate FT-product.
5 Process description

5.1 Introduction

The fuel plant is designed for gasification of biomass producing a synthesis gas to be synthesised into a Fischer-Tropsch product with recovery of low-grade heat for industrial and district heat use. The plant will consist of the following process islands:

- Air separation plant: Oxygen and nitrogen production with supply and storage
- Biomass gasification plant: Feedstock handling, preparation, storage, drying, feed mechanism, gasification, reforming, gas cooling, gas cleanup
- Gas cleaning and conditioning plant: Gas compression, gas clean-up with shift and sulphur and CO\textsubscript{2} separation
- Fischer-Tropsch synthesis plant: Compression, Fischer-Tropsch synthesis, ATR, PSA, HPC and distillation, storage and tank station
- Power and steam system plant: Steam turbine and gas/biomass boiler with combined heat and power production, BFW, steam and cooling water system.

Note the difference in the Fischer-Tropsch plant of the Brista and the Igelsta plants, where the Igelsta plant does not include the PSA, HPC and distillation processes. Simplified process flow diagrams of the units for the two plants are shown below.

Figure 12. Simplified process flow diagram of Brista plant. © Nykomb Synergetics 2009.
5.2 Air separation plant

The Air Separation Unit (ASU) has the purpose to provide the plant with oxygen and nitrogen gases. ASU’s can operate according to different air separation technologies such as cryogenic, PSA, VSA, etc. For this plant the cryogenic ASU is chosen as it will be most cost-effective with respect to the plant size and the service it shall provide. Cryogenic ASU’s can be procured as standardized units by several competing vendors.

To supply the required quantity of oxygen with a high purity, a simple cryogenic air fractionation process will be provided. The process consists of the following features:

- Compression of process air utilising a combined main and booster air compressor
- Pre-cooling of air utilising a direct process cooler and an evaporative cooler
- Air purification by molecular sieves
- Double rectification column with sieve trays in pressure part and packings in the low pressure part
- Expansion turbine system with oil brake
- Internal compression by liquid pumping and evaporation (redundant pumps).
There is a slight modification to the standard ASU preferred for the plant. In the typical cryogenic ASU, air compression is done by two air compressors, a main compressor and a booster compressor. Both compressors are cooled by an air cooler outside the compressor building. However, the temperature rise by compression is in excess of 120 °C. This allows a portion of the compression heat to be extracted as district heat. The proposed modification is that the main compressor shall comprise of two cooling sections, a district heat cooler and a final cooler respectively. The proposed compressor design is shown in Figure 14 below. With standard ambient air (15 °C and 1013 hPa), the portion of heat for district heating is approximately equal to the portion requiring final cooling.

![Figure 14. ASU compressor.](image)

### 5.3 Biomass gasification plant

#### 5.3.1 Biomass handling

The biomass feed can be transported to the plant by railway, sea and road depending on location. In this report, two locations are investigated, which is described above, with different conditions. Most biomass fuel today in Sweden is transported by truck and will be here described. However, there is a growing market with fuels transported by ship and train and we believe that there are cost-benefits to be gained for a developed biomass market.

A normal procedure for receiving fuel is as follows. When the truck enters the plant gates the truck passes through a weighing station, where the load weight is determined by weighing the truck before and after unloading. Random sampling is carried out in order to check fuel quality in terms of composition, specific heat content, particulate distribution, and moisture content.
The primary storage for the fuel feed is roofed and a reserve large storage is outdoors. Conveyers or front loaders then transport the fuel to the intake of the gasifier building. The front loader operator is tasked with assuring an adequate distribution and a visual inspection of the storage volumes. The storage piles have to be managed to avoid self-ignition. An off-site buffer storage area may be used for periods of gasifier plant shut down.

A magnetic separator monitoring the conveyer belt flows will assure that any magnetic metal objects in the fuel are removed prior to processing of the fuel feed in a crusher. The crusher sizes the fuel in pieces on average 30-50 mm, not exceeding 100 mm, for the feed mechanism. The crushed fuel, before drying, will be transported by a conveyer to the roofed storage and further to the gasifier unit with its drier and day storage silo.

### 5.3.2 Biomass drying

The received biomass is dried as to improve performance of gasification and combustion. Drying is heat consuming as the moisture in the wood chips are evaporated by contact with warm air. As a rule of thumb one tonne of water is removed by one MWh of heat. There are advanced drying technologies under development which allows part of the latent heat to be recovered. An ongoing development is claiming removing 2.2 tonne water / MWh heat. Once this technology is proven it can be incorporated into the plant. This will save heat which can then be available for district heating.

For this project a belt drying system with a simple evaporative process is chosen. This is a proven technology and fits well a plant treating large biomass volumes. The process is shown in Figure 15 below.

![Figure 15. Drying process.](image-url)
Biomass with a moisture content (MC) of 50 % enters the dryer, 1. Ambient air, 3, is heated to 90 °C before drying, 4. The warm and dry air picks up biomass moisture in that the air exiting the dryer, 5, has 90 % RH. The dried biomass, 2, exits the dryer with MC of 20 %. The estimated performance per tonne received biomass is shown in Figure 16 below.

<table>
<thead>
<tr>
<th>Biomass as received</th>
<th>MC 50 %</th>
<th>6 °C</th>
<th>1.00 ton/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dried biomass</td>
<td>MC 20%</td>
<td>25 °C</td>
<td>0.62 ton/h</td>
</tr>
<tr>
<td>Removed water</td>
<td></td>
<td></td>
<td>0.38 ton/h</td>
</tr>
<tr>
<td>Ambient air</td>
<td>74% RH</td>
<td>6 °C</td>
<td>0.41 m³/s</td>
</tr>
<tr>
<td>Vented air</td>
<td>90% RH</td>
<td>45 °C</td>
<td>1.50 m³/s</td>
</tr>
<tr>
<td>Heat requirement</td>
<td></td>
<td></td>
<td>364 kW</td>
</tr>
<tr>
<td>- whereoff latent heat</td>
<td></td>
<td></td>
<td>265 kW</td>
</tr>
<tr>
<td>- whereoff sensible heat</td>
<td></td>
<td></td>
<td>120 kW</td>
</tr>
</tbody>
</table>

Figure 16. Dryer performance.

5.3.3 Gasification process

The dry feed will be transported to the feed mechanism for the gasifier reactor unit. The reactor unit includes four separate vessels: Feed vessel, two parallel lock hoppers, and a reactor input vessel. The lock hoppers are filled and pressurised on an oscillating basis through valves and will send the feed on to the reactor input vessel, which is connected to the reactor.

The gasification system consists of the gasifier reactor, cyclone, start-up heater and the oxygen/steam/recycle gas feeding system. The function of the gasifier is to convert solid feedstock to product gas of quality suitable for fuel synthesis using oxygen, recycle gas and steam as gasification media. The gasifier is a pressurized fluidized bed gasification system, e.g. supplied from Andritz/Carbona.

The feedstock is fed into the gasifier, where it de-volatilizes and the remainder of char is gasified and partly burnt to maintain sufficient gasification temperature. The product gas contains:

- Main combustible components: CO and H₂
- Inert components: N₂, CO₂ and H₂O
- Contaminants: CH₄, H₂S, COS, NH₃, HCN, HCl and vapour phase alkalis.

The raw gas leaving the gasifier cyclone also contains fine entrained solid particles as contaminant. The gasifier reactor accommodates the fluidized bed and the freeboard area. The fluidized bed contains char, ash and dolomite. The disengaging/freeboard area is a suspension of char and ash elutriated from the fluidized bed.
The bulk of the entrained particulate matter from the gasifier is separated from the raw
gas flow in a cyclone separator. The cyclone has to be efficient enough to keep dust
concentration below a level acceptable for tar reformer. The separated dust is returned
through the cyclone dip leg to the fluidized bed where the returned carbon will further
be gasified.

The gasifier ash discharge system removes and cools the discharged solids (bed material
consisting dolomite and fuel ash) from the gasifier at system pressure and high
temperature. The solids removal applied in this case is dry removal based on water-
cooled cooling screw and lock-hoppers. The cooling screw and related equipment are
cooled by medium pressure cooling water.

Fuel is fed into the lower section of the bed where rapid drying, flashing of volatiles,
and gasification takes place. The gasifier works at 10-20 bar pressure and 850-950 °C.
The syngas obtained from the biomass fuel contains carbon monoxide, hydrogen,
methane as combustible components, and carbon dioxide and water vapour as inert
components. In the gasifier reactor, heating, pyrolysis, combustion, and gasification
take place in a very complex reaction pattern. Schematically, all reactions may be
summarised as reactions (1) – (5):

\[
\begin{align*}
&\text{C} + \text{O}_2 \rightarrow \text{CO}_2 \quad (1) \\
&\text{C} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO} \quad (2) \\
&\text{C} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO} \quad (3) \\
&\text{C} + \text{CO}_2 \rightarrow 2 \text{CO} \quad (4) \\
&\text{C} + 2 \text{H}_2 \rightarrow \text{CH}_4 \quad (5)
\end{align*}
\]

5.3.4 Gas reforming, cooling and cleaning

In order to combat tar and methane which needs to be minimized to enhance the process
yield a gas reformer is installed. The reformer system decomposes methane and tars and
heavy hydrocarbons into hydrogen (H\textsubscript{2}) and carbon monoxide (CO) in a catalytic
reaction, also to avoid tar condensation in the down stream process equipment.
Depending on catalyst type ammonia can also be partly decomposed in the tar reformer.
Tar reformer is a refractory lined vessel, which accommodates catalyst blocks. Noble
metal or nickel-enhanced catalyst is applied to decompose tars and ammonia in product
gas. The catalyst blocks are cleaned from dust by CO\textsubscript{2} blowback.

There are some relevant studies that detail more the tar problem, see [12], [64], [71].The
hot product gas leaving the reformer is then cooled in a multi-step cooling system. The
function of the gas cooler is to cool hot product gas down to the temperature level
required by the gas filter, i.e. to 250 °C. The first section of the gas cooling system is a
steam generator followed by a super heater and feed water preheater. The gas cooler
generates high-pressure steam, which is used in the steam plant to generate power.
The product gas is filtered at 250 °C after the first section of the gas cooling. The gas-filtering unit includes metal filter candles and a pulsing counter-current system with nitrogen. The filter ash is extracted from the bottom of the pressure vessel into a filter ash silo. After the filter the product gas may also be flared. Flaring will be used at start-up and shutdown and in emergency situations.

Cooling and scrubbing systems include a water-cooled heat exchanger and a pressurised water scrubber. Water is used in the scrubber to wash and cool the gas to 40 °C. The scrubber water (process water) is of cooling water grade and the process water is purified in a separate loop. The scrubbed gas is then led to the shift reactor. The gas cooler is a heavy-duty heat exchanger for cooling high temperature, dust laden and corrosive gases.

5.3.5 Utility gases

The gasifier will use carbon dioxide for inertisation of the storage silos for the dry fuel, for fuel input, and for ash discharge systems. The carbon dioxide will be taken from the exit stream of the CO₂ separation unit, but storage will be within the gasifier unit. The gasifier unit will have additional availability of nitrogen from the ASU for the fuel feed system and for the cleaning of filters.

Pressurised carbon dioxide and nitrogen is brought into the gasifier vessel from a gas system, including high pressure compression and additional storage for emergency situations. Oxygen will be used for gasification and also for the syngas reforming process. Oxygen will be delivered at the required pressure piped from the ASU to the process units.

5.4 Gas cleaning and conditioning plant

5.4.1 Overall description

For the downstream Fischer-Tropsch synthesis process there are very high requirements on the gas, where it needs to be removed of virtually all sulphur compounds (<1 ppm) and other contaminants. This is mainly because of risk of catalyst poisoning. In addition, the gas needs to be of optimum stoichiometric ratio of H₂ and CO, which can be done with a water-gas shift converter. Stochiometrically, the volume relationship between hydrogen and carbon monoxide must satisfy the following relation (1) in order for the synthesis to have the best possible efficiency.

\[
\frac{H_2}{CO} = 2.0-2.1
\]  (1)
This \( \text{H}_2/\text{CO} \) ratio gives the maximum conversion of syngas per pass since it equals the usage ratio over the catalyst inside the reactor, in case of a Co-based catalyst. Hence, an optimum synthesis gas gives a better product yield and lower production costs, which is very important because of the high specific investment costs on the processes. Thus, there is a need to clean and condition the gas and there are multiple ways on how to configure and choose different processes to meet the demands.

There are basically two gas cleaning processes to choose from, chemical and physical gas washes. For a synthesis process with stringent demands on the feed gas, it is vital to choose a gas wash process which can meet all cleaning targets by far and has a proven operation track record. The Rectisol gas process was chosen as it is one of the most selected processes for syngas production with chemical synthesis and executes possibly the highest cleaning performance found, in this type of system.

In this process plant there are essentially four processes, first gas wash, shift converter, second wash and then a regeneration section.

### 5.4.2 Rectisol process, first wash unit

The Rectisol process is very flexible and can be configured depending on the final products that are desired from the gas. The actual layouts of the process can vary considerably and specific designs can only be obtained from process licensors.

The process is as follows, from the gasification island, the cooled gas is further compressed in a two-stage gas compressor and fed to the first Rectisol wash unit, having a temperature of around 30°C. The Rectisol unit is a physical wash using methanol as absorbent. In the process, \( \text{H}_2\text{S}/\text{CO}_2 \) are removed selectively. Absorption of acid gases takes place at around -40°C.

A pre-wash stage is included as additional safeguarding step to remove water, small amount of tars (mainly naphthalene), benzene or other condensable compounds from the raw gas, before entering the first absorption column in order to avoid clogging of the equipment. The contaminated methanol from the pre-wash is regenerated separately from the main methanol stream, by using extraction and decanting.

The cooled and pre-treated gas from the pre-wash section is fed to an absorber column tower, the first gas wash unit, where it is washed in a counter current with methanol. The \( \text{H}_2\text{S} \) in this section is completely removed together with the other sulphur compounds (\( \text{H}_2\text{S} + \text{CO}_2 <0.1 \text{ ppm} \)). The \( \text{CO}_2 \) content is simultaneously reduced by contact with lean methanol at 40°C. The \( \text{H}_2\text{S} \) and \( \text{CO}_2 \) loaded methanol streams are expanded and dissolved syngas is released, compressed, cooled and recycled to the first absorption column.
5.4.3 CO shift conversion

In order to achieve an optimum composition of the gas for the synthesis, the ratio of hydrogen to carbon monoxide has to be adjusted. In order to increase the hydrogen content in the raw syngas, it is brought to a shift reactor where carbon monoxide reacts over a sulphur-tolerant catalyst with steam to form hydrogen and carbon monoxide as per below (1).

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2 \quad (1)
\]

Thus, between the two Rectisol wash units a shift reactor is placed. The reactor starts at 225 °C and is exothermic. This means that the temperature of the gas when it leaves the shift reactor has increased to about 410 °C. The outgoing gas stream is heat exchanged against the incoming gas stream in order to increase the temperature to the required 225 °C. Since a part of the carbon monoxide can be reformed, a part of the stream is bypassed and mixed with the outgoing shifted gas. The treated gas is brought to the carbon dioxide separation absorber.

The CO shift catalyst is of a conventional iron and chromium oxide catalyst, operating at 320-340 °C inlet temperature [46]. The reactor is adiabatic and the released reaction heat results in a temperature increase, to be recovered as LP steam. IP steam is injected to the stream entering the shift reactor to heat the gas and add the required steam for the water gas shift reaction. The inlet temperature is around 300 °C by heating with steam as well as heat exchange with the outgoing product gas. Produced LP steam and additional district heating is exported to the steam plant. The final cooling is achieved by cooling water down to 30 °C.

5.4.4 Second wash unit and regeneration

The cooled gas from the CO shift, free of sulphur, is fed to a second CO\(_2\) wash section. The gas is fed to the second absorption column and contacted with lean methanol from the hot regeneration section. The treated gas from the CO\(_2\) wash section is mixed with the bypass stream and the total mixed gas is the product syngas of the Rectisol plant to be sent to the synthesis plant.

H\(_2\)S and CO\(_2\) wash sections have a common regeneration section. A pre-wash system for heavy hydrocarbon removal is required only for the H\(_2\)S wash. The hydrocarbon compounds are extracted and purged in a liquid hydrocarbon stream. The small amounts of separated compounds are burnt in the boiler to recover the heat. To increase the H\(_2\)S content in the sour gas fraction and to decrease the refrigeration demand, CO\(_2\) is stripped by gaseous nitrogen to also recover the heat of solution.
The sulphur compounds are released in the hot regeneration section, by heating with LP steam. The sour gas is not sufficiently high in sulphur volumes to justify a sulphur recovery plant. As the requirement on sulphur considered with respect to the national legislation can be fulfilled with co-combustion this stream is taken to the biomass boiler along with other off gases. The levels of sulphur in the stack are well below what is stipulated by legislation.

5.5 Fischer-Tropsch synthesis plant

5.5.1 Fischer-Tropsch synthesis

The German chemists Franz Fischer and Hans Tropsch discovered the Fischer-Tropsch (FT) process in the 1920’s. The FT process is the synthesis of long-chain hydrocarbons from syngas (H\(_2\) and CO) according to:

\[
\text{CO} + 2\text{H}_2 \rightarrow \text{\text“-CH}_2\text{“} + \text{H}_2\text{O} \quad (1)
\]

The chain growth reaction takes place on the surface of a heterogeneous catalyst. The polymerisation mechanism results in a product mixture of \(C_{1+}\), which means that lower hydrocarbons, such as \(\text{CH}_4\) and LPG, always will be produced as by-products. The major products are un-branched saturated hydrocarbons, paraffins, but some olefins are also produced, especially among the lower hydrocarbons. The major olefins are terminal olefins. Among the saturated products, straight-chain paraffins and some 2-methyl-branched paraffins dominate. Primary alcohols are usually the major oxygenated products.

The conventional catalysts are either iron- or cobalt-based. Temperature, pressure, \(\text{H}_2/\text{CO}\) ratio and catalyst determine whether a light or a heavy syncrude is produced. Generally, heavier products are favoured by a high pressure and a low temperature. The ideal molar proportion of \(\text{H}_2/\text{CO}\) is about 2 for a Co catalyst. Only at this ratio a theoretical syngas conversion of 100 % is possible, since the syngas ratio is equal to the usage ratio over the catalyst according to reaction (1).

The product distribution for the Fischer-Tropsch synthesis is generally simplified by the ASF (Anderson-Schulz-Flory) model, where \(\alpha\), the chain growth probability factor, is assumed to be independent of chain length. For maximum yield of FT-diesel, \(\alpha\) should be as high as possible. The synthetic fuels produced via the Fischer-Tropsch synthesis will need certain modifications and improvements before they can be used as jet fuel, i.e. meet same specifications as petroleum based Jet A-1, and diesel. There are currently two FT operating modes [29], [80]:

- High-temperature FT (HTFT): 300-350 °C, Fe-based catalysts, production of gasoline and linear low molecular mass olefines. Significant amounts of oxygenates are also produced. Diesel may be produced by oligomerization of the olefins.
- Low-temperature FT (LTFT): 200-240 °C, either Fe- or Co-based catalysts, production of high amounts of paraffins and linear products and the selectivity to high molecular mass linear waxes can be very high. The primary diesel cut and the hydrocracking of the waxes yield excellent diesel fuels. The primary gasoline cut needs further treatment to obtain a high octane number.

A Co catalyst is chosen because it has a high FT-activity, a high selectivity to linear paraffins, a high resistance towards deactivation and because it can operate at high syngas conversion levels compared to Fe-based catalysts. The catalyst is assumed to consist of 20 wt % Co and 80 wt % support material (for instance Al₂O₃ or MgO). Thus, to produce kerosene and diesel and other straight-chained hydrocarbons, the Low Temperature Fischer-Tropsch (LTFT) process is the most preferable.

The reaction occurs in a slurry phase reactor (SPR) or in a tubular fixed-bed reactor (TFBR) using Co catalyst. It is optimised towards maximum wax production, since it is commonly accepted that the highest FT diesel yield is achieved by producing waxes, which then are hydrocracked into the diesel fraction [29]. For further detailed information of the FT process and the performance in a biorefinery with biomass gasification, see these studies, also as benchmarking for other process concepts [17], [45], [74].

The FT reactions are highly exothermic why it is very important to rapidly remove the heat from the catalyst particles in order to avoid deactivation, due to sintering and coking, and to avoid high formation of undesirable methane [29]. Thus, the removal of the heat of reaction, ca. 25 % of the calorific value of the syngas, is probably the major problem in practical applications of the FT synthesis [80]. The better the isothermicity of a FT-reactor, the higher the average temperature in the reactor can be and hence the higher the production rate per gram of catalyst [69].

A SPR is chosen since it is simple, has good mixing abilities and allows for a relatively high reaction temperature, due to a close to isothermal operation that prevents hotspots. Therefore, the SPR enables higher reaction rates per gram of catalyst compared to the TFBR which has a poorer temperature control. In an SPR it is also easier to regenerate the catalyst and the pressure drop is lower. Statoil recently set up a FT pilot plant in South Africa with a Co-based catalyst in an SPR.

First, the process gas is passed over a desulphurisation guard bed since the catalyst is highly sensitive to poisoning. This is an extra safety measure, which is preferred, but not always the case for commercial plants. This depends on the very high reliability on the upstream wash unit. To secure the catalyst also under transient conditions, a guard bed may be installed but is really an additional safety measure that may be omitted in a well-designed plant.
Then, syngas is fed to the bottom of the SPR reactor. The bubbles rise up through the column, passing the liquid phase in which the catalyst particles are suspended. The most common catalyst for this type of reactor is the Co-based supported catalyst. The lighter hydrocarbon products are gaseous and continue to rise through the column together with the unreacted syngas. At the top of the column the gaseous product are taken out.

As shown in Figure 17 below, in the FT-reactor hydrocarbons are produced from the syngas. Indicatively, after the FT-reactor, the heavier hydrocarbons ($C_{16+}$) are sent to as FT-product to a refinery (the Igelsta plant) or the HPC (heavy paraffin conversion) unit for upgrading (cracking and isomerisation), and then separated in different fractions in the distillation column (the Brista plant).

The lighter fractions from the FT-reactor ($C_1$–$C_{15}$) are sent to a three phase separator, where water and $C_5$–$C_{15}$ are condensed. The $C_5$–$C_{15}$ fraction is separated from the water and sent to the HPC. The $C_1$–$C_4$ fraction out from the three-phase separator is used for the $H_2$-production needed for the HPC. Part of the gases (purge gas) produced in the $H_2$-production unit is sent to the biomass boiler to be combusted. To increase the yield of the process, some of the gases out from the $H_2$-production unit are recirculated back to the FT-reactor.

---

**Figure 17.** A block flow diagram of the process, where the Brista plant has in addition to the Igelsta plant a PSA plant, a Heavy Paraffin Conversion unit and a Distillation unit.
5.5.2 Auto-Thermal Reforming

As mentioned above, hydrogen needed for the hydrocracking of the FT waxes in the HPC unit are produced by reforming of the light gases C1-C4 from the FT-reactor. As also CO will be produced in the reforming process, this CO and part of the H2 are recycled back to the FT-reactor in order to increase the yield to heavier FT products. There are different kinds of reforming processes, for example steam reforming (SR), partial oxidation (POX) and auto-thermal reforming (ATR). A separate POX could be chosen as it is robust and less complex than an ATR, however, much oxygen is needed and lot of valuable syngas energy is converted to heat [55]. Therefore, an ATR from was chosen in this study.

The Auto-Thermal Reforming (ATR) unit is a stand-alone process, in which the entire hydrocarbon conversion is completed in a single reactor based on a combination of partial oxidation and adiabatic steam reforming. The reactor features a refractory-lined pressure vessel with a burner, a conical combustion zone, and a catalyst bed [16], [41].

Unlike the tubular steam reformer, no pressure-bearing or high-alloy internals are required, and catalyst loading and unloading is straight forward and fast. The burner is the key element in the ATR. It mixes the hydrocarbon and oxidant feed-stocks, and by internal combustion in the flame, heat is provided for conversion of the hydrocarbons. Careful design of the burner nozzle is required to ensure a flow pattern which both mixes efficiently and protects the refractory and burner itself from the hot flame core.

High pressure steam is generated when cooling the ATR effluent. The ATR is capable of operating without carbon formation at a much lower steam to carbon ratio than tubular steam reforming, hence, the HP steam generated by the cooling of the ATR effluent is sufficient both for process steam for steam consuming units and for power generation in a steam extraction high pressure steam turbine.

5.5.3 Brista plant, FT-product upgrading

In 1989, Shell and partners announced the building of a commercial Shell Middle Distillate Synthesis (SMDS) plant in Bintulu (Malaysia) for the conversion of natural gas into transportation fuels. The capacity of the plant is ca. 500 000 tonnes per year of HCs from remote natural gas reserves [80]. The SMDS process involves three steps: syngas manufacture, Heavy Paraffin Synthesis (HPS) via FT, and Heavy Paraffin Conversion (HPC). The products, mainly kerosene, gas oil and naphtha are separated by distillation.

The HPS follows the ASF polymerization kinetics. Shell uses a proprietary Co-based catalyst probably promoted with Ru or Re. The desired product is a long-chain HC wax (large α is wanted). The reactor is a fixed bed one. The catalyst has a life-time of over one year, and is regenerable [80]. The gaseous products with boiling points above that of the gas oil are recycled to the HPC reactor.
The selectivity is dependent on the process severity and on the conversion per pass. The theoretical maximum thermal efficiency for methane conversion to linear HCs, based on LHV, is 78%. Wender stated in his review from 1996 that the Shell plant would work at 65% thermal efficiency. Both the kerosene and the gas oil meet all relevant specifications.

Hydrocracking is a catalytic oil refinery process where heavy gas oils and vacuum gas oils are converted into lighter products, for example naphtha, kerosene and diesel oil. The process involves the cracking of a relatively heavy oil fraction into lighter products, during which C–C bond breaking takes place, in the presence of hydrogen. Hydrocracking can be viewed as a combination of hydrogenation and catalytic cracking, and the overall hydrocracking process is exothermic. The hydrogenation requires a hydrogenation catalyst, while the cracking reactions precede via carbenium-ions and therefore require an acidic catalyst [60].

Isomerisation is another catalytic oil refinery process which involves rearrangement of the atoms within the hydrocarbon molecules. The most important reaction in the isomerisation plant is branching of straight hydrocarbons to increase the octane number. Isomerisation processes of practical significance in petroleum chemistry are migration of alkyl groups, shift of a single-carbon bond in naphthenes and double-bond shift in olefins. Hydroisomerisation is needed for better cold-flow properties.

For the sake of upgrading FT-products, the choice of process in the current study is the HPC process developed by Shell and used as a part of their SMDS. In a HPC-unit, hydrocracking and isomerisation are combined over a dual-function catalyst. The long, waxy components in the hydrocarbon-mixture are hydrocracked selectively to the desired products. Simultaneously, isomerisation occurs to some extent to improve the cold flow properties of the product [70]. The operating pressure in the HPC is 25-35 bar and the temperature is 350 °C. A suitable catalyst for this process is a 3 wt % platinum catalyst on an alumina-silica support [9].

The products are then brought into a distillation unit where mainly the boiling point ranges is governing different cuts into two products, naphtha and kerosene bio-jet fuel where remaining heavy wax products are recycled back to the HPC unit.

The HPC unit needs hydrogen and therefore we need to incorporate a process that can extract pure hydrogen. The Pressure Swing Adsorption (PSA) fits very well with the objective to purify hydrogen from a gas stream. The PSA process is based on the principle that adsorbents are capable of adsorbing more impurities at a higher gas-phase partial pressure than at a lower partial pressure. Impurities, such as carbon monoxide and hydrocarbons, are adsorbed in a fixed-bed adsorber at high pressure and then rejected as the system pressure “swings” to a lower level. The hydrogen is not adsorbed.
The Polybed PSA process operates at ambient temperature and is a semi batch process that uses multiple adsorbers to provide constant feed, product and off gas flows. When an adsorber has reached its adsorption capacity, it is taken off-line, and the feed is automatically switched to a fresh adsorber. The hydrogen product leaves the system close to the feed gas pressure. The off gas (impurities and the hydrogen losses) is available at low pressure as fuel.

A hydrogen product with very high (>99.9 vol-%) purity can be produced because of the almost complete adsorption of the impurities. The high purity is, however, achieved at the cost of a lower hydrogen yield (about 80%).

5.5.4 *Igelsta plant, FT-product upgrading at refinery*

The FT-product can from this location be transported by truck or by ship. For both ways of transport the FT-product needs to be warmed in that it stays fluid and can be pumped from and to the transporter. With import to the refinery, the FT-product will be stored in a dedicated storage tank to control the share of FT in co-processing. The FT-product is some 192 000 tonnes per year, which is a small amount compare to the total imports to the Preem refinery of maximum 11.4 million tonnes. The refinery will be run in block operation, with and without FT product.

![Simplified flow diagram of the refinery upgrading process at the refinery.](figure18)

Together with crude oil FT-product is co-processed in a crude and vacuum distillation unit. FT-product and crude oil are heated up and distilled in two steps, first 370 °C and just over 1 bar, and then the heaviest part is distilled at 410 °C and around 15 mmHg. The separation gives six fractions: fuel gas, naphtha, kerosene, heavy diesel oil, vacuum gas oil (VGO) and heavy fuel oil. FT-product ends up mainly in vacuum gas oil and lighter.
VGO is led to the hydrocracker unit. The VGO is hydrocracked to reduce the chain length. The hydrocracking tends to reduce all of the hydrocarbons in the feed. When the feed includes hydrocarbons that are already in a desired range, for example, the distillate fuel range, hydrocracking of these hydrocarbons is undesirable. Therefore FT product is distilled before hydrocracking.

VGO is preheated, filtered and pumped to the reactor system pressure (150 bar). VGO is then mixed with hydrogen, further preheated to around 380 °C and sent to the reactors. The reaction section contains one reaction stage in a single high pressure loop. The hydrotreating and hydrocracking reactions taking place in the reaction stage occur at high temperature and pressure. A high hydrogen partial pressure is required to promote the hydrocracking reactions and to prevent coking of the catalyst. An excess of hydrogen is recirculated in the reactor loop for reactor cooling, to maintain a high hydrogen partial pressure, and to ensure even flow distribution in the reactors.

In the first reactor, fresh feed is partially converted to product. Sulphur and nitrogen are also removed and aromatic content is reduced. In the second reactor, the feed is further hydrocracked to produce the desired products. The cracked products from the reactors are recovered in the fractionation section.

The reaction section contains additional equipment for separation of hydrogen-rich gas from the reactor effluent. The gas is compressed and recycled back through the high pressure reactor loop. The purpose of the fractionation section is to separate reaction section products into fuel gas, naphtha, kerosene, diesel and unconverted oil (UCO).

The make-up hydrogen compression section consists of three identical parallel reciprocating compressor trains, each with three stages of compression. During normal operation two trains are in use and compress make up hydrogen from offplot to the hydrocracker reaction section pressure. The hydrogen is combined with hydrogen recycle gas in the hydrocracker reaction section to form reactor feed gas.

Kerosene from distillation unit and from hydrocracker is blended to jet quality into ships and sent to airports. Hydrotreated kerosene is blended in case of problem to meet the jet specification. Butane and lighter from the FT-product itself and from the hydrocracker is assumed to be used as fuel in the distillation process and in the hydrocracker.

### 5.6 Power and steam system plant

Note the description of the steam system, steam turbine and boiler below refers to the Brista plant. The Brista plant comprises of the complete set of process units. The Igelsta plant is simplified as it produces only syncrude FT-product and thereby excludes the HPC, the PSA, the fuel distillation and associated systems. Details about the steam system for the Brista plant and Igelsta plant are provided in the Simplified steam scheme in respective Figure 19 and Figure 20.
The plant process produces and consumes steam. For an energy efficient handling of the steam, three steam headers at three pressure levels are required. The steam headers not only connect steam producers and consumers in the plant but are also part of a boiler and a steam turbine system, allowing production of electric power and district heat in an efficient way.

The three steam headers are nominated HP, MP, and LP steam. The pressure levels of the three steam headers are selected on basis of the best operating pressure of the steam generators connected to the headers. Two important steam generators are the FT reactor cooling and the HPC reactor cooling as both reactors are strongly exothermic and generate significant amount of steam. The two reactors operate with catalysts where the catalyst temperature is crucial for the chemical reaction process. As the temperature operating window of the catalysts is narrow, it is preferred to cool the reactors with water boiling at saturation temperature corresponding to the pressure of the system. Other steam generators in the plant are associated with gas cooling and are not as critical with respect to steam pressure.

The HP pressure is set to 86 bar as this is the saturation pressure of 300 °C governed by the temperature requirement by the HPC reactor. 86 bar is also a suitable pressure for cooling of the gasification raw gas as well as cooling of the ATR recirculation gas. Hence, these three steam generators make up the steam provided to the HP header.

The MP pressure is set to 15 bar as this is the saturation pressure of 198 °C governed by the temperature requirement of the FT reactor. 15 bar is also the pressure of the gasification steam and reformer steam required by the gasifier. Further, 15 bar steam is used as steam for the Shift reactor, regeneration of Rectisol fluid, ATR and reboil steam in fuel distillation.

The LP pressure is set to 4.3 bar as this pressure is sufficiently high to provide usable steam for the steam turbine. 4.3 bar is also a suitable pressure when condensing water out of moist gas after the Shift reactor. LP steam is further used as deareator steam and for regeneration of Rectisol fluid.

5.6.1 Biomass boiler

Details about heat pick-up from the boiler of the Brista plant and Igelsta plant are provided in the Simplified Steam Scheme in respective Figure 19 and Figure 20.

The biorefinery plant has many steam consumers and producers and to balance them all a biomass boiler is needed with a steam system, which can integrate all streams. In addition, this will also provide necessary power and steam for the biorefinery, at startup and during operation. A Bubbling Fluidized Bed (BFB) boiler is selected although there are other boiler designs that would work equally well. The fuel to the boiler is the same as the dried biomass fed to gasification. Using dried biomass as boiler fuel will assure high boiler efficiency and low stack losses.
Primary air and recycled flue gases can be fed at specific needs up through the fluidized bed. Secondary air and off gases from other processes in the biorefinery plant can be fed directly into the combustion zone. The air distribution is governed by valves and blowers in order to maintain low emissions even with a variety of different fuels.

The boiler comprise of only one steam generator, 15 bar. The steam generator has dual functions. This steam generator is necessary to allow start-up of the plant as the gasifiers require steam for bed fluidization and for the gasification reactions. The 15 bar steam generator would normally not produce steam during operation. However should the steam turbine operation be unfavourable, e.g. produce much wet steam at the LP turbine exit, then 15 bar superheated steam can be produced by the boiler and fed to the turbine’s 15 bar level.

5.6.2 Steam turbine

Details about the steam turbine for the Brista plant and Igelsta plant are provided in the Simplified steam scheme in respective Figure 19 and Figure 20.

The steam turbine comprises of a HP, MP and a LP staged turbine on a single shaft. HP steam from the HP steam header is fed to the boiler for superheating prior to entering the turbine. The MP steam header is connected to the entry of the MP turbine. Under normal operating condition, the MP header has excess of steam which would go to the turbine.

The LP steam header is connected to the entry of the LP steam turbine. Under normal operating condition, the LP header requires steam and LP steam will bleed off the turbine. The pressure at the LP turbine exit is set to 2.0 bar as to allow steam condensation at a temperature suitable for producing district heat. The same hot water is used also for heating of air for drying of biomass. The split of heat available for drying and for district heat turned out to be about 50/50.

For periods when there is no district heat demand, the exit of the LP turbine could be connected to a bottoming condenser as to increase the production of electric power. The bottoming condenser is not provided in the schemes in Figure 19 and Figure 20 for simplicity reasons. For the Brista plant case a closed loop air cooling unit would provide the heat sink for the bottoming condenser. For the Igelsta plant case sea water cooling would provide the heat sink.
Figure 19. Simplified steam scheme of the Brista plant with steam headers, consumers and producers and biomass boiler.
Figure 20. Simplified steam scheme of the Igelsta plant with steam headers, consumers and producers and biomass boiler.
5.7 Balance of plant

5.7.1 Utilities and off-sites

In this section not all support systems listed are detailed as it is not within the scope of this study but the main systems of importance are further described to some extent. Utility systems and off-sites refer to all installations within the respective process unit, which supply supporting production media or constitute interfaces between the process units. Typically those systems are specified as per below.

The utility system includes the following:
- Raw water / service water / process water
- Cooling water system, alternatively an air-cooled system for the external cooling
- Steam system
- Pressurised instrument and plant air system
- Flare system
- Electric power system (up to 11 kV)

Off-sites include the following:
- Civil work (foundations, pipe racks with interconnection pipelines, roads, etc.)
- Buildings
- Emergency power system
- Waste water treatment facilities system (presumed external, or alt. internal)
- Sewer systems
- Fire water system
- Chemicals dosing system.
6 Material and energy balances

6.1 Study alternatives

In this study project the production of bio-jet fuel has been studied for two plant locations with two plant configurations. The closest location to Arlanda Airport, Brista was configured for a complete plant with bio-jet fuel production together with by-products naphtha, heavy diesel and district heat. The distant location, Igelsta was configured for a simpler plant where an intermediate FT-product is made which is shipped to a refinery for further upgrading, where apart from district heat at Igelsta, several by-products are made, like naphtha, heavy diesel and unconverted oils.

Because of the power consumption of the processes and to balance the steam needs a biomass boiler has been added in both plants. However, for the bulk of the power, biomass based power could be imported from a large central plant with large district heat network, taking use of all of the energy. This study has though placed the biorefinery plant adjacent with a combined heat and power plant for partly fuel logistic synergies and the available district heat network.

As the work proceeded it became, however, clear that for the Igelsta plant the production of bio-jet fuel could not easily be maximised at the refinery and to keep the calculation basis of 50 000 tonnes per year of bio-jet fuel we needed to enlarge the plant. The result is a plant much larger than what can be accommodated at this location. However, this location is firstly only showed as an example and therefore the results are still valid. Second, the difference in plant size makes it possible for a scale economy analysis which was recommended at project start.

6.2 Process calculations

Details about the steam system for the Brista plant and Igelsta plant are provided in the Simplified steam scheme in respective Figure 19 and Figure 20.

Fuel for the facility has been assumed as chipped wood biomass comprising forestry chips, grot, wood rejects/discards, sawdust or other wood residues. The fuel is then gasified in a fluidized bed reactor to a cleaned, cooled product gas which is then cleaned and conditioned into a syngas, see following gas compositions.
<table>
<thead>
<tr>
<th>Component</th>
<th>Product gas</th>
<th>Syngas</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂, hydrogen</td>
<td>42.2 % vol.</td>
<td>63.9 % vol.</td>
</tr>
<tr>
<td>CO, carbon monoxide</td>
<td>37.4 % vol.</td>
<td>32.0 % vol.</td>
</tr>
<tr>
<td>CO₂, carbon dioxide</td>
<td>18.6 % vol.</td>
<td>2.5 % vol.</td>
</tr>
<tr>
<td>CH₄, methane</td>
<td>0.8 % vol.</td>
<td>0.9 % vol.</td>
</tr>
<tr>
<td>H₂O, water</td>
<td>0.7 % vol.</td>
<td>0.5 % vol.</td>
</tr>
<tr>
<td>N₂, nitrogen</td>
<td>0.2 % vol.</td>
<td>0.2 % vol.</td>
</tr>
<tr>
<td>H₂S+COS, sulphur</td>
<td>100 ppm</td>
<td>0 ppm</td>
</tr>
<tr>
<td>NH₃+HCN</td>
<td>0 ppm</td>
<td>0 ppm</td>
</tr>
<tr>
<td>Cl, chlorine</td>
<td>2 ppm</td>
<td>0 ppm</td>
</tr>
</tbody>
</table>

Table 2. Gas compositions of the product gas leaving the gasification plant and the syngas leaving the gas cleaning plant.

The syngas is then calculated with the Fischer-Tropsch synthesis process, which have been based on the ASF (Anderson-Schulz-Flory) model (see below left Figure 21) for the product distribution, where α, the chain growth probability factor, is assumed to be independent of chain length and is approximately 90 %, i.e. a CO conversion of 90 % and a C₅⁺ selectivity of 78 % [42].

Then, the higher hydrocarbons (C₅⁺) can be calculated for hydrogenation and cracking according to the SMDS process, where a medium-severity cracking was used to determine the product distribution before final distillation (see below right Figure 21). These reaction conditions under-lies the calculations in the current study.

Figure 21. Left figure: Anderson-Schulz-Flory model diagram with product composition for given α number. Right figure: Shell FT-product hydrogenation and hydrocracking diagram for product oils with given carbon numbers.
It should be noted that there is an uncertainty of the product composition of the FT-product from the FT synthesis unit as it depends on the catalyst and the reaction conditions as well as the reactor. However, the calculations made have been modelled from stated reactions and have been cross-checked with other studies and references.

The second step with a hydrocracker is more difficult to calculate as it depends on the Shell process with a HPC, heavy paraffin conversion unit with simultaneous hydrocracking and hydrogenation, where the data from above Figure has been used to model the final FT-product before distillation into products.

Lynch describes the Shell SMDS process with the Heavy Paraffin Conversion unit as cracking and isomerisation of oils to lighter fractions at mild conditions, 30-50 bar and 300-350 °C. The dual function of the catalyst is imperative to the performance of this process [76].

Few references can generally be found on FT product composition, yield and energy efficiency but Dry states that the LTFT process yield high amounts of paraffins and linear products and the selectivity to high molecular mass linear waxes can be very high. During the 1970s the selective hydrocracking of FT wax was investigated at Sasol R&D using a Ni/Mo supported silica-alumina catalyst. Under mild conditions and recycling the product heavier than diesel, the wax was cracked to extinction. The final product distribution was about 80 % diesel, 15 % naphtha and 5 % C₁-C₄ gas.

In addition, L. P. Dancuart, R. de Haan and A. de Klerk, from Sasol [20] found that for a 34 000 bpd plant with the proprietary SPD process of Sasol the yield was 73 % diesel, 24 % naphtha and 3 % LPG, on an oil equivalent basis. There is thus a possibility to achieve a yield similar to this.

According to Shell the Jet A-1 product is a hydrocarbon with a carbon chain length of 8-17 atoms and boiling point interval of 150-300 °C. According to BP Aviation Fuel their product has an initial boiling point of 156 °C and fuel recovered is 10 % at 167 °C, 20 % at 172 °C, 50 % at 188 °C, 90 % at 234 °C and end point at 258 °C.

In summary, the below Figure 22 shows the calculated distillation curve for the hydrocracker product, with boiling points giving the temperature range for the jet fuel of 150-300 °C and consequently indicated yields of naphtha, bio-jet fuel and heavy diesel fuel oil. The results are in conformity with the above results on diesel production.
There can also be a question whether the distilled Shell product could be of Jet A-1 standard. However, according to the website of Shells, they have now a FT-derived product that has been tested. The product GTL Aviation Fuel has been used to power the world’s largest passenger airplane – an Airbus A380. It is thus fair to say that a product suitable for certification can be made.

In the Igelsta case, the results have been calculated with the existing hydrocracker process unit and distillation into fuel products that are produced today. There has been no further change or optimisation assumed for the process and only an additional volume of FT-product that is hydro-cracked together with conventional feed in the refinery.

Generally, in crude oil refineries heavy-end upgrading is done by thermal cracking (visbreaking) or fluid catalytic cracking (FCC). For example, ExxonMobil reports of a wax hydrocracker with an inlet temperature of 370–400 °C. Thus, the crackers found on refineries today are most likely not all too well suited for a FT wax product and this result in lower yield to jet fuel or diesel. The governing factors are catalyst, feed composition, wanted products, reactor conditions, process looping to enhance yield.
6.3 Plant results

The production of bio-jet fuel has been fixed as calculation basis for 50 000 tonnes per year. Therefore, the plant size is different for the two alternatives, where the Brista plant is of 290 MW and Igelsta plant of 610 MW. The estimated operation is 8000 hours per year with 5000 hours of heat production. The products have been assumed for the following properties

<table>
<thead>
<tr>
<th>Product</th>
<th>Density</th>
<th>Heating value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphtha</td>
<td>687 kg/m³</td>
<td>12.35 MWh/tonne</td>
</tr>
<tr>
<td>Bio-jet</td>
<td>804 kg/m³</td>
<td>11.99 MWh/tonne</td>
</tr>
<tr>
<td>Heavy diesel</td>
<td>754 kg/m³</td>
<td>12.24 MWh/tonne</td>
</tr>
<tr>
<td>UCO</td>
<td>930 kg/m³</td>
<td>11.56 MWh/tonne</td>
</tr>
</tbody>
</table>

Table 3. Assumed properties of the plant products.

The material balance for streams is then summarised in Table below. The boiler plant can vary its output of heat depending on the operation of the steam turbine unit of the power island. In the case of a self-supported plant the power boiler is bigger, which also gives options. With the steam turbine operated in condensing mode maximum electricity is produced and when the turbine is operating in back-pressure mode more heat is produced.

The energy efficiency from biomass to fuels is 46 % for Brista and 44 % for Igelsta. Finally, the total energy efficiency with heat included is 79 % for Brista and 73 % for Igelsta (main results are shown in below Table).
### Table 4. Material and energy balances for the plants at Brista and Igelsta.

Please note that the net power balance is negative which means that to correctly calculate the biomass efficiency this imported power is calculated as biomass with an efficiency of 40% for a condensing plant. In addition, at the refinery, there are consumption of steam, hydrogen and power as well as there is production of light gases from the hydrocracking of the FT-product. Steam and power is balanced with the light gases and the net consumption is hydrogen, here calculated as biomass energy with a conversion factor of 65%.

The district heat production is partly based on assumptions of available heat as this project is limited on detail to closely identify and calculate all heat streams possible. The cooling water is calculated as the maximum cooling need possible, when all losses like stack and biomass dryer heat losses have been subtracted for. The cooling need is thus lower than this in reality but for a safe margin we have accounted the maximum.
6.4 Plant logistics

The planned facility will be located in the vicinity of a population centre with good road connections. Extended vehicle traffic in the immediate vicinity can be assumed not to entail any significant negative influence on the surroundings, nor on adjacent industry. The chosen scale of the proposed plant is such that the number of vehicles on the road network will not significantly burden surrounding housing and industry.

The following Table, referring to the plant when fully operational, shows calculations of the logistic flows, mean number of truck movements per day. Distributed over workdays, the daily flow may occasionally be somewhat higher. For the Brista location, the bio-jet fuel will most likely be pipe-lined and not delivered by truck but for comparison with another location the estimate is of relevance. For Igelsta there is possibility of ship transport for the biomass but the location is not well suited for receiving large volumes of biomass by ship. Still it would amount to possibly about one ship every day.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Brista</th>
<th>Igelsta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Flow</td>
<td>Daily transport</td>
</tr>
<tr>
<td>Biomass</td>
<td>108 t/h</td>
<td>80 trucks or 2-3 trains</td>
</tr>
<tr>
<td>FT-products</td>
<td>270 t/day</td>
<td>9 trucks (or 0.06 ship)</td>
</tr>
<tr>
<td>Total</td>
<td>&lt;100 trucks</td>
<td>&lt;200 trucks</td>
</tr>
</tbody>
</table>

*Table 5. Estimated plant transport logistics for Brista and Igelsta plants, with estimated capacity by train as 1000 tonnes and by ship as 5000 DWT.*
7 Economy

7.1 Capital investment

The investment cost has been based on an extensive in-house data base with budget quotations, which have been updated to 2Q 2009 and scaled to the studied plant size. The investment cost for the parts has thus been assessed by using in-house information and applying accepted factor and index methods for updating. Due to the rapid fluctuations in steel material and engineering costs the last few years, scaling using relevant indices (CEPCI index etc) has been applied to include these changes.

For this brief study, some approximations have been made and where scaling is necessary this have added an additional uncertainty. It is the belief that the total accuracy is better than ±50 %. The costs below for each process island are given as turn-key, i.e. including erection and civil works. The following results are shown.

The capital investment was calculated with an inflation of 2 %, a debt interest of 6 %, equity of 15 % (debt/equity ratio of 80/20) and a loan period of 20 years – a weighted average cost of capital of 7.80 %. The equivalent operating hours is estimated as 8000 per year with a district heat production of 5000 hours per year. This is based on the assumption of an N\textsuperscript{th} plant, which is commercial. The exchanges rates were as of 16 September 2009 1 EUR = 10.20 SEK, 1 USD = 7.00 SEK.

<table>
<thead>
<tr>
<th>Investment cost</th>
<th>Brista</th>
<th>Igelsta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air separation plant</td>
<td>178 MSEK</td>
<td>278 MSEK</td>
</tr>
<tr>
<td>Gasification plant</td>
<td>1103 MSEK</td>
<td>1728 MSEK</td>
</tr>
<tr>
<td>Gas cleaning &amp; conditioning plant</td>
<td>535 MSEK</td>
<td>777 MSEK</td>
</tr>
<tr>
<td>FT-plant</td>
<td>1156 MSEK</td>
<td>1473 MSEK</td>
</tr>
<tr>
<td>Boiler and steam turbine plant</td>
<td>284 MSEK</td>
<td>485 MSEK</td>
</tr>
<tr>
<td>Balance of plant (a)</td>
<td>794 MSEK</td>
<td>1165 MSEK</td>
</tr>
<tr>
<td><strong>Equipment and assembly</strong></td>
<td>4070 MSEK</td>
<td>5926 MSEK</td>
</tr>
<tr>
<td>In-direct costs (b)</td>
<td>1014 MSEK</td>
<td>1513 MSEK</td>
</tr>
<tr>
<td><strong>Total costs</strong></td>
<td>5084 MSEK</td>
<td>7439 MSEK</td>
</tr>
<tr>
<td><strong>Total costs (EUR / USD)</strong></td>
<td>500 MEUR / 726 MUSD</td>
<td>729 MEUR / 1063 MUSD</td>
</tr>
</tbody>
</table>

Table 6. Investment costs for the plants at Brista and Igelsta.

Notes:

a) In-house estimate which includes utility feedstocks and off-sites comprising land and buildings, roads and pipelines and centrals and lines for electricity, water etc.

b) In-house estimate, which includes site costs, temporary and spare equipment, storage, owner’s cost (project development, permitting and approval, detailed engineering, commissioning and start-up costs etc), working capital, financing and legal fees, interest during construction etc.
The total investment has been calculated as 5.1 billion SEK (500 MEUR or 726 MUSD) for Brista and 7.4 billion SEK (729 MEUR / 1063 MUSD) for Igelsta, as seen in above Table. The relatively high investment cost shown in this report has a number of underlying reasons. In the design work, the basis has been to implement most solutions that would be available for a very large-scale plant. Product yields, availability and technical efficiency have thus been prioritised at this stage.

Also, some of the processes considered have been designed outgoing from API standards used in oil and petrochemical industries. This includes very high requirements on equipment in terms of redundancy and mechanical design. Considerable cost savings can be achieved by lowering the requirements somewhat.

### 7.2 Production costs

The production cost has been calculated with below assumed prices of energy and commodities. Firstly, the revenues are given e.g. district heat which is exported. Then the total yearly costs are given, with the resulting the production costs as 8300 SEK (812 EUR / 1183 USD) per cubic meter and 5000 SEK (490 EUR / 714 USD) per cubic meter bio-jet, respectively.

The basis for the costs have been the current Brent oil price which was $67 per barrel as of 16 September, which relates to the revenues of naphtha and diesel with additional energy and carbon dioxide taxes, as per below.
Table 7. Estimated energy prices and annual costs for Brista and Igelsta plants.

Notes:

a) The naphtha sales price has been calculated as current Brent oil price with $2.5 penalty per barrel Brent oil and current petrol carbon dioxide and energy tax of 5520 SEK/m³ as a green fuel for petrol blend, stated by Preem.

b) The heavy diesel sales price has been calculated as current Brent oil price with $8.0 added per barrel Brent oil and current diesel and EO1 heavy fuel oil carbon dioxide and energy tax of 3804 SEK/m³ as a green fuel for diesel and heavy fuel oil blend, stated by Preem.

c) This cost is given by Preem as the cost for refining the bio-jet on an operation cost calculated as 5% reduction in product value, which is then calculated from the total product value. This cost includes the operation cost including utilities and no regard for the investment cost is taken.

The district heat price of 450 SEK/MWh has been taken, which is the list price from 1 January 2009 for Södertörns Fjärrvärme AB, which is the sales company of Söderenergi which owns the Igelsta combined heat and power plant. The list price is 410 SEK/MWh and an additional capacity fee which has been calculated as 40 SEK/MWh, resulting in 450 SEK/MWh. The price is relatively high for a producer but reflects new capacity.

The heat price on the consumer side from 1 January 2010 in Stockholm is listed by Fortum Värme as 462 SEK/MWh from Jan to April and Oct to Dec. In addition, there is a fixed part which is 350 000 SEK per year and 15 SEK/MWh for large consumers (>7500 MWh/year) and a capacity price of 375 SEK/kW. All exclusive of VAT.

The biomass price has been taken from Prisblad för biobränslen, torv m.m. Nr 3 / 2009 from the Swedish Energy Agency where the prognosis for 2Q 2009 gives fuel prices ranging 173-175 SEK/MWh for wood chips and forest by-products. The fuel price has been increasing rapidly last years, but this plant has also flexibility to use low-grade biomass which has lower cost.
The power price has been taken from Nord Pool spot price for Sweden with an additional Electricity certificate and distribution cost, giving 480 SEK/MWh, as the total price for purchased electricity.

A sensitivity analysis gives the following results, where the factors biomass price, district heat price, investment cost and availability have been changed with 10%. It can be seen that for Brista the change range is 7.5-9.1 SEK with the biggest change in investment cost and availability, whereas for Igelsta the change range is 3.6-6.4 SEK and as a very large plant biomass price is the largest influencing factor.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Change</th>
<th>Brista</th>
<th>Igelsta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bio-jet cost</td>
<td>-</td>
<td>8.3 SEK/litre</td>
<td>5.0 SEK/litre</td>
</tr>
<tr>
<td>District heat price</td>
<td>+10 %, 500 SEK/MWh</td>
<td>7.9 SEK/litre</td>
<td>4.3 SEK/litre</td>
</tr>
<tr>
<td>District heat price</td>
<td>-10 % 400 SEK/MWh</td>
<td>8.6 SEK/litre</td>
<td>5.7 SEK/litre</td>
</tr>
<tr>
<td>Biomass price</td>
<td>+10 % 200 SEK/MWh</td>
<td>8.9 SEK/litre</td>
<td>6.4 SEK/litre</td>
</tr>
<tr>
<td>Biomass price</td>
<td>-10 % 160 SEK/MWh</td>
<td>7.6 SEK/litre</td>
<td>3.6 SEK/litre</td>
</tr>
<tr>
<td>Investment cost</td>
<td>+10 %</td>
<td>9.1 SEK/litre</td>
<td>5.8 SEK/litre</td>
</tr>
<tr>
<td>Investment cost</td>
<td>-10 %</td>
<td>7.5 SEK/litre</td>
<td>4.2 SEK/litre</td>
</tr>
<tr>
<td>Availability</td>
<td>+10 %</td>
<td>7.6 SEK/litre</td>
<td>4.1 SEK/litre</td>
</tr>
<tr>
<td>Availability</td>
<td>-10 %</td>
<td>9.1 SEK/litre</td>
<td>6.1 SEK/litre</td>
</tr>
<tr>
<td><strong>Total range</strong></td>
<td><strong>7.5-9.1 SEK/litre</strong></td>
<td><strong>3.6-6.4 SEK/litre</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Table 8. Sensitivity analysis of bio-jet fuel production costs.*
8 Environmental impact

The overall environmental effects of using FT-fuel are positive, with reduced emissions as the main effect, both sulphurs and particles are reduced. To what extent NO<sub>x</sub> is reduced is not clear if not slightly increased due to a cleaner combustion. If biomass is used the overall CO<sub>2</sub> balance is likely to be very positive. Further, since the FT-process can be fed from different kind of waste, sustainability is a natural property of the system.

8.1.1 Environmental effects

Fuel produced with the FT-process is pure, without sulphur and aromatics. The lack of sulphur and aromatics has several effects beneficial for the environment. Except for the reduced contribution to acid pollution, no sulphur dioxide (SO<sub>2</sub>) nor sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) aerosol emissions, the burning is cleaner, with fewer particles, an advantage both for the local air quality around airports and as a reduced contrail formation.

For FT-diesel this has been confirmed in several studies [24], [25], results which seem to hold also for turbine engines, see [37], [38], [39]. Swedish studies [26], [10] also show that FT-fuel is less toxic than conventional fuel. The weight distribution of molecules in a FT-product is also more concentrated with lower abundance of short hydro-carbon chains, which makes the fuel less volatile, another advantage for the fuel handling and local air quality.

However, since the FT-fuel fraction of the total amount of fuel is limited these positive effects are reduced. Presently the expected specification to appear will allow up to 50% FT-fuel which, if mixed to that proportion, significantly will have positive environmental effects.

In the alternative fuel certification roadmap generic FT-based fuel is planned to be certified to 100%. This will depend on technological solutions to replace sulphur (which is needed for lubricate reasons in the fuel system) and aromatics (which are needed to make seals swell). DeWitt et al. argues in [27] that there might be a blend of aromatics which solves the swell problem of seals but does not increase particles and soot formation. The resulting environmental effects will in that case be significantly positive.

8.1.2 Sustainability, lifecycle and emissions

Recently biofuels have gathered increased attention from a sustainability and lifecycle perspective. There are several aspects of sustainability, a spectrum of questions are raised, from competition with foodstocks, impact on biodiversity and emission of green house gases (GHG). The Steering Board of the Roundtable on Sustainable Biofuels (RSB) has published principles for the production of sustainable fuels [65]. The document gives guidelines how to analyse sustainability from a wide perspective.
For the project discussed in this report, forest industry residuals is the target biomass to be used, for which the availability and sustainable production is thoroughly analysed in several reports [57], [58]. In general, the availability of forest origin biomass is good in Scandinavia and Baltic without compromising a sustainable re-growth and land use.

### 8.1.3 Life Cycle Assessment of green house gases

To assess the overall CO₂ balance several parameters need to be analysed including the complete production process with transportations both of biomass and end products. In previous chapter the calculations show a net reduction of the CO₂, considerable compared to fuel sourced from crude oil for the suggested solution. To illustrate how different biomass fuels compare to conventional fuel sources as oil, coal and natural gas a normalized life cycle GHG intensity for a range of jet fuel pathways are depicted in the Figure 23 below.

CCS denotes Carbon Capture and Storage. *Without land use change* means simply that the Palm and Soy is grown on land previously unused, or no land use is changed, and *Land use change* could mean deforestation when rain forest is destroyed to make place for Palm oil fields. This is sadly inefficient from a GHG point as from other aspects. *Without land use change* does not automatically imply that the overall social-environmental effects are small since unused land is not the same as unusable land. True sustainable solutions should look at using for feedstock unusable land.

![Figure 23. Normalised life-cycle GHG intensity, showing relative values [3].](image-url)
8.2 Gas clean-up requirements

In the chain of processes included in plant the temperature is high in the gasifier (>900 °C) and in the synthesis plant (>200 °C). Any need for cooling in between will lead to loss of efficiency and increased capital costs. However, the need to reform methane and tar requires high temperature (900 °C) and therefore filters and reformers that withstand these gases and conditions are critical.

Different volatile organic compounds from benzene to heavy molecular tars will form in the fluidized-bed wood gasification system. The definition of tar is the sum of organic components heavier than benzene. The amount of tar, higher hydrocarbon compounds, that occur in biomass gasification can be as high as several hundreds or even several thousands ppm for low temperature tars. Tar will impose serious limitations in the use of producer gas due to fouling of downstream process equipment, and high maintenance costs. Tar is removed by reforming and methane reforming is performed with same catalyst, although is not a requirement for the function of the process units.

Other important gas cleaning work is to remove sulphur, alkalis and trace metals, as well as nitrogen compounds, cyanides and chlorides and ash. Their concentration will depend on the feedstock composition and on the gasification conditions. In the gas conditioning step prior a synthesis the hydrogen to carbon monoxide ratio needs to be optimized as well as carbon dioxide removed. Therefore there are much higher and more complex processes involved with a fuel synthesis plant.

8.3 Emissions to air, land and water

8.3.1 Air emissions

Drying of biomass fuels may cause releases of terpenes and other volatile wood components into the atmosphere and into water. Some of these components can be trapped with filters if there would be a problem. The Rectisol unit will release small amounts of residual gas (primarily carbon dioxide) in the separate steps where nitrogen is used for regeneration. Circulating carbon dioxide for pressurisation and inertisation of the gasifier unit will also be released to the atmosphere.

No environmental standard values for this plant can be established until the detailed process design is completed. Indicatively, it may be stated that such values will be below the standards set by the national and municipal authorities and certainly below emissions from conventional heat and power plants. Certain amounts of radiant heat and heat in residual gases will be transferred to the atmosphere.

Summing up, emissions will be low and in principle only low levels of sulphur, nitrogen oxides or particulates are emitted into the atmosphere from the boiler.
8.3.2 Solid waste

Solid residues collected from particle filters and process water treatment will probably contain high concentrations of unburned organic material and small amounts of tar. This residue should be destructed through combustion. The ash quantity depends largely on the fuel type. The ash from the bottom section of the gasifier contains important minerals and should be returned to the forest or agricultural lands through pelletisation for simple transport and distribution.

8.3.3 Water emissions

Part of the nitrogen contained in the biomass fuel will be converted into ammonia (NH$_3$) and a minute quantity of hydrogen cyanide (HCN). Ammonia and hydrogen cyanide and metal complexes of Na, K, As, Co, Cu, Cr, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, Zn, and V, naturally contained in biomass, may be expected to dissolve in the process water used for scrubbers and in condensates from the gas coolers. Process water will be purified by conventional methods in a separate water treatment plant before release to the recipient or the municipal sewage system. Thus, the process water will contain low concentrations of pollutants and is assumed to be treated in a separate unit.

The gasification plant requires no special water quality. All water supplies to gasification plant can be typical power plant quality i.e. gas cooler feed water is boiling feed-water, cooling water is normal cooling water, etc. The water consumed by the gasification plant is the gasification steam and the gas cooler drum blow-down, all other water flows will be returned to the steam plant. The gasification steam flow rate depends on the feed moisture of the fuel.

Residual waste heat will be evacuated from the plant by cooling water into the adjacent recipient. The flow of cooling water depends on season and temperatures. Energy losses in the plant will appear as temperature gradients in cooling water recirculated back to the recipient, alternatively an air-cooled system can be used.

8.4 Noise pollution

The plant will be designed to minimise the release of noise; sources of noise will be contained by building elements or otherwise to be dampened to meet the Environmental Protection Agency’s requirements for external industrial noise. The most important potential sources of noise will be the front loader, various pumps, fans, and gas compressors in the different process units. Also under special operating conditions, if and when gases from the plant are routed to the flare, specific noise effects may be registered.
9 Conclusions and discussion

9.1 Economic parameters

As said previously, safety is the foremost important aspect of aviation fuel. However, the financial side is crucial as well with tight economical conditions for the aircraft operators. The price for aviation fuel follows the oil market and has been estimated as 124% of crude oil [51] (at a barrel price of $100). Despite the improving fuel efficiency of modern aircraft, fuel is aircraft operators’ largest single expense, overtaking personnel costs in 2005. Aircraft operators can not be expected to pay more for a bio-based fuel than for a conventional Jet A-1 with the exception of the compensation for the emission trade system for aviation, to be implemented in Europe by 2012 which might compare to a margin of 5-15% of petroleum based fuel.

9.1.1 Historical and future oil prices

In 2003 the oil price was about $30 per barrel (and in 1999 as low as $10). The price then increased dramatically and continuously to an all time high of $147 in 2008. Since, the price has fallen rapidly and gained stability around $70 per barrel (see Figure 24). IATA analysis [51] points to a future oil price of around $100 per barrel in 2010 (normalised prices), increasing at least with $1 per year the coming 20 years. Like earlier fluctuations the future oil price will depend on many different factors and yet unknown political events.

![Brent Crude Oil Futures Close (Front Month)](image)

Figure 24. Brent crude oil price development, © SPI 2009.
9.1.2 **Aviation fuel price**

At Arlanda Airport, three different oil companies supply aviation fuel through AFAB. The companies are Statoil, Shell and AFCO, where AFCO is affiliated company to Air BP Sweden AB, Kuwait Petroleum Aviation Sweden AB and Texaco International Sales & Services AB. The airline companies could purchase aviation fuel via contract to a specific oil company or according to list price.

The contracted fuel prices are due to commercial reasons highly confidential, while the list price is normally available. Unfortunately, it is expected that the majority of the fuel is sold through contract, which make it difficult to compare the prices for FT produced aviation fuel. The list price for aviation fuel varies between the oil companies, e.g. 1 Oct, 2009 the Shell price was 6900 SEK/m$^3$ and Statoil reported 5900 SEK/m$^3$, all taxes and fees excluded.

Platts gives the list price at Rotterdam for Jet A-1 as $577 per tonne (7 October 2009), which gives a price of 4.02 SEK/kg. The density may vary, therefore, the unit price in litre would be on average about 5.00 SEK/litre. With the transport, storage and distribution costs the fuel price at Arlanda is then in line with an average price of Statoil and Shell.

In Europe the ETS is to be implemented in the aviation sector in 2012. It is hard to predict the future price of emission allowances but it will probably be in the span of 5-15 % of the fuel price. Since the allowance cost for bio-based fuel is zero this is the margin for a higher production cost for bio-based fuel making it cost neutral to aircraft operators compared to conventional fuel. During 2008 the price of emission allowances varied a lot, linked to the global crisis and oil price. A deeper analysis of this can be found in [11], [56], [23].

9.1.3 **Biomass price**

There are studies of the biomass price but since the markets are local, compared to oil, it is not obvious how the market will develop. In contrast to oil, biomass is very voluminous and transportation cost is not negligible. For the purpose of FT-production in Sweden forest industry residuals would naturally be the biomass source and a versatile, efficient transport network must be considered when planning a FT plant.
9.2 Different sources of bio-fuels and production processes

As stated above FT-based bio-fuel is the only alternative for commercial aviation fuel available in short term. However, there are several other ways to produce fuel from biomass and currently a number of initiatives (see e.g. the algae project from Sapphire Energy [78] and a comprehensive overview of the field in [51]) are started or planned. The US Navy even has a research program with the aim to study the possibilities using sea water for fuel production [43]. With enough energy input the water could be cracked into hydrogen and oxygen, and the CO$_2$ dissolved in the sea used as the carbon source.

9.2.1 Biomasses, present and future possibilities

Although this report is concerned with the transformation of by-products from the forest industry into aviation fuel there are several other sources that can feed an FT-plant. From the pulp industry black liquor is a possible source, municipal waste exceeds 400 kg/capita/year in many parts of the world, and agriculture residuals is estimated to almost $10^{12}$ kg/year in Europe. These are all possible sources, all with different cost profiles and technical possibilities and difficulties.

Sustainable grown biomass is another alternative. There are several candidate crops available. To achieve sustainability they should not compete with food crops, preferable be grown on land unsuitable for cereal or food oil crops. Jatropha, a plant that produce seeds (toxic to humans and animals) containing lipid oil and can grow in difficult soil conditions is one. Camelia is another energy crop, from which the waste can be fed to chickens. The most promising, but yet to be proven in large implementations, is micro algae which can be grown in polluted salt water. The most important advantage is the expected growth rate, which exceeds other oil crops by up to 15 times in oil produced per square kilometre. A figure often quoted is that algae production on 70 000 sq kilometres (approx. size of Ireland) could cover the current world demand of aviation fuel. However promising estimate, before any real size demonstrations are made, the actual figures are yet to be established.

The sustainability of different crops is assessed in a widely cited paper [79] and it is shown that using biomass for fuel production is not a guarantee for a reduction in GHG emissions compared to conventional fuel.

9.2.2 Production processes

FT, described in detail above, is necessary when the biomass comes in form of cellulose. For biomass that is high in oil content, as soya, palm oil, jatropha, camelina and algae, other processes can be used to produce fuel. After extracting the oil from the biomass there are different ways to refine it into aviation fuel. Although promising if successful there are still many difficulties to overcome using this approach. Since the biomass is not used to produce syngas the issue of contamination from metal residues like alkali or other compounds, more knowledge and possibly new technology is necessary to be put in place before such alternatives become commercially available.
9.3 Selecting the processes

The plant configuration selected in this study comprises several process units integrated to form a complex. Every process unit of the complex has previously been commercially demonstrated in other facilities, except for pressurised biomass gasification with oxygen. Other processes for gas cleanup and Fischer-Tropsch synthesis have been commercialised in large plants, primarily within the petrochemical industry worldwide.

However, placing an EPC contract is a complex process and it is not self-evident to procure any process despite its commercial status. Nevertheless, the most important process within the plant is the gasification of biomass for the production of a clean syngas in full scale, as well as the integration of all processes in the complex. In addition, there is no biomass gasification technology which is available commercially at larger scale. The technology maturity should be addressed in further development.

Gasification constitutes the preferred option for large scale efficient conversion of biomass into non-conventional forestry industry products like power, heat and fuels. Basically, there are three main different gasification reactor technologies applicable with directly heated fluidized bed, in-directly heated fluidized bed and entrained-flow reactors to choose from. The most widely tested reactor with biomass is the fluidized bed. This technology can primarily be supplied by Andritz/Carbona as well as in principle by other vendors like Foster Wheeler, Uhde, Envirotherm etc.

A most interesting plant demonstration is done by the German company Choren Industries GmbH (privately owned and as minority shareholders Shell Deutschland Oil GmbH, Daimler AG and Volkswagen AG), which uses an entrained-flow reactor integrated with a pyrolysis step that feed the reactor with converted biomass. The reactor lends itself for an easy upscaling but demands a fuel that can be fed for an instant gasification reaction in a flame. The plant was completed April 2008 with Fischer-Tropsch diesel synthesis and is scheduled for production next year with 18 million litres of BTL products [68].

An area of concern for synthesis is the variability in the syngas composition with different biofuels. This is particularly relevant where multiple sources of biofuel will be used. Particularly relating to pressurised gasifiers there could be concern in the use of ceramic candle filters for dust removal prior the scrubber.

Nevertheless, the process selection described has been carefully estimated and based on decades of experience a competitive process configuration is given with the design basis and objectives in mind. Further technical improvement and optimizations are possible but requires separate studies.

Until recently, the FT technology was not seen as being commercially competitive in comparison with conventional refining of crude oil. However, the increase of the oil price due to the shortening of oil reserves and the environmental legislations to reduce pollutant and greenhouse gas emissions drive companies to invest in these technologies.
Shell was the first company to launch itself into synthetic fuel production from natural gas at its Bintulu site in Malaysia. This small production unit (originally 12 500 barrels per day, BPD) has been operational since 1993. Despite the economic opportunities for FT-technology it is not available as for other processes because of the fierce market competitiveness among oil companies. The technology studied could be supplied by Statoil, Sasol Chevron, Shell, Exxon Mobil. As with biomass gasification, there is need for a close cooperation in order to attract the commitment to sell or license the technology.

### 9.4 Plant reliability and availability

The configured process scheme is entirely based on well proven and commercially available technologies and equipment with guaranteed performance from competing vendors, except for the gasification plant. Although experiments and development is currently performed to achieve proven performance there is an upscaling step for this kind of plant.

The reasonable simple and straight-forward process configuration, but with some integration between plant units and heat exchange between process streams contributes to as much as possible easy and reliable operation of the facility. However, the plant is complex and should be carefully designed in the next phase to overcome any questions on reliability and availability.

Adequate maintenance record for the ASU, gas cleaning and conditioning and biomass boiler units, are well documented from extensive commercial operation in the international power and petro-chemical industry. Fluidised bed gasifiers are available for power and heat applications, also as pressurised units but not with oxygen as gasification medium. Gas CO-shift conversion and gas compressors are widely used within the chemical and petroleum industries.

The high system pressure downstream of the gas compressor provides a buffer of syngas, thus, stabilising plant operation especially during load changes. Operation of the FT-synthesis on a very pure fuel gas will lead to low maintenance demand for the FT-section. A planned shut-down is estimated to 3 weeks per year.

### 9.5 Plant scale analysis

The fluidized-bed gasification technology is potentially the most significant using solid fuel utilizing synthesis technology of high efficiency and environmentally acceptable performance. The specific investment cost of fluidized-bed is moderate compared to indirectly heated fluidised bed (double-bed) gasification technology, which can not be of same larger scale either. However, the entrained-flow plants may well be preferred for a very large plant but with the costly requirement of a pre-treated fuel that meet specific targets for the pressurisation and an extremely low retention time in the reactor.
The different gasifier concepts at different biomass fuel scales, are thus in-direct heated fluidized bed for a smaller plant possibly up to 100 MW per reactor, directly heated fluidized bed is limited to possibly 250 MW per reactor and the entrained flow reactor up to about 1000 MW (like the reactor of Choren). This estimate is shown for comparison purposes and not seen as strict limitations of the reactors. In conclusion, for a large plant the direct fluidized bed technology is estimated to be preferred although an economic analysis and energy comparison have not been done.

The optimum scale of a plant depends also on the availability of biomass in the surroundings and the market for its products, as well as the technology being used. In general it is not economical to transport biomass further than 100-150 km radius distance by truck from the plant. However with changing markets and new biomass production plants coming in to place this depends on location and situation.

### 9.6 Possible technical improvements

Based on earlier experience and results, this study has chosen one possible configuration and design base. However, there are many variables and in terms of reviews of a number of alternative combinations of gasifier pressures, recirculation quotients, fuel moisture contents, recirculation etc can be made, only for the biomass gasification plant. In addition, there is the possibility to integrate a gas turbine for the offgas or separate product gas to enhance the power production over a standard steam turbine. The plant would cost more and increase the complexity but the efficiency would be higher. Some studies that detail the technology status can be found at [15], [67].

A number of different processes have been briefly evaluated. There are, however, many alternative processes and configurations than what were chosen. In conclusion, there are a several optimisations, which should be made additionally. In order to achieve this, firstly, thorough engineering process evaluations with the suppliers should be made. Secondly, complete process modelling to calculate their performances is needed. It is a belief that this not only would improve the energy and economy results with higher accuracy but also would ensure in the long run necessary durability, reliability, availability and maintainability for a well-engineered large plant like this.

### 9.7 Technical and economical results

The main results are very promising, showing high efficiency and competitive production costs. There is option for much optimisation as there are several variables and alternatives that have not been calculated in detail. The objective here was to investigate a plant which would be relatively simple and robust with reliable performance. Still it must be said that the processes are complicated and on their own a major undertaking task.
The investment cost is rather steep but the plants are also large to produce 50 000 tonnes of bio-jet to make Arlanda Airport carbon-neutral in terms of aviation fuel for air traffic. With the technical optimisation process there is room for reducing the investment costs, however, the uncertainty of these calculations and results limits on how defined conclusions can be made.

The Brista plant shows production costs that are not competitive with today’s conventional jet fuel at a crude oil price of $67 per barrel. However, with future emission trading included in the price and a slightly larger plant it is likely that this plant would be competitive. Still the Igelsta plant shows several benefits with an FT-product that is shipped to a refinery for upgrading into a jet fuel. Already this is tentatively competitive, albeit at very large scale. And a presumption is that a smaller, 400 MWth plant would still be competitive. There are thus economical arguments for a biorefinery to be located at a CHP plant as a base with very good biomass logistics and potential that would produce a FT-product.

Interestingly the other airport in Stockholm, Bromma Airport, have an LTO fuel use of about 14 300 tonnes (2008) and with same assumption as for Arlanda the bio-jet fuel consumption would be about 5300 tonnes per year. Thus, with a 10 % increase of the biorefinery to 55 000 tonnes per year the whole of Stockholm City would have carbon-neutral air emissions from the air traffic. Stockholm could therefore lead the way of becoming 100 % green and reduce the oil dependence significantly.

It is fair to say that the process showed is the preferred alternative over other biomass based jet fuels (origin like algae, coco-nut, rapeseed etc) that is demonstrated or suggested. A strong argument is that the produced bio-jet fuel is valid for use as blend according to today’s standards with conventional jet fuel.

In conclusion to this report, the bio-jet fuel product would most likely be accepted as jet fuel blend and this report shows two interesting plant configurations where an intermediate FT-product for further upgrade into bio-jet fuel production would be competitive already with today’s prices and costs. It is therefore a summarising recommendation that this work is continued for a detailed feasibility study with supplier contacts and further technical optimisation. The basis for a plant would be the location at a CHP plant for the district heat network but also the most important biomass logistics and option of power production.
10 Abbreviations and acronyms

The following abbreviations and acronyms used in the report are here explained.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACARE</td>
<td>Advisory Council for Aeronautics Research in Europe</td>
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<tr>
<td>AFAB</td>
<td>Arlanda Bränslehantering AB</td>
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<td>AVTUR</td>
<td>Aviation Turbine Fuel</td>
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<td>AVGAS</td>
<td>Aviation Gasoline</td>
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<td>AGR</td>
<td>Acid Gas Removal</td>
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<tr>
<td>ASU</td>
<td>Air Separation Unit</td>
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<tr>
<td>ACARE</td>
<td>Advisory Council for Aeronautics Research in Europe</td>
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<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
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<tr>
<td>ATR</td>
<td>Auto-Thermal Reformer</td>
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<tr>
<td>BFB</td>
<td>Bubbling Fluidised Bed</td>
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<td>BFW</td>
<td>Boiling Feed Water</td>
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<td>BTL</td>
<td>Biomass To Liquids</td>
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<tr>
<td>BLG</td>
<td>Black Liquor Gasification</td>
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<td>BLG MF</td>
<td>Black Liquor Gasification with Motor Fuel production</td>
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<td>CTL</td>
<td>Coal To Liquids</td>
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<tr>
<td>CFB</td>
<td>Circulating Fluidised Bed</td>
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<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
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<td>CO</td>
<td>Carbon monoxide</td>
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<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
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<tr>
<td>CAAFI</td>
<td>Commercial Aviation Alternative Fuels Initiative</td>
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<tr>
<td>CEPCI</td>
<td>Chemical Engineer’s Production Cost Index</td>
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<td>DH</td>
<td>District Heat</td>
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<td>DWT</td>
<td>Dead Weight Tonnage</td>
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<td>DSTAN</td>
<td>UK Defence Standardization</td>
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<tr>
<td>DARPA</td>
<td>Defence Advanced Research Projects Agency</td>
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<tr>
<td>ECATS</td>
<td>Environmentally Compatible Air Transport System</td>
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<td>ETS</td>
<td>Emission Trade System</td>
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<tr>
<td>EPC</td>
<td>Engineering Procurement Construction</td>
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<td>FAA</td>
<td>Federal Aviation Administration</td>
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<tr>
<td>FT</td>
<td>Fischer-Tropsch</td>
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<td>GTL</td>
<td>Gas To Liquids</td>
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<tr>
<td>GE</td>
<td>General Electric</td>
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<tr>
<td>GROT</td>
<td>Grenar och Toppar (Branches and tops)</td>
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<tr>
<td>GHG</td>
<td>Green House Gas</td>
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<tr>
<td>HRJ</td>
<td>Hydro-treated Renewable Jet</td>
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<td>H₂</td>
<td>Hydrogen</td>
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<tr>
<td>HHV</td>
<td>Higher Heating Value</td>
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<td>HRSG</td>
<td>Heat Recovery Steam Generator</td>
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<td>HP</td>
<td>High Pressure</td>
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<td>HPC</td>
<td>Heavy Paraffin Conversion</td>
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<td>IATA</td>
<td>International Air Transport Association</td>
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<tr>
<td>kWe</td>
<td>kilowatt electric</td>
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<tr>
<td>LHV</td>
<td>Lower Heating Value</td>
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<td>LP</td>
<td>Low Pressure</td>
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<tr>
<td>LTFT</td>
<td>Low Temperature Fischer-Tropsch</td>
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<td>kWh</td>
<td>kilowatt hour</td>
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<tr>
<td>kWith</td>
<td>kilowatt thermal</td>
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<td>mg</td>
<td>Milligram</td>
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<tr>
<td>MC</td>
<td>Moisture Content</td>
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<tr>
<td>MJ</td>
<td>Mega-joules</td>
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<tr>
<td>MW</td>
<td>Mega-watt</td>
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<tr>
<td>MIT</td>
<td>Massachusetts Institute of Tech.</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>ppm</td>
<td>Parts Per Million</td>
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<tr>
<td>PARTNER</td>
<td>Partnership for Air Transportation Noise &amp; Emission Reduction</td>
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<tr>
<td>PSA</td>
<td>Pressure Swing Adsorption</td>
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<td>RH</td>
<td>Relative Humidity</td>
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<td>RSB</td>
<td>Roundtable on Sustainable Biofuels</td>
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<tr>
<td>SEK</td>
<td>Swedish Krona</td>
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<tr>
<td>SPR</td>
<td>Slurry Phase Reactor</td>
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<tr>
<td>SMDS</td>
<td>Shell Middle Distillate Synthesis</td>
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<tr>
<td>TFBR</td>
<td>Tubular Fixed-Bed Reactor</td>
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<tr>
<td>US</td>
<td>United States</td>
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<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>UCO</td>
<td>Unconverted Oils</td>
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<tr>
<td>VSA</td>
<td>Vacuum Swing Adsorption</td>
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<td>VGO</td>
<td>Vacuum Gas Oil</td>
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<tr>
<td>XTL</td>
<td>(X)-Anything To Liquid</td>
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</table>
11 References

11.1 Internet

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Fortum www.fortum.se
GTC www.gasification.org/
GTI www.gastechnology.org/
Grontmij www.grontmij.se
IEA Bioenergy www.ieabioenergy.com/
LFV www.lfv.se
Lurgi www.lurgi.de
Nord Pool www.nordpool.com
Nykomb Synergetics www.nycomb.com
Preem www.preem.se
SAS www.sas.se/sv/Om_oss/
Sasol www.sasol.com
Shell www.shell.com
Skogsindustrierna www.skogsindustrierna.org
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Appendices

A  Stockholm-Arlanda Airport

B  Fischer-Tropsch research at KTH
A Stockholm-Arlanda Airport

Stockholm-Arlanda is Sweden’s largest airport and an important hub for both the Stockholm region and Scandinavia – with 167 destinations around the world, and extensive ground transport services to and from other parts of the Stockholm region. Running an airport is all about maximizing the benefits of aviation while minimizing its negative consequences.

A.1 Environmental achievements

Stockholm Arlanda Airport has an extensive environmental programme containing continuous work with minimizing the effects from the airport and the connected aviation and ground transport. The environmental work includes minimizing noise issues, decreasing emissions to air and water, attaining a high recycling of waste material, minimizing energy consumption and much more. The environmental issues have a high priority at the Airport.

Local air quality is an important issue to Stockholm-Arlanda airport. The concentrations of pollutants in the air at the airport are similar to those in an average middle sized town in Sweden. Measurements of pollutants and inventories of the effects on trees close to the airport are conducted continuously every month respectively yearly.

For the LFV group, the Swedish State enterprise that owns and operates Stockholm-Arlanda, the climate change issue has been a high priority for many years. Through a series of measures in the space of four years, LFV has more than halved the carbon dioxide emissions from its own operations at Stockholm-Arlanda. These operations include space heating of buildings, electricity consumption and the company’s own airport vehicles where fossil fuels gradual are exchanged for renewables. LFV’s goal is to reduce its own carbon dioxide emissions at Stockholm-Arlanda towards zero by 2012. Stockholm Arlanda Airport also work close together with airline companies and ground transport companies/authorities to achieve emission reductions connected to aviation and ground transports to and from the airport.

A.2 Ground transports to and from the airport

Stockholm-Arlanda has one of Sweden’s largest train stations. The airport is served by regional trains, commuter trains and high-speed trains from central Stockholm. Air passengers and airport-based employees may also choose to travel on a number of different bus and coach routes. Several bus routes to and from the airport are already served by ethanol-powered buses, and during 2008 Airport Coaches began running its vehicles on locally produced rapeseed-based diesel. The intention of the public transport authorities serving the airport is to ensure that by 2011, 90 % of the buses providing service to and from Stockholm-Arlanda will be powered with renewable fuels.
But is it possible to increase the share of passengers and employees choosing public transport to 50% when already 45% is a high level?

First of all, to enable as many people as possible to choose public transport, it must be sufficiently reliable and efficient. Timetables and the location of routes must be adapted to the existing needs of passengers as well as airport-based employees. Today LFV furnishes public transport authorities with facts about passenger flows to and from the airport, and on Stockholm-Arlanda’s website there is information about public transport to and from the airport. Stockholm-Arlanda has also expanded its marketing of public transport to and from the airport. Certain measures are already in place, among other things clear information starting in the arrival hall about available public transport choices.

To increase the percentage of employees who utilise public transport alternatives to and from their workplace the public transport alternative’s attractiveness has to increase. The possibility of creating a common subsidised public transport card for employees based at the airport are therefore being investigated. LFV also pursues a continuous dialogue with public transport authorities to better adapt timetables to the working hours of airport-based employees. The airport is open round the clock and employees must be in place before the large flows of passengers early in the morning and during the evening and night. The conditions for onward travel from the train station to various workplaces in the airport area have also been improved.

An internet-based service which is offered to all LFV employees at Stockholm-Arlanda makes it easier to find someone to share a ride with to work. The ride-sharing service works both for regular commuting and for single trips.

But there is still a lot of room for improvement when it comes to regional public transport – today driving a car is the only alternative from a number of areas. When it comes to improving the accessibility of public transports to and from the airport, LFV has established a forum for ground transport companies where these actors can pursue a continuous discussion of improvement measures for public transport to and from the airport. Through this forum, opportunities are created for traffic operators to continuously coordinate public transport to Stockholm-Arlanda.

A.3 Ground transport at the airport

During the past years airport-based cars and other vehicles have gradually been replaced by vehicles with the lowest possible emissions, for example biogas or hybrid cars. Vehicle purchasers of other actors have been influenced by the discount LFV offers on the cost of vehicle permits for environmentally clean cars. A vehicle permit is required if the vehicle is to be used within the airport fence.
In 2008 Stockholm-Arlanda Airport initiated a project to reach 100% clean vehicles and to ensure the supply of bio fuels for vehicles operating within the airport by 2012. As a first step to involve other airport-based companies and organisations, LFV conducted a vehicle and machinery inventory focusing on the top-ten users of ground service equipment and vehicles. Next step is a plan for a bio fuel transformation or adaptation of all fossil-fuelled vehicles and machinery operating within the airport. To be able to make the special airport diesel-powered vehicles fossil fuel-free LFV is looking into the potential for using biodiesel or biodiesel blends, most likely based on rapeseed (canola) oil. A bio diesel solution is likely to be the only short-term way to make special airport vehicles fossil fuel-free. In order to make way for modern electrical instead of diesel-powered machinery, electricity infrastructure is also being looked into.

Today, it is possible for airport vehicles as well as passengers cars to fill up the tank with both biogas and ethanol at Stockholm-Arlanda. However, in order to be able to reach our goal we are improving the infrastructure and thus the availability of renewable fuels, primarily biogas and ethanol E85, at the airport. In order to reduce fuel consumption among the vehicles operating at the airport, training in eco-driving are being implemented among employees.

A.4 Air navigation improvements

A green approach means that an aircraft descends continuously from its cruising altitude to the runway. By descending continuously, instead of in stages, the aircraft requires almost no engine thrust, thereby saving fuel and reducing emissions. Green approaches were introduced at Stockholm-Arlanda during 2006 as a part of a collaborative project between LFV and Scandinavian Airlines (SAS). Today green approaches to Stockholm-Arlanda are being carried out jointly by LFV, 60 airlines and international air traffic control organisations.

In “green approaches”, the pilot relies on new technology to determine the aircraft’s landing time at an earlier point in time than before. This means that the aircraft can glide during the final stage of landing, with its engines running at lower speed and without unnecessary waiting time in the air. Fuel consumption and noise are reduced, at the same time as flight precision is improved. For travellers, this results in more reliable arrival times and more rapid processing at the airport. For airlines, the advantages are fuel savings and a more optimally timed logistic process for aircraft turnarounds. Since green approach trials started in January 2006, more than 10 000 such approaches have been conducted at Stockholm-Arlanda. By 2012, 8 out of 10 approaches to the airport shall be offered a green approach.
A.5 Energy consumption at the airport

Stockholm-Arlanda Airport consumes as much energy as a city of 25 000 people. Areas as large as one hundred European football pitches need to be cooled in summer and warmed in winter. Today the airport mainly uses biofuel-based, piped-in district heating and green electricity.

Stockholm-Arlanda Airport has a designated unit, Arlanda Energy, focusing on the airport’s energy issues such as electricity and indoor climate. Its task is to improve the airport’s energy operations, reduce energy consumption and lower the environmental impact of energy use.

Today the airport mainly uses biofuel-based, mostly wood pellets, piped-in district heating. Since Arlanda Energy was formed, it has expanded the district heating system throughout the airport, including airport-based companies and organisations, thereby greatly reducing the use of oil heaters. Arlanda Energy is now developing solutions for the last handful of oil-fuelled heaters at the airport and by 2010 the last oil-fired energy production units will be taken out of service. LFV, which owns, operates and develops the airport, purchases “green electricity certificates” equivalent to its entire electricity consumption. These certificates guarantee electricity production from exclusively renewable sources, that is, wind, solar, hydropower and/or biofuels. LFV’s net carbon dioxide emissions from space heating of its own buildings and from the production of the electricity that it purchases are thus regarded as being zero.

But energy consumption is not only associated with environmental impact, but also with large costs. Through different measures over a two year period LFV has reduced its energy consumption at Stockholm-Arlanda by 18%. This is equivalent to a full year’s consumption at Göteborg-Landvetter Airport, Sweden’s second largest airport. The target for 2010 is that LFV’s energy consumption at Stockholm-Arlanda shall be 30% lower than it was in 2005.

A.6 The aquifer – the world’s largest energy storage unit

The Brunkeberg Ridge runs in an arc from Stockholm via Stockholm-Arlanda to Uppsala. Within the ridge groundwater, confined between layers of sandstone and rock, creates a submerged aquifer area next to the airport. With temperature storing properties like a giant “thermos” this huge groundwater reservoir, the aquifer, is used to make energy production at Stockholm-Arlanda both cheaper and more environmentally friendly.
The construction of an aquifer-based heating and cooling storage system at Stockholm-Arlanda began during the autumn of 2008, and the system was taken into service during 2009. In the aquifer waste heat or waste cold is seasonally stored. Warm water is stored during summer to be used for heating during winter. Cool water is stored during winter to be used for cooling during summer. Utilising the geothermic properties of the aquifer will reduce the airport’s annual electricity consumption by 4 GWh and its district heating consumption by around 15 GWh, for a total equivalent to the energy consumed by 2000 single-family homes each year.

How will this system work at Stockholm-Arlanda? In summertime cold water pumped out of the aquifer is used for ground source cooling in the existing district cooling system. The thereby heated water is then returned and stored on the warm side of the aquifer. In the wintertime the flow direction is reversed, and the aquifer storage system delivers low-grade heat from the aquifer storage system’s warm side, at about +15 °C, to preheat ventilation intake air in buildings and in ground heating coils to melt snow in aircraft parking stands. When the water returns to the aquifer, it has cooled back to about +5 °C, and this cool water is stored on the cool side of the ridge until next summer.

The volume of the aquifer is about two million cubic metres of which 30 % is water. In the system no groundwater is consumed; instead the same quantity that is pumped up is also returned to the groundwater reservoir.

With the aquifer-based energy storage system renewable cooling and heating is supplied efficiently to the airport. The aquifer at Stockholm-Arlanda is up to now the world’s largest energy storage unit and up to six or seven times as efficient as other energy storage units. Earlier cooling of LFV’s buildings at Stockholm-Arlanda have largely been employing water from a nearby lake, Halmsjön, enabling the airport to reduce the number of cooling units containing environmentally hazardous CFCs (freons). With ground source cooling from the aquifer storage system in summertime and lake water cooling from Halmsjön in wintertime 100 % of the airport’s cooling needs comes from our own renewable energy production.

A.7 Aero engines

Aircraft used for commercial flights normally weigh more than 6 tonnes. At the upper limit are the Boeing 747 with a maximum take off weight of about 400 tonnes, and the Airbus A380 with some 580 tonnes. However, the A380 is too large for Arlanda airport.

These aircraft are almost always powered either turboprop engines or jet engines. Internally both types have a gas turbine that converts the chemical energy in the fuel to mechanical energy. Gas turbines are preferred over piston type engines because of better maintenance records, higher power to weight ratio, and also a higher maximum power. The economical as well as the technical choices are also influenced by the fact that the conversion efficiency is higher for the gas turbine.
Turboprop engines use most of the mechanical energy to drive an external propeller, which then drives the aircraft. These engines are mostly suited for aircraft with speeds up to some 600 km/hour. Above that the efficiency of propellers is reduced when tip speeds exceed the speed of the sound, but modern propeller technology has increased the speeds at which turboprops can be used.

Jet engines, or turbojets, are used at higher speeds. Commercial jet liners generally fly below the sound speed, but these engines can also be used for speeds above the sound speed with properly designed aircraft. The engine produces thrust by accelerating the air and combustion gases that pass through it. In modern engines only a part of the flow actually passes through the combustion system or core engine. For large commercial engines this can be a tiny fraction. The air that passes through the engine but not through the core is accelerated by a system of fans that essentially are propellers inside a kind of shroud.

Engine size is affected by many criteria. The ability to accelerate to take-off speed along suitably long runways is critical to air safety. Essentially the combination of available runway length and take-off speed and weight puts a limit on the propulsive power generated by the engines that are necessary to have on an aircraft. A second criterion that affects engine size is the ability of the aircraft to climb. And a third criterion is to produce enough power at cruise to propel the aircraft at the design speed.

Generating thrust at low speeds is however vastly different from generating thrust at high speeds. Doing this with the same engine on the runway and at cruise means some trade off has to be made, and this is one important part of aircraft design.

Power is generated in the engines by burning fuel and converting the energy of the hot and high pressure gases to mechanical energy by turbines. The fuel flow during take-off of a Boeing 747, powered with four RB211-524H, is about 1.91 kg/sec and engine, or between 4 and 8 tonnes per hour depending on the specific aircraft and load. The amount of chemical energy released by burning this fuel corresponds to some 325 MW [37]. Only about 35 % part of this is however converted into useful mechanical energy and of this only some 80 % into useful thrust. The limits on this conversion are set by thermodynamics and propeller or fan efficiencies.
B Fischer-Tropsch research at KTH

B.1 Division of Chemical Technology

With considerable help from Prof. Sven Järås and Ph.D. student Sara Lögdberg, et al of the School of Chemical Science and Engineering at the Royal Institute of Technology (KTH) a wider and deeper understanding and modelling of the Fischer-Tropsch process has been made of which the authors would like to acknowledge. In addition, Ass. Prof. Krister Sjöström has also provided knowledge in biomass gasification process technology. This combined on-going research since many years have based some of the process selections and the material and energy balances. Their current research is described more in this chapter.

The Division of Chemical Technology is involved in the study of industrial systems for chemical conversion of matter and energy. Research interests include catalysis and catalytic processes, biomass fuels from gasified biomass, process analysis as well as reaction engineering and system analysis. The research is mainly focused on environmental aspects and a sustainable development. The turnover is about 20 MSEK/year of which 10–12 MSEK concern the way gasification of biomass and the following upgrading to fuels (mainly Fischer-Tropsch).

Within the framework of these areas, the following projects are carried out:

- Gasification of biomass for production of CO, H\textsubscript{2} and CH\textsubscript{4} of different ratios.
- Analysis of total tar in producer gas
- CO\textsubscript{2}-neutral diesel from gasified black liquor (FT)
- Partial oxidation of methane to CO and H\textsubscript{2} and Gas-to-liquid processes
- Preparation of biodiesel and Fischer-Tropsch gasoline from waxes
- Preparation of fuel from waste products
- Process development of co-production of Fischer-Tropsch Diesel and Synthetic Natural Gas (SNG) from biomass derived syngas
- Production of ethanol from synthesis gas
- The catalysed water-gas-shift reaction
- Development of high-temperature stable catalytic combustion catalysts for rocket engines
- Development of protein-based nano-system for drinking water treatment
- Energy efficient reduction of exhaust emissions from vehicles
- Next generation heat-integrated fuel reformer for automotive applications.

The staff in the department amounts to 25 employees headed by Prof. Sven Järås. The scientific team comprises one professor, two associate professors, three researchers and fifteen PhD students. Members of this group have many years of experience, from both industry and university, in the preparation and characterisation of catalysts (both zeolites and transition metal based catalysts) and catalytic processes. The Division has so far been involved in more than 25 European projects.
B.2 Description of FT research

A recently started project is *Preparation of biodiesel and gasoline from waxes produced by the Fischer Tropsch process* with research leader Professors Magali Boutonnet and Sven Järås with Francesco Regali. The project concerns the development of a method that produces bio-based diesel and gasoline. This is of great interest as this study also concerns wax hydrocracking with the objective of bio-jet fuel production.

The project is a cooperation between the Universities Chalmers and KTH, and is based upon the Fischer-Tropsch process (FT) for diesel and gasoline production. The FT process starts from a synthesis gas consisting of CO and H₂ from gasified biomass and produces among other things waxes and light hydrocarbons. The project consists of three parts:

1. Co-gasification of biomass with PET coke (residue from a refinery) to synthesis gas,
2. Development of a hydrocracking catalyst which is tailor made for waxes and the problems around bio-based fuels and that produces wanted diesel and
3. Development of a heterogeneous alkylation catalyst and process for the light hydrocarbons (C₂ – C₄) which produce specially gasoline.

The foremost current project of interest is *CO₂-neutral diesel from gasified black liquor* with research leader Professors Sven Järås and Magali Boutonnet with Sara Lögdberg. The objective of the project is to study the production of CO₂-neutral diesel from gasified biomass (black liquor) by the Fischer-Tropsch (FT) process. The starting point is to investigate how the selectivity to heavy waxes (the precursor to diesel), and the activity in the FT-process are affected by the size of the cobalt (or iron) particles on the catalyst, possibly in combinations with support materials with different pore sizes.

This is done with the aim to improve the state-of-the-art FT-catalysts so as to increase the selectivity to the desired product (i.e. heavy waxes), and hence to reduce the cost for the active metal/s. This will first be tested for a feed gas with a molar H₂/CO ratio of 2.1, which is the optimal value for production of heavy waxes. Later, a feed gas resembling the composition of the synthesis gas obtained from gasified biomass without water-gas-shift (WGS), will be tested. This implies e.g. a lower H₂/CO ratio and a higher water content of the feed gas.

The research work has been performed in close cooperation with the Department of Chemical Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim and part of the work also included the department of Chemical and Biological Engineering at Chalmers University of Technology in Gothenburg.
The department of Chemical Engineering at NTNU has 20 years of experience in FT and a close collaboration with StatoilHydro. The FT experiments were up to 2008 run at NTNU by Sara Lögdberg, but since the beginning of 2009 there is a FT set-up working at KTH which is used for further studies on FT and methanation (synthetic natural gas).

The FT research at the division was hitherto financed mainly by the Swedish Energy Agency and the work has focused on development of cobalt-based FT catalysts. The fields of interest with respect to FT at KTH, NTNU and Chalmers during the recent years include for instance:

- Elucidating what parameters govern the FT selectivity and activity
  - Co particle size
  - Support material
  - Pore size
  - Water partial pressure in the reactor
  - Conversion level
  - Effect of secondary reactions (olefin readsorption)
- Preparation of catalysts with high selectivity to longer hydrocarbons (e.g. \( S_{5+} \)) and high activity
- Elucidating the FT mechanism
- Investigation of using gasified biomass as a feedstock to FT synthesis by means of using a \( H_2 \)-poor synthesis gas (\( H_2/CO < 2.1 \)).

Some of the recent achievements of the above-mentioned three departments, with collaborators, will be briefly touched upon here. As to the FT activity it has been found that for Co particle sizes above approximately 6-8 nm the site activity is relatively constant, irrespective of support material [1,2]. When rhenium (Re) is added as promoter, which increases the reducibility of Co and thereby the number of active sites, a slightly higher site activity has been found. However, by using SSITKA (steady state isotopic transient kinetic analysis) it was found that the true intrinsic site activity was not affected by the presence of Re, but that Re increased the site coverage of active species leading to the hydrocarbon products [2]. By using SSITKA it was recently shown that for Co particles smaller than 6 nm, the intrinsic site activity is lower [3].

As to FT selectivity it has been found that when using an inert support material, such as carbon nanofibers, the selectivity to \( C_{5+} \) decreases with decreasing Co particle size under 6 nm, while the \( S_{5+} \) is constant for larger Co particles [3]. Borg et al. [4] showed that when using the incipient wetness impregnation technique (IW) on \( \gamma \)-Al\(_2\)O\(_3\) with different pore sizes (4 - 24 nm), a positive correlation was obtained between the pore size and the \( S_{5+} \).
However, as also the Co particle sizes (10-15 nm) were positively correlated with the pore sizes, which are a drawback of this preparation technique, it was not possible to determine whether the effect was due to the Co particle size or the pore size. A later study, in which a different preparation technique was used, allowed for preparation of differently sized Co particles on a single γ-Al₂O₃ support (pore size ~11 nm) [5]. The \( S_{C5^+} \) increased with Co particle size up to 8 nm and then slightly decreased and levelled out.

For an \( \alpha \)-Al₂O₃ support (pore size ~16 nm) the maximum \( S_{C5^+} \) was obtained at 11 nm after which the \( S_{C5^+} \) declined with increasing Co particle size. For a similar Co particle size, the \( \alpha \)-Al₂O₃ supported catalysts, however, always had higher \( S_{C5^+} \) than the \( \gamma \)-Al₂O₃ supported [5]. This was also found for TiO₂-supported catalysts with pore sizes of approximately 250 nm [6]. For TiO₂-supported catalysts, however, an increase in \( S_{C5^+} \) with increasing Co particle size was observed for the whole range of studied Co particle sizes (10-33 nm) [7]. Conclusively, there is a Co particle size effect on the \( S_{C5^+} \) within each support material, but no overall trend. Hence, also the properties of the support material, physical or chemical, determine the \( S_{C5^+} \).

In a paper currently in preparation [8] recent findings are described showing that irrespective of the catalyst properties (e.g. Co particle size, support material, degree of reduction, wt % of Co, Re addition or not), the selectivities (\( S_{C1^-C6} \) are measured) are correlated with each other in a specific way for each set of experimental conditions (see Figure 25 below).

The existence of these correlations implies that from only one selectivity, e.g. \( S_{C1} \), the higher selectivities may be estimated reasonably well. The existence of these correlations also tells some things about the mechanism of FT on Co-based catalysts. For instance, it may be concluded that methanation and chain-growth occur on the same type of catalytic sites.
As it was found that TiO$_2$-supported catalysts had high S$_{C5+}$ even with small Co particle sizes, an alternative preparation technique to the standard IW technique was developed [9] to prepare relatively small Co particles on TiO$_2$, since small Co particles would give a higher activity per gram Co (as long as they are larger than 6 nm). The microemulsion (ME) technique resulted in a 60% higher C$_5^+$ production rate (gC$_5^+$/gcat,h) for a 12wt% Co/TiO$_2$ catalyst, as compared with the IW-prepared, as measured after five days on stream. The smaller Co particles of the ME-prepared catalyst however deactivated more rapidly than the larger ones.

The research on using a H$_2$-poor synthesis gas directly in a FT reactor has resulted in two publications [10,11]. It is well known that there is a positive correlation between the partial pressure of H$_2$ and the FT activity. The general conclusion from the two publications is that both single-metal Co or Fe catalysts, and bimetallic Co-Fe catalysts, did not have a high enough water-gas shift (WGS) activity to produce the stoichiometric amounts of H$_2$ needed for the FT reaction, and hence the activity was much lower for these runs compared with the stoichiometric runs (i.e. H$_2$/CO = 2.1) due to the lower partial pressure of H$_2$. 

Figure 25. S$_{C1}$-S$_{C4}$ vs S$_{C5+}$ for 37 different Co-based catalysts in period A (gray, filled symbols) and B (open symbols). Conversion in period A is different for each catalyst varying between 3.5% and 30%. Conversion in period B is ~40%. Experimental conditions: fixed-bed reactor, 483 K, 20 bar, H$_2$/CO = 2.1, catalyst pellet size 53 - 90 μm. Regression lines are based on data points obtained in period B.
Also mechanical mixtures of Co catalysts and traditional WGS catalysts (Cu-based) have been tested, but even though a high WGS activity was achieved (i.e. an increased H₂ concentration), the mixture gave a lower FT production rate (per gram Co) than the single Co catalyst (per gram Co). The reason for this unexpected behaviour remains unclear, but one may speculate that the partial pressure of water, one of the main FT products, is more important for the FT activity than what has hitherto been reported in literature. A high WGS activity automatically implies a low water partial pressure in the reactor as the formed water is reacted with CO to form H₂ and CO₂.

References:

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