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# Aviation Biofuel Production in Sweden

## An Insight into the Potential of Forestry Biomass as a Feedstock

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# Abstract

Civil Aviation is one of the fastest growing sectors on earth, for which emissions currently account for between 2 and 3% of the global total (International Air Transport Association, 2013). Decarbonising the aviation sector is a key challenge on the international agenda, for which sustainable alternative fuels stand as playing a future role. Biofuels for aviation (biojet) have shown to be energy efficient, safe and generate significant emissions savings (Faaij & van dijk, 2012). Efforts are currently underway to accelerate biojet fuel development through establishing global and regional supply chains for commercial production, yet high production costs, relative to fossil based fuel production stands as the fundamental hurdle preventing commercial scale production.

The Nordic region is characterised as having good potential for biofuel production, prompting studies throughout Norway, Finland and Denmark. Similar environmental conditions are found within Sweden, yet a Swedish regional investigation into biojet production opportunities is yet to be carried out. This research identifies key opportunities and barriers to establishing a biojet production system within Sweden using available forestry biomass as a feedstock.

Findings indicate that the availability of forestry biomass resources, infrastructure and knowledge present within the Swedish system could support the establishment of a biojet system, yet high production costs and a lack of policy support create unfavourable market conditions. Future efforts to establish biojet uptake in Sweden may include lobbying for policy change at the national level to recognize aviation emissions when setting policy targets. The process of facilitating collaboration through linking actors in the field, both within Sweden and throughout the wider Nordic region, is an essential non-technical component to streamline future potential supply chain pathways.


**Keywords:** Biojet, Forestry, Advanced biofuels, Aviation, Biorefinery

# Executive Summary


### *Background*

Since the Wright brothers built the first gliders over a century ago, modern day aviation has played a key role in the process of globalization and regional development. The ability to travel great distances over short time-spans allows the luxury of trading goods, seeing sights and meeting people previously not deemed possible. The year 2014 will see more than three billion people board an airline somewhere in the world, with a significant portion disembarking in a different country to takeoff. Passenger demand is increasing faster than ever before, thanks to rapid growth of the middle-east and Asia-Pacific region, particularly China.

An unfortunate drawback to the rise in modern aviation aviation is that it is a large contributor to environmental degradation through greenhouse-gas (GHG) emissions, culminating in between 2 and 3% of total global carbon emissions. The raised global environmental concern has prompted airlines to set the world's first set of sector-specific climate change targets, for which biojet fuels are nominated as a key factor in achieving. Currently there are efforts to develop a business case for biojet production, using advanced feedstocks in the Nordic region. To date, studies have been undertaken in Norway and Denmark, yet a thorough nation-wide investigation for Sweden is yet to be carried out.

### *Aim*

The main objective of this thesis is to investigate the opportunities and barriers to producing biojet in Sweden's using advanced forestry biomass as a feedstock. Sweden is a significant producer of forestry biomass, with a well-supported bioenergy sector. The main research question therefore guiding this study is *"what are the main opportunities and barriers for producing biojet in Sweden from forestry resources?"*

In addition, key guiding questions included to shape the analysis are also proposed:

- *How are forestry biomass resources likely to be allocated in the future?*
- *What conversion technologies are available?*
- *What is the role of networks and social interactions with Sweden's bioenergy system?*

### *Method*

The study involved the micro-investigation of three key areas, forming chapters two, three and four of this thesis. These aspects included a review of current investigations happening elsewhere in the world; a review of knowledge regarding bioenergy systems and the processes behind the technical and social components; and finally an in-depth look at Sweden's energy system and existing environment with regarding to biomass sources and infrastructure.

The framework selected was adapted from the writings of McCormick (2007), and involved the selection of six key aspects, representative of the key technical and non-technical aspects of bioenergy systems. The technical components include the biomass resources, supply systems and conversion technologies and how they are manifested within a Swedish context. Non-technical factors, that had in previous studies served as core barriers to bioenergy system establishment were then assessed also in light of the Swedish context to identify how common non-technical barriers may serve to drive or constrain a system make-up for biojet in Sweden, given the competing uses that exist for biomass material. Two main theoretical channels were considered in light of the research, and included innovation systems and strategic niche

theory. Although not directly employed within the analytical framework as key headings, these concepts were used to place emphasis on the most important aspects.

Data collection was conducted through a series of semi-structured interviews and questionnaires to understand how the organizational structure of actors, organizations and firms are arranged in the current bioenergy sector, how institutions influence biomass allocation and other activities affecting biofuel development, including opportunities to utilize feedstocks, and the nature of firms to adapt to changes (resilience) to the incumbent regime.

## *Key Findings*

Drivers to a biojet production system within Sweden include common global drivers, such as pollution reduction and fuel security, while local drivers for biojet uptake, such as regional economic development, the removal of biomass through 'thinning' to improve biomass growth, utilisation of industrial plant residues and energy forest establishment for improving soil conditions are common drivers to all biofuels, including biojet. Therefore a biojet uptake within Sweden must be triggered through the introduction of producer incentives favouring biojet production over other fuels competing for the same resource, such as biodiesel or methanol, as well as demand oriented instruments that manipulate the price of biojet fuel to equal or lesser than regular fuel in the short-term, until such time as the technology is able to develop and become naturally cost-competitive. In general, the main barriers to biojet uptake are production costs and political ambitions, and as such, drivers to biojet production are generally stymied by a lack of political support, stemming from the international nature of the aviation industry and the treatment of international aviation fuel as a duty free commodity.

The most suitable conversion technologies available today for the production of biojet, given the nature of the biomass available in Sweden, are the Fischer-Tropsch and Alcohol-to-Jet pathways, yet it is noted that such pathways may be deemed obsolete in the near future given the speed at which new technologies are being developed. There exists a range of firms at the forefront of biofuel technology research within Sweden that also serve to link research institutions and governments to actors in the bioenergy field, including biomass producers, biofuel companies and fuel purchasers. Such organisations are crucial drivers in any bioenergy system and would contribute to driving a biojet system in Sweden.

On a global scale, it was found that in order to reach the global IATA 50% reduction target by 2050, a significant portion of the world's bioenergy dedicated for other uses would be displaced. Within Sweden, it was found that in order to achieve an initial integration of 2% biojet fuel into the commercial mix in Sweden by the year 2020 using forestry biomass, it would require approximately 6.5 % of the equivalent amount of energy currently used per year to produce all transport biofuels in Sweden (approximately 0.44 TWh or 1.61 PJ).

## *Conclusions*

Overall findings suggest that the existing technical conditions within Sweden are conducive for the development of a biojet production system. However, market conditions for biojet in Sweden remain uncompetitive due to the added cost involved in producing biojet fuels when compared to traditional fossil based fuels. Political incentives promoting bioenergy production heavily support the production of road-based biofuels, often incentivising actors holding pivotal access to the resources, technology and infrastructure required for biojet fuel production to invest resources into alternative fuels for the road transport sector. The formation of a global market based measure to reduce aviation emissions has the potential to reform the way aviation is integrated into national emissions reductions targets, thereby potentially generating favourable economic conditions and a revised incentive framework in the future.

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# 1 Introduction

## Global Greenhouse Gas Emissions, Transport and Biofuels

There is overwhelming consensus among climate scientists that anthropocentric greenhouse gas (GHG) emissions are a cause of climate change (IPCC, 2013). Transportation fuel demand, which currently accounts for almost a quarter of global anthropocentric carbon emissions, is predicted to increase significantly in the coming decades in the presence of high oil prices as emerging economies develop and more people have access to motorised transport (Kim, Sen, & Maravelias, 2013; IEA, 2012). Decoupling growth in the transport sector from carbon output presents a key barrier to sustainable development, and will involve a range of implemented strategies across various sectors involving different actors. Demand is growing for new technologies and raw materials that fulfil the needs of transport fuel while offering lower $CO_2$ emission profiles to fossil fuels. Biofuels present a very promising case to fill this role, yet still remain a controversial issue from a range of perspectives (Hillman et al., 2008; Mohr & Raman, 2013).

All combustible biological matter is considered bioenergy and can include wood, crop material, liquors from pulp production, domestic waste and industrial waste. Biofuels include energy carriers[1] that are derived from biomass or biological materials, whose application can lead to life cycle emissions savings when substituted for fossil-based fuels. Living biomass absorbs carbon dioxide ($CO_2$) through photosynthesis, thereby offsetting a portion of the $CO_2$ released through the production of the biofuel and the combustion process. The main drivers supporting the increased uptake of biofuels as an alternative to fossil fuels are fuel security and the potential for net GHG reductions. Production steps involved in biofuel production include feedstock growing, harvesting, pre-processing, transportation, conversion/refining and distribution.

Biofuels can be refined and used to replace traditional motor transport fuels, yet are often unable to compete effectively with incumbent fuels without institutional support. The United Nations Intergovernmental Panel on Climate Change (IPCCs) 5$^{th}$ Assessment Report, *Bioenergy and Climate Change Mitigation: An Assessment* (2014) confirms that bioenergy has an important future role, yet acknowledges that further work is required to observe, verify and measure impacts arising from indirect land use change (iLUC). The plantation of an energy crop can limit the availability of land and resources for the production of other crops. This may result in the exploitation of new land that would not otherwise have been exploited had the energy crop not been established. Resulting effects from iLUC can include biodiversity loss, increased climate change effects, and unstable food prices (Ulmanen et al., 2009). The potential impacts arising from iLUC can be severe, and must be managed appropriately if first generation biofuels are to be seriously considered as a long-term global solution (IPCC, 2014).

The sustainable deployment and use of biofuels must consider economic, social and environmental aspects in balance, which presents challenges to bringing biofuels to market. Recent conjecture regarding the methods of measuring and monitoring iLUC and the associated environmental issues has seen 'next generation' biofuel development, utilizing low impact feedstocks such as wastes and residues. Recent amendments to the EU Renewable Energy Directive (EU RED) has prompted an increased uptake in more advanced feedstocks, including the use of wastes and residues. An EU Press Release stated: *"for biofuels to help us combat climate change, we must use truly sustainable biofuels. We must invest in biofuels that achieve real*

[1] Examples of standard biofuels include pellets, ethanol or biogas

*emission cuts and do not compete with food. We are of course not closing down first generation biofuels, but we are sending a clear signal that future increases in biofuels must come from advanced biofuels. Everything else will be unsustainable".* (EU, 2012)

Advanced or next generation biofuels are produced from lignocellulosic, non-food or residue based raw materials that exhibit low GHG emissions from a lifecycle perspective and result in low or zero iLUC impacts. There are several inherent advantages and future challenges in bringing advanced biofuels to commercial scale production. They are able to utilize the carbon stored within waste biomass, therefore turning waste into a resource. Fast growing perennial energy crops can grow in a wide variety of soil types where other plants cannot, and can have positive impacts on the soil including erosion protection and improved carbon storage, while requiring little resource input (Börjesson, 2008). Despite the inherent sustainability advantages, achieving the production volumes of biofuel from advanced feedstocks necessary for a significant improvement to anthropocentric $CO_2$ emissions is difficult given the relatively limited feedstock supply. Furthermore, residues can be often expensive and labour intensive to collect (Näyhä & Horn, 2012; Xie & Huang, 2013). They require additional processing steps, need to be harvested in very large volumes to produce commercial quantities of fuel and can be unpredictable in times of adverse weather events (IPCC, 2014).

Overall, the cost of bringing new biofuels to market remains a key technical barrier to deployment, with most biofuels produced around the world unable to compete with fossil based diesel or petroleum without assistance through subsidies (MASBI, 2013; Worldwatch Institute, 2007). It is therefore important that opportunities to reduce costs throughout the supply chain are realised, which involves looking into addressing both technical and non-technical issues.

## Why Interest in Biofuels for Aviation?

Aviation is one of the fastest growing and fastest polluting sectors on earth. The International Air Travel Association (IATA) have signalled their intention to become more sustainable through setting numerous key targets and a four-pillar strategy. The development and availability of commercially competitive aviation biofuels (biojet) is an inherent component of this strategy. From the perspectives of the airlines, the use of biofuels in the aviation sector represent the only realistic alternative to incumbent jet fuels in the near-term. Therefore it s argued that biofuels should be prioritized for the aviation sector.

Jet A-1 is a type of jet fuel designed for gas turbine engines, and accounts for more than 95% of commercial fuel (ATAG, 2012). Demand for jet fuel is expected to double by the year 2050, driven by population growth and the emergence of newly industrialised economies bringing more people out of poverty. Also confronting the future of the aviation sector is the price of fuel, which has more than tripled in Europe since the year 2000, prompting Airlines to run on narrower profit margins than in previous years. The raised cost of fuel means that it now accounts for to up to a third of an airlines operating costs (Gegg, Budd, & Ison, 2014). This has contributed towards airlines desire to develop alternative fuels, yet less willing to pay a premium for the fuel. It is therefore up to the customer or through government support that a price premium on biojet can be absorbed.

The introduction of sustainable alternative fuels for aviation is one such method for a lower carbon footprint. Other innovations include improved aerodynamics and operational efficiency, and smarter operational management of airspace. The development of biojet has progressed rapidly since the idea was conceived in 2007, exemplified by test flights since 2008, regulatory approval for passenger flights in 2011, and over 1,500 subsequent passenger flights.

Studies conclude that the production of biojet fuels can reduce life-cycle GHG emissions when compared to fossil-based jet by 60-80%, dependent upon the many variables that are involved in the selected production process (Ramboll, 2013).

Technical specifications require that alternative jet fuels must be of drop-in quality, meaning they can be mixed with regular jet fuel for engine performance as good or better than regular fuel. This allows the use of existing petroleum refining and distribution infrastructure. In order to be accepted as Jet A-1, an alternative fuel must comply with the following certifications:

- ASTM D7566 – Standard specification for aviation turbine fuel containing synthesized hydrocarbons.

- ASTM D4054 – Standard practice for qualification and approval of new aviation turbine fuels and fuel additives.

Three production technology pathways have been approved in accordance with ASTM D7566, namely the Fischer-Tropsch synthesis (FT), Synthesized Iso-Paraffinic (SIP)[2] and Hydroprocessed Esters and Fatty Acids (HEFA) method, for blends not exceeding 50%[3]. All approved methods differ in the raw materials used and processes applied, with varying benefits and challenges.

Drivers to commercial production of biojet fuels include fuel security and climate change mitigation, but these drivers are often overridden by high capital production costs, unfavourable policy settings and the nature of countries to protect their best interests at detriment to the whole. The principle of common but differentiated responsibilities encorporated into the Kyoto Protocol is not suitable for dealing with assigning emission limits on aviation, owing to the homogenous nature of airlines operating across different regions of the world. Alternatively, assigning unilateral targets and environmental regulations can create competition distortion (ATAG, 2012), highlighting the need for market based measures operating beyond national borders.

At the EU level, the recent inclusion of aviation into the EU ETS signals attempts to monetize aviation pollution across international borders, while the Netherlands have included aviation fuels in their renewable energy target under the EU's Renewable Energy Directive. The 38th ICAO assembly in 2013 saw agreement from governments to develop an equitable single market-based mechanism to regulate emissions derived from international aviation at the next ICAO assembly meeting in 2016 for implementation by 2020 (International Civil Aviation Organisation, 2013b).

## 1.1 Problem Definition

Aviation is making an increasingly large contribution to climate change. Aviation emissions are expected to rise by 3% per year (European Commission, 2013; Köhler, Walz, Marscheder-Weidemann, & Thedieck, 2014), and the combustion of aviation fuel currently accounts for 12% of total transport emissions and 2-3% of global emissions[4] (Blakey, Rye, & Wilson, 2011; Telkamp, 2012; IPCC, 2013).

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[2] This production pathway was only recently approved in June 2014

[3] 50% blends of drop in biojet fuels are the maximum blending amount alowed due to the low aromatic compound presence in synthetically derived fuels.

[4] This 2-3% figure however is somewhat misleading. Firstly, most international flights are taken by the wealthy residing in developed economies, for which the proportional $CO_2$ emissions are higher. Emissions from fuel processing and transportation, aircraft manufacturer and maintenance and airport operations are not included in figures.

Bringing biojet fuels to the aviation fuel market is one of several contributing strategies to achieving the IATA goal of reducing 2050 aviation emissions to 50% of 2005 levels[5]. The development of a national biojet production system can reduce GHG emissions, boost national energy security, and drive regional development through local environmental gains, economic growth, employment and technological innovation.

Scoping studies can highlight business development opportunities to investors and relevant information to policy-makers. Studies throughout Europe, the Middle East, the U.S. and Australia show how differences in environmental conditions and land uses can lead to differences in the feedstocks selected for biofuel production, and the nature of social, economic and environmental considerations that must be addressed when planning to establish a biofuel supply chain. There are currently efforts to explore the possibilities of building a business case for biojet production in the Nordic region using regionally sourced feedstocks. To date, studies have been undertaken in Norway and Denmark, but a formal investigation in Sweden is yet to be carried out. To date, no biojet production facilities exist in Sweden.

The key barrier to biojet deployment throughout the world is production costs. In addition to government support and the formulation of a global market mechanism, a streamlined supply chain is essential to reduce costs and encouraging commercial development of biojet fuels. Reduced production costs can be realised through careful planning, strategic selection of feedstocks, leaner production methods and optimized logistic operations. (Worldwatch Institute, 2007).

Forestry biomass covers more than half the land area of Sweden, supports large globally dominant industries for materials and energy, and provides over 22% of Sweden's energy, a figure that has more than doubled in the last 20 years (Swedish Energy Agency, 2014). The amount of forest material collected for biofuel production has high potential to be increased sustainably (Swedish Energy Agency, 2014). This raises interesting questions concerning the future origin and type of biofuel produced in Sweden, and whether the future production of biojet fuel could be managed in unison with road based biofuels. The main objective of this paper is therefore to provide factual information that may highlight potential development possibilities for a biojet supply chain in Sweden, focusing on forestry biomass as a future feedstock.

## 1.2 Research Aim and Focus Question

It is a commonly held view that existing energy and transportation systems are characterized by lock-in and or inertia and are particularly resistant to change (Van der Laak, Raven, & Verbong, 2007). This creates a range of technical and social barriers for new sustainable innovation systems. Biojet produced from advanced biomass feedstocks can play a role in decarbonising the international aviation sector, yet deployment is constrained by costs in competition with fossil fuels and the lock-in of the incumbent socio-technical regime. R&D efforts have overcome many technical aspects, resulting in thousands of demonstration flights and a number of commercial flights using biojet fuels, yet core processes crucial in the organization of an established value chain are still lacking, most notably when it comes to sourcing and processing feedstock. This thesis investigates some of the drivers and barriers of Sweden's forests to supply advanced feedstocks for integration into a biojet production chain. The research undertaken aims to investigate a number of key topics, including:

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[5] The goal of securing a 50% reduction of 2005 global aviation net emissions levels by 2050 was proposed by IATA, ACI, ICCAIA and CANSO.

- The future availability of advanced forestry biomass within Sweden;
- Sweden's energy supply and future demand with regard to forest resources;
- Lignocellulosic biomass conversion technology readiness; and
- Logistical support aspects.

Like any bioenergy system, a successful biojet value-chain involves close communication between a wide array of actors from different knowledge backgrounds, along with the optimization of technical factors. It is therefore important when examining drivers or barriers to producing biojet in a particular region, such as Sweden, to map out who the key actors are and which actions are likely to have the most impact on the success of the system.

A wide range of potential drivers and barriers to the establishment of bioenergy systems exist (McCormick 2007). For this study, core components critical to the formation of a bioenergy system are selected and assessed against Swedish conditions to evaluate the applicability of a biojet production system.

The main research question guiding this study is ***"what are the main drivers and barriers for producing biojet in Sweden from forestry resources?"***

In order to answer this question, the following guiding questions are proposed:

- *How are forestry biomass resources likely to be allocated in the future?*
- *What conversion technologies are available?*
- *What is the role of networks and social interactions with Sweden's bioenergy system?*

## 1.3 Methodology and Analytical Framework

Biofuels receive considerable institutional support in Sweden for road transport, but not for aviation. Technological capacity exists, however the future prospects for aviation biofuels remain uncertain. Research is needed to identify barriers and opportunities for creating a value-chain in a Swedish context, to inform a broader Nordic feasibility study planned for the 2015[6]. The schematic diagram in Figure 1 outlines the thesis research journey in a sequential fashion.

[6] The Nordic Feasibility Study is an initiative undertaken by the Nordic Initiative for Sustainable Aviation.

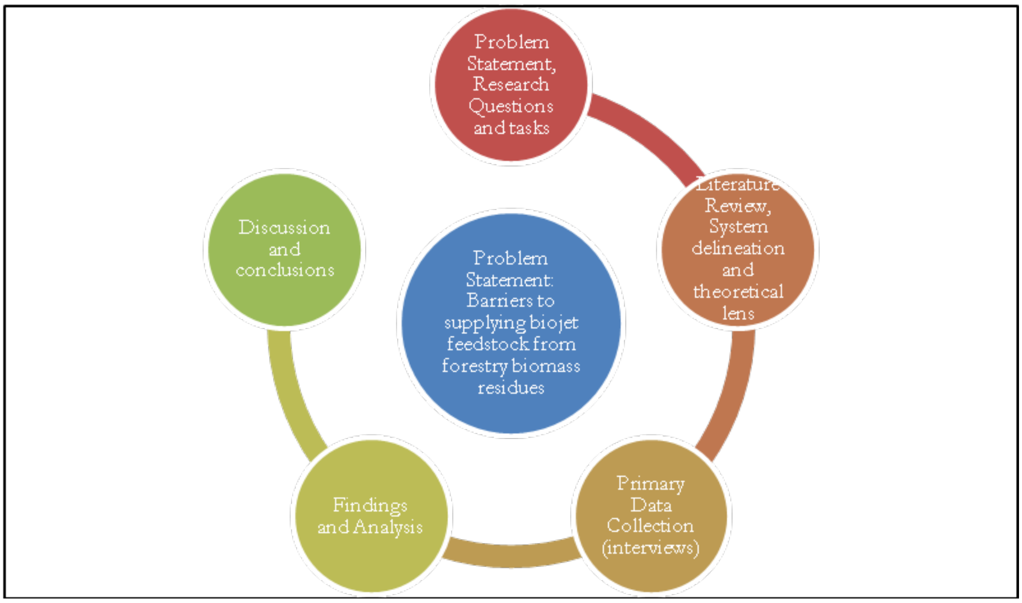


*Figure 1: Research Design*

Preliminary discussions with bioenergy experts and readings suggested studies investigating biofuel production within Sweden should focus on forestry resources, given recent updates to the EU RED favouring advanced feedstocks and the well established industry infrastructure and know-how (Thomas Ekbom, Personal Communication, 2014). This helped direct my focus towards Sweden's forests and the potential role of forestry biomass for aviation biofuel production in Sweden, in particular the harvesting, production and processing phase of biofuel value chain development. Such knowledge provided initial direction to conduct a literature analysis on the state of knowledge of biojet fuels and existing initiatives relevant to the topic. This analysis focused on data triangulation by utilizing various types of resources and publications representing different interests, such as journals, industry publications, government reports, webpages and trade publications. This, along with further discussions with NISA representative Martin Porsgaard, allowed the identification of actors and roles relevant to the topic.

Subsequently, the next stage in the process was to align the subject matter of the study with proven concepts found in literature. Selecting an analytical framework is important because it provides an interpretation for phenomena or process and can guide data collection and analysis.

### 1.3.1 Theory and analytical framework

The selected topic involves studying the critical factors affecting the establishment of a bioenergy system, and several literary theories were reviewed. Innovation systems theory establishes bioenergy systems as comprised of actor networks, driving diffusion through competing, collaborating and interacting (Bergek et al., 2008). Strategic niche management (SNM) is derived from evolutionary theory, and is supported by Schot at al., (2008) and others as a way of explaining how successful innovations emerge, develop and gain commercial acceptance from initially undefined markets. It is a way of describing the mechanisms by which new technologies receive support on the basis of expectations or perceived inherent problems within the incumbent system, and can be used as a way of explaining why an innovation trajectory may succeed or fail (Kemp, et al., 1998). A niche is therefore formed to create a protective space for nurturing improvement through learning, R&D and building the regimes necessary for mainstream acceptance.

Systems are metaphysical constructs and are used by researchers to gain a better understanding of reality. Many researchers, including McCormick (2007), Geels (2004), Hekkert & Negro, (2009) and others have applied systems based thinking to the establishment and expansion of bioenergy systems in Europe and other parts of the world.

This study is unique in the sense that the bioenergy system in focus – Swedish biojet production from forestry biomass – does not currently exist, and is devoid of a market owing to production costs that are unable to compete with incumbent jet fuel production. One aim of this study therefore is to map out the structural elements inherent to a successful bioenergy system, and assess the Swedish conditions for whether or not such components exist. This assessment can then provide insight into the extent to which they could potentially help drive the establishment of biojet production. Conversely aspects inherent to system establishment that are missing or lacking in the Swedish context can be identified and assessed as barriers to establishment.

McCormick (2007), identifies and analyses a range of case studies for expanding bioenergy systems around Europe, concluding that bioenergy systems are comprised of several core components, including *biomass resources; supply systems; conversion technologies; and energy services*. The emergence of a new bioenergy system, such as biojet fuel development from forestry resources within Sweden, must have the foundations for deployment of each core component to be viable. Furthermore, common non-technical barriers including *economic conditions, know how* and *institutional capacity*, and *supply chain coordination* are identified by McCormick & Kåberger (2007) as affecting the development of bioenergy. These aspects have been considered in light of existing and projected Swedish conditions to provide insight on prospects for the establishment of a biojet production system based on forestry biomass within the Swedish context. The components/barriers framework, as adapted from McCormick and Kåberger (2007) is presented in Figure 2.

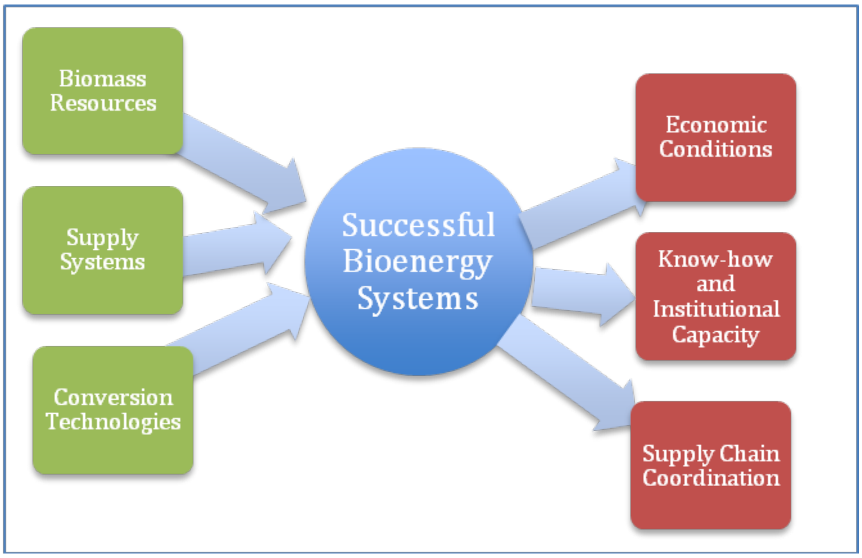


*Figure 2: Key bioenergy system components for expanding bioenergy in Europe. Adapted from McCormick* (2007)

### 1.3.2 Data Collection

Data collection was conducted through a series of semi-structured interviews and questionnaires to understand how the organizational structure of actors, organizations and firms are arranged in the current bioenergy sector, how institutions influence biomass allocation and other activities affecting biofuel development, including opportunities to utilize feedstocks, and the nature of firms to adapt to changes (resilience) to the incumbent regime. This understanding was critical to understanding the views of various proponents in analysing the future prospects of biojet fuel production within Sweden. Interviewees were given the option of conversing over the phone or via an email questionnaire. A total of seventeen (17) candidates were interviewed for the study. All transcripts were compiled following the interview, and interviewees independently approved all quotations included within the study. The interviewee list, along with their representation and date interviewed is provided in Table 1.

*Table 1: List of interviewees and professional profiles*

| Name | Profile |
|---|---|
| Tibblin, Gustav | Business Development Director at Sodra, an economic association managing forestry operations for more than 51,000 forestry owners in Southern Sweden. (Tibblin, personal commincations, 22nd August, 2014). |
| Wintzell, Jan | Business Development Director at Sveaskog, Swedens largest forestry company, controlling 14% of Sweden's forests. (Wintzell, personal communications, 25th July, 2014). |
| Renmarker, Peter | Peter is a chemical engineer and sales manager at Sunpine, a second generation biofuels company located in Piteå, Sweden. Renmarker, personal communications, 5th July, 2014). |
| Karatzos, Sergios | Sergios is a senior manager for Project development at Steeper Energy, a private company specializing in second generation biofuel production through their patented hydrofaction technology. (Karatzos, personal communications, 8th August, 2014). |
| Lindstead, Jan | Jan is the CEO of a small consultant company with a focus on commercialisation of cellulosic ethanol in Örnsköldsvik. (Lindstead, personal communications, 15th August, 2014). |
| Westerberg, Ulf | Ulf is the business development manager for Solander cleantech at Piteå Science Park, a knowledge cluster concerned with bioenergy, biofuel and biorefinery operations. (Westerberg, personal communications, 26th June, 2014). |
| Kempe, Alice | Alice works within biofuels and biorefinery R&D and demonstration. The Swedish Energy Agency provides support and funding for renewable energy ventures within Sweden. (Kempe, personal communications, 26th June, 2014). |
| Karyd, Arne | Arne is a Swedish private researcher with a background in economics, aviation and transport. (Karyd, personal commincations, 13th June, 2014). |
| Nyström, Ingrid | F3 are the Swedish Knowledge Centre for Renewable Transportation Fuels. They are both a research platform and provide information to companies and the public. They are financed by the Swedish Energy Agency and the region of Västra Götaland. (Nyström, personal communications, 13th June 2014). |
| Porsgaard, Martin | Martin is the Director for NISA – the Nordic Initiative for Sustainable Aviation, who serves to promote the commercialization of renewable jet fuels through coordinating collaboration and strengthening networks along the supply chain. (Porsgaard, personal communicatons, 12th June, 2014). |
| Valk, Misha | Misha is a business development manager at SkyNRG, an aviation biofuel production company based in the Netherlands. (Valk, personal communications, 12th June, 2014). |

| | |
|---|---|
| Tornqvist, Frederik | Frederik is the manager for renewable aviation fuels for NesteOil, a refining and marketing company with a focus on renewable fuel production (Tornqvist, personal communications, 18th June, 2014). |
| Börjesson, Pål | Pål is a professor at Lund University and is author of over 50 accredited publications over the last 10 years. His work focuses on bioenergy and biomass, and is an expert of the Swedish system. (Börjesson, personal communications, 18th June, 2014). |
| Larsson, Thorbjorn | Thorbjörn is the Vice President of Statoil F&R Aviation AS, part of Statoil Fuel and Retail, who are a Norwegian Multinational oil and gas company. Statoil Fuel & Retail Aviation supply fuel to more than 75 airports throughout the Nordic region. (Larsson, personal communications, 9th June, 2014). |
| Bruce, Lena | Lena is the Vice President at Svebio, the Swedish bioenergy network. Svebio is a non-profit organization containing members with interests in biofuel developments. Svebio also contributes input to decision-makers around bioenergy related policy. (Bruce, personal communications, 9th June, 2014). |
| Sjöberg, Therése | Therese is an environmental officer within the Swedish Transport Agency, a Swedish government agency under the Ministry of Enterprise, Energy and Communications. (Sjöberg, personal communications, 10th June, 2014). |

Findings were sought to evaluate the applicability of a biojet production system through strength in possessing qualities relating to key bioenergy system components.

## 1.4 Scope

Sweden was selected as a case study for several reasons. It's standing as a global leader in the production and export of bio-based materials[7] and previously successful use of biofuels to reduce its dependence on oil, improve the economy and reduce it's national GHG emissions indicates the existence of knowledge and experience critical for biojet production. In addition, relatively little research has been conducted within Sweden when compared to other surrounding countries, such as Denmark, Norway Finland and the Netherlands. The study is limited to opportunities for producing biojet fuel within Sweden to replace both domestic and international aviation jet fuel, and focuses on the specifications of Jet A-1 as defined by the ASTM D7566 standard.

The prospect of biojet production in Sweden presents a range of challenges. One key challenge focus upon within this study is that of supply – where and how can feedstocks within Sweden by sustainably sourced in the cheapest way possible, and prioritized for use in the aviation sector in the face of many existing well established users of biomass? Sweden's forestry is chosen as the focus as it is by far the largest source of biomass within Sweden, contains well established industries (through the pulp and paper and saw-log industries), thereby possessing well-established networks, infrastructure and know how in extracting biomass sustainably for a variety of uses. The emphasis for this study is to look within these boundaries at both technical and non-technical factors that affect the establishment of bioenergy systems, to highlight potential drivers and barriers to a future biojet value chain utilizing forestry biomass as a resource. Feedstocks studied were scoped to include forestry

[7] Sweden sits behind only Canada in terms of exported wood products.

residues and energy forests (advanced feedstocks) to avoid issues concerning iLUC and conjecture regarding the environmental sustainability of biofuels.

## 1.5 Audience

The target audience for this thesis is mixed. Content of this study may interest firms interested in promoting business development for biojet fuels within Sweden and the broader Nordic region. This study is also intended to provide relevance for policy-makers who are interested in understanding the long-term prospects for biomass resources in Sweden, as well as formulating strategies for prioritizing future biomass stocks and reducing emissions in the aviation sector.

## 1.6 Disposition

This thesis is based upon academic journals, industry reports, guidelines and stakeholder interviews.

Chapter one is designed to provide the reader with a background to the bioenergy topic and the global drivers and barriers for biofuels within the aviation industry. This chapter also introduces the reader to the main focus of the research, as well as key themes of innovation systems theory, evolutionary theory and strategic niche management underpinning the findings and analysis.

Chapter two serves investigate the effect of achieving industry targets for biojet on the global bioenergy industry, to identify key stakeholder initiatives and relevant feasibility studies from around the world, and to review the broad base of knowledge on aviation biofuel developments.

Chapter three introduces the nature of biomass as a limited resource, and as such, identifies strategic management as a vital component in ensuring biomass is utilized in the most optimal way. A review into the development of advanced biofuels in the form of lignocellulose in light of LUC impacts is included to justify the advanced feedstock and conversion methods examined. Following on from this, the emerging biorefinery concept is introduced in light of residue and waste streams within Sweden's forestry industry, forming a key resource stream in Sweden that could potentially be used for biojet fuels in the future.

Chapter four focuses squarely on the case study of Sweden, firstly by highlighting relevant policy affecting the drivers behind allocation of biomass, as well as energy supply and demand. It is under this context that a short-term target for biojet development within Sweden is posited. A review of Sweden's most recent trends in terms of the industrial and energy sectors are briefly explored to understand the main competing areas for biofuel resources, before underlining Sweden as a relatively modest user of aviation fuel on the global scale. This chapter also investigates the volumes of forestry biomass available in Sweden now and in the future, and draws from expert opinion the future potential production of transport biofuels using advanced feedstocks in Sweden based on current studies and trending research.

Chapter five reintroduces the analytical framework selected and presents the findings, categorized into aspects considered inherent to a successful bioenergy system. These aspects, *biomass resources*, *supply systems* and *conversion technologies*, are considered, in addition to analysis of non-technical aspects critical to bioenergy expansion in Europe, which include *market conditions*, *know how and institutional capacity* and *supply chain coordination* in the context of biojet production in Sweden from forestry biomass.

Chapter six presents key points of discussion and reflection that have been formed in light of the research and findings, suggesting directions for future research, while Chapter seven presents the conclusions in light of research questions posed in chapter one.

# 2 Aviation Biofuel Investigations from around the World

*The purpose of this chapter is to investigate the effect of achieving industry targets for biojet on the global bioenergy industry and to review a broad base of knowledge on aviation biofuel developments.*

The global aviation industry provides direct employment to over eight million people and a further 58 million indirectly. It is often the sole mode of transportation for tourists and is also a vital component for the global trade of low volume, high value goods. What is clear is that aviation is here to stay, and hydrocarbon based fuels will be the primary source of energy powering aviation in the coming decades. Over 273 billion litres of jet fuel were used by commercial operators in 2012, responsible for the release of 689 million tonnes (or 2% of all global $CO_2$) emissions (ATAG, 2012). The environmental impact of aviation combined with the nature of aviation being embedded into the economy has prompted significant recent progress in reducing the carbon footprint of the aviation sector, including better fuel burn efficiency, more energy efficient operations and infrastructure and technological development. One aspect whose potential is yet to be realized is that of biojet fuels, which according to the Air Transport Action Group (ATAG) could reduce aviation's $CO_2$ footprint by as much as 40% (ATAG, 2012).

## 2.1 Industry Targets

The International Air Transport Association (IATA) have called for an overhaul of international aviation $CO_2$ emissions, setting commitments to stabilize carbon emissions from 2020 with carbon-neutral growth, and to reduce emissions to 50% of 2005 emission levels by 2050 (See Figure 3).

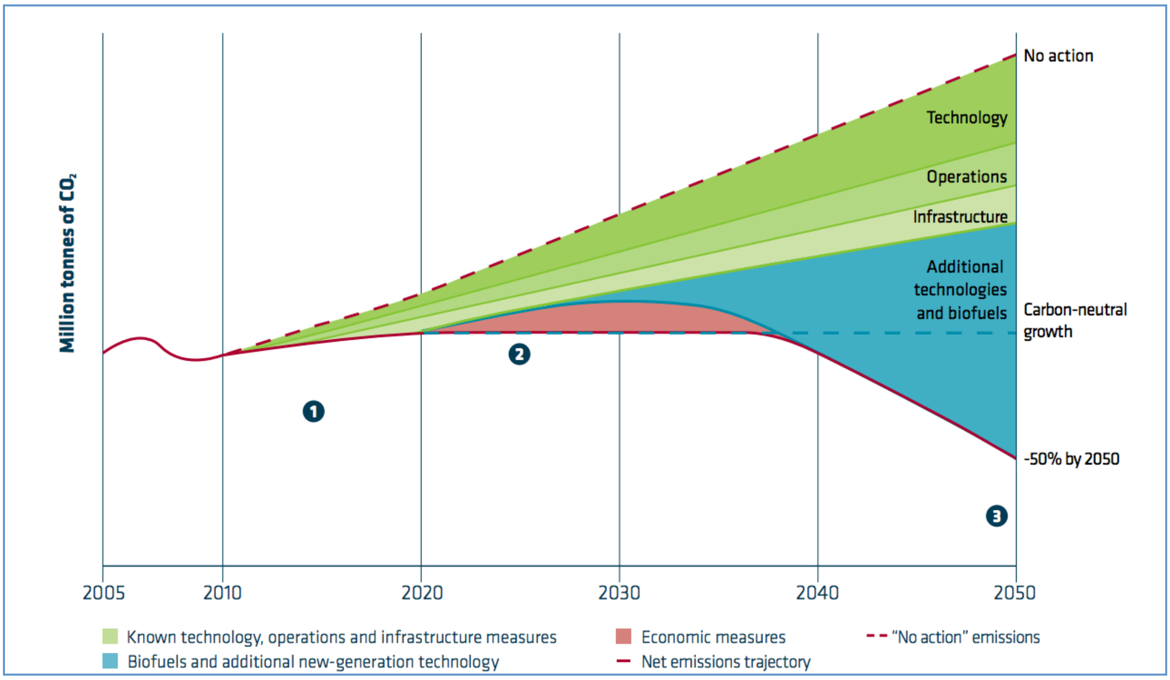


*Figure 3: IATA based industry commitments. 1: 1.5% fuel efficiency per year until 2020; 2: Carbon neutral growth from 2020; and 50% of 2005 emission levels by 2050. Source: IATA, 2013*

In order to achieve these targets, a four-pillared strategy is proposed, for which biojet is identified:

1. Improved technology, including commercial biojet deployment;
2. More efficient aircraft operations;
3. Modernisation of air traffic systems; and
4. Market-based measures, such as the proposed global MBM earmarked for implementation in 2020.

IATA have arguably set very ambitious targets as illustrated in Figure 3 in aiming for net carbon neutral growth from 2020 and a 50% reduction on 2005 emission levels by 2050. According to ATAG, these goals correspond to a biojet fuel implementation rate of 1% by 2015, 15% by 2020, 30% by 2030 and a 50% blend-in rate by the year 2040 (Air Transport Action Group, 2009). The expected annual growth rate of jet fuel demand in terms of compounded annual growth rate (CAGR) is between 2.2% (IATA Economics, 2010) and 3% (Faaij & van dijk, 2012), suggesting the 220 million tonnes of jet fuel consumed in 2012 would will swell to 404.6 million tonnes by 2040 (using the 2.2% growth estimate). This would require an injection of more than 200 million tonnes of biojet by 2040 under the ATAG roadmap, equating to approximately 14.5 EJ of biomass demanded for biojet production globally[8], assuming a 60% conversion factor.

The potential for biomass supply in the future on a global scale depends on a variety of factors, ranging from population and dietary trends, to forest and crop productivity and land availability (Hoogwijk et al., 2003). Studies undertaken by Berndes et al. (2003) and more recently Searle and Malins (2014) estimate the total global biomass supply in 2050 will be between 60-120 EJ/yr, with 10-20 EJ/yr in biofuel, 20-40 EJ/yr in electricity and 10-30 EJ/yr in heating. Within these figure, energy crops are expected to have the greatest impact, while forestry, crop residues and wastes can make up between 10-20 EJ/yr in energy potential. Research within Europe suggest bioenergy yields in the near future will be in the order of between 4 EJ/yr in the short term to potentially 23 EJ/yr[9] in the long-term (McCormick 2007). Such figures mean that in order for the 2040 global target to be reached, almost all biomass used for global biofuels production would need to be allocated for biojet, thereby disrupting production of other biofuels. It also suggests that bioenergy within Europe can be significant but can not meet all energy needs of the future, underlining the ongoing role of incumbent energy producers, strategic allocation of biomass resources and other alternative energy sources, such as solar, wind and hydro, for a transition to a fossil free economy.

A similar conclusion is reached in a report prepared by the Sustainable Way for Alternative Fuels and Energy for Aviation (SWAFEA), in 2011 (Novelli et al., 2011). The report undertook a number of assessments for biomass availability against energy demand for aviation for two scenarios consistent with IATA targets (carbon neutral growth of aviation from 2030 at 2020 levels; and the ambitious 50% reduction of 2050 emission levels to 2005 levels). Both of these targets, according to SWAFEA, represent enormous challenges, requiring very rapid ramp-ups of biofuel production under both scenarios. It was concluded from this report that to reach the 2020 carbon neutral growth objective from 2030, it would be theoretically possible given biomass potentials, but would require 52% of available biomass allocated to biofuels.

Calculations based on available and predicted conversion figures and theoretical potentials show that in order to reach the IATA 50% reduction target, a significant portion of the

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[8] The White Paper on Sustainable Jet Fuel by SkyNRG (Faaij and Van dijk, 2012), use a fuel conversion factor of 1 EJ of energy for every 23 million tonnes of jet fuel

[9] 1 exajoule = approximately 278 terrawatt hours

world's bioenergy dedicated for other uses would be displaced (Novelli et al., 2011). The report also concluded that Europe is likely to be dependent on biofuel imports, and has predicted capacity to produce 38% of required biofuels under the 2020 carbon neutral scenario based on European biomass stocks. In terms of life cycle GHG emissions, it was shown through studies that all considered biofuel production pathways have potential for GHG emissions reductions[10], and their ability to reach the 60% reduction threshold for compliance under the RED depends strongly on the process and cultivation pathway, influenced significantly by agrochemical inputs (Novelli et al., 2011). It is also reported that all potential benefits may be negated if land use change is associated with feedstock production, and that land use change has a higher overall impact on life cycle emissions than the rest of the whole fuel production chain.

Sustainable Aviation (2012) from the UK have released a report detailing a modified road-map to that provided by ATAG. The report estimates that by 2050, biojet fuels will offer between 15 to 24% reductions in $CO_2$ emissions, and a 25 to 40% penetration of biojet into the global market. The goal of reaching a 50% reduction in aviation emissions to 2005 levels by 2050 is still achieved under the road-map, but includes greater savings through the mechanism of carbon trading, as well as fuel burn reduction, both to current and future aircraft. The Sustainable Aviation UK road-map is provided in Figure 4.

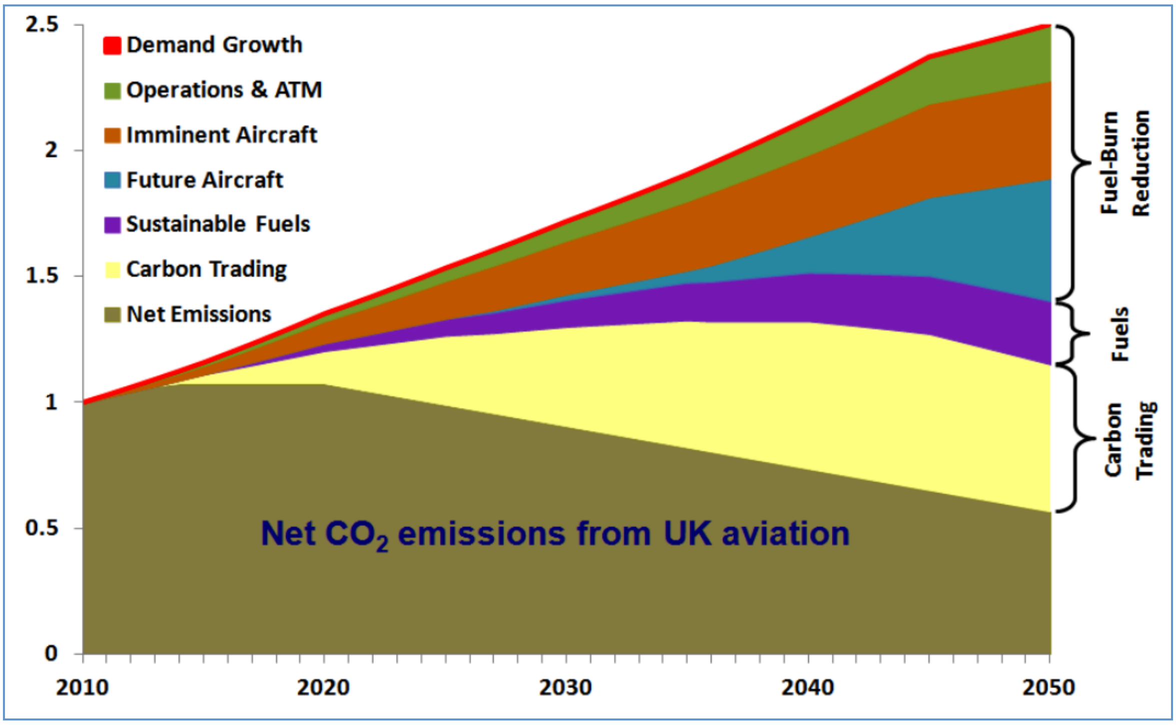


*Figure 4: Road map to 50% of 2005 aviation emission levels by 2050 in the UK (Source: Sustainable Aviation UK, 2012)*

[10] The SWAFEA study undertaken for the European Commission considered Natural Gas to liquid using FT, Hydrotreated Renewable Jet (HRJ) from rapeseed, camelina, palm oil and jatropha, and lignocellulosic biomass.

## 2.2 Biojet Industry Initiatives and investigations

*There are currently a multitude of relevant companies, partnerships and consortia initiatives supporting the acceleration of biojet commercialisation at all stages of the supply chain around the world. This chapter serves to outline the most important in driving a global biojet supply chain and explaining why such aspects are important.*

### 2.2.1 Consortia Initiatives

Consortia initiatives are crucial to developing biojet supply systems owing to the wide range of actors involved in bringing bioenergy systems to market. They allow legislators, biofuel producers, airlines and manufacturers to communicate in a neutral forum to build and develop synergies. Generally there are two types of groups, those that seek to develop each stage of the supply chain (from harvesters, transporters, developers and users), to develop fuel themselves, and those with a more regional focus whose aim is to connect fuel users with producers to facilitate dialogue and the functioning of networks.

Several important initiatives actively working towards producing affordable and sustainable biojet are coming out of the U.S., primarily due to the favourable access to knowledge, resources and infrastructure that exists within the mid-west region. The region is characterized specifically by high jet fuel consumption[11] and access to funding and technology largely through the U.S. Military. The most prominent initiatives include MASBI[12] in the Midwest United States, CAAFI[13] and NARA[14]. MASBI is focused on developing agricultural systems, cleantech development, biomass resources, funding and existing infrastructure and funding to collaborate and generate a regional biojet supply chain (Midwest Aviation Sustainable Biofuels Initiative, 2013). CAAFI is an initiative involving a coalition of airlines, aircraft manufacturers, energy researchers and producers and U.S. Government agencies seeking to promote energy security and environmental sustainability through biojet fuel advancements.

NARA is an initiative lead by the Washington State University, consisting of a coalition of stakeholders, namely private industry and educational institutions, seeking to build a regional supply chain producing biojet from forestry residual feedstocks in the Pacific Northwest region of the U.S. The initiative seeks to build upon favorable governmental support and regional conditions including large regional deposits of under-utilised forestry residues and high oil dependence to convert wood to biojet along with other high value products (such as biochemical) through the alcohol-to-jet conversion process through conversion of woody biomass to isobutanol, an intermediate product that can also be converted to solvents, paints and renewable rubber. Relevant studies emerging from this initiative that may be useful for the development of a regional biojet supply chain in the Nordic region include:

- Developments in silvicultural methods to improve forestry harvest and biomass yields;
- Studies investigating the impact of an increased biomass harvest upon native wildlife and ecological cycles to encourage sustainable forestry practices.
- Methods to minimise costs in biomass harvest, collection and transportation, such as onsite drying, trailer improvements and improved forest access.

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11 The United States consumes more jet fuel

12 Midwest Aviation Sustainable Biofuels Initiative

13 Commercial Aviation Alternative Fuels Initiative

14 The Northwest Advanced Renewables Alliance

- Genetic engineering research to develop new lines of tree species that may improve the yields of valuable molecules through forest biomass, such as petro-chemical substitutes, and lines that can be more easily broken down for conversion processes.

Moving to within Europe, ITAKA[15] is an initiative striving to make significant steps toward establishing a European biojet supply chain from camelina and used cooking oil, in line with the fulfillment of the short term EU Advanced Biofuels Flight Path Initiative[16] objectives. Other regional initiatives throughout Europe are also prevalent, and function primarily to draw actors together the facilitate knowledge sharing and supply chain coordination. NISA[17] is an organization covering the Nordic region seeking to streamline interactions between stakeholders for the acceleration of biofuels in aviation, while the Aviation Initiative for Renewable Energy (AIREG) in Germany is also striving to accelerate biojet technology deployment within the Germany region. The Sustainable Aviation Fuel Users Group (SAFUG) was established in 2008 to drive the development of biojet supply chains. SAFUG members collectively consume more that a quarter of the worlds current jet fuel demand, and actively support the sustainable production of biojet fuels through advocacy of the Roundtable for Sustainable Biofuels (RSB), an association that defines a number of key principles that must be complied with in order to become sustainable RSB certified fuel.

### 2.2.2 Investigative Publications

A number of studies throughout Europe, the US and the Pacific have detailed production and supply related conditions for biojet production pertaining to the localities studied.

A report commissioned by Avinor, SAS and the Federation of Norwegian Aviation Industries, authored by Ramboll investigated possibilities for sustainable A-1 biojet production system in Norway between 2020-2025. The study applied the EU sustainability criteria as defined under the RED, and based all modeling on advanced feedstocks. Forest biomass was nominated to be the most important feedstock for a Norwegian based biojet system over the short-term owing to its large forestry reserves, and micro and macro algae showing promising potential beyond 2025. It was concluded that 7 TWh in mostly logging residues could be harvested sustainably, and, if converted completely into biojet, could supply 230 million litres.

Two conversion processes considered for this study included thermochemical processing and gasification of forest biomass (FT synthesis) and the refinement of bio-alcohols to Jet A-1 (Alcohol-to-Jet, AtJ). Conversion processes are an important factor affecting profitability of a bioenergy system. The HEFA process, although considered more technologically mature, was not considered for this study owing to high prices of non-edible oil based feedstock, and unsuitable conditions for domestic oil seed growth. The study concluded that a biojet production system based on the FT or ATJ conversion methods is both technically and economically feasible between 2020-2025 in Norway, depending on the sales of byproducts. Given the similarities in both availability of forestry biomass and climatic conditions, it seems logical to apply the conversion selecting criteria displayed in this study to that of Sweden.

This view is supported through a recent pilot study conducted by Värmeforsk, Grontmij and

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15 Initiative Towards sustAinable Kerosene for Aviation

16 The EU Advanced Biofuels Flight Path Initiative was launched in 2011 by prominent biofuel-supporting airlines such as KLM, Lufthansa and British Airways in association with leading biofuel producers UOP, NesteOil and others to create a roadmap towards sustainably producing 2 million tonnes of biojet fuel within the EU by 2020. The initiative is non-binding and sets goals and targets aligned to this overall strategy.

17 Nordic Initiative for Sustainable Aviation

Swedavia (Ekbom, Hjerpe, & Hermann, 2009), investigating pre-conditions for a biorefinery plant for Sweden's largest airport – Stockholm Arlanda, using wood as a feedstock in the form of woodchips and sawdust. The study is based on advanced gasification technology and FT synthesis to process biojet fuel with associated district heating, and assessed two different site configurations in Brista and Igelsta. The production volume was set at 50 kton of biojet production per year, which would allow Arlanda to run carbon neutral, or reduce carbon emissions by 150,000 ton/year with a 10% biojet blend.

Operation figures for onsite jet fuel production (modeled by the Brista site) would require an energy input of 293 MW running at 8,000 hours per year, with 5000 hours of heat production. In addition to the 50 kton of biojet fuel, the plant would produce 17.9 kton/yr of Naphtha, 21.4 kton/year of heavy diesel, and 96.9 MW of energy for use in the district-heating network. The plant would run at 79% thermal efficiency, with a total biojet fuel yield of 25%. The capital costs for such a project at Brista would amount to 500 Million EUR, with biojet production costs calculated at 8300 SEK (812 EUR)/$m^3$. The study concluded that biojet production from such a plant would most-likely be accepted as a jet fuel blend with the oil price at around US $67/barrel in the presence of an effective emissions trading mechanism or equivalent. Feedstock supplying input energy for the plant was assumed to be in the form of woodchips comprising of forestry residues, grot, wood rejects and sawdust, and considerations were made for use of nearby refining capacity in Gothenburg. Despite considerations for upstream logistics, including domestic and imported biomass sourcing, transport via ship, road and rail and provision for onsite storage capacity onsite, details regarding domestic feedstock availability and harvesting and collection logistics are not discussed in detail.

A report prepared by the consultancy company NIRAS (Wormslev, Tang, & Christian, 2014) seeks to explore the opportunities existing within the Denmark that can support the development of biojet fuels, for informing policy-makers and investors. The report focuses on identifying whom the key stakeholders are, which feedstocks are the most suitable given cost and technical limitations and arguments for the concept of integrated processes with other sectors. The emphasis of the report revolves around technological development opportunities and also the development of networks to facilitate coordination between producers, suppliers, legislators and users. The report finds that although the RSB scheme of certification is robust, global agreement on environmental sustainability indicators is still a challenge to globally sustainable biojet production. The report acknowledges technological capacity within Denmark through several pioneering research institutes and universities, and nominates the Fischer-Tropsch, HEFA and Alcohol-to-Jet pathways as all being promising in a Danish context, in the presence of co-production in a biorefinery setting leveraging existing crude oil refinery infrastructure. Under these conditions it is argued that the Danish demand for energy and feed from biomass can be met in addition to the production of biojet fuel.

One of the most significant barriers identified within the Danish study is that of feedstock availability, which is dominated by biological waste from the meat and dairy industry, and argues that as the supply of petroleum oil weakens, the allocation of biomass should be prioritised for the production of transport biofuels for which there is no other fuel alternative (such is the case with aviation, marine and heavy trucks). The second key barrier mentioned is that of added costs of biojet, when compared to regular jet fuel. Such costs are estimated upon the costs of feedstocks, logistics and production (split into investment and operation costs). It is claimed the cost of producing biojet fuels can be reduced over time through scale effects, technology improvements and improved logistics. The final key barrier to the establishment of a biojet system in Denmark it is claimed concern the upstream processes of the logistics chain (feedstock production and collection), which can be unpredictable, costly and more complicated than securing raw crude oil.

An Australian study undertaken by Sinclair Knight Mertz (Sinclair Knight Merz, 2013) examined the capacity of available feedstocks to produce biojet fuel in the region. The study found overall that the production is feasible from a technical perspective, yet the commercial readiness of conversion facilities for both HEFA and FT synthesis presents challenges, along with the price and availability of feedstocks. Key feedstocks identified included natural oils from Eucalyptus, Mallee plantations, and tallow for HEFA technology, and MSW for FT synthesis. It was found that biofuel products could be integrated into supply and distribution infrastructure, yet modifications are required to standard refineries to process natural oils into aviation fuel. Additionally, hydrogen is needed at these refineries to process the natural oil or tallow feedstock. It was also stated that the production of biojet from natural oils and tallow feedstock would be unsuitable under a biorefinery setting, due to the increased production of lower value products (naphtha and gas). In terms of financing options, energy grants under the (Cleaner Fuels) *Scheme Act* 2004 outlines provisions for both bio-diesel and renewable diesel production, yet not for biojet, thereby incentivising production of the former over biojet.

# 3 Understanding Bioenergy Systems

*This chapter sets out to describe the nature of bioenergy in replacing fossil fuels for our energy needs. It is designed to provide a contextual and critical backdrop for analyzing Sweden's forests as a bioenergy provider in the future amidst advancement in technology and the emerging perspectives about how to define a sustainable bioenergy system.*

## 3.1 Climate change and the Role of Renewable Energy

Energy is a vital component for the basic functioning of a modern society, yet unfortunately, our conventional energy production systems are not conducive to sustainable development (Reddy, 2000). $CO_2$ emissions have risen by more than 40% following the industrial revolution of the 1800's (IPCC, 2013, IEA 2013), and 78% of total GHG emissions between 2000 and 2010 can be attributed to fossil fuel combustion (IPCC, 2014). The leading challenge in sustaining a liveable biosphere in the future is to create a productive economy that is largely fossil-fuel independent, an ambition by which wide-scale adoption of renewable energy technologies will play a major role. Climate change mitigation scenarios undertaken by the IPCC set to a global climate of less than 2 degrees warming (recommended to avoid the most severe effects) are characterized by atmospheric $CO_2$ levels of 450 ppm or less by 2100 (IPCC, 2014). As of June 2014, the level of $CO_2$ in the atmosphere was 401.3 (NASA, 2014), suggesting a "business as usual" approach will lead to rises in global temperatures of between 3.7 and 4.8°C, leading to impacts including *"substantial species extinctions"* and *"large risks to global food security"*. The IPCC in its *Summary for Policy Makers, In: Climate Change 2014, Mitigation of Climate Change* report mentions that large cuts in emissions through changes in energy systems and land use are required, to effectively reduce global emissions output in 2050 to between 40-70% lower than 2010 levels, and transition to near zero $GtCO_2$ eq or below by 2100 (IPCC, 2014).

The IPCC emphasises that drastic action can be implemented through a number of options to reach the 450 ppm scenario target; yet general requirements include a tripling to quadrupling of clean energy supplies we currently use. The report mentions low and zero carbon energy supply from renewable sources, nuclear energy, natural gas, fossil energy with carbon dioxide capture and storage (CCS) and bioenergy with carbon capture and storage (BECCS) technologies as being integral to reductions. Also instrumental to such a shift are drastic changes in land use through afforestation and reduced deforestation, for which sustainable bioenergy production is inextricably linked to. Renewable energy is the fastest growing power generation sector, and is expected to make up a quarter of total global supply by 2018 (IEA, 2013). 2011 figures presented by the IPCC show the relative role of bioenergy proportional to global energy supply, and the dominance of biomass as an energy source, accounting for 79% of renewable energy supply (see Figure 5). Forecasted growth in bioenergy is expected, yet at a slower rate than other renewable sources. Biofuels for transport is predicted to account for nearly 4% of global oil demand for transport in 2018, up from 3% in 2012 (IEA, 2013).

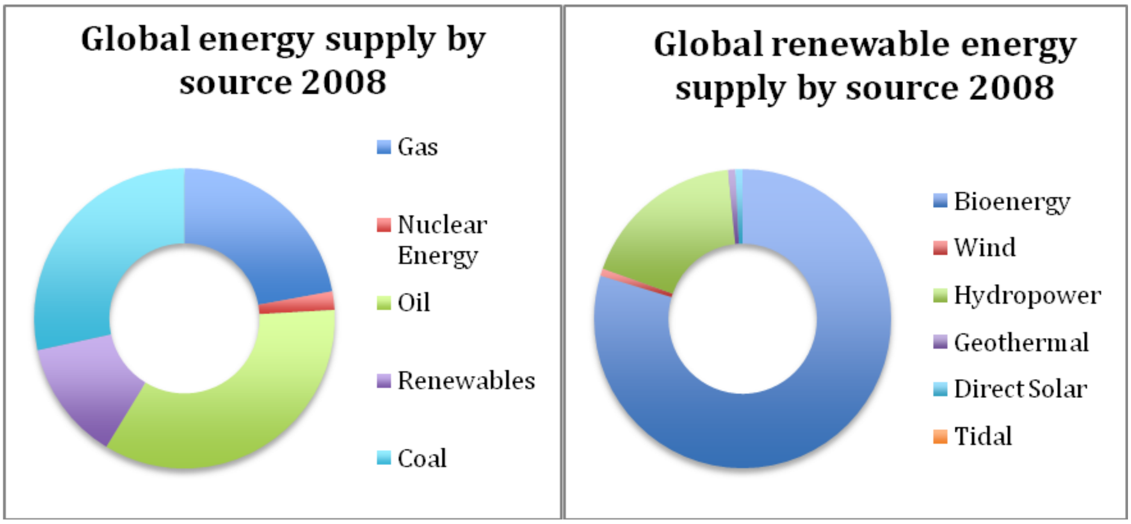


*Figure 5: Total energy supply and renewable energy supply 2008 by source (source: IPCC, 2011)*

The incremental increase in renewable energy is the result of a number of things, including strong incentives provided by government policy, the declining cost of technologies over time through economies of scale and enhanced learning processes (Edenhofer et al., 2011).

According to Edenhofer et al. (2011), it is theoretically possible to fulfil the total global energy demand using renewable energy. The sun provides many times more energy than we could ever put into use, yet our abilities to convert and store it restrict our capabilities. The role of biomass can account for a large portion of this energy, as shown in Figure 5, yet constraints on global net primary productivity through land and resource scarcity means bioenergy will not be sufficiently available at any one moment to replace fossil fuel demand (Liska, 2013; Borejesson, 2008). The future role of bioenergy as an legitimate source of climate friendly energy is thus more a question of how our limited biomass feedstocks can be managed in the most sustainable and "optimal way", amidst complexity owing to the multitude of raw materials, conversion processes, fields of application and competing uses in differing contexts.

## 3.2 What is a Bioenergy System?

Bioenergy is an umbrella term given to all energy derived from biomass, and can include biomass resulting from forestry, agricultural or livestock residues, short-rotation forest plantations, energy crops or organic municipal solid waste. Bioenergy systems can exist in many different forms, such as liquid (transportation fuel), solid (wood pellets) and gas (biogas), be utilized under a range of applications (such as transport fuel, combined heat and power, domestic heating), and be converted using any number of technologies (biological, thermal or mechanical).

Of the renewable energy options available, bioenergy offers a considerable proportion of total supply (see Figure 5) and can provide benefits including climate change mitigation, improved energy security, employment, industrial growth and opportunities for greater exports. Yet despite being banded in the "renewable energy" bracket, bioenergy must be looked upon in a separate light to other renewable energy technologies, owing to its unique complexity and varied nature, which ultimately can constitute a major barrier to bioenergy deployment (Buchholz et al., 2009). Börjesson (2008) states that because bioenergy is a predictable and constant energy carrier, and is the only renewable energy alternative existing as a carbon based fuel, it provides a uniquely straight forward option for replacing oil in the transportation sector. Berndes et al. (2008) points out that biomass is relatively inexpensive compared to other climate friendly alternatives, and due to its physical morphology as renewable stored carbon, has limits to its usage. Unlike other alternative renewable energy sources, this can result in exploitation and unsustainable practices, which ultimately requires additional care in land management with respect to local needs and conditions.

Bioenergy systems, as described by McCormick (2007) and Geels (2004), are more complex than other renewable energy technologies as they often involve a long and segmented production chain, integrated across actors and sectors of different backgrounds and levels of knowledge. The standard bioenergy production chain comprises of both the technical aspects, such as feedstock sourcing, logistics, and conversion technology, along with the overarching social aspects including the web of policies and actors that control the flow of materials and activities through partnerships and networks. Consideration of this complex structure is crucial when investigating the many factors driving the sustainable expansion of bioenergy systems.

This holistic perspective is also important in understanding linkages between actors driving synergies and to ensure that enhancing one component will not negatively influence another through land use change (Berndes & Börjesson 2007). Buchholz et al. (2009) discusses the multidimensional nature of bioenergy systems, comprising of social, economic and environmental components that all require attention according to context and stakeholder perspective when planning bioenergy project implementation. As noted by McCormick (2007), often the non-technical issues distinguished through social and organization innovation processes are those that are often overlooked when implementing innovation systems.

## 3.3 Sustainability issues of biofuels

Humans have used biofuels in their basic form for thousands of years, yet wide-scale deployment of liquid biofuels for transportation was stimulated in response to concerns for energy security by a series of oil crises just over four decades ago in the 1970's. Today, biofuels are the most widely used renewable alternative to oil-based transportation fuels such as gasoline and diesel (Saddler et al., 2012), yet evidence from biofuels research reveals a high degree of complexity in their application from a sustainability perspective (German, et al., 2013), traditionally associated with first generation biofuels, and more recently questioned with regard to second generation (Mohr & Raman, 2013).

First generation or traditional biofuels are made from sugars or oils derived from crops such as corn, sugarcane or maize, and lead to the establishment of many of the prominent biofuel policies and infrastructure shaping commercial deployment of both ethanol and biodiesel in the world today (Ulmanen et al., 2009). Although production of first generation biofuels will continue to dominate production in certain regions of the world where they are cost competitive within well developed markets (such as Brazil), their inputs to the global total will be ultimately be limited in comparison to next generation cellulosic feedstocks (Worldwatch Institute, 2007).

Despite the relative size and promise of biofuels in the umbrella of renewable energy, evidence from biofuels research show that the question of whether or not biofuels can be sustainable in the long term is one that can not currently be definitively answered (German et al., 2011; Telkamp, 2012).

The *Biofuels and Sustainability Challenge* report published by the FAO in 2012 concludes that concern over biofuel production relates to first generation feedstock production and climate change impacts through unsustainable land use, food security concerns linked to feedstock economics driven by increases in demand, cost competitiveness of advanced biofuel technologies in the face of limited production capacity and difficulties in measuring sustainability and formulating effective policy through initiatives, regulations or directives. It is concluded that efficient feedstocks are not always environmentally or socially sustainable, as backed up by SkyNRG's *White Paper on Sustainable Aviation Biofuels* (Faaij & van dijk, 2012), and those that are environmentally sustainable are often not economically viable. Sugar cane expansion into grazing areas, for example, can push livestock systems into the forests, such as the case in Brazil. While palm oil (for biodiesel production), a highly efficient source with large net GHG reduction potential is often implemented on environmentally sensitive land, such as drained peatlands, resulting in $CO_2$ emissions grossly outweighing the savings.

The IPCC Working Group II's contribution to the *Climate Change 2014: Impacts, Adaptation and Vulnerability report* echo some of these conclusions, attesting that although traditional biofuels remain an integral component for mitigating climate change, unsustainable cultivation of energy crops and increasing water demand may in fact be exacerbating climate change further (Kiger, 2014). The report also concludes that trajectories, targets and strategies must be managed carefully to consider competing uses for land and the effects of iLUC (IPCC, 2014). Recent revisions in legislation, further research, and recalculations of biofuel capacity in light of studies reflect this perceptional shift, shown through increased support of more sustainable 'next generation' or advanced biofuels. However despite this, difficulties remain in assuring sustainable biofuel development, namely through a lack of consensus in measuring impacts of iLUC through life cycle assessment.

The EU Renewable Energy Directive was introduced in 2009 (RED-2009/28/EC) to mandate a 20% share of renewables by 2020, and a 10% goal of renewables in transport within the European Union, with specific sustainability criteria set out in its articles 17, 18 and 19. Biofuels not produced in accordance to criteria, which sets out GHG emission savings and land use requirements, cannot be counted within this target nor be eligible for financial support under the directive. From 2017 onwards, all biofuel will need to result in 50% GHG savings profile and 60% for 2018 onwards. Methodology for measuring GHG savings are defined as the sum of: (1) extraction and cultivation of feedstock; (2) land-use change; (3) processing; and (4) transport and distribution. Carbon emitted from the biofuel combustion is assumed to be zero due to the carbon absorbed during the life of the plant, and deductions can be made based on improvement of soil improvement leading to greater carbon storage and co-generation of electricity. The lack of specificity has prompted numerous initiatives around the world into formulating sustainability frameworks and certification schemes. The Roundtable for Sustainable Biomaterials (RSB) is generally considered the most widely recognized and transcribes requirements outlined under the RED.

Controversy regarding the sustainability of biofuels produced under the directive stem from the perception that iLUC was not sufficiently incorporated into the criteria, resulting in mandates being unlikely to deliver significant GHG reductions by 2020 (Malins, 2013). Furthermore, the assumption that all biomass combustion is carbon neutral is also under scrutiny. This has prompted amendments to both the RED and Fuel Quality Directives in an attempt to include iLUC and to limit the amount of biofuel produced from food derived feedstocks, which were recently placed at a 7% cap (Union, 2012; Voegele, 2014). Further incentive for advanced biofuel uptake is also given through a multiple-counting mechanism towards renewable targets under the RED, which includes 28 different feedstocks. It is commonly stated throughout the literature that options to promote iLUC-free bioenergy growth can be achieved through increased productivity of lignocellulose-based biofuels grown on low carbon pasture land, increasing residue-based biofuel production or biofuels based on waste organic materials as feedstock (IEA, 2010; Borejesson, 2008). It is reported that the ambitious emissions savings for 2018 will be very difficult to achieve using first generation feedstocks (Lendle & Schaus, 2010).

What is obvious from the literature is that local conditions must be considered and assessed in light of a range of criteria determining which feedstock and production path is most suitable. A recent study undertaken by Arup URS in the UK has analysed feedstocks included in the multiple counting function for suitability in light of changes to the RED. The report (Arup URS, 2014) has developed a framework to determine the most suitable feedstock and conversion methods deserving of additional policy support. Key criteria used within the assessment undertaken included:

- Priority of waste and residue feedstocks
- Consideration of The classification of land used for feedstock production (if applicable)
- Competing uses and potential substitute resources
- Lifecycle GHG emission profile
- Economic viability
- Feedstock availability

Börjesson (2008), defines an environmentally sustainable bioenergy system based on advanced forestry residues as being comprised of four key aspects, outlined in Table 2, and concludes that both willow and poplar appear promising in terms of resource efficiency in Southern Sweden. Other conclusions show forestry residuals as being energy efficient in comparison with several first generation crops, while also being environmentally efficient.

*Table 2: Aspects of an environmentally sustainable bioenergy system based on advanced feedstock (Adapted from Börjesson, 2008)*

| Aspect | Description | Application to Sweden Bioenergy |
|---|---|---|
| Resource Efficiency | Unused residual products, such as forestry slash should be used as far as possible for energy purposes. | In regard to total energy output per hectare, Willow and Poplar[18] appear promising among crops not competing with food. |
| Energy | Energy losses must be minimized throughout the bioenergy supply chain. The input of energy should | Studies show energy forest and forest residuals, such as forestry slash, poplar and straw require |

[18] When grown on good arable land in Southern Sweden

| | | |
|---|---|---|
| Efficiency | be as low as possible in proportion to the energy harvest obtained. The refined energy as an end product should be used with high efficiency. The lower the input energy as a proportion of energy harvest, the higher the energy efficiency | little input energy (<5%) in comparison to other crops including wheat, rapeseed and sugar beet[19]. Energy losses in in the production of bio-based vehicle fuels are higher than firing for heat and electricity. |
| Environmental Efficiency | Bioenergy systems should seek to maximize GHG emission savings, while not creating new or exacerbating existing environmental problems. | The removal of forest fuel and energy crops in Sweden can be undertaken without any major impacts to the environment. Slash removal can cause nutrient loss, however this can be mitigated through ash recycling and nitrogen addition if required. Slash removal can result in the reduction of nutrient leakage and acidification in southern Sweden.<br><br>Perennial crop harvest generally incurs lower environmental impact than annual energy crops such as grain or oil plants. Furthermore, perennial crops reduce soil acidification and require less energy input. |
| Cost Efficiency | Least cost biomass fuels should be used first, often residuals. Conversion and refinement should be undertaken using the least costly method. | Feedstock costs and the cost of biomass can be difficult and varies among companies, furthermore, many processes are patented and details surrounding costs are typically not publicly available. |

According to the above table, it would appear that a bioenergy feedstock that is efficient in terms of resources, energy, environment and cost would naturally dominate the bioenergy scene. However this may not necessarily be the case. Buchholz et al. (2009) brings to light the complex nature of decision-making in bioenergy, which involves stakeholders typically from diverse backgrounds and levels of knowledge. Such diverse perspectives creates added difficulty in aligning interests through communication channels, highlighting the importance of social platforms in decision making around the development of bioenergy systems. Such a sentiment is echoed by McCormick (2007) who states that the social components to streamlining bioenergy supply chains are crucial, yet often overlooked.

Barriers to socio-political legitimacy, as outlined by Aldrich (2014) can significantly stunt business activity with regard to renewable energy technologies, and can contribute toward the situation with biofuels. Policy-makers will typically lose confidence in complex systems where understanding is debated, leading to a lack of supportive policy and detracting key stakeholder investment, as well as influencing general public perception. Complexity surrounding the plethora of variables throughout the entire biofuel production supply chain (feedstocks, conditions, technologies), adding to the cross sectorial origins of actors and interested industries creates difficulty for individuals to relate to it, stymieing investor confidence and breeding public debate.

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[19] Assuming a 50km transport distance to energy plant, harvest during early spring in Southern Sweden.

Due to difficulties associated with measuring the total impacts of bioenergy systems, such as issues connected to LUC and the varying environmental and social standards across international borders, there is yet to be a globally harmonized set of sustainability criteria for biojet fuel production. This can lead to uncertainty amongst key actors in bioenergy systems, which can serve to inhibit progressive biofuel targets, policy and investment (Kempe, Personal communication, 26th 2014). As stated by Lüdeke-Freund et al. (2012), the development of assessment criteria and tools are not able to be developed in line with the increasing demand for biofuels and new feedstock concepts.

Trade offs between fuel, food and the environment are not a new phenomena (Liska & Heier, 2013), yet unbridled economic and population growth, stated by the IPCC as the two most important factors driving emissions from fossil fuel combustion (IPCC, 2014), has placed added strain on our natural and agricultural systems to supply resources for maintaining growth while upholding its core natural values. Ultimately this means the consequences of trade-off decisions are on a much larger and far reaching scale, and the degradation of the natural environment as a result of increasing land productivity only serves to perpetuate the problem. There are numerous types of advanced feedstocks that can be converted to biofuels, and selecting which is most viable depends on a number of factors including the location, alternate uses, technology and availability of the feedstock material. Waste and residues feedstocks, such as lignocellulosic forestry residues and energy crops that do not compete with food (Tilmann et al., 2009) are one such material that may exist in abundance and avoid land use problems earlier mentioned (IPCC, 2014).

## 3.4 Converting Lignocellulose to Biojet Fuel

Advanced biofuels are made from lignocellulose, woody crops, or agricultural residues that do not compete with food, and are seen by many as playing a key future role within the biofuels industry, both in Europe and abroad (Worldwatch Institute, 2007; ICCT, 2014). The primary goal of second-generation biofuel production is to avoid land-use problems by averting competition for resources with other plants, through the use of non-food crops and residues left over from other activities.

The key challenge in production of second generation biofuels is in the additional difficulty in converting lignocellulosic feedstocks into fuel by breaking up the constituent components of wood (cellulose, hemicellulose and lignin), which generally is more complicated (more processing steps) and more costly to process than many first generation feedstocks. Advanced biomass processing technologies represent various stages of technical maturity, from basic combustion of wood for heating purposes, to advanced thermochemical conversion for processing of advanced feedstocks into a particular transport biofuels (Worldwatch Institute, 2007).

A key tool formulated collaboratively by the US Department of Agriculture, the US Federal Aviation Administration, and Research and Innovative Technology Administration for CAAFI is the Fuel and Feedstock Readiness Level (FSRL) Tool. The tool has been developed for would-be biofuel producers or anyone that is interested in supply feedstock or interested in acquiring a stake in bringing biojet fuels to market. The tool specifically identifies the necessary steps involved in bringing bio-based feedstocks to market as biojet fuels, and has been developed on the basis that absolute knowledge of efforts and requirements to complete the supply chain among supply chain participants will minimise transaction costs and increase investment surety and accuracy of business plans (Steiner et al., 2012). The tool can specifically be used to identify gaps in a feedstock supply chain designed for a conversion process.

Biofuels produced from forestry residues or fast-growing trees for bioenergy are more favourable in terms of socio-economic and carbon emission intensity when they are connected to a 'long-term' forest growth strategy that integrates their production with other uses, a recent study by the Swedish Knowledge Centre for Renewable Transportation Fuels F3, has found (Lundgren, 2013), also noting the sustainability of the production system is more important than the finished type of biofuel. A system established for Sweden using forestry material should therefore be energy efficient and not compete with today's forestry production or with agriculture in Sweden.

### 3.4.1 Conversion Technologies

There are a number of main conversion technologies capable of turning biomass into synthetic jet fuel. These technologies rely on a number of types of raw materials, which can be the result of purpose planted energy crops (such as energy forest allotments), forestry and agricultural residues or from organic waste. As outlined in Figure 6, there are two primary pathways for producing liquid fuels from biomass.

The **thermo-chemical conversion method** can be used to gasify cellulosic biomass by exposing it to very high temperatures (600-1100 degrees Celsius) in the absence of oxygen resulting in an intermediate product called syngas (a mixture of carbon monoxide, carbon dioxide, hydrogen and methane). The syngas can be further converted to a liquid fuel (such as synthetic diesel) using advanced catalytic conversion methods, such as **Fischer-Tropsch**. An advantage of this method includes the fact that all wood constituents, including lignin, can be converted into a fuel, yet the main barrier to this process is the capital cost required in establishing a commercial plant, and keeping the equipment clean. Pyrolysis is similar to the gasification pathway in that it exposes the biomass to high temperatures (475 degrees) in the absence of oxygen, yet produces bio-oil rather than syngas, with solid charcoal and a light gas (similar to syngas) as byproducts. According to sources, bio-oil does not mix well with petroleum products, and is more suited for stationary electric power than for use as a transportation fuel (Worldwatch Institute, 2007).

The **biochemical conversion pathway** involves breaking down the cellulosic components into sugar molecules, which are acted upon by specialized bacteria or yeasts through fermentation to convert the sugars into ethanol fuel. The initial breaking down of the biomass involves an intense pre-treatment stage (usually through steam or acid application) to break the components into a slurry. The ethanol or butanol fuel can be used directly under certain applications or can be further upgraded into paraffins or jet fuel, using the **Alcohol-to-Jet** conversion process, currently in certification phase by ASTM. The fundamental disadvantage of this process is the relative difficulty of breaking down the lignin component of the wood, resulting in a loss of resource efficiency.

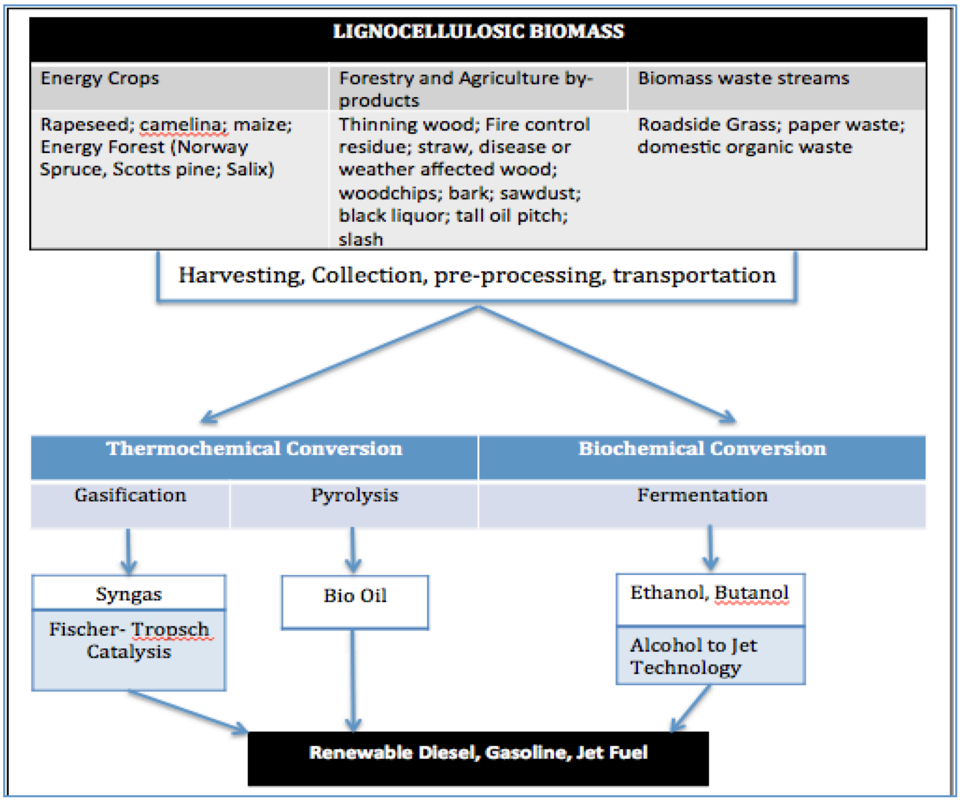


*Figure 6: Advanced feedstock processing pathways to transport biofuels*

Reviewing the various second-generation biofuel production pathways from lignocellulose highlights the broad and complex nature of biomass systems, whereby different methods and technologies may be more suitable given the best available feedstock and existing infrastructure. Saddler et al. (2012) explains that thermochemical conversion methods, such as Fischer-Tropsch conversion of gasified biomass and pyrolysis oils may be the most likely methods currently available for production of alternative jet fuels given their ability to produce large volumes in a relatively small number of steps. The Worldwatch Institute (2007) also postulates that woody biomass as a feedstock is more likely suited to gasification and FT-synthesis because it contains a high proportion of lignin, which biological processing is unable to process into high value fuel. Other recent studies suggest the alcohol-to-jet pathway may be more viable in the future through improved economies of scale (Midwest Aviation Sustainable Biofuels Initiative, 2013), or through a combined system involving a number of feedstocks and integrated conversion technologies.

### 3.4.2 Emerging Technologies

According to experts at the forefront of producing biofuels today, ASTM approval is a robust and effective tool for certifying new processes, yet should not be used as a measure to suggest ASTM approved pathways are more ready for market. The Fischer-Tropsche pathway was originally developed for syngas production from coal and natural gas, while aspects of the HEFA technology may have been leveraged from previously existing biodiesel production methods (Karatzos, Personal communications, 8th August, 2014). It is therefore important to consider emerging technologies, which are being developed throughout many different parts of the world in association with a range of airlines.

A number of these developments are potentially relevant for conversion of forestry biomass in Sweden. LanzaTech are a company working in association with Swedish Biofuels AB, who have developed technology to produce biojet fuels from waste gases generated within steel mills, in addition to the conversion of ethanol to biojet through the Alcohol to Jet Process (see section 2).

Steeper Energy are a company who, along with their research partners at Aalberg University, Denmark and the Univeristy of Alberta, Edmonton Canada, specialise in hydrofaction technology enabling the conversion of non-food feedstocks to hydrofaction oil and biofuels. The technology works through the application of supercritical heat and pressure to feedstocks including straw, wood chips, palm residue, sawdust, bagasse, manure, peat and sludge. The main product is oil that can be transported and upgraded using existing petroleum infrastructure. Hydrofaction oil can be burned directly for electricity, dropped-in for use as sulfur-free marine fuel or upgraded further to produce drop in jet fuel. One of the key benefits of this technology over others is that it can process biomass of high moisture content, and produce bio oil with much lower oxygen content than pyrolysis oil.

### 3.4.3 Getting the most out limited biomass stocks

Increased valorization of residue materials through increased R&D and technologies is creating new markets for various residue and byproduct materials. Improving the value of byproducts can help to boost biodiesel and ethanol industries (Martin, 2013), while creating new markets for the products themselves. As new technologies emerge that are able to extract antioxidants, pigments and other valuable molecules from materials formerly seen as good only as combustible waste used for heat for application within food and cosmetic industries, the economic cost gap associated with bringing biofuels to market can be reduced.

A recent study undertaken by Ekman et al. (2013) found that they were able to extract betulin from birch bark in Sweden, normally used for energy purposes, by using liquid carbon dioxide mixed with ethanol. Betulin is a known anti-inflammatory with anti-bacterial properties, and has been linked to both cancer and HIV treatment (Fujioka et al., 1994). Such extraction steps are seen as complimentary technologies as they do not prohibit other uses such as combustion for heat and energy production and can be integrated into the existing industry infrastructure.

As discussed by Börjesson, (2008), there is a justified debate around the most optimal way to utilise Sweden's waste and residual biomass reserves, instilling competition between biomass users. Some believe biomass fuels should be used for generating electricity and heat, as most is already done, rather than upgrade to vehicle fuel, since this would result in the greatest total reduction in GHG emission reductions. There is also a line of thought supporting the notion that road transportation fuel is a more effective use, that argues the production of fuels such as methanol is easier to produce and still possesses the added benefit of breaking oil dependence (Karyd, personal communications, 13th June, 2014). Although there is no right or wrong answer as to how best to manage biomass, it is clear that some particular uses under certain conditions are more favourable than others (Börjesson, 2008).

### 3.4.4 Are forest biorefineries the answer?

As stated by Saddler et al. (2012), fossil fuels, the lifeblood of most of the world's industrial economies, are known to be the major cause of increasing anthropocentric GHG emissions and are becoming increasingly more expensive and environmentally risky to exploit. Concurrently, many well-established forest-based industrial sectors are experiencing upheavals affecting product demand. A prime example of this being the rapid development of digital media significantly reducing the demand for paper and newsprint, thereby stimulating change in the way the pulp and paper industry develop their future product portfolio, towards expanding the range of uses for their products (Tibblin, personal communications, 22nd August, 2014). It can also be expected, according to Saddler et al. (2012) that new groups traditionally not interested in forestry materials will begin to turn towards trees as an answer for future production of products traditionally produced from crude oil.

Academics and industry actors proclaim that the future production of biofuels may be most efficiently implemented through biorefineries. Biorefineries are plants that can produce both fuels and co-products are in volumes corresponding to the cascading nature of value of each product to society (Saddler et al., 2012). An integrated biorefinery producing biojet may first extract high value compounds, such as pharmaceuticals and biochemical molecules, before converting the residuals and other biomass products into lower value products such as biojet fuel and incineration for heat. This model effectively mimics extant petroleum refineries where fuels are produced alongside biochemical and other materials. It is also argued that the co-production of low volume, high value products alongside biofuel can potentially make the difference in the cost-gap currently prohibiting many biofuels from being commercially competitive with incumbent fuels, as shown in Figure 7 (Wormslev, 2014). This is exemplified in the petroleum industry, whereby petrochemicals making up around 5% of the volume generate the majority of profit. Under a biorefinery setting, the fuels would ideally make up the bulk of production, while biochemical and pharmaceuticals may bring out the majority of the profits (Worldwatch Institute, 2007).

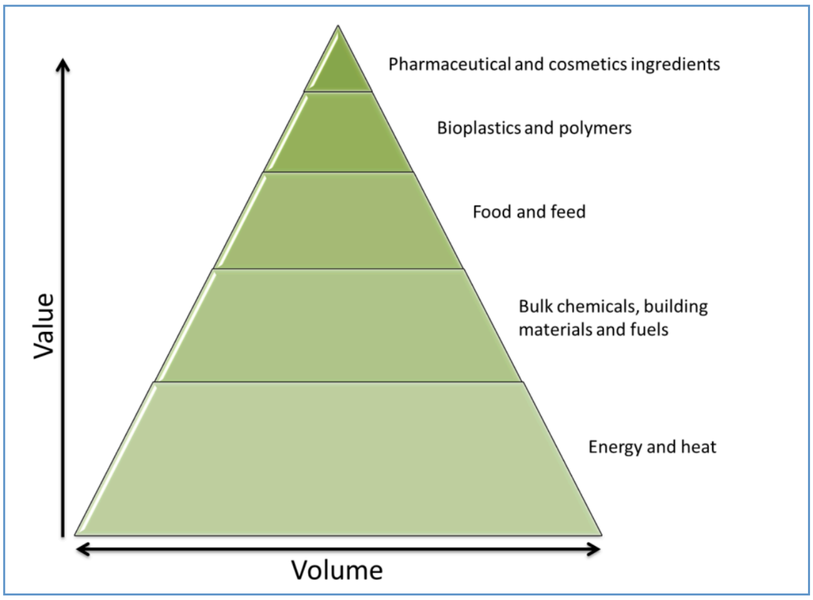


*Figure 7: Biorefining pyramid showing relationship between volume and value of different biobased products (Source: NIRAS, 2014)*

One key aspect integral to bringing biorefineries to commercial phase is heat integration. This refers to the ability of the plant to take heat generated from some unit operations to meet heat requirements in others. Integration of heat flows in the most beneficial way possible is referred to as 'pinch analysis' and is a key aspect in the upgrade of existing oil refineries. The forest based biorefinery will continue to have its core products and markets based on tradition (lumber, pulp and paper), yet increasing interest from outside will seek ways to leverage existing knowledge from sectors such as pulp and paper to extract maximum value of biomass by supplementing fossil-fuel energy. For the forest biorefinery to be commercialized in the future, synergistic opportunities with complementary industries and stakeholders must be optimized.

Over the last century of oil exploration and refinery operations, it has become increasingly clear that low volume high quality products such as chemicals or plastics would emerge as the key profit item, but because these materials are in relatively low demand, there is a risk that the market could become saturated quite quickly over the long-term (Karatzos, personal communications, 8th August, 2014). Increasing demands for energy diversity and changes to the demands of forestry products are signalling shifts in many forestry industries. According to Saddler et al., (2012), the pulp and paper industry is best positioned to evolve into a biorefinery approach that would enable easier diversification of product streams through existing expertise in separation, handling chemical, waste and water recycling. These skills can be leveraged to manufacture lignin and cellulose-derived products beyond traditional pulp and paper products.

Embodiment of the biorefinery concept and holistic supply chain in practice can be seen in Piteå in Sweden's north, whereby thermal gasification processes are utilised to produce crude tall diesel from the pulping process at commercial scale. The Solander Science Park operates a number of projects including the Sunpine biorefinery and Chemrec (responsible for black liquor gasification). The Sunpine plant takes the tall oil from the black liquor in nearby pulp and paper plants, converts it to tall oil diesel, and then ships the oil to a Preem refinery in Gothenburg where it is hydrogenated and processed into Preem ACP Evolution Diesel.

# 4 Sweden's Energy System and Bioresources

*The point of departure for this chapter is to examine the drivers for the existing bioenergy system in Sweden today, and to explore the growth of this system as a proxy for a future aviation biofuel value chain.*

Sweden is one of the most environmentally exemplary countries in the world. GHG emissions for the country as whole have been declining for some time, and are now among the lowest in the EU and OECD both on a per-capita and as a proportion of GDP basis (IEA, 2013). Over the course of the last four decades, Sweden have decreased their GHG emissions significantly in the face of large increases to GDP, setting the example to other countries that it can be possible to link economic growth with proactive climate policies and initiatives. The year 2012 saw Sweden emit 58.3 million tonnes of $CO_2$ equivalent, a figure that is 20% lower than it was in 1990. Decarbonising the transport sector is anticipated to be a significant challenge, but one which will be imperative in reaching Sweden's target of a further 40% emissions reduction by the year 2020 compared to 1990 levels, which according to recent studies are achievable through careful planning and effective policy measures.

Although only a minor contributor to global jet fuel consumption[20], the growth of the aviation sector in Sweden represents a larger proportion of its emissions than the global average[21]. The implementation of biojet fuels into a commercial supply system is designed to facilitate decarbonisation of the global aviation sector, measured through emissions savings by a specific year (50% emission reductions in 2050 on 2005 levels). In addition to climate change mitigation, a biojet system may serve to boost regional employment and energy security, particularly as Sweden is 100% dependent on oil imports, 42% of which from Russia (IEA, 2014). This dependence on Russia for oil may lead to future market volatility in the face of geopolitical tensions, or rising prices in the quest to secure more oil from other neighboring countries. The production and use of biojet can help reduce this risk.

Sweden's expanding forests account for over 85% of its bioenergy output, of which only a fraction (around 5%) is used to produce transportation biofuel. As shown in Figure 8, domestic aviation within Sweden is very much centred on its main airport – Stockholm Arlanda, and the majority of airports are located in the central and southern parts of the country. Given that there is great potential to improve biofuel production in Sweden using forestry biomass (Lantz et al., 2007), an investigation into potential biomass availability from major forestry industries is critical if Sweden is to become a biojet producer in the future.

[20] According the to Global Economy website (www.globaleconomy.com), and the US Energy Information Administrations, Sweden ranked 21st on the list of global jet fuel consumers in 2012, behind New Zealand, Portugal and Greece.

[21] This can be explained in part to Sweden's low emissions profile created as a result of an extensive district heating network and uptake of renewable energy sources.

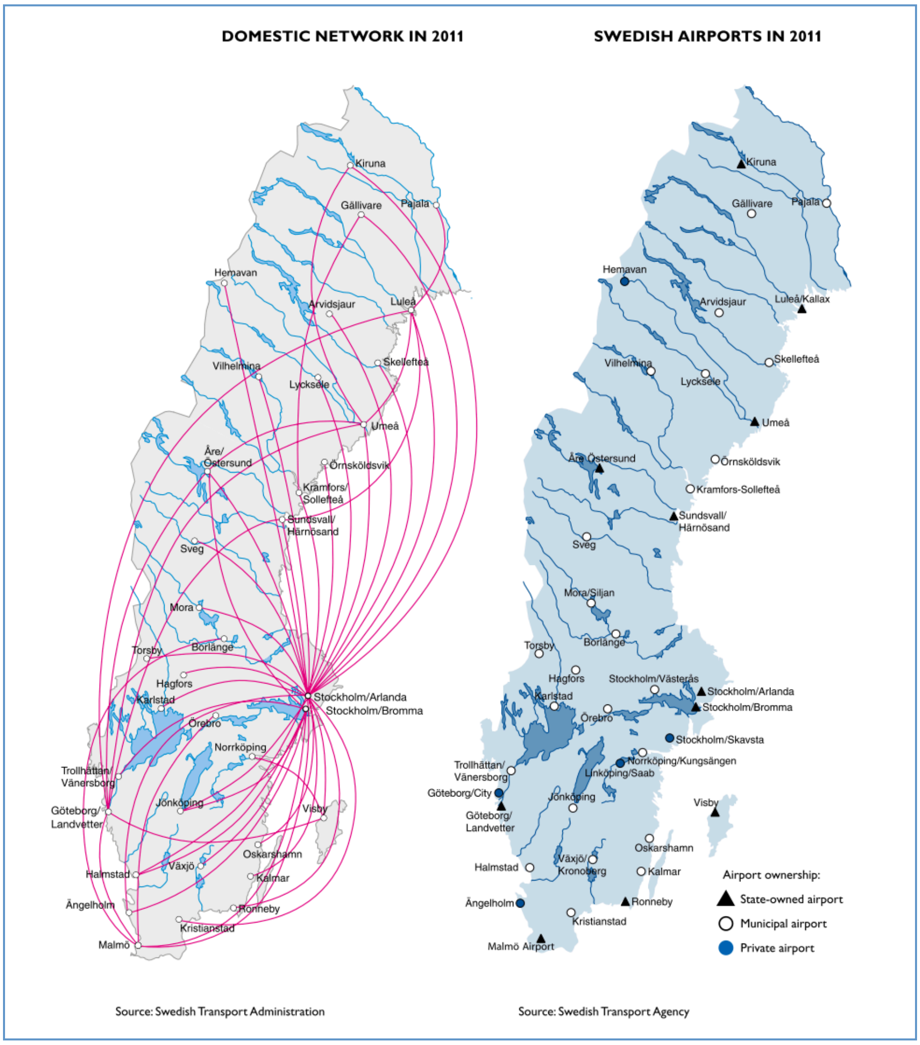


*Figure 8: Sweden's domestic flight path landscape (left), and the locations and ownership of Sweden's airports (right) (source: Swedish Transport Agency, 2012)*

### 4.1.1 Formulation of a Biojet Production Target for the Swedish System

The rate of biojet implementation over time in accordance with development capacity (comprised of technology readiness, availability of raw materials and sustainability criteria among other components) through the use of a road map is important to the transition toward fossil fuel independence. It is well documented throughout innovation literature that the initial stages of development carry the most risk, as technologies have not yet been proven to work at scale, and transaction costs are high until 'learning by doing' processes ignites cost reductions through a streamlined production chain. Technological learning and development is achieved mainly through research and development, up-scaling and collaboration between stakeholders, as shown through typical learning curves (Shum & Watanabe, 2009).

This theory implies that once the first plant is built, scale effects and investor support will follow, potentially leading to rapid growth and deployment. For this reason, initial biojet blends must be cautious, and not introduced too high or too quickly, with faith that future deployment will be easier thanks to scale effects. Implementation road maps have been prepared in light of research by both IATA and the Sustainable Aviation group in the UK, and are discussed in Section 2.1. Based upon these targets, and the similarities of reasoning and available resources, a baseline target of 2% biojet into the total Swedish supply of jet fuel by the year 2020 seems reasonable. According to the U.S. Energy Information Administration, the year 2012 saw Sweden consume on average 19.12 thousand barrels of jet fuel per day, including both domestic and international aviation bunkers. This amounts to over 1.1 billion litres or 938,000 tonnes of jet fuel[22]. Assuming a 2.2% growth rate (IATA Economics, 2010), this figure will be expected to be 1.116 million tonnes by 2020.

A 2% drop-in target for Sweden by 2020 would require the production of 22,320 tonnes of biojet fuel, or 26.4 million litres. The White Paper on Sustainable Jet Fuel by SkyNRG (Faaij and Van dijk, 2012), use a fuel conversion factor of 1 PJ of energy for every 23,000 tonnes of jet fuel. Using this calculation it is predicted that 0.97 PJ of energy would be needed to be utilized solely for biojet production, which, when considering a 60% conversion efficiency factor, rises to 1.617 PJ. This equates to approximately 0.44 TWh of energy.

## 4.2 Regional and Domestic Climate Change Policy

### 4.2.1 Integrated Climate and Energy Policy

Sweden's *Integrated Climate and Energy Policy* (2008/09:162 and 163) sets out the following targets in collaboration with and beyond the 20/20/20 targets of the EU. The current situation in Sweden is that aviation emissions are not counted within emissions reduction targets formulated in accordance with the Climate Roadmap for 2050. This represents a key institutional barrier to an established biojet system. Key targets from this policy are outlined in Table 3 (adapted from IEA, 2013).

*Table 3: Goals and targets set out within Sweden's "Integrated Climate and Energy Policy", and their relevance to aviation biofuel supply chain development*

| Temporal Scope | Goal |
|---|---|
| Short-Medium Term (2020) | 40% reduction in GHG emissions compared to 1990 outside of the EU-ETS with two thirds in Sweden and one third through foreign investment elsewhere in the EU of by use of flexible mechanism |
| | At least 50% share of renewables in gross final energy consumption |
| | At least 10% share of renewables in transport sector |
| | 20% more efficient use of energy compared to 2008 |
| Long-Term priorities | Phase out fossil fuels in heating by 2020 |
| | Fossil free transport fleet by 2030 |
| | Third pillar in electricity supply, next to hydro and nuclear to reduce vulnerability and increase energy security |
| | Sustainable and resource efficient energy supply with zero net GHG emissions by 2050 |

[22] Assuming a conversion factor of 1,183 litres of jet fuel to the tonne

The Fossil Free Fleet initiative by the Swedish Government is part of the overall goal of creating a cleaner, more efficient and transport-friendly nation towards zero net GHG emissions by 2050. Biofuels for transport under this strategy are set to be increased from 7 TWh in 2011 to 20 TWh (72 PJ) in the domestic supply. It is predicted under modelling performed for this initiative, that biofuels will make up 50% of car propulsion energy by 2030 and 60% by 2040, before declining to 40% in 2050 as a result of electricity powered cars (60% by 2050) (SOU, 2013, fig. S2). Under this strategy, biofuels are intended to be boosted through the introduction of a quota obligation[23], and increased investment in research and development efforts in second-generation biofuel technologies. An incentive scheme to stimulate the production of next generation biofuels would see a producers receive a premium that would be covered by increasing the price of all fuels, both fossil and bio-based. Although developments in advanced biofuel technologies could serve to improve the costs of biojet fuel production in Sweden through knowledge spillovers, emissions from aviation are not included within the initiative, thereby offering no incentives for investors or companies potentially interested in a biojet system.

The Chicago Convention in 1947 placed conditions that ensured international fuel would be supplied tax free so as to prevent price distortions that would favour purchases from countries with the lowest tax rates. As a result of this, and the overall international nature of flying and the presence of foreign airlines throughout all major cities in different countries, emissions from international aviation are not included in national emissions reduction targets under the Kyoto Protocol or reported under the IPCC. This does not put aviation on the map when policy makers formulate emissions reduction strategies to inform environmental policy, resulting in policies and targets, such as the FFF and carbon tax in Sweden that do not stimulate the market for emission reductions in aviation though supporting uptake of biofuels.

### 4.2.2 Carbon Taxation reform

The year 2009 saw a reform of the energy and $CO_2$ taxation system in Sweden to streamline tax levels towards GHG emission reductions based on energy content. The reform also saw other forms of transportation and industrial installations outside the EU-ETS included to induce even greater cuts to emissions to meet future emission targets (2009/10:41). Aviation fuel however is not subject to either tax, for the fact that it is an international product and taxing it would cause competition distortion.

### 4.2.3 Climate roadmap 2050

The roadmap document, prepared by the Swedish Environmental Protection Agency, aims to facilitate Sweden towards GHG neutral (zero net GHG emissions) by 2050 in the most cost-efficient way possible. The analysis uses a number of scenarios based on emissions trajectories for different sectors in accordance with all energy and climate policies for Sweden in 2020 and onward, and assumes new nuclear plants will replace existing reactors and the implementation of CCS and biogenic CCS technologies. Key elements to achieving the goal, as stated in the report summary, include long-term domestic emissions reductions, increasing the net uptake of carbon in forests and fields, and purchasing allowances on international

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[23] Some details regarding the quota obligation needs more work. There are plans to introduce a quota system based on proposals referred by the Government to the Council on Legislation, and then increased in staged from 2020 onwards until 100% is reached

markets. Increased investment in R&D in emission intensive industries, such as the pulp and paper industry are identified as priority items. A crucial sector with the most potential for bringing about emissions reductions is that of transport, evidenced in the ambition for a fossil free fleet by 2030. It is reported that the greatest reductions to transport will be through increased funding for R&D and the push to commercialise new technologies promoting fossil free energy and vehicle efficiency.

### 4.2.4 EU Emissions Trading Scheme

As a member state of the EU, Sweden is obligated to act under the regime of the EU-ETS cap-and-trade system that was established in 2003 and implemented in 2005 as a result of the Kyoto Protocol. The system sets union-wide goals for environmental conditions such as emissions reductions, with individual allowances handed out to individual states over three trading scheme periods (2005-2007, 2008-2012 and 2013-2020). Harmonised allocated rules are replacing incumbent national allocation plans with auctioning being the main allocation method. Aviation emissions were included into the trading scheme in January 2012.

## 4.3 Sweden's Energy Use

Sweden is a large and sparsely populated country of around 1,600 km in length with an environment that ideally supports its bioenergy system, providing over that 22% of its total energy supply, the second largest in all IEA member countries (Rosillo-calle, Teelucksingh, Thrän, & Seiffert, 2012). The bulk of Sweden's energy supply is produced through crude oil, hydropower, nuclear power, and biofuels (see Figure 9) contributing to a relatively low carbon footprint from energy. Sweden's pioneering status in reducing fossil fuel dependency is attributable to the rise in the share of biofuel uptake, where despite rising industrial output, the use of oil in Sweden has fallen by more than 40% of the proportion of total energy supply between 1970 and 2007 (Huete & Dahlbacka, 2009). Within Sweden, bioenergy supplies more than a third of final domestic energy use (Svebio Website, 2014).

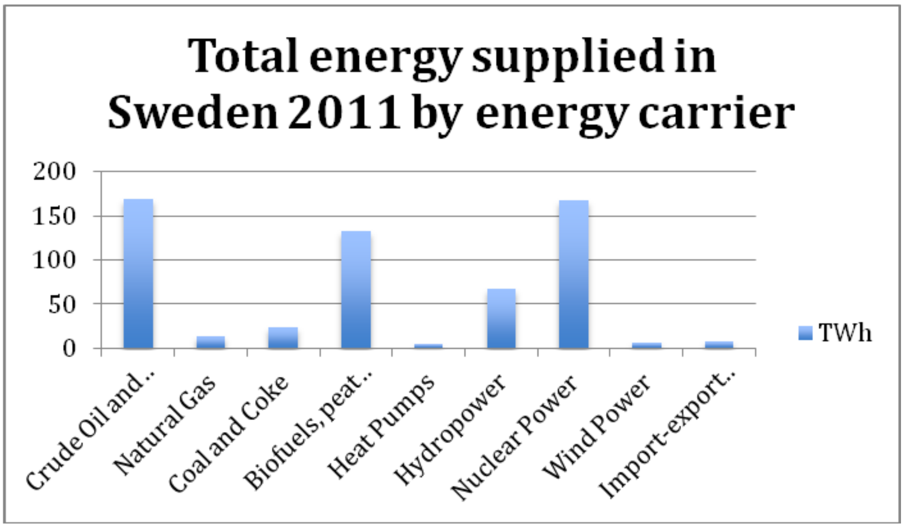


*Figure 9: Source SEA Energy in Sweden Report 2013*

According to Svebio, several factors have significantly contributed to the success of bioenergy implementation within Sweden, including long-term policy support, effective market-based mechanisms (namely the carbon dioxide tax, introduced in 1991, the green certificate scheme, introduced in 2003, and the tax exemption for transport biofuels), and skills in fuelling the thriving forestry sector. The high demand for heat, and relatively limited access to fossil fuels are mentioned by McCormick (2007) as also bearing significance. Over 130 TWh of bioenergy were used in 2011, used predominantly in the industrial and electricity sectors, followed by residential and services. Transport biofuels, although only relatively new, made up less than 7 TWh in 2011.

Bioenergy is very well developed in Sweden for a number of reasons. The large forests provide an abundance of biomass, combined with the knowledge and skills to produce bioenergy, while the high demands for heat and the presence of the district-heating network creates a predictable and ongoing demand. Supportive policies and measures in place such as the carbon tax and biofuel subsidies have encouraged actors to produce more biofuels to facilitate a shift away from fossil fuel dependence (McCormick & Kåberger, 2007).

Sweden's total energy use, by sector shows that 379 TWh of energy was used in 2011, split between industry (144 TWh), Residential and services (144 TWh) and Transport (90 TWh). Within each of these sectors, biofuels play a role, most significantly in the industry sector (54 TWh), dominated through use of residues to maintain the operations of plant facilities. The residential and services sector (17 TWh) has nearly doubled its use of wood fuels in the last decade, through mainly unrefined wood fuels used for heat and electricity (CHP plants), spurred by the rising costs of rising oil prices and supportive policy for converting to biofuels. Biofuels used in Sweden are primary produced domestically, however between 5 and 9 TWh are imported each year, with the majority of this energy used in the district heating system (SEA, 2013).

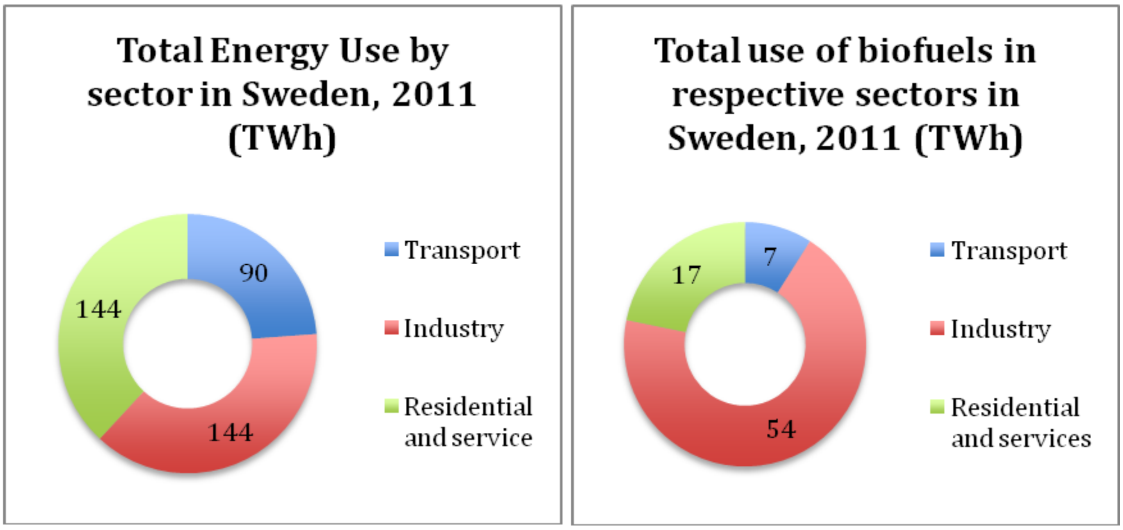


*Figure 10: Source - SEA Energy in Sweden report, 2013*

### 4.3.1 Sweden's industrial sector

Approximately 80% of Sweden's GHG emissions are derived from industrial facilities (SEA, 2013)[24]. Biofuel use within industry provides a significant amount of energy and enables industries that process biomass to run at low cost through combustion of biomass residues for internal operations. This essentially limits the availability of mill residue materials for production of transport biofuels as their value is already being exploited efficiently. A successive transition from oil towards biofuels saw a near doubling of biofuel use in industry

[24] This amount is influenced in part by overall low levels of carbon dioxide output from electricity generation within Sweden thanks to nuclear and hydropower facilities.

between 1970 and 2011, and any emerging innovation systems looking to use forestry residues must consider the energy balances of these industries and the implications of competing for residue resources (Börjesson, Personal Communication, 2014).

Within Sweden, very few large industries dominate industrial energy use, as illustrated below in Figure 11, with pulp and paper accounting for more than half (52%) according to 2011 figures (SEA, 2013). Within pulp and paper, electricity and black liquor, the byproduct from the pulping process, form the main energy carriers. The black liquor is traditionally combusted within a recovery boiler for the production of steam for energy. The iron and steel, chemicals, and wood products industry collectively comprise around 25% of Sweden's industrial energy use. The wood processing industry accounts for 5% of industrial energy use, and uses mainly biofuels for operations (see Figure 11).

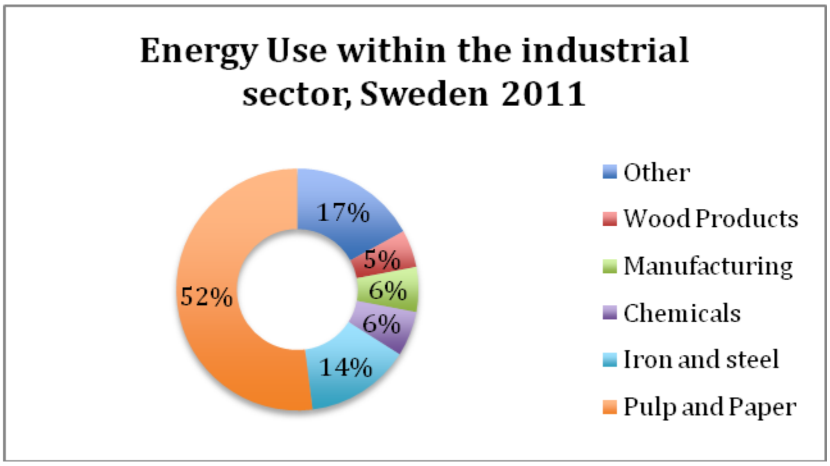


*Figure 11: Source – SEA Energy in Sweden Report, 2013*

The year 2012 saw a reduction in the price of electricity, coal and wood chips, with a rise in fuel oil and natural gas, facilitating the transition away from fossil fuels and fuel oil. Further manipulating demand of energy carriers within Sweden's industrial energy use is a number of market-based instruments and financial based incentive mechanisms. The most significant of these is the EU ETS, for which all large plants (over 20 MW) are included. An electricity certificate system was introduced in 2003 that gives industries incentives to produce their own renewable electricity. Energy Audit Cheques (EKCs) have been developed in Sweden for the purpose of encouraging large industrial energy users to improve their environmental performance through introducing and maintaining EMS. EKCs are issued to large industrial companies whose energy usage exceeds 500 MW/year, and operate to cover half the costs (to a maximum of SEK 30,000) of an energy audit. Such incentives to utilize onsite renewable energy essentially make it more difficult to secure feedstock at a low price (let alone gate-fee) for the production of biojet fuel.

### 4.3.2 Sweden's Transport Sector

Transport accounts for a quarter of Sweden's total energy use, with 94% of transport energy consumed in road transport (SEA, 2013). Total energy use in Sweden's transport sector has declined following a period of rapid growth between 2000 and 2008. This trend has been the result, among other factors, of reduced petrol use and the increase usage of diesel fuel as a result of changes to car fleet and supportive policy. Sweden's transport sector is fuelled largely by oil, followed by biofuels, electricity and natural gas (see Figure 12).

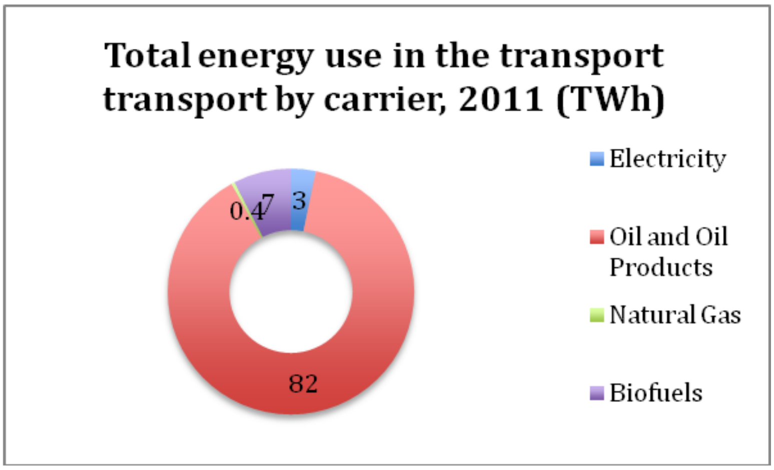


*Figure 12: Source - SEA Energy in Sweden Report, 2013*

The growth of transport biofuels in Sweden has been stimulated by the energy and carbon tax that have put an implicit price on carbon from vehicle fuels as well as electricity, introduced at the beginning of the 1990's. In addition to the energy and CO2 taxes, the introduction of the electricity certificate scheme in 2003 and EU ETS in 2005 have also played roles in bringing about reduced transport emissions. Such measures effectively raised fossil fuel prices to make cleaner alternatives, such as biofuels more cost competitive, thereby stimulating uptake. Aviation fuels are not subject to carbon dioxide taxation primarily due to their international nature and the need to keep prices internationally competitive. This inadvertently creates an added economic hurdle for biojet fuels to compete on cost with incumbent jet fuels.

### 4.3.3 Transport Biofuels in Sweden

Transport biofuels in Sweden have been developed from a point of almost negligibility in 2003, to occupying almost 10% of the domestic fuel share in 2012, represented by ethanol, biodiesel and biogas. Current transport biofuels in use within Sweden are currently produced almost entirely for road transport, for which demand has been most recently stimulated through policy facilitating growth of biodiesel. This, along with amendments to energy and carbon taxation systems have had significant impact on the development of these biofuels, which in 2012 included approximately 400,000 $m^3$ of biodiesel (4 TWh) and roughly the same volume of ethanol (2.5 TWh) consumed in Sweden.

The production of transport biofuels in Sweden is currently not sufficient to meet demand, resulting in a strong reliance upon other (mostly EU countries) for both biofuel and biofuel feedstock imports. Recent research suggests however, that Sweden has the resources and technical capacity to vastly increase the amount of domestically produced transport biofuel without impacting on environmental integrity or competing industries (SEA, 2014).

Diesel, now the most significant biofuel in Sweden by energy content (and growing), can be produced as either HVO and FAME (synthetic diesel). FAME uses methanol as a main ingredient, produced mainly from rapeseed oil imported from elsewhere in the EU. HVO is produced from mainly waste oils, such as crude tall oil, palm oil or slaughterhouse waste. Most of the HVO produced in Sweden utilizes crude tall oil from its pulp and paper industry, and is an intermediate fuel that can be upgraded into biojet fuel. FAME fuels on the other hand are similar to petroleum diesel and unsuitable for aviation due to their lower energy content and higher freezing point.

The ethanol used within Sweden is produced mostly from cereals, such as wheat, barley and rye, and is used in low admixtures for normal petrol and in high admixtures for alternative fuels E85 and ED95. Roughly half of ethanol supplied in Sweden is produced domestically while only a third of feedstock is grown in Sweden. The portion of ethanol not produced from cereals as a feedstock (about 20%) is produced from fermentation of sulphite liquor, a by-product of the chemical pulp and paper industry (Huete & Dahlbacka, 2009). The main producer of ethanol from grain in Sweden is Agroetanol, located in Norrkoping, and from the spent liquor by SEKAB in ornskoldsvik. SEKAB have also developed a technology through a demonstration plant in collaboration with Umea and Lulea universities in Sweden to produce ethanol from wood and cellulosic fibres, allowing waste products such as bagasse and wheat straw to be converted. The production of ethanol using such feedstocks presents both drivers and barriers to the establishment of a biojet production system. Alcohol-to-jet technologies provide capabilities to convert ethanol into biojet through a deoxygenation process, yet the strengthened markets for ethanol production for use in the road transport sector combined with the lack of market incentives in aviation means it is currently both more difficult and less profitable to upgrade this material into jet fuel. A list of ethanol producers in Sweden, according to Huete & Dahlbacka (2009) is provided below.

*Table 4: Ethanol Production Sites in Sweden (Adapted from Huete and Dahlbacka, 2009)*

| Company | Area and Products | Production Capacity/year | Feedstock |
|---|---|---|---|
| Lantmannen Agroetanol AB, Norrkoping (operational) | Ethanol; animal feed; carbon dioxide | 57 million litres | Cereal |
| Lantmannen Agroetanol | Ethanol | 150 million litres | Cereal |
| SEKAB/Domsjo Fariker AB, Ornskoldsvik | Paper pulp; ethanol; steam | 18 million litres | Wood Raw material (sulphite liquor) |
| SEKAB E-Technology | Research/pilot plant | 2 million litres | Wood Raw material |
| Nordisk Etanolproduktion AB, Karlshamn | Ethanol | 135 million litres | Wheat |
| NBE Sweden AB Pilot Plant, Sveg | Ethanol | 3,000 tonnes | Wood Raw Material |

Other second generation biofuels via biomass gasification of particular feedstocks can produce syngas, which can then be refined to produce a range of fuels, including FT-diesel, Dimethyl ether (DME), methanol, hydrogen and synthetic paraffinic kerosene (SPK). In order to be classed as renewable and be exempt from the energy and carbon taxes in the Swedish system, biofuels must comply with the relevant sustainability criteria, set out under *The Sustainability Criteria for Transport Biofuels and Liquid Biofuels Act (2010:598).*

### 4.3.4 Aviation Fuel Use and Infrastructure in Sweden

Comparatively to other countries, Sweden is not a large consumer of aviation jet fuel, yet emissions from aviation as a portion of the total are more representative in Sweden than for the global average (IEA, 2012). Aviation fuel usage has historically been quite low, accounting for between 4 and 5% of Sweden's total GHG emissions (IEA, 2012; Swedavia

Website, 2014). Annual air traffic in Sweden is predicted to grow by around 2% annually, made up mostly of growth in international transport and reduced domestic aviation (IEA, 2012). A recent report prepared by Värmeforsk has calculated that the production of 50,000 tonnes of biojet fuel supplied to Sweden's largest airport – Arlanda, would enable the airport to go carbon neutral (see section 2.2). The other most notable development relating to the development of biojet fuel in Sweden involves the installation of a fixed storage facility for aviation biofuel for Kalstad airport. Participating actors are SkyNRG in collaboration with Statoil aviation and the cleantech cluster organisation the Paper Province.

Although being fully dependent on international relations for crude oil imports, Sweden is a net exporter of several refined oil products. There are three main companies that operate some five refineries within Sweden (see Figure 13). Preem AB operates the two largest, representing around 80% of the countries total distillery capacity (IEA, 2011). St1 operates the next largest refinery in Gothenburg, recently bought from Shell, and Nynas Refining own and operate two smaller refineries, specialising in bitumen production. Three quarters of the oil retail market in Sweden is managed by large international companies Preem, Statoil, QK-Q8 and St1. The Swedish Petroleum and Biofuels Institute represent these companies.


*Figure 13: Oil Infrastructure Map of Sweden (Source: IEA, 2012)*

Sweden's total distillation capacity is 435 thousand barrels per day (approx. 19.05 billion litres/year) that in 2011 supplied 316 kp/d on average. The largest refinery is located along Sweden's west coast at Lysekil by Preem, with a capacity of over 200 kb/d. There are three further refineries located in Gothenburg, owned by Nynas, St1 and Preem accounting for about 45% of distillation capacity (IEA, 2013). There is a smaller fifth refinery located in Stockholm. Oil distribution is dependent upon road transportation for consumers and retail outlets. In terms of storage, there are 30 coastal and inland facilities located around Gavle, Stockholm, Norrkoping, Malmö and along the east coast.

## 4.4 Sweden's Biomass Supplies

In order to identify key barriers and drivers for a biojet system from a forestry based feedstock in Sweden, it is necessary to understand the amount of biomass within the system, and the mechanisms determining how it is extracted and allocated. The resource availability of Sweden's biomass is based on a number of limitations detracting from the theoretical potential of biomass extraction. Such limitations can be economic, environmental, social or based on markets, as detailed within this chapter.

### 4.4.1 Sweden's Forestry Stocks

Sweden's biofuel market has always been intrinsically linked to its forests, which currently cover over 60% of the countries landscape. Geographically, Sweden has a relatively sparse population, good transportation networks and rich forest abundance, as shown in Figure 13. This figure also illustrates the distribution of the forest stock, which is most dense in the central and southern regions of the country, presumably due to a more favourable growing climate. The forests are important to the Swedish people, not only for the economic prosperity they bring when harvested sustainably, but also for recreation and wellbeing. Sweden's forestry activities optimally seek to find a balance between economic uses and environmental non-use values, reflected through forest policy objectives and sector goals (Govt. bill 1992/93:226).

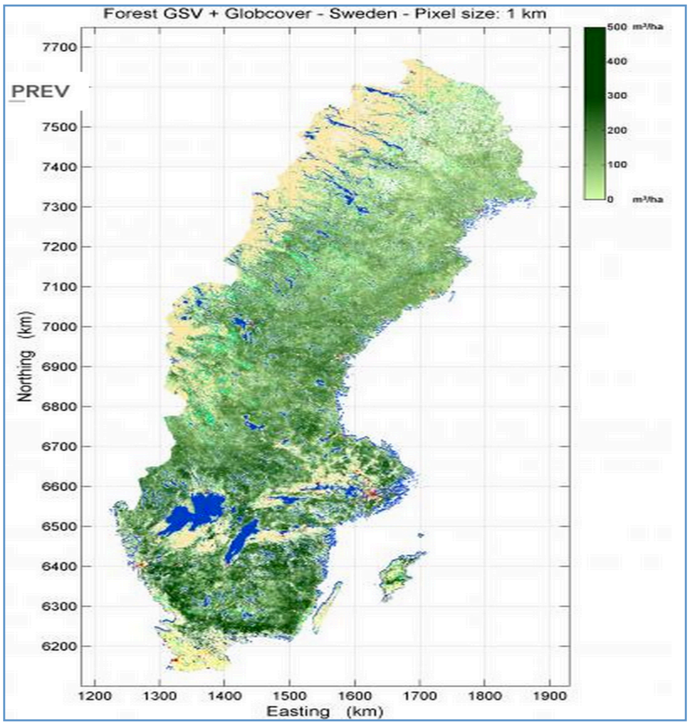


*Figure 14: Forest growing stock volume of Sweden, 2006, represented as shades of green between 0-500 cubic metres per hectare (Source: European Space Agency)*

The production of wood is an instrumental component in Sweden's bio-based economy. The country is ideally placed as a global leader in technology, knowhow and investment with regard to bio-based products, accounting for proportionally large shares of the world sawn timber, paper and pulp exports, despite occupying less than 1% of the worlds forests. Forestry biomass accounts for more than 85% of bioenergy sourced in Sweden, dominated by the Scots Pine and Norway spruce tree species in almost even amounts. The remaining wood consists of hardwood and other coniferous trees. It is estimated by Staffas et al., (2013) that there is approximately 3000 million $m^3$ of forest in Sweden, which is growing in absolute terms by approximately 120 million $m^3$ per year, of which roughly 90 million $m^3$ per year is harvested (See Figure 15). This leaves a net growth of 30 million $m^3$, which is accounted for through an increase in net volume rather than increasing forest area. This surplus is essential for sustainable forestry operations.

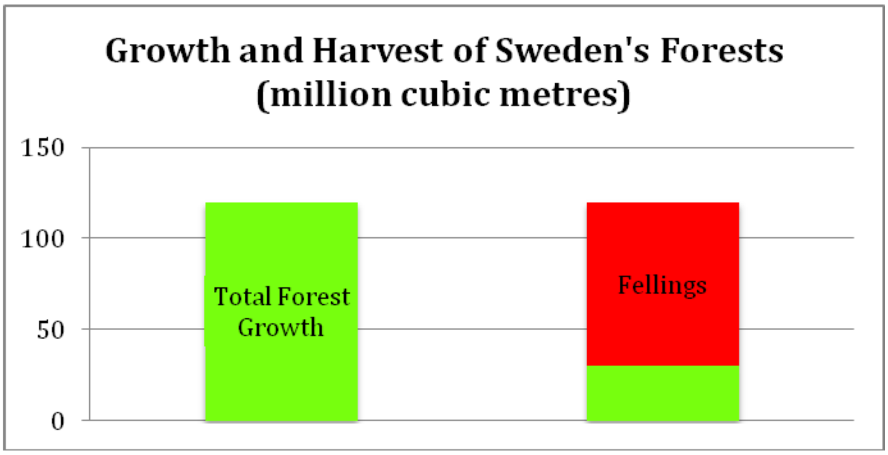


*Figure 15: Source - Staffas et al., 2013*

Looking closer into how the timber harvested is utilized and distributed in Figure 16, approximately 70 million cubic metres of underbarked wood is distributed evenly between the sawn timber and pulp industries. The wood fiber industry in Sweden is over 40% larger than the saw and plywood industry purely through the transfer of residue material.

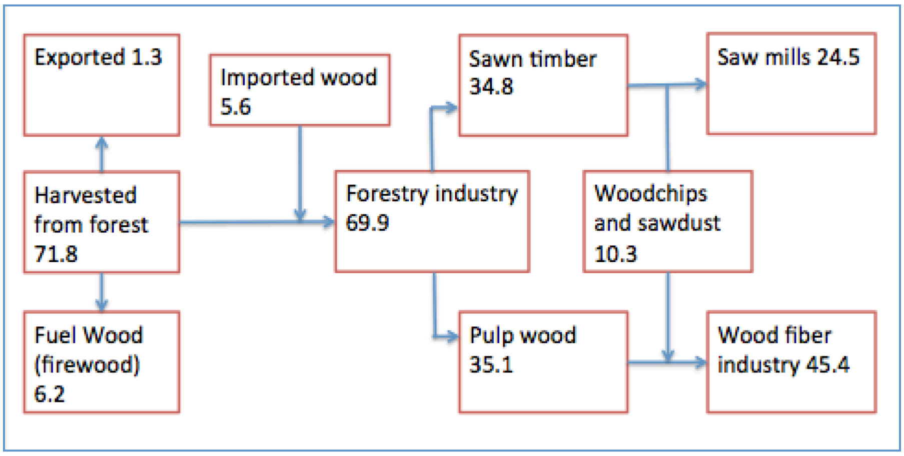


*Figure 16: Distribution of underwood forestry wood in million cubic metres. Source: Swedish Forestry Industries, 2013*

Ownership in Sweden's forests is divided among 50% private owners, 25% State owned companies and 25% public owners. More than 30% of forest owners live in a municipality other than where their forest lot is located, and vary in their views and objectives as to how the forests should best be managed (Swedish Forest Agency, 2007). Approximately 10% of Sweden's forestland is protected for biodiversity purposes, located mostly in Northern Sweden.

Sweden's production of bio-based products represents a key component of its GDP through exports. Sweden is the world's second largest combined exporter of paper, pulp and sawn wood products, behind Canada, and play a vital role in Europe's fibre chain through raw material provision to Germany, Italy and France (Swedish Forestry Industry, 2011). When examining changes in the way biomass is allocated, it is important to consider Sweden's imports and exports of biomass products, as changes in biomass usage can have an impact upon international markets. Table 5 outlines a list of imported and exported amounts of forestry biomass for Sweden.

*Table 5: Trade of forestry biomass products, Sweden 2013 (source: Swedish Forestry Agency, 2013)*

| Forestry biomass material | Imported amount | Exported amount |
|---|---|---|
| Roundwood | 6,700,000 $m^3$ | 833,000 $m^3$ |
| Woodchips and particles | 1,400,000 $m^3$ | 363,000 $m^3$ |
| Pellets | 1,200,000 $m^3$ | 376,000 $m^3$ |
| Sawdust | 69,000 $m^3$ | 47,000 $m^3$ |
| Sawn and planed wood | 410,000 $m^3$ | 11,700,000 $m^3$ |
| Particleboard | 702,000 $m^3$ | 50,000 $m^3$ |
| Plywood | 185,000 $m^3$ | 42,000 $m^3$ |
| Wood pulp | 471,000 tonnes | 3,700,000 tonnes |
| Paper and Paperboard | 922,000 tonnes | 10,600,000 tonnes |

### 4.4.2 Changing Markets for Bio-based Products

Historically, the price trends of wood products and biomass have shown considerable fluctuations over time (UN, 2011), driven by product demand shaped by markets, along with resource availability, the price of energy and relative costs of forestry operations. It has also been noted through several studies that the price of biomass is influenced by the price of crude oil (Sinclair Knight Merz, 2013). The emergence of new wood commodities and technologies are changing the way residue streams are utilized and placing increased value on wood, which ultimately is reflected through the market price. During the first oil crisis of the 1970's commodity prices peaked and generally fluctuated considerably until the 1990's whereupon prices for most wood commodities have steadily been declining. As incentives through policy encourage the development of using biomass for energy, the demand and competition for residual products, such as woodchips, increases, leading to an increase in market price.

A changing climate for uses of wood residuals, and the subsequent surge in demand and price for wood products, serves to benefit landowners as they can demand higher prices, however the increased raw material costs can reduce the international competitiveness of the traditional forestry industry products, such as pulp and roundwood (UN, 2011). This can see biomass such as forestry thinning biomass, which was typically purchased by the pulping industry at a very low price, being outcompeted for price by Sweden's energy sector.

Overall, Sweden has seen a reduction in the amount of logging residues harvested in recent times, while importation of residue biomass products has increased as they have become cheaper to source than those produced in Sweden, where the price of wood chips has risen significantly over recent years. This has created an excess of residues within Sweden, for which industries producing them must find ways to utilise, potentially providing an opportunity for the production of biojet fuel.

The forestry industry within Sweden use high value bi-products for heat and electricity such as lignin and sawdust. This material could be switched for lower grade materials for heat while the lignin and sawdust could be used to produce transport biofuels, yet clear economic benefits to the pulp and paper industry would need to accompany any change to the production system (Börjesson, personal communications, 18th June, 2014).

It is also speculated that future economic growth in the EU region will drive up demand for forest industry products, leaving only logging residues available for energy purposes in the long run. Despite this, high petroleum prices, combined with advances to conversion technologies are making cellulosic biofuels more economical. Biofuels coming from Sweden's forests for use in the road transportation system are exempt from energy taxes, which effectively functions as a tax subsidy for bioenergy producers to incentivize wider deployment. R&D efforts within Sweden in recent years have been focused on making better use of a larger portion of available biomass resources, including the development of biorefinery technologies and capacities.

### 4.4.3 Forestry Management in Sweden and Methods to Improve Forest Yields

Forestry management in Sweden is undertaken on a compartmentalised basis, whereby segments of forest are harvested in blocks. Inferior trees are pruned when trees reach 2-4 metres and left in-situ as fertiliser, and also thinned when trees reach 12-22 metres to promote optimal growth for the most desirable trees. Such thinning provides up to 25-30% of harvested wood, and is a process that optimizes economic value from forestry operations. Harvesting can occur from 60-70 years after plantation in Sweden's south, or 90-120 years in the north, and involves cutting while leaving some remaining biomass for environmental preservation. The potential to increase biomass yields from the forest therefore must either increase biomass growth (reduce growth cycles) or to increase the retention of harvest from other areas of the tree.

The standard forest tree is comprised of the stem wood, the stump and the branches and tops (GROT). The stemwood occupies the majority of the tree and is the most valuable portion, allocated for primary uses such as the pulp and roundwood industries. The GROT section of a tree is very proportionally nutrient rich, and contains a lot of nitrogen affecting plant growth. Studies suggest that nitrogen is the most important growth nutrient and an increase of GROT harvest may demand nitrogen replacement (SEA, 2014), however other studies suggest the growth effect is temporary and doesn't lead to a permanent decrease in land productivity (Engell, 2011). It has also been researched that forest thinning reduces growth in the remaining stand in the first two ten-year periods in Norway Spruce and the second ten-year period for Scots Pine stands, meaning if the forest owners wish to compensate for this loss they must fertilize the area, adding extra cost (SEA, 2014).

According to a study undertaken by the Swedish Energy Agency (2007), there is considerable potential to increase forest fuel extraction without decreasing possibilities[25] of achieving other societal environmental and forest production objectives, so long as a number of basic core management principles are implemented, namely:

- Extracted branches, tops and stumps come mainly from conifers
- Ash recycling is implemented where required
- Extraction of deadwood is prioritized away from key habitats and nature reserves
- Extraction of branches and stumps is undertaken only on land with good load-bearing capacity

Stump harvesting has been reported to be an ineffective practice over the short-term for a variety of reasons including biodiversity loss (through habitat destruction), disturbed carbon circulation and the presence of course sediments such as soil, stones and dust. It is however noted through several studies that stump harvesting could become a more efficient practice in the long-term. Stumps contain low nitrogen levels, and it has been shown that well-implemented stump harvesting can reduce root rot (Vasaitis et al., 2008). Recommendations from the Swedish Forestry Agency suggests harvesting of conifer stumps in entirety, while leaving 15-25% of the volume of spruce and pine stumps respectively for sustainable forestry practice (Stendahl et al., 2013).

Other methods mentioned throughout other studies that can improve forest harvest yields sustainably include the use of fertilizers, the introduction of biotechnology and improved forest handling. Researchers from the Swedish University of Agricultural Sciences claim that fertilizers for forestry plantations can make the difference in ensuring that both the bioenergy and forestry industries can achieve levels of biomass extraction according to demand in a sustainable manner (Linder, Bergh and Lundmark, 2008). The biggest constraining factor to growth in the Swedish forests is not climate or slow growing species, but rather a shortage of nitrogen. Nitrogen fertilization of forestry biomass was introduced in the 1960's until concerns over acidification of watercourses caused by fertilizer leakages meant that the practice was essentially stopped through general advice by the Swedish Forest Agency. Experts predict that up to 20 cubic metres per hectare additionally can be grown through fertilization for a normal dose (150 kg per hectare). The difference in growth levels from the 1980's during fertilization to now, according to experts, is about 2 million cubic metres of forest raw material per year, equivalent to just over 4 TWh that could be used to replace fossil fuels ( Börjesson, Linder, & Lundmark, 2008).

Another method of improving harvest yields is through biotechnology breeding programs, which can increase short-term forest cultivations by up to 50% (von Arnold, 2008). Just as agricultural crops have improved breeding through intense cultivation, fast-growing forestry trees can be provided similar treatment. Improvements based on genetic variation, breeding with genetic markers and selective breeding using improved seed is all methods that must be considered if forestry harvest in Sweden is to increase in the future.

More efficient and cheaper sourcing of biomass can result through better handling and

[25] The study undertaken by the Swedish Energy Agency Estimated that the levels of forestry extraction could theoretically be increased by 75% on 2011 levels.

improved logistics of biomass. Improved methods can not only improve yields, but also result in reduced environmental impact and in a more time efficient manner, translating to cost savings.

### 4.4.4 Swedish Forestry Biomass for Biofuel Production

Currently, there is almost no forest timber that is harvested specifically for the purpose of producing biofuel in Sweden (Staffas et al., 2013). Forest fuels used for bioenergy in Sweden, apart from firewood and a small proportion of energy crops, rely upon the supply residue materials that can be categorised as either primary or secondary residues.

Primary residues are those taken and processed as virgin material, and include thinning timber, post harvest tops and braches and rejected quality timbers, while secondary residues refer to those that have undergone some form of processing, and include mill residues (saw dust, woodchips), bark, black liquor, tall oil and tall oil pitch. Figure 16 outlines the supply of biomass fuels in Sweden for the year 2005, and shows the high contribution of black liquors and the relatively small contribution of Swedish bioenergy supply from energy crops.

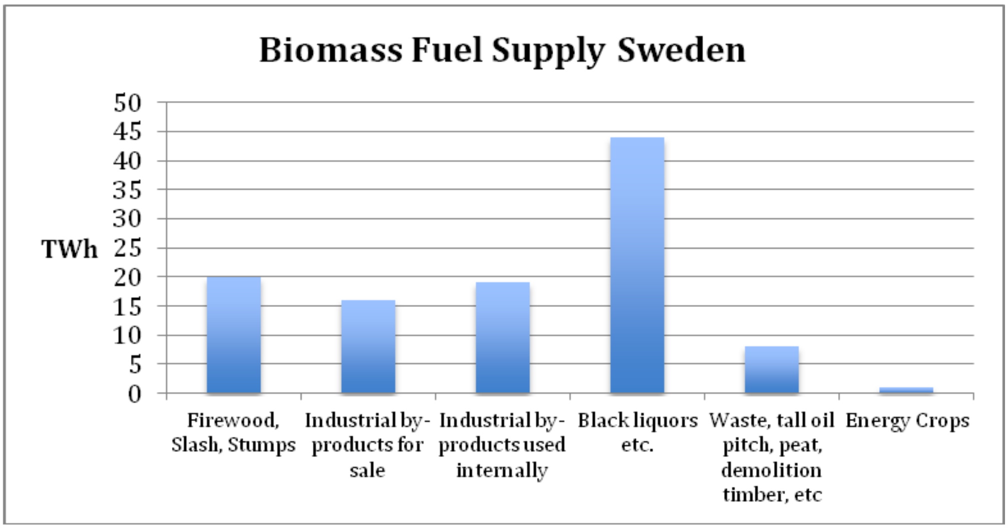


*Figure 17: Source: Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, 2008*

These materials often comprise of a significant share of total biomass entering the system, and thus provide a considerable income stream or energy source for bi-product producers. The distribution of bioenergy use in Sweden is dominated by industry use and district heating, largely the result of imported residues and the bi-products from primary industrial activities, such as pulp and paper production (Swedish Energy Agency, 2014). Sweden is currently very resource efficient and utilizes almost all mill residues for plant energy and heat purposes, although it has been acknowledged by several industry actors that the energy efficiency measures at existing Kraft pulp mills creates the potential to take out volumes of lignin for the production of biofuel components (Tibblin, personal communications, 22nd August, 2014).

### 4.4.5 Forestry Biomass as a Transport Biofuels Feedstock

When considering the notion of increasing the amount of biomass allocation for the production of transport biofuels, it is very important to consider the effect on material supply for other products and services, which can also find a use for the biomass. The most important aspects to consider in the utilization of forestry biomass for transport biofuel production include the limitations placed on the theoretical amount of biomass that could be extracted, and to optimise conversion and process efficiency to get the maximum output as a ratio of input (Staffas et al. 2013). Börjesson (2014) speculates that when considering future biofuel potential in Sweden, it is very important to define the theoretical potential, and also consider the various spheres of limitations that limit the actual potential, including social, ecological, economic and market aspects. One of the main barriers, according to Börjesson (2014) in unlocking the theoretical potential for biofuels in Sweden relates to market barriers as a result of a lack in institutional support.

Within the next 20-30 years, including such limitations, Börjesson (2014) estimates that there will be approximately 55-75 TWh of biomass potentially available for the production of transport biofuels, without competing for other forestry activities and complying with existing sustainability criteria, with a significant majority of this biomass derived from forestry residues. Using both biochemical and thermal gasification technologies, it is estimated that up to 60-75% of energy content in the biomass can be converted into high value biofuels. In releasing this potential, it is therefore possible, according to Börjesson (2014), to replace around one third of transport fossil fuels with biofuels within Sweden, not considering the effect in increasing vehicle fuel efficiencies, at a similar cost to biofuels today such as HVO and biodiesel from rapeseed[26]. Estimates of available biomass derived from forestry residues in Sweden by the year 2050, according to Börjesson (2014) include 21.3 TWh of stumps, 17.1 TWh of tops and branches, 9.4 TWh of available pulpwood.

[26] The production costs of existing commercial biofuel systems in Sweden today, such as HVO and rapeseed biodiesel are between 7-8 SEK. It is expected that future biofuel will be of similar cost. The production costs of petrol today are about 5 SEK per litre. When the carbon tax is included the production cost of producing the fuels are cost competitive.

# 5 Findings and Analysis

*Given technological development and forestry biomass volumes, the production of a biojet supply system in Sweden is technically possible using forestry biomass residuals, yet is unlikely for mostly non-technical reasons. Through identifying the common components and dynamics of a technological innovation system framework, drivers and barriers to the successful deployment of such a system are brought to light and analysed.*

## 5.1 Theoretical background and conceptual reasoning

The oxford dictionary defines the process of innovation as to "make changes in something established, especially by introducing new methods, ideas, or products". Innovation is a process that is linked to progression, learning and Darwinian evolution, whereby selective adoption (institutions governing market selection) of a particular mutation (innovation) leads to a relative increase in importance of some aspects and a reduction in others (Raven, 2006). Innovation results from the interactive ecology of actors, and can be used to describe a wide range of aspects and societal demographics. It is a non-linear process, is forever changing through the dynamism of its components, and is closely linked to innovation spillovers, where positive synergies are realized through the formation of industrial districts[27].

The use of an analytical framework helps the researcher to categorise or interpret a process or phenomena. It has been established through the earlier works of (McCormick 2007), that a framework embedded within innovation literature and the process of technological change can be applied for an understanding into barriers and drivers affecting the expansion of bioenergy systems. Understanding the common inner-workings by which an idea develops from concept to commercial scale is vitally important in sustainable policy making for developing emerging bioenergy technologies, such as establishing commercial supply chains for biojet systems. For the purposes of this thesis, theoretical literature exploring both innovation systems and strategic niche management were researched. The two theories closely interact in that they both deal with innovation and the processes behind technical change, vital to understanding drivers and barriers to common to emerging bioenergy systems.

Historically, the process of innovation was understood to be a linear process (see Figure 18), which proved to be influential in directing policy decisions for many decades and was advised by prominent neoclassical economists (Hekkert & Negro 2009). However more recently, the linear model has been criticized for ignoring the iterative learning process, involving feedback loops, which has since become an integral part in shaping our modern understating of the innovation process (McCormick, 2007). It is claimed by several authors that the most important framework to understand the complete innovation process is the innovation systems framework (Hekkert & Negro 2009), which allows examination of the innovation process embedded within the wider socio-economic environment.

[27] This notion is also inherently linked to the concept of Industrial Dynamics, as explored through the works of Carlsson & Eliasson (2003).

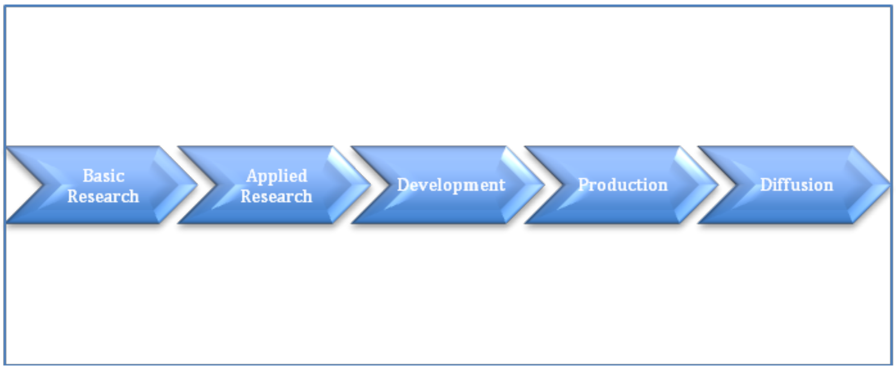


*Figure 18: Linear model of innovation, as presented by Hekkert & Negro, 2009*

A number of different versions of innovation system concepts have been put forward in the literature, detailing national, regional, sectorial or technological systems concepts (Hekkert & Negro, 2009; Lynn, Mohan Reddy, & Aram, 1996; Robinson, 2009; Sagar & van der Zwaan, 2006), and all deal with diffusion as a process driven by flows of technology and information between actors. Economic growth, or diffusion of an innovation system, is created when creative innovators interact with economic actors through selection (Carlsson & Eliasson, 2003). The concept has been defined by Carlsson and Stankiewicz (1991) and more recently by Saleh (2010) as "*a dynamic network of agents operating in a specific technology area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology*".

The application of a Technological Innovation Systems (TIS) framework serves to explain the nature and rate of technological diffusion, and the motivators behind why a particular sustainable energy technology has developed and diffused into society, while others have not. Analysis can focus on system components (structures), which are made up of actors, networks and institutions and are defined as being relatively stable over time. The concept of examining a specific technological innovation is linked to the notion of technological niches, which also provides further reasoning for why certain innovations will fail despite showing proof of concept.

Strategic Niche Management (SNM) identifies technical change as a shift toward unlocking dominant technological regimes (incumbent technologies) through overcoming a number of common barriers, both technical and social, through the creation of protected niches as incubators for essential development processes, such as learning and the creation of networks. Evolutionary economics argues that well established technological systems, such as jet fuel production from crude oil, are embedded within their own technological *regimes,* driven by rules based upon cognitions, beliefs, organization structure and scientific methods between firms (Raven, 2006; Kemp, 1998). Incumbent dominance exists primarily due to the ability of incumbent firms to adapt to the institutional platform by which emerging technologies may struggle. SNM suggests that successful innovations can be enabled through the creation of protected design spaces, for which the institutional structure is built to support in addition to niche external processes to bridge the gap between demonstration and R&D to market introduction, involving interrelated social and technological change. This concept is also explored in the innovation systems literature, referring to the building of knowledge through learning as cumulative causation.

McCormick (2007) outlines a bioenergy has four inherent technical components. These are *Biomass sources, supply systems, conversion technologies* and *energy services.* Furthermore, common barriers including *economic conditions, know how* and *institutional capacity*, and *supply chain* *coordination* are identified by McCormick & Kåberger (2007) as affecting the development of bioenergy, which can otherwise be known as critical factors (Roos et al., 2008). These aspects can serve to provide insight into whether or not the existing system infrastructure, such as the institutional framework, supply systems and energy demand could be utilised to drive the formation of a bioenergy system, or emerge as barriers to establishment.

With the innovation and strategic niche management literature in mind, the framework selected for this study, adapted from McCormick (2007) uses the four key components of bioenergy systems to map out the Swedish preconditions that would either technically support or constrain a biojet system. Critical factors for the implementation of bioenergy systems in Europe are then assessed against the Swedish existing environment as markers for analysing fundamental non-technical components (see Figure 19). These aspects are used as subheadings to identify and analyse the key aspects within the Swedish system that can drive or serve to inhibit the establishment of a biojet production system using forestry biomass as a feedstock.

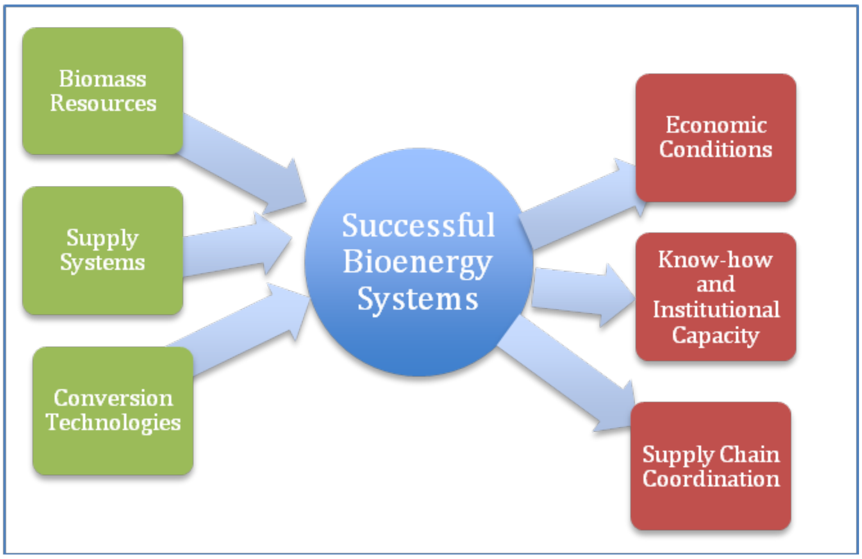


*Figure 19: Key bioenergy system components (left in green) and barriers (right in red) for expanding bioenergy in Europe. Adapted from McCormick* (2007)

## 5.2 Drivers and barriers to a Swedish Biojet System

The literature identifies a number of drivers and barriers to the establishment of sustainable bioenergy systems. When investigating drivers to the establishment of bioenergy systems, it is important to define the term 'benefit' and what it means when assessing drivers. A benefit, as discussed by McCormick (2007), is a positive impact arising from the implementation of a bioenergy system. This benefit can be manifested across many different spheres, such as cleaner air, greater economic profit and better social standards, yet may not serve to benefit the interests of those who count, such as the investor (Carter, 2001).

It is also relevant to recognize the local, regional and global scales in which drivers can originate, as well as the environmental, social and economic spheres having influence. Climate change mitigation and improving energy security are global drivers for bioenergy systems around the world. When analyzing the aspects driving a bioenergy system on a more regional setting, such as the case for the present study in Sweden focusing on the forest as a feedstock resource, it is important to analyse how regional and site specific attributes can influence implementation, as well as consideration of global drivers.

Barriers are defined as obstacles to the implementation of the bioenergy system under focus may manifest themselves also in a variety of contexts, including physical, economic, social, environmental and market related barriers. In order to identify and understand barriers to bioenergy system establishment, understanding the local conditions and the nature of cause-and-effect relationships between aspects interacting within the system is crucial.

### 5.2.1 Biomass Resources

The first question to be answered in the study relating to biomass resources is "*how are forestry biomass resources likely to be allocated in the future?*" This question can be partially answered through presenting findings indicating how the future demand and supply of Sweden's forestry resources may look, drawing upon interviewee opinions and findings from literature.

Ultimately, Sweden's forests can create drivers for bioenergy system establishment through the exploitation of forestry material for the production of finished products and biofuels, which in turn can improve the economic conditions and social standards of the region. The forestry sector accounts for 4% of its national GDP, 12% of industry employment (2% overall), and accounts for a major source of revenue through exported goods derived from forest products. Additionally forestry biomass has enabled Sweden to become a world leader in renewable energy, with forestry biomass accounting for more than 80% of biofuels consumed within the country.

Demand for forestry resources within the Swedish system are essentially divided between a few large users, for the production of material products, such as pulp, paper and finished wood products, and the production of energy either directly or through energy carriers. It is expected that the demand for the large forestry based industries, such as roundwood, timber and pulp will remain strong over the coming decades, although it is noted amongst many biomass experts and representatives from forestry companies that the markets creating the demand for forestry products are shifting (Wintzell, personal communication, 25th July, 2014). Expansion of electronic ICT has translated to a dramatically reduced demand of newsprint, printing and writing paper, which has overall lead to decreases in pulp production and affected business growth, which may serve to benefit the bioenergy sector through increased availability of biomass. Future demand for the sawmill industry appears more promising than that for pulp and paper, for which the bioenergy sector looks set to benefit from in the form of residues.

Government incentives aligned to Sweden's *Integrated Climate and Energy Policy* will facilitate a growing demand for biomass to produce bioenergy and more specifically liquid biofuels for road transport over the coming decades. The current amount of 7 TWh of road biofuels is expected to double by the year 2030, while total demand for wood sources will increase from 122.2 million $m^3$ to 152.8 million $m^3$ by 2030, according to Mantau et al. (2010).

Sustainable management of biomass resources is instrumental in driving the establishment of a bioenergy system. As noted in section 4.4.1, the total volume of Sweden's forest is 3 billion $m^3$, which is growing by 120 million $m^3$ per year while 90 million $m^3$ is harvested. The surplus created between the differences in growth to that harvested is essential to forestry management (Börjesson, personal communication, 28th June, 2014) and any increases to the amount extracted will require improved forestry techniques, which may include methods included within section 4.4.3.

In terms of future biomass supply, several renowned sources have noted that there is large capacity to harvest a larger portion of wood from the forest without compromising the ecological core functions of the forest, both through increasing harvesting operations and capturing more residues. Areas of abundance are predominately in the south and central regions of the country, dominated by Scots Pine and Norway spruce tree species.

Gustav Tibblin, the director for business development at Sodra, believes that it will be possible to extract at least an additional 20 million $m^3$ of raw biomass from Sweden's forests within the next 20 years without competing with surrounding forest industries. This figure, if it were all to be converted into biofuels, would equate to roughly 20 TWh (Tibblin, Personal communication, 22nd August, 2014), suggesting that the technical potential of biofuel production is much larger than what is currently produced. Bioenergy experts predict similar potentials. Börjesson (2014) estimates that there is 55-75 TWh of biomass (including energy crops, manure, and forestry residues) potentially available for biofuels within the next 10-15 years, without competing for other forestry activities and complying with existing sustainability criteria. Using both biochemical and thermal gasification technologies, it is estimated that up to 60-75% of energy content in the biomass can be converted into high value biofuels, potentially replacing a third of all fossil based road fuels.

The majority of future biofuel production will rely mostly on residue feedstocks from the forestry sector, owing to the procedures ad costs involved in collecting and transporting logging residues (Börjesson, personal communication, 28th June 2014; Jan Wintzell, personal communication, 25th July, 2014). The availability of industrial residual products is therefore dependent on the future demand of wood based industries such as pulp and paper and sawmills, and the abilities of industries to use their own residues, which according to industry actors does not create a great deal of surplus material available for transport biofuel production. This is demonstrated through the fact that many plants are actually net energy producers. Saw mills will typically use residues to generate steam and heat for drying biomass, while pulp mills combust their liquor in the form of black liquor for powering plant operations and steam. Additional surplus in residues may be created through improving the energy efficiency of the plant being used, or alternatively they can be bought at a price equal or greater to the price of the energy value attained from the material (Westerburg, personal communications, 26th June, 2014).

Sweden's forestry industries are very efficient at utilizing their current residual products for heat and electricity in-house, and any attempt at purchasing residues will need to balance the energy needs to make it profitable for the industries currently using them. The pulp and paper industry are characterized as being resistant to change, meaning any changes to the incumbent system to capture their residues currently being used for energy purposes will need to exhibit economic benefits to them (Börjesson, 2014, personal communication). In terms of logging residues, there is in excess of 30 TWh of energy in the form of tops and branches left in-situ following logging activities in Sweden that are not being utilised owing to the difficulty and energy input required to collect, transport and process them. Sustainable forestry processes, such as thinning operations and the establishment of energy crops, can serve to promote the additional biomass resources for the production of biojet fuel, if advanced collection and transportation techniques are performed, such as whole tree harvesting.

Dedicated energy plantations show a great deal of potential within Sweden owing to the large amounts of existing fallow land[28], combined with developments allowing for faster forest growth for species such as hybrid poplar aspen, using conventional agriculture and short rotation growth cycles. This could potentially open up the potential for willow, poplar and aspen plantations, which have a very short rotation period and show promise within Sweden as a biofuel feedstock. (Börjesson, personal communication, 28th June 2014).

As noted in section 4.3.4, the recent report by Värmeforsk states the supply of 50,000 tonnes of biojet would allow Stockholm Arlanda to run carbon neutral. The required energy capacity for an integrated plant to produce this volume is reported at 300 MW, running over 8,000 hours per year (Ekbom, Hjerpe, & Hermann, 2009). This would call for the use of approximately 2 million cubic metres of solid roundwood per year. The 2% baseline target set for biojet production in Sweden outlined in section 4.1.1 would demand the distributed production of approximately 22,000 tonnes of biojet fuel, or 0.97 PJ of energy (1.6 PJ or 0.44 TWh assuming a 60% conversion factor), if the same conversion methods were applied as in the Arlanda case. This essentially means that around 6.5 % of the equivalent amount of energy used today to produce transport biofuels in Sweden (approximately 7 TWh), would be required to produce biojet fuels in the year 2020 for account for 2% of the total demand.

### 5.2.2 Supply Systems

Supply systems form a crucial component in the formation of any bioenergy system, fundamentally due to the importance of transport efficiency and large number of processing steps along the supply chain. If the biomass resources exist but the infrastructure to transport and process the biomass is lacking, then the system will not be successful. Sweden possesses supply systems supportive of bioenergy systems, given the relatively substantial amount of energy derived from biofuels. Such supportive aspects include the extensive physical production infrastructure providing logistical support, such as transportation networks (road, rail and maritime), proximity to district heating networks, the forest and industries, as well as the non-physical aspects governing the system, such as a tight and well managed system of sustainable forest management governing the forestry activity within Sweden, and R&D activities through government, private companies and research institutions.

A key driver for biofuel expansion within a particular region such as Sweden are the controls over supply chain management aspects, such as chain-of-custody certification, when each node in the supply chain, from harvesting, to pre-processing, to transport and distribution is contained within a single jurisdiction. As shown within Figure 8, Figure 13 and Figure 14, Sweden has several large ports, airports, areas of biomass within fairly close proximity in the central and southern regions of the country. This supplemented by extensive road and rail networks would serve to support several biojet production plants co-located with existing forestry industry plants and transportation networks. Within Sweden today there are many actors working towards optimising the logistics of harvesting biomass from the forests, processing and transporting it in the most cost efficient and environmentally friendly way. The Forestry Research Institute, Skogforsk, specialise in delivering knowledge and research to industry actors and the public regarding products and practices that contribute to a more profitable and sustainable use of the forest, promoting the goal to strengthen the forestry industries competitiveness. Key research areas include forestry management techniques, logistics and tree improvement

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[28] Under Swedish law, 5-10% of a farmers land must be left fallow. This land may not be used to produce food, but can be used to grow energy crops, however FSC certification requirements prohibit the planting of more than 5% of plants of foreign species.

According to (Ekbom et al., 2009) the advantage of Brista as a site selected for establishment of an FT plant for biojet production is its close connection with Gavle, which has a port that is close to the forests of central and northern Sweden, that can be used for sourcing biomass. There is also a CHP plant in Brista, where biomass is delivered by truck but will soon be delivered by train. This transportation network, along with a direct pump of fuel that already exists from Brista to the airport can be utilised in a FT plant. Furthermore, it is also important to note that Stockholm City is expanding to the north, which will require more heat, thereby being a potential user of the large amounts of heat that is typically produced in the FT synthesis process.

A key example of how a holistic supply chain can be implemented leveraging knowledge, resources and infrastructure is the Sunpine plant based in Piteå. As described in section 3.4.4, tall oil, skimmed from the top of the black liquor in the pulping process, is upgraded into a crude tall diesel on-site and shipped south to the Preem refinery in Gothenburg, where it is upgraded into biodiesel. This process has been in operation since 2010, currently produces 100,000 $m^3$ of biodiesel per year, and is already generating a net profit. Further upscaling of the plant is, however limited by the availability of tall oil, which is a relatively scarce residual product from the pulping process (Renmarker, personal communications, 5th July, 2014).

It is also found, not surprisingly, that a highly segmented supply chain intersecting international and socio-political borders can lead to difficulty in driving a sustainable bioenergy supply chain, despite the advantages outsourcing skills and resources can bring. SkyNRG is a global market leader in sustainable jet fuel, currently supplying more than 20 carriers across the world and acquiring feedstock from many different regions. As such, a major production barrier to biojet throughout many areas of the world, after the high production cost, is the limited volume of certifiably sustainable renewable diesel, under the RSB standard[29] (Valk, personal communication, 12th June, 2014).

### 5.2.3 Conversion Technologies

There are many conversion processes potentially involved in the production of biojet fuels, yet owing to the relative infancy of some technologies, only three methods have been officially approved for commercial deployment. Selection of the most suitable process depends largely on the type of available feedstock and available infrastructure. As outlined in Section 3.4.1, both the Fischer-Tropsch and Alcohol-to-Jet conversion methods are currently considered the most appropriate for production of biojet within Sweden using forestry biomass as a feedstock, given both the nature and availability of key feedstock streams in the region. The following table summarises perceived strengths and weaknesses to such conversion methods in Swedish context.

*Table 6: Strengths and weakness of candidate conversion technologies for biojet production in Sweden*

| Conversion Process | Strengths | Weaknesses | Key Companies |
|---|---|---|---|
| Fischer-Tropche (FT) | • All components of biomass can be converted to biojet<br>• Proven Technology (more so however | • High capital costs<br>• Uncertainty of technology at a | • NSE Biofuels (Finland) |

[29] One exception is the U.S., where there are large volumes of used cooking oil.

| | | | |
|---|---|---|---|
| | for coal, rather than biomass)<br>• High carbon conversion<br>• Feedstocks can be sourced cheaply<br>• Low operating costs, with no requirement for additional hydrogen | commercial scale<br>• Impurities can cause deactivation of catalysts<br>• Large biomass volumes to central plants required to avoid high logistical costs | • Solena (U.S.)<br>• Bioliq (Germany) |
| Alcohol-to-Jet (AtJ) | • All processes already used in petrochemical industry<br>• Fuel contains aromatic compounds<br>• Only very small amounts of hydrogen required | • Food derived alcohols are cheaper to produce<br>• Process has not yet been optimized for biojet process.<br>• High opportunity costs when converting ethanol, as political framework creates a more lucrative market for ethanol over biojet fuel in Sweden. | • Lanzatch (NZ)<br>• Swedish Biofuels AB (SWE)<br>• GEVO (U.S.) |

In terms of key actors in the region with capabilities, Swedish Biofuels AB specialise in the alcohol-to-jet process, while Solena are a biofuels company heavily involved with FT synthesis and plasma gasification technology projects within the European region. Other biofuel companies that utilise the HEFA production method, such as Neste Oil, may show promise as potential supplier, particularly since Neste Oil have a production facility in Porvoo, Finland that uses mostly wastes and residues as feedstocks.

### 5.2.4 Economic Conditions

Economic conditions refer to the aspects faced by emerging bioenergy systems surrounding cost competition, and are heavily influenced by policy measures and governmental support. The economic conditions surrounding an emerging technology, such as biojet production, can either serve to drive or inhibit system expansion.

A key finding of this study is confirmation that government support is crucial to the success or failure of biojet as a future technological system. All biofuels capable of meeting the ASTM quality standard will be significantly more expensive than fossil kerosene for the aviation industry until at least 2020 based on direct costs (European Commission, 2013). Airlines typically operate on very tight profit margins, with fuel costs comprising the largest cost component. This does not give airlines room to purchase and absorb extra costs for the purchase of alternative fuels sold at a higher price, thereby locking out the biojet consumer market. Futhermore, as stated by McCormick (2007), consumers will purchase cheap rather than green, thereby emphasising the role of governments in create incentive frameworks.

Energy markets do not account for the full spectrum of positive benefits created through bioenergy systems, such as improved air quality (otherwise known as positive externalities). Markets therefore often need to be manipulated in order for emerging renewable energy systems to survive and undergo learning so that they can subsequently compete with incumbent technologies on cost. This process of progressive growth through interaction and reinforcement of system functions is referred to throughout SNM and innovation systems literature as cumulative causation, and relies on the production of creative design spaces otherwise referred to as protective niches. Examples of such processes driving bioenergy include taxes, subsidies and support schemes, which have contributed greatly to the development of ethanol and biodiesel production and use within Sweden over the past decade, as well as the facilitation of bioenergy usage in the district heating sector.

Biojet development within Sweden and the rest of the Nordic region is currently still in demonstration phase, and political support is crucial for shaping economic conditions to bridge the gap to create commercial viability for the technology (Kempe, personal communications, 26th June, 2014). Securing long-term investment remains a huge challenge, particularly as up front capital for plants and equipment can be significant. Financial institutions will lend only if the technology is shown to be economically viable, and in the presence of government support (Tibblin, personal communications, 27th August, 2014).

Reluctance by governments to provide economic support for reduced aviation emissions arises from the international nature of the aviation industry, and the fact that international aviation emissions are not counted within Kyoto emission targets[30]. International emissions levels are recorded on the basis of aviation 'bunker'[31] fuels purchased by a particular country. An effective method for monitoring and managing aviation emissions has not been reached after more than 12 years of negotiations, which according to a report from the European Federation for Transport and Environment (2009), can be put down to developed economies wanting global measures so as to avoid competitive distortion, but influential emerging economies believing the principle of common but differentiated responsibilities should prevail meaning responsibility to take mitigating action should lie with the developed economies.

The lack of a globally harmonised policy for regulating the environmental impact of international aviation creates disincentives for national governments to formulate regulative policy, as this can create an uncompetitive environment and airlines will simply divert routes to where more lenient policies apply. The Chicago Convention on International Civil Aviation in 1944 set a range of specific rules of airspace, which included *Article 24* stating that aircraft fuel shall be free of duty (International Civil Aviation Organisation, 1944), so as to eliminate competitive distortion between states. This clearly allows international aviation to operate in a free and equitable manner yet creates difficulty for alternative products that attempt to compete with incumbent jet fuels for price. This difficulty is exacerbated when the raw materials and intermediate products to the alternative fuels competing with jet fuels can be processed to produce other products, such as biodiesel for road transport, for which economic incentives for producers exist. This general situation is what many within the aviation industry refer to as an 'unleveled playing field', whereby the opportunities for environmental and economic gain through developing biojet fuels are prohibitively constrained by favourable economic conditions created for the road sector, which are created to contribute towards several key policy goals, such as those outlined in section 4.2.3.

After more than 15 years of discussions through the ICAO platform, it was decided to develop and adopt a global MBM, designed to curb the environmental impact caused from international aviation by introducing an implicit price on carbon emitted in the sky and avoid

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[30] Only domestic emissions are included in the national total when reporting to the United National Framework Convention on Climate Change (UNFCCC). There is a responsibility of nations for accounting for international aviation emissions to ICAO.

[31] Bunker fuel is any fuel used traditionally on ships and acquired its name form the containers used to store the fuel. The term has been applied to aviation fuel also.

a patchwork of regional and national schemes, such as the EU ETS, which has so far been ineffective. Specific details on the MBM are scheduled to be announced in 2016 for implementation in 2020 (International Civil Aviation Organisation, 2013c), yet what is clear is that the measure must cover all emissions from flights covered under the scheme and also consider the varying maturation of aviation in different countries. At the moment, the favoured mechanism is an emissions trading scheme, whereby emission levels from 2020 would be recorded as baseline and capped for proceeding years. Participants would then be required to purchase emissions offsets for any exceedances to the cap, for which biofuels could be integrated into. If effective, an MBM would change the way aviation emissions are accounted for in much the same light as road based biofuels. This could ultimately serve as a key driver for biojet development as it would essentially improve the value of alternative cleaner fuels proportionally to fossil based aviation fuels. Governments would therefore be obligated to provide support to remain internationally competitive. In terms of specific supportive instruments, biofuel mandates have been shown to be effective in generating biofuels production, as seen in the Swedish biofuels for road-transport sector, yet can fail to deliver environmental and GHG reducing targets, thereby potentially negating the effect of developing biofuels over conventional fuels (Philp, Guy, & Ritchie, 2013).

Experiences regarding mechanisms imposed for first generation biofuels within the EU suggest imposing a tax on the carbon content for fuels, accompanied by a mandatory certification scheme, can be effective in promoting development for biofuels favouring those with superior GHG emission profiles, such as second generation technologies.

### 5.2.5 Know-how and Institutional Capacity

Bioenergy systems are comprised of a number of structural components, yet in order to facilitate the flow of technology and information between actors through networks, a combination of know-how and institutional capacity is needed. Quite often, those who make the decisions that affect the overall success or failure of an innovation system are not those with the most developed knowledge on the topic, so therefore an important driver to the successful establishment and diffusion of a bioenergy system is not only the level of knowledge acquired, but the successful communication of knowledge to important actors. Knowledge and technological experience is key in gaining confidence from investors for bioenergy system establishment. One of the key barriers holding back several promising emerging conversion technologies is the fact that the processes have not yet been proven on a large scale (Porsgaard, personal communication, 12th June, 2014).

Sweden is a country characterized by extensive experience and knowledge in renewable energy development and biofuels in particular. Several key actors exist that seek to accelerate learning and the capacity of institutions to make informed decisions relating to bioenergy within a Swedish context. The Swedish Knowledge Centre for Renewable Transportation Fuels (also known as f3), financed by the Swedish Energy Agency and the region of Västra Götaland, are both a research and information platform to enhance technological development and inform companies and the public around sustainable transportation fuels. F3 are partners with a range of stakeholders, from government agencies including the Swedish Energy Agency, to frontline research institutions such as Chalmers University and industry actors such as prominent oil refining companies (such as Preem AB) to connect knowledge chains and translate knowledge in the lab to savings in energy and costs in the field.

Knowledge clusters in the field also exist on more local scales within Sweden, which serve to drive innovation developments with regard to biorefining technology and the development of new transportation biofuels. The Solander Science Park in Piteå was established in 2011 and involves a network of more than 40 companies within the local region, in addition to close collaboration with the Energy Technology Centre in Piteå, Luleå University and Umeå University. Companies included within the cleantech cluster range greatly in size and areas of expertise, with members such as Smurfit Kappa from the pulp and paper industry to Chemrec, a second-generation biofuel technology company.

The core function of the cluster is to leverage knowledge and integrate processes for mutual benefit, which has manifested itself through the creation of a number of new companies based upon collaborative efforts. Such companies include Sunpine (as outlined in section 3.4.4 and 5.2.1), and PiteEnergi, who specialise in small-scale cogeneration systems based on biomass. Although biojet fuel cannot be produced directly from the tall oil managed by Sunpine (due to the high amounts of fatty acids in the feedstock and the relatively limited volumes produced), much of the know-how regarding mobilisation of actors and business models based on biorefining technologies could benefit a biojet system (Renmarker, personal communications, 5th July, 2014).

When dealing with forestry biomass, it is clear that synergies between supply chain actors are crucial in driving industry best practice to optimise a profitable and sustainable use of forest resources. The Swedish Forestry Research Institute (Skogforsk) is a research institution focused on harvesting and logistics methods, as well as facilitating collaborative initiatives such as BSG (Fuel Technical Liaison). This is a working group consisting of members from each segment of the forest fuel supply chain to share information, research and experiences to strengthen the learning function for developing forestry based fuel supply chains. Currently there are no direct efforts to develop a supply chain for biojet fuel based on the forestry resources, however the transfer of such an initiative would certainly help reduce transaction costs and optimise logistics operations.

One key aspect that can constrain bioenergy development, as outlined by McCormick & Kåberger, (2007) is that bioenergy is regarded among both public and political spheres as a fuel of the past (Hall & Scrase, 1998). Although bioenergy is generally accepted as a legitimate form of energy generation in Sweden (as evidenced through the large portion of energy generated from biofuels, see Figure 9), scepticism regarding the abilities of biojet fuels to generate the types of gains claimed by the airline proponents can affect political decisions and ultimately constrain biojet development.

Opposition to the uptake of biojet can be derived from two main lines of argument. There are those who feel that the primary function of the forest is biodiversity conservation, and that it is not something that should be exploited for maximised economic growth[32]. The second line of opposition rests upon how biomass usage should be prioritised. Residual forestry material, such as tops and branches, can be used to produce fuels (such as methanol) for use in the road transport sector with less processing steps than biojet fuel, while still fulfilling the objective of reducing fossil fuel dependence (Karyd, personal communications, 13th June, 2014). A counter to this latter argument is that bioenergy resources should be prioritised to replace fossil fuel applications for which there is no other alternatives, as stated within the *WWF 2050 Energy Vision* (Ecofys, OMA, & WWF, 2011). The road transport industry has access to additional technologies, while the Maritime industry are considering liquefied natural gas. Bio-based liquid fuels are needed in the aviation sector, and the

[32] The greens party in Sweden have an ambition within Sweden to set aside more forest for conservation (Tibblin, personal communication, 27th August, 2014).

production of bio-based chemicals can be co-produced to improve the feasibility of the production process (Börjesson, personal communication, 18th June, 2014).

### 5.2.6 Supply Chain Coordination

The makings of a successful bioenergy system depends upon the strength of the system's technical components, such as the availability of biomass, conversion technology and supply systems. Such aspects, as outlined in Sections 5.2.1, 5.2.2 and 5.2.3 are strong when examined in a Swedish context, owing to the already well-developed bioenergy sector, well-managed forests and high levels of technical knowledge. What is also inherent to a successful functioning bioenergy system is coordination of independent actors to streamline the fuel production process at minimal cost. Biomass suppliers, biofuel producers and energy consumers are the major actors in a biojet supply chain, whom are all dependent upon one another for the flow of resources to generate value and drive a successful chain. This interdependence can drive what McCormick (2007) terms the 'chicken and egg' problem, whereby making investment decisions for one bioenergy system component in the absence of the other can create difficulty to the establishment of a system.

The forestry industry in Sweden provides its bioenergy system with resources in the form of primary and secondary residues, as outlined in Section 4.4.4. One of the strengths of the system in Sweden in driving a bioenergy production is the well established nature of forestry management, whereby a few core companies manage the majority of forestry operations, with linkages between forestry owners, forestry companies and forestry industries. Furthermore, Approximately 80% of all Swedish forest land is certified under either the FSC[33] or PEFC[34] certification schemes. This sets strict standards with regard to management, quality standards and traceability of forestry products. One of the clear drivers therefore of using domestically sourced forestry feedstocks is that sustainability criteria become easy to monitor and implement. Sveaskog AB (state owned) are Sweden's largest forest owner, whose function is to manage forestry operations of 14% of the Swedish forest, covering both state and private lands, selling sawlogs, pulpwood and biofuel to a range of industries through their own logistical operations. What is clear is that some degree of vertical integration over the biofuel production process, from harvesting to transport and pre-processing as is the case for the Swedish forestry industry, creates some control of supply chain operations.

LRF are a forestry owner's organization managing operational forestry for all of their members, ensuring that sustainable forestry management is maintained. Sodra are an economic association under LRF, based in Växjö, who own just more that half of all the privately owned forest in the Southern region they represent. Sodra also own a range of companies who trade in both the Swedish and International markets, providing stable markets for forestry products. The group has four key business areas including sawn and planed timber goods, interior products, pulp and paper and biofuel. The close relationship that Sodra have with bioenergy companies has already driven the formation of a number of second generation biofuel projects, including the Sunpine plant in Piteå (Sodra is part owners and one of the founders of Sunpine) and more recently plans to create transport biofuels from woody biomass upon the site of Norway's only Kraft pulp mill located in Tofte, Norway. The selection of this site is based on the sites access to transport networks and its strong potential for handling large volumes of wood. Specific details about the conversion

[33] Forest Stewardship Council

[34] Programme for the Endorsement of Forest Certification

technology or type of fuel produced for the plant are yet to emerge, it is likely the plant will run on roundwood feedstock (Tibblin, personal communications, 27th August, 2014).

Although well established networks of bioenergy components serve to favor a biojet system in Sweden based on forestry resources, it has also created well established process regimes that have developed to utilise residue resources efficiently. Thus any new bioenergy stream would thereby induce competition. Competition for biomass residues used to produce steam and electricity by sawmill and pulping plants, along with road transportation biofuels can serve as a barrier to coordinating supply chains as incentive structures can be misaligned through the presence of competing users. In contrast to competition between users, synergistic relations between actors are a clear driver to any bioenergy system, including that of a biojet system derived on forestry biomass feedstocks. Two key types of relationships that are instrumental in driving synergies within regional supply chains for biojet fuel production and offtake agreement and public-private partnerships (PPP's).

### *Offtake agreements*

An offtake agreement is a legal contract between two parties that stipulate the purchase of a specific amount of a good from one company to the other over a specific period of time. Offtake agreements can provide sellers with the surety of selling their resources within a given time frame and a guaranteed profit, which in turn can help to acquire financing from lenders as it shows there are willing buyers in place. Buyers can also benefit as the agreement essentially hedges the price against future price fluctuations and future shortages. Offtake agreements are particularly important for biojet development as they provide purchasing surety between airlines and biofuel producers, improved chances for financing support through the certainty of market demand and represent a dedicated commitment by airlines to support biojet fuels as a future product. There are a number of notable offtake agreements in place around the world, some are yet to reach the supply stage and others are already in progress.

British Airways, in collaboration with biofuels company Solena have committed to building the worlds first waste-to-biojet fuel facility, with the feasibility assisted by a gate fee for the waste supplied, generated due to the landfill tax in the UK. British airways have made a long-term commitment to commit 50% of funding for the plants construction, as well as the purchase of 50,000 tonnes of biojet per year for a 10-year initial period. The plant is expected to convert around 575,000 tonnes of post recycled waste otherwise destined for landfill or incineration into 120,000 tonnes of both biojet and biodiesel fuel using Solena's integrated technology through the Fischer-Tropche process.

The site for the project, the former Coryton Oil refinery in Thurrock, Essex, was selected based on its ideal transport linkages and existing storage and pipeline infrastructure and is due to commence operations in 2017. The project's main challenge and greatest risk will be its integrated technological conversion process, which although has been demonstrably proven in its individual parts, is still yet to be tested operationally at this scale and as one unified process.

Hong Kong airline Cathay Pacific has entered into a 10-year, 375 million gallon offtake agreement with Fulcrum Bioenergy, a U.S. based company committed to developing a technology to convert municipal solid waste into biojet fuel. This volume represents 2% of the airlines total fuel demand. According to Fulcrum, construction of its first commercial plant is planned for the end of 2014, and is planning on a multi-site production strategy, within close proximity to the Cathay Pacific Network, primarily in North America (Cathay Pacific Press Release, 2014).

Boeing have recently set themselves the internal industry target of 1% biojet integration by the year 2015, which is being kick started by an offtake agreement signed by United Airlines with biofuel company AltAir for 5 million gallons per year from the year 2015. Meanwhile Dutch airline KLM has signed an offtake agreement with the ITAKA supply chain consortium for the purchase of 4,000 tonnes of biojet fuel derived from camelina crops using the HEFA conversion process. Also through this initiative, Finnish oil company NesteOil has supplied German airline company Lufthansa with enough biojet to power 1,187 domestic flights, and will supply its patented NExBTL to fuel the initiative.

### *Public-Private Partnerships (PPPs)*

A public-private partnership is a business relationship between a private-sector company and a government agency who collaborate for mutual benefit to the public, and have been mentioned by many experts to be an important factor for the future development of biojet supply systems (Porsgaard, personal communications, 12th June, 2014). PPP's are a key example of a network, one of several key components of innovation systems, that can serve to create synergies and information sharing between actors for mutual benefit (Bergek et al., 2008).

PPP's can allow the leveraging of ideas, technology and innovation from the private sector into the public sphere for public benefit, and can help to secure funding and investor interest through long-term commitments. PPP's in biojet can be manifested through collaborative initiatives between private biomass producers, fuel producers or technology developers with government agencies, who can serve to connect the strategies of government through policy and legislation to those of private companies (IATA, 2013).

A noteworthy example of PPP's driving biojet development is in the U.S., where federal agencies are supporting a 1 billion gallon biojet target by 2018 through the farm-to-fly initiative. The initiative involves aircraft manufacturer Boeing, the U.S. Department for Agriculture, The U.S. Department of Energy and the aviation trade organisation Airlines for America to set up a series of regional supply chains around the country.

It is also important to note that ideas and expertise can be leveraged across international borders. This has been exemplified in the case of Swedish Biofuels AB and New Zealand biofuels company Lanzatech funded through research contacts issued through the U.S. Department of Defence Advanced Research Projects Agency. Lanzatech are developing a patented process to convert carbon monoxide-rich gas (a bi-product from steel mills usually expelled as $CO_2$) into ethanol, while Swedish Biofuels AB are owners of a patented Alcohol-to-Jet process, and together are partnered with Airline company Virgin Atlantic with plans to introduce the fuel in commercial quantities to China and India within the next three years (International Air Transport Association, 2013).

Other significant public sector led initiatives include the case of Indonesia, whose government has set legally binding provisions to include 2% of biofuels within the aviation mix by 2016 (International Civil Aviation Organisation, 2013a). Within Europe, the EU has granted nearly 10 million euros for the development of a network for sustainable aviation fuel, engaging numerous airlines, aircraft manufacturers, and biofuel developers (European Commission, 2013).

# 6 Discussion

### 6.1.1 Research Aim and Legitimacy of Research Questions

The fundamental research aim of this thesis was to investigate the possibilities of Sweden's forests to supply advanced feedstocks for integration into a biojet production chain. The preface to this topic is that airlines around the world are aiming to reduce their emissions through introducing alternative and sustainable fuels to the market, calling for studies investigating the drivers and barriers to commercial production under a variety of contexts. Data was collected both from the field through a series of interviews and a literature review.

The study involved the micro-investigation of several key areas, forming chapters two, three and four of this thesis. These aspects included a review of current investigations happening elsewhere in the world; a review of knowledge regarding bioenergy systems and the processes behind the technical and social components; and finally an in-depth look at Sweden's energy system and existing environment with regarding to biomass sources and infrastructure.

The research questions selected attempted to essentially capture the main components to determine whether or not a bioenergy system is applicable to a particular setting. By focusing on the technical aspects of future biomass availability and conversion capabilities, combined with the role of social interactions, through partnerships, synergies and networks, opportunities and challenges for future business growth in Sweden for biojet are highlighted.

Throughout the course of the study, a number of questions have arisen that may provide input for further study. Among them, a deeper look into the potential of key emerging conversion technologies, such as Hydrotreated Depolymerized Cellulosic Jet (DC) and Direct Sugar to Hydrocarbon to Jet (DSHC) and their applicability to the Swedish context would be very useful, particularly as there is significant likelihood that the prominent conversion method for biojet production is one that is yet to be approved by ASTM.

One debate explored within this thesis, yet still unresolved is how should Sweden's future biomass be prioritised? There is a range of competing users and philosophies, each with stake in the valuable wood resource. In the context of a changing market, the conversion of wood into biojet fuels is just one of several ideas for biomass usage, for which its fate is ultimately decided by consumers and politicians. Speculation regarding items such as the price of crude oil, and the implications of rapid advancement in electric mobility, as predicted in the Swedish 2050 roadmap, will have significant influence over how biomass is allocated. The outcome from the 38$^{th}$ ICAO assembly in 2016, in regards to the formulation of a global MBM for international aviation emissions could also be a game changer on the political front for biomass allocation.

### 6.1.2 Methods and Choice of Analytical Frameworks

The framework selected was adapted from the writings of McCormick (2007), and involved the selection of six key aspects for measuring critical factors in the establishment and expansion of bioenergy systems. The methodology employed sought firstly to map out the various key components common to all bioenergy production systems, namely the biomass resources, supply systems and conversion technologies and how they are manifested within a Swedish context. Non-technical factors, that had in previous studies served as core barriers to bioenergy system establishment were then assessed also in light of the Swedish context to identify how common non-technical barriers may serve to drive or constrain a system make-up for biojet in Sweden, given the competing uses that exist for biomass material.

Retrospectively, the analytical framework provided a good approach for identifying the key components critical for the establishment of a bioenergy system, and consideration of non-technical factors allowed me to express the impact of social networks, the power of information transfer and the role of institutions in shaping behavior. Upon reflection however, I feel that more time and research could have been allocated toward investigating the potential of neighboring regional areas for provision of biojet fuel or feedstocks, to add more weight to the argument that a domestic production system within Sweden is justified. Despite this, it is still considered that exploring the drivers and barriers to bioenergy establishment in Sweden in respect of biojet development is useful, even if used to supplement a broader regional study.

The two main theories considered in light of the research, innovation systems and strategic niche theory, although not directly employed within the analytical framework as key headings, certainly helped guide my thoughts in terms of the most important aspects for developing a major bioenergy supply chain. The notion that an innovation system is comprised of a dynamic mix of actors communicating and collaborating with each other through networks shaped by the overarching framework put in place by the institutions allowed me to look at the existing system in Sweden with a much more critical insight.

### 6.1.3 Relevance and accuracy of results

The results reported are the result of both information attained through personal communications with interviewees, along with insights and interpretation of data and trends from available literature. In terms of analysing sensitivity of results, the introduction of a global MBM through the ICAO, planned for implementation by 2020 arguably has the potential to drastically affect the way biomass resources are allocated in the future, and could essentially change the way aviation emissions are viewed politically in Sweden, which currently receives very little, if any support. The results regarding conversion technologies may be obsolete in several years time, such is the rapidly developing and changing nature of the industry. During the course of writing this thesis, a production pathway was ASTM approved, with several others likely to be approved imminently. It is very difficult to predict with technologies will work and which others won't on a large scale, and so these results only reflect those, which have a higher degree of scale confidence.

Certain aspects of the findings from this study are considered generalisable to other contexts. As aviation is a global industry, many of the political barriers prevent biojet production are equally applicable across many international borders. Similarly, aspects and insights within this thesis could be applied across into different disciplines concerned with sourcing, handling and utilization of Sweden's transportation and refining infrastructure, or producing biofuels for applications other than aviation.

# 7 Conclusions

Existing conditions within Sweden support bioenergy development. The resources, infrastructure and expertise could support the establishment of a biojet system available under today's conditions, however high production costs and the lack of long-term policy support prohibit commercial scale deployment. The following conclusions were reached in light of research questions posited in Chapter 1.

### *How are forestry biomass resources likely to be allocated in the future?*

- The country has large and geographically extensive bioresources, logistics infrastructure and expertise to sustainably convert biomass into biofuels.

- Opportunities to improve biomass yields from the forest are most pronounced in the south and central regions of the country, dominated by Scots Pine and Norway spruce tree species.

- There is considerable potential to increase forest fuel extraction without decreasing possibilities of achieving other societal and environmental forestry production objectives, so long as a number of basic core management principles are implemented.

- Future biomass demand will be split between bioenergy, pulp and paper and sawmill industries, however shifts in the balance of demand could see more biomass for bioenergy and less for pulp and paper.

- Future supply of biomass within Sweden will grow significantly based on what is harvested today. There is significant potential within Sweden's forests to provide enough biomass to support significant transport biofuel growth over the next 30 years.

- To make biojet feasible, feedstocks must be easily available and sourced at very low costs.

- Primary forest residues are much more expensive to harvest and transport than pulpwood or timber. Processed forestry residues such as black liquor, bark and lignin are the most ideal streams for the production of transport biofuels in terms of logistics, yet using these streams requires outcompeting existing users.

- Biomass for transport biofuels are likely to be produced within biorefinery plants co-located to industry infrastructure.

- An excess of processed forestry residue materials has been created through the reduced price of imported wood chips in recent years, which may serve as an opportunity for procurement of biojet feedstock.

### *What conversion technologies are available?*

- The most suitable conversion technologies available today for the production of biojet in Sweden are the Fischer-Tropsche and Alcohol-to-Jet pathways, yet it is noted that such pathways may be deemed obsolete in the near future given the speed at which new technologies are being developed.

- It is likely that future systems will integrate into a biorefinery setting, whereby biojet fuel will be one of several outputs.

### *How do institutions within Sweden drive/constrain bioenergy development? How might this situation change in the future?*

- Sweden is a world leader in R&D for bioenergy related technologies.

- There exist a range of key organisations that are embedded in research that serve to link research institutions and governments to actors in the bioenergy field, including biomass producers, biofuel companies and fuel purchasers. Such organisations are crucial drivers in any bioenergy system and would contribute to driving a biojet system in Sweden.

- The formation of a global market based measure with special provisions concerning biojet to reduce aviation emissions has potential to reform the way aviation is integrated into national emissions reductions targets, thereby potentially generating favourable economic conditions in the future.

- Political incentives for bioenergy production heavily support road-based biofuels, which currently inhibits biojet development. Future efforts to establish biojet uptake in Sweden may include lobbying for policy change at the national level to recognize aviation emissions when setting policy targets.

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