Biomass for Bioenergy and/or Transportation Biofuels:

Exploration of key drivers influencing biomass allocation

by

William James Cadham

A THESIS SUBMITED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(FORESTRY)

THE UNIVERSITY OF BRITISH COLUMBIA

(VANCOUVER)

April 2015

ABSTRACT

Biomass is the world's largest source of renewable energy and it is likely to remain so until at least 2035 (IEA, 2013a). Globally, there should be enough biomass available to meet growing demand. However, biomass is predisposed to being used locally possibly resulting in limited domestic supply in countries where biomass is already used extensively (IEA, 2009). This could potentially result in competition between bioenergy or biofuels applications. The work described here explored the current and potential bioenergy/biofuel uses of biomass both globally as well as regionally, with a focus on Brazil, Denmark, Sweden and the United States. In each of these countries, biofuels or bioenergy are already important parts of their energy mix. For all of the countries studied the major drivers to use biomass for energy/fuels were: energy security; the desire to mitigate climate change; prevailing regional economic interests, and; the potential that bioenergy/biofuels are cheaper than fossil derived alternatives. Government support policies for bioenergy and biofuels are examined within the context of each of the four drivers.

It was apparent that there is limited competition for biomass between bioenergy and transportation biofuel applications. This situation is likely to continue until advanced biofuels technologies become much more commercially established. In each of the four countries biomass is predominantly used to produce bioenergy (heat and power), even in those regions where biofuels are significant component of their transportation sector (United States, Brazil and Sweden). The vast majority of biofuel production continues to be based on conventional sugar, starch and oil rich feedstocks, while bioenergy (heat, power, residential, industrial) is produced almost exclusively from forest biomass with agricultural biomass playing a small, but increasing, secondary role. As current and proposed commercial scale biomass-to-ethanol facilities almost exclusively use agriculture derived residues (corn stover, wheat straw, sugar cane bagasse), it is likely that, if there is ever to be competition for biomass feedstock's for bioenergy/biofuel applications, it will be for agricultural based biomass with co-product lignin and other residues used to concomitantly produce heat-and-electricity on site at biofuel production facilities.

PREFACE

This dissertation is the original intellectual property of the author, W. Cadham.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

First and foremost I would like to thank Dr. Jack Saddler for his supervision and guidance. His positive, yet critical approach pushed me to set a higher standard for my academic abilities.

A special thank you to Dr. Susan Van Dyk, her feedback and clear insights during the drafting phases were essential to the completion of this thesis. My sanity is intact thanks to your timely support during the moments of peak frustration. Thank you.

Thank you to my committee member, Dr. Dave Cohen for his valuable feedback and challenging questions and to Dr. Paul McFarlane for his input during the foundation of stages of my thesis work. Dr. Harry Nelson for his time and comments during the final stages of my thesis project.

Dr. Warren Mabee, thank you for directing me to pursue my MSc with Dr. Saddler. I would not be here without your advice.

A final shout out to all of my friends and family who helped calm my frustrations with kind words and bicycle rides.

"The mountains are calling and I must go" –John Muir

CHAPTER ONE: INTRODUCTION AND BACKGROUND

1.1 Introduction

This thesis performs exploratory research to address two questions regarding biomass utilization for bioenergy and biofuels. The first, "what is the current status of competition for biomass between bioenergy and biofuels?" and the second, "what conditions might lead to biomass being used to produce biofuels rather than bioenergy?".

It begins with a detailed background of global aggregate energy trends, focusing on: how biomass is consumed for both bioenergy and biofuels, and the rationale for the dominance of fossil fuels within the global energy mix. International biomass consumption trends are compared to global availability and trade, to elucidate the potential for competition between bioenergy and biofuels technologies for feedstock. This review highlights that although competition for biomass between bioenergy and biofuels is absent at a global level, it may occur regionally.

The second half of the background section reviews key information pertaining to the second research question regarding conditions influencing biomass allocation decisions. Although all four drivers discussed: energy security concerns, climate change mitigation desires, prevailing economic interests and cost-competitiveness of bioenergy/biofuel technologies, have all previously been well established in the literature as critical in renewable energy, and biomass development, this thesis strives to identify how these drivers direct biomass allocation to bioenergy or biofuels.

The second chapter of the thesis introduces the methods employed for this exploratory research. The rationale for country selection is discussed and the objectives of the country analyses are outlined. The benefits of exploratory research are highlighted.

The third chapter of the thesis examines potential bioenergy/biofuel uses of biomass in Brazil, Denmark, Sweden and the United States, independently. The relative importance of each of the four drivers and how they directed biomass allocation in each country was explored. Conclusions were drawn for each country individually.

Chapter four compares the findings across each country study to infer broader patterns with respect to: the importance of biomass in the energy mix, chief biomass applications, the status of biomass competition and the influence of the four identified drivers on biomass allocation. In addition to the four drivers, the importance of policy in biomass allocation decisions is addressed within each previously identified driver.

The final chapter distills the major conclusions from this thesis work, addresses the limitations of exploratory research, and discusses avenues for future research.

1.2 Background

Oil is currently the world's predominant source of energy, partly due to its flexibility of end use (energy, transportation, chemicals, etc.) and it will likely remain the dominant global fuel source for several decades to come. Renewable energy has expanded in recent decades, primarily due to government support, currently constituting 13% of the global energy mix with it projected to increase to possibly one-third by 2050 (International Energy Agency {IEA}, 2013a). Biomass is the largest source of the world's renewable energy and it is projected to remain so through to 2035 (International Energy Agency {IEA}, 2013a). Although biomass is predominantly used (60%) in traditional heating and cooking applications in developing countries, its use in modern, high-efficiency bioenergy and transportation biofuel applications (40%) is increasing (IEA, 2013a).

At a global level, there appears to be enough biomass available to meet the projected increases in biomass-based energy demand (IEA, 2013a). However, biomass availability differs greatly by region and, in some countries, there is not enough of a sustainable domestic supply to be able to meet increasing national demand. As a result, it is anticipated that a constrained local biomass supply will create competition for the limited resources. Although a wide range of end products can be generated from, predominantly, forest derived biomass, (lumber, food, paper products, chemicals, etc.), the work in this thesis has focused on the possible competition for biomass between bioenergy and transportation biofuel production.

In the competition for biomass, if net energy output is the primary goal, biomass will always be preferentially used for energy (heat and power) as opposed to biofuels as bioenergy allows for the recovery and use of more of the intrinsic energy (calorific value) within biomass than does its conversion to biofuels (Ohlrogge et al. 2009). However, the decision for biomass utilization is more complex. Unlike electricity generation (which can employ solar, hydro and wind power), renewable substitutes for transportation fuels are limited to electric vehicles and biofuels (as outlined in table 1). In some applications, such as long-distance transportation, biofuels are the most likely alternative to fossil fuels especially in long-haul trucking, marine and aviation applications.

Although a number of studies have looked at what drives the development of low-carbon technologies (Lund, 2007; Gan and Smith, 2011; Hultman et al. 2012), little work has looked at the conditions that might influence the allocation of biomass to either bioenergy or biofuels applications. Thus, one of the goals of the work described here was to assess current and possible future biomass feedstocks competition for bioenergy/biofuels applications and the historical, current and future drivers that have and might continue to significantly influence biomass allocation and use. A multitude of drivers are able to influence biomass allocation decisions, however this thesis is restricted to a discussion of the possible authority of energy security, climate change mitigation, prevailing economic interests and the cost-competitiveness of energy technologies.

Table 1: Fossil fuel and renewable energy sources for both the stationary and transportation sectors.

Energy Source	**Stationary**	**Transportation**
Fossil Fuel Energy	Coal Oil Natural Gas	Gasoline Diesel Natural Gas Aviation gasoline
Renewable Energy Substitutes	Bioenergy Hydro Wind Geothermal Solar Ocean/Tidal	Transportation Biofuels Electrified Transportation

1.2.1 Global energy trends

Understanding global energy trends is a vital component when trying to discern how and why energy resources have been and might be allocated. An initial goal of the work was to look at the world's current energy mix, the overall contribution of renewable energy and biomass derived energy/fuels in particular. Both renewable and non-renewable energy sources are considered to provide context to the scale of biomass-based energy technologies. As described in the second chapter of this thesis, alternative energy options must be considered when attempting to understand biomass allocation decisions.

1.2.1.1 Trends in the global energy mix

Adequate provision of energy services is a keystone feature of economic development. In recent decades, worldwide energy production and consumption has risen exponentially as most of the developing world strives to advance their economies. The world's primary energy supply has increased from 255 exajoules (EJ) in 1973 to 549 EJ in 2011 (IEA, 2013a). As illustrated in figure 1, fossil fuels are the dominant energy source, accounting for 82% of the world's primary energy demand in 2011 while renewable energy contributed 13% and nuclear 5%.

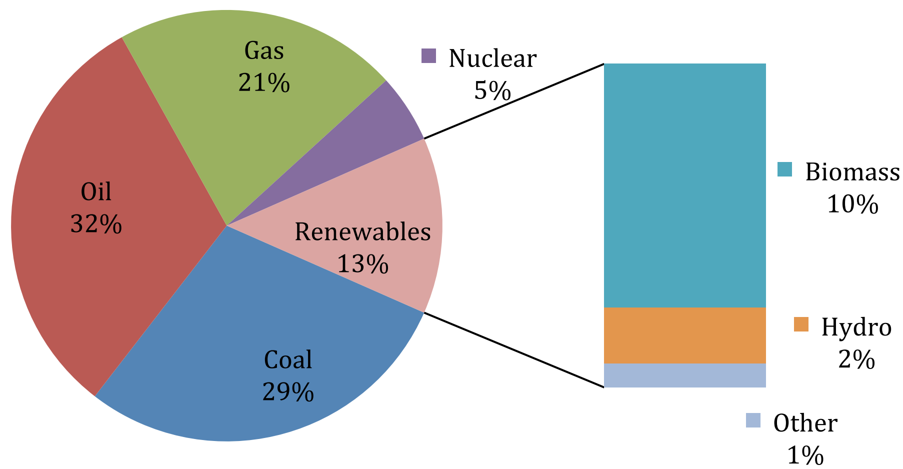

Figure 1: Global energy demand by energy source in 2011 (adapted from IEA, 2013a). *Renewables is the sum of hydro, bioenergy and other renewables as categorized by the IEA. Note that biomass is the largest renewable energy resource (76.9% of renewables).

The world is in a transition period as many long-standing regional energy trends are changing and the distribution of accessible energy resources around the world is shifting. Declining conventional oil reserves, increasing accessibility of unconventional oil and gas and expansion of renewable energy technologies means different regions, not previously rich in energy resources are emerging as major global energy producers. Long-time energy importers, such as the United States, are becoming more energy self-sufficient due to the development of unconventional oil and gas technologies. Improved access to unconventional oil is also leading to increased petroleum exports from Canada (tar sands) and Brazil (deep water) (however, Brazil remains a net importer) (IEA, 2012b). In some countries, such as Denmark and Sweden, widespread development of renewable technologies, particularly bioenergy and wind, has drastically improved energy self-sufficiency. In contrast, countries such as China, Japan, India and some members of the European Union (EU) are expected to grow their reliance on energy imports in the coming decades (IEA, 2013a). The significant shift in the allocation of energy resources and changing energy demands will influence how energy is traded, with energy surpluses and shortages emerging in new areas.

1.2.1.2 Renewable energy trends

In 2012, renewable energy accounted for 13% of the world's total energy mix (figure 1) (IEA, 2013a). Energy security concerns in some regions increased the development of renewables, as these technologies allowed countries not endowed with conventional energy resources to increase their domestic energy production. Additionally, countries looking to mitigate the effects of climate change have invested heavily in renewable energy sources to reduce energy related carbon emissions. As global energy trends continue to change, the emergence of energy security concerns in some countries, combined with climate change mitigation desires is expected to increase demand for renewables by 75% between 2012 and 2035, growing to 18% of global total primary energy demand (Alagappan et al. 2011; Hultman et al. 2012; IEA, 2013a). Figure 2 outlines global aggregate renewable energy consumption by source for 2011, highlighting the dominant biomass component.

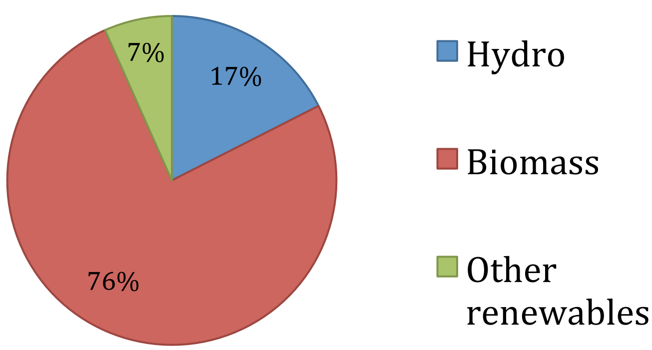

Figure 2: Global aggregate renewable energy consumption by source in 2011 (original figure data from IEA, 2013a).

1.2.1.3 Fossil fuels continue to dominate

Despite the observed shift towards renewable energy development, the world's energy mix is expected to remain dominated by fossil fuels. The IEA prediction for 2035 is that fossil fuels will still be the dominant source of energy, accounting for ~76% of primary energy demand that year (IEA, 2013a). The dominance of fossil fuels, especially oil, as an energy source remains due to factors such as poor cost competitiveness of alternative energy technologies and limited energy substitutes in transportation (Alagappan et al. 2011, IEA, 2013a). Cost competitiveness of renewable energy technologies is often cited as a major impediment to widespread commercialization (Alagappan et al. 2011; Gan & Smith, 2011). Relative to fossil fuels, renewable energy technologies are still developing and are typically subject to high initial generation costs. Technological barriers, such as the intermittent nature of some renewable energy technologies and a lack of large-scale electrical storage capabilities, complicate their integration into the current electricity grid (Mathiesen et al. 2011). The combined influence of these factors means that it will take some time before the world can wean itself off its dependency on fossil fuels (IEA, 2013a).

Proportionally, the transportation sector is most reliant on fossil fuels. In 2012, petroleum products accounted for more than 90% of transportation energy, equal to 47 million barrels per day (mb/d) or 54% of total global oil consumption (IEA, 2013a). Expectations of increased transportation demand in all forms, led by growing personal light-duty vehicles (PLDVs) and freight in developing Asia, are expected to lead to a transportation oil demand of 58.8 mb/d by 2035 (58% of global oil demand) (IEA, 2013a). Oil is ideal for transportation applications as it is energy-dense and easily refined into a number of liquid fuels. Alternatively, renewable energy substitutes for transportation are limited, especially when compared to those accessible for stationary energy. Although there are several fossil fuel and renewable energy resources suitable for stationary energy production, there are far fewer for transportation (table 1) where only electric vehicles and biofuels are viable alternatives. Biofuels are an attractive option as blends can be consumed in the current vehicle fleet while electrification will prove difficult in long-haul freight, marine and aviation applications (Karatzos et al. 2014).

1.3 Biomass

Within the context of this thesis, biomass feedstocks include sugar and starch rich crops (i.e. sugarcane, corn and sugar beet), oil crops (i.e. palm, soy and mustard), lignocellulosic agricultural and forestry residues (i.e. wheat straw and forest slash) and energy crops (i.e. switchgrass and short-rotation willow). Algal biomass is currently, and will likely be for the foreseeable future, a niche product and was therefore not considered.

As mentioned earlier, although current biomass use is dominated (60%) by developing countries traditional heating and cooking applications, modern bioenergy and transportation biofuels account for a significant and growing proportion of biomass use (40% of biomass) (Chum et al. 2011). The share of traditional biomass applications within total biomass-based energy is declining and by 2035, traditional biomass applications are projected to provide only 28.5 EJ, down from 31.1 EJ in 2011, while modern biomass applications are expected to generate 48.9 EJ, up from 23.3 EJ (IEA, 2013a).

Of the possible renewable energy resources, such as wind, wave, tidal, geothermal, solar, etc., biomass has the potential to be most interchangeable with fossil fuels as it can satisfy both stationary and transportation energy needs (table 1). Globally, the demand for biomass for both bioenergy and transportation biofuel applications is expected to grow (Chum et al. 2011; IEA, 2013a). Thus, it has been suggested that because biomass can be used for stationary and transportation energy uses, competition for biomass will increase significantly (IEA, 2009; Chum et al. 2011).

1.3.1 Biomass applications

The various ways of converting biomass into energy (heat and power) and biofuels is reviewed in the following sections with reference to more detailed technology reviews available in the literature (Damartzis & Zabaniotou, 2011; IEA, 2012d; Karatzos et al. 2014).

1.3.2 Bioenergy

Modern bioenergy is dominated by combustion, with highly efficient technologies (up to 90% intrinsic energy recovered) employed, including small and large-scale boilers, domestic pellet furnaces, combined heat and power (CHP or co-gen) and district heating (DH) facilities. Some of these are stand-alone facilities or integrated within industrial operations and used in residential heating applications (IEA, 2012d). As mentioned earlier, bioenergy technologies generally have a much higher efficiency as compared to biofuel production (Ohlrogge et al. 2009). In some jurisdictions, such as Denmark and Sweden, bioenergy has and will continue to make a significant contribution to heat and power production (~20% of total energy demand) (IEA, 2013b). The technologies used by biomass-based power plants, co-firing facilities and biomass-based cogeneration facilities are reviewed below.

1.3.2.1 Biomass-based power plants

The most established method of biopower production in stand-alone facilities is the steam-powered turbine (IEA, 2012d). In this system, the combustion of biomass in a boiler produces heat, which heats water or oil to generate steam, which powers a turbine to produce electricity. The overall efficiency is heavily contingent upon the facility's scale and, typically, large-scale 30-100 MW_e facilities are required to make biomass based steam-powered turbine processes economically viable. Plants of this size achieve efficiencies in the

18-33% range, somewhat lower than fossil fuel facilities of a similar scale (IEA, 2012d). It should be noted that the economic attractiveness of a number of small (5-10 MW_e) steam facilities is increasing across Europe and North America as biomass feedstocks, such as pellets, become more available at relatively lower costs (IEA, 2012d).

1.3.2.2 Co-firing

Biomass co-firing with coal has emerged as a popular method of bioenergy production with over 150 facilities worldwide using this strategy to try and reduce their carbon emissions (Al-Mansour and Zulawa, 2010). The combined combustion of biomass with fossil fuels to create heat and power is one of the most cost-effective methods of transforming biomass into electricity and heat (Al-Mansour and Zulawa, 2010). Co-firing leverages the existing infrastructure of coal power plants, offering the opportunity to increase the proportion of renewables in the primary energy mix and reducing GHG emissions associated with coal combustion, with Scandinavian countries, Germany, Belgium, the Netherlands and the United Kingdom being leaders in this application (Al-Mansour and Zulawa, 2010).

The three basic systems that have been used to co-fire biomass with coal are direct, indirect and parallel co-firing, all of which have been proven and are currently used at the industrial scale (IEA, 2009). In direct co-firing, biomass is combusted with coal in proportions ranging from 5-10%, simply by mixing the two fuels. Direct co-firing requires only a minor capital investment for biomass pretreatment and feed-in systems (IEA, 2013d). However, in this application relatively homogenous feedstocks are required. Forest biomass in the form of industrial pellets is the ideal feedstock for direct co-firing as they provide the consistency needed for optimal facility performance (IEA, 2013d). The intrinsic characteristics of agricultural residues create challenges with direct co-firing operations, effectively limiting their suitability as a feedstock (IEA, 2009).

Although indirect or parallel co-firing techniques, in which biomass and coal are fed into the boiler separately, can be employed to abate the challenges of agriculture feedstocks, these systems are more capital intensive than direct co-firing (Fernando, 2009). Indirect co-firing often involves the gasification of solid biomass prior to its combustion with coal, offering higher feedstock flexibility and the ability to clean the fuel gas prior to combustion, minimizing its effects on the boiler and improving longevity of the infrastructure. This type of system is currently employed in the 167 mega-watt electric (MW_e) Lahti plant in Finland where 17% biomass is combusted with a mixture of coal and natural gas (Al-Mansour and Zulawa, 2010).

1.3.2.3 Co-generation of heat and power from biomass

Co-generation can significantly increase the overall efficiency and competitiveness of a stand-alone biomass-based power plant or industrial facilities, such as pulp mills, by employing the waste heat. Typical overall (thermal + electrical) efficiencies are within the range of 80-90% (IEA, 2012b). In stand-alone CHP facilities, the low-grade steam left over after power production is used for heating services in residential or commercial buildings where district-heating infrastructure is available. Heat recycling, is an important step in biomass co-generation. It has been shown to reduce power production costs by 40-60% in those stand-alone facilities within the 1-30 MW_e range by recovering the exhaust heat from electricity generators and using it to create steam (IEA, 2012b). For domestic and commercial applications, the scale of the CHP facilities is sometimes constrained by the heat demand within the region it is servicing and this is further complicated by the seasonal nature of this demand. As is the case with district heating, interest in supplementing CHP systems with cooling technologies is increasing, with the hope of further improving the efficiency and economics of the process.

Industrial biomass-based CHP facilities typically combust process residues, such as black liquor (a by-product of the Kraft pulping process) or bagasse (a waste stream from the sugar-cane industry) to generate electricity and low-grade steam (Sixta, 2006). The power and excess steam produced is used upstream within the processing facility. This process has been part of best practices in Kraft pulp mills since the introduction of the Tomlinson recovery boiler in the 1930s (Sixta, 2006). Combustion of black liquor originally emerged as a way to recycle expensive pulping chemicals, while the benefits of heat and power production was only realized more recently (Sixta, 2006). A number of government programs have provided subsidies and grants to improve the recovery systems within chemical pulp mills (U.S. Department of Energy (DOE), 2010). The largest share of bioenergy production in North America comes from the operation of recovery boilers at Kraft mills. In the United States, 60% of all wood used for bioenergy primarily occurs within this industry (U.S. Energy Information Agency (EIA), 2012).

1.3.3 Transportation biofuels

Transportation biofuels are generally categorized as either conventional (also called first generation) or advanced (second generation) fuels, with this definition influenced by either the nature of the feedstock and the greenhouse gas emission reductions achieved (as compared to fossil fuels) (Schnepf & Yacobucci, 2013). Conventional or first generation biofuels include bioethanol based on sugar or starch and biodiesel using tallow, palm or oilseed. Advanced biofuels can be defined as non-food feedstock derived and include biomass-derived diesel, cellulosic biofuels, and non-cellulosic advanced biofuels. They are expected to show improved emissions reductions compared to conventional biofuels (typically ~50% GHG reduction over fossil fuels, although regionally specific). All biomass derived biofuels have lower conversion efficiencies as compared to that of biomass used for combustion to produce heat and energy (Ohlrogge et al. 2009).

Beyond these first (conventional) or second (advanced) generation classifications, transportation biofuels can be either liquid, such as bioethanol, biodiesel and "drop-in", or gaseous (biogas) fuels. Bioethanol and biodiesel are the principal commercially available biofuels, currently contributing approximately 3.2% by volume to global transportation fuel demand (IEA, 2014). These fuels can be consumed independently or blended with conventional fuel products. Blending of up to 10% bioethanol with 90% gasoline is already common practice in the United States while Brazil typically blends ethanol between 18-25% (IEA, 2013a; USDA, 2013). Flex-fuel automobiles can accommodate blends containing as much as 85-95% ethanol. Presently, drop-in biofuels, defined as biomass-derived fuels that are functionally equivalent to petroleum fuels and compatible with petroleum infrastructure, represent a small fraction (less than 2%) of global biofuel markets, while bio-gas is even smaller (less than 1%) (IEA, 2013a; Karatzos et al. 2014). Although the global use of biofuels as a proportion of total transportation fuel demand is small, in regions such as the U.S. and Brazil, biofuels contribute between 10-25% to the automobile fuel mix (IEA, 2014).

Several different pathways exist for producing biofuels. Most of the current bioethanol production occurs via the fermentation of sugars into ethanol using enzymes, such as amylase, to hydrolyze the starch to sugar. Current biodiesel production proceeds via chemical conversion of lipids into fatty acid methyl esters. Biogas is produced via anaerobic digestion. Biochemical conversion of biomass into liquid fuels typically involves the use of enzyme or microbial catalysts to hydrolyse carbohydrates to simple sugars. Although liquid fuel production (ethanol) from starch and sugars are fully commercialized processes, cellulosic ethanol is just beginning commercialization with agricultural residues used as the primary biomass feedstock (Chundawat et al. 2011; Jorgensen et al. 2007; Menon and Rao, 2012). The predominant use of agricultural residues as the biomass feedstock has encouraged the co-location of these biomass-to-ethanol facilities with existing sugar/starch to ethanol facilities.

As mentioned earlier, drop-in biofuels are currently only produced in small quantities. Technological pathways to produce drop-in biofuels include: oleochemical, thermochemical and biochemical processes. Oleochemical based processes involve the catalytic removal of oxygen from the fatty acid chains of oil-crop derived lipids to transform them to diesel-like fuels. Oleochemical fuel products have already been tested for commercial applications in the aviation sector. However, high feedstock costs (4-8x higher than lignocellulosic biomass) and questions surrounding oil-crop sustainability is limiting their growth. Thermochemical processes that can be used to make drop-in biofuels include pyrolysis or gasification which also require a subsequent upgrading step. Bio-oils from pyrolysis can be enhanced to drop-in biofuels with the addition of hydrogen via hydrocracking. A major impediment to development of pyrolysis-based drop-in biofuels is the sourcing of low-cost hydrogen. Syngas products of gasification can be condensed to drop-in liquid biofuels by Fischer-Tropsch synthesis. Complications arise due to the low energy density and high level of impurities in biomass-derived syngas, making the process capital intensive (Karatzos et al. 2014). Biochemical processes that have been used to make drop-in biofuels typically involve the fermentation of sugars to long-chain alcohols, isoprenoids and fatty acids. The microorganisms and feedstock involved in the process determine the possible end products, with both gasoline and diesel/jet drop-in biofuels feasible (Weber et al. 2010). For more detailed information on oleochemical, thermochemical and biochemical drop-in biofuel processing please refer to Karatzos et al. (2014).

1.4 Biomass availability

Recent work has suggested that, even when sustainable harvest practices are considered, 94-150 EJ/yr of biomass will be available by 2030, and 200.1-502.4 EJ/yr by 2050, thus supply will remain greater than demand projections (~108 EJ in 2035) (IEA, 2009; IEA, 2013a; IRENA, 2014). The IEA and IRENA projections are based on amalgamated data from a host of national biomass availability reports, in an attempt to condense the information to be applicable at the global scale. Despite the abundance of biomass at the global level, unlike oil, the vast majority is used locally with some biomass rich regions such as Scandinavia, unable to keep up with their expanding domestic demand. In countries such as Denmark and Sweden, where biomass/bioenergy is already extensively utilized, they are encountering increasing challenges in sourcing sufficient biomass for bioenergy or biofuels (IEA, 2009; Qiu et al. 2012). In contrast, countries such as Brazil and the US, have enough of a feedstock supply to meet both current domestic and international demand (Perlack et al. 2011). Figure 3 below illustrates global variation in potential 2030-biomass supply by region, noteworthy differences can be observed in regional biomass availability. Biomass availability is subject to influence from a suite of variables including but not limited to: predominant industries, biomass feedstock type, climate, government harvest regulations and geography, however a discussion of these is beyond the scope of this thesis. Thus biomass availability is drawn from a literature review of key studies assessing potential global biomass supply.

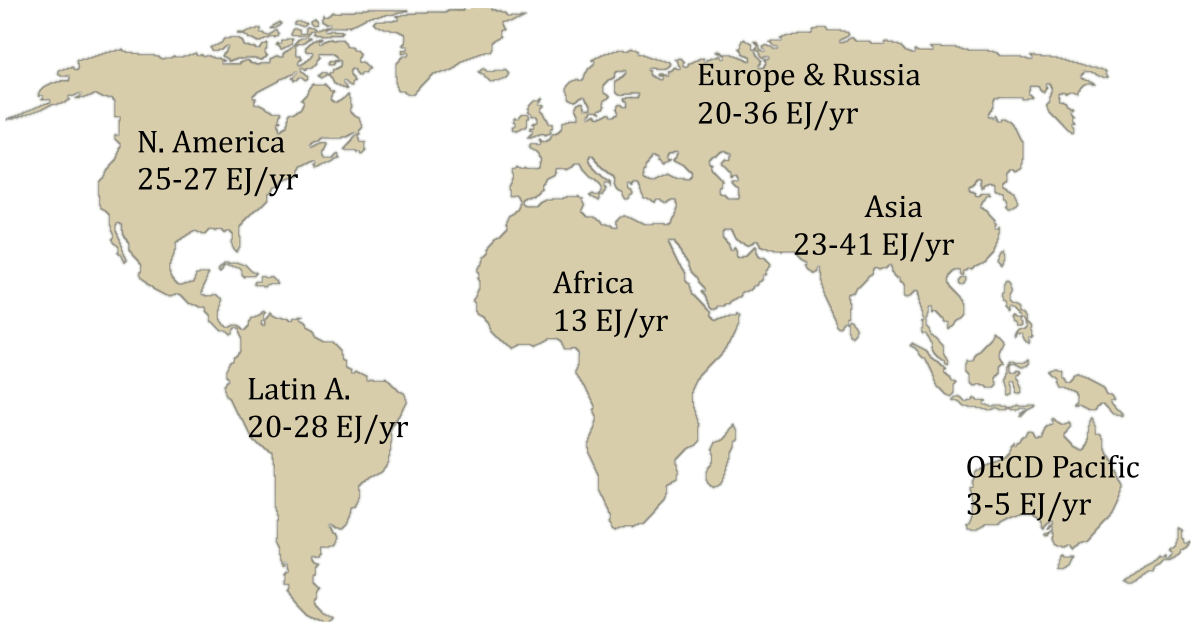

Figure 3: Global estimates for biomass potential in 2030, all ranges in exajoules per year (adapted from IRENA, 2014).

International trade of biomass feedstocks and energy-dense biomass-based products (i.e. pellets and biofuels) has become an important supply component in regions where biomass consumption exceeds domestic supply. Figure 4 outlines three major biomass-based energy products and their global trade routes, with intra-European trade being excluded for simplicity. Trade volumes of modern bioenergy are difficult to discern due to the existence of a variety of commodity codes (biofuels are often traded as agriculture products) and poorly reported trade data. Thus, estimates range between 0.4-1.0 EJ/yr (Lamers et al. 2011; Lamers et al. 2012; IEA, 2013d). Despite the reported differences in trade volumes, there is a consensus that the international trade of biomass-based energy products is increasing. When comparing figure 3 and 4 it is apparent that regions with high global estimates for biomass supply potential in 2050 (North and South America in particular), are also current export hubs for biomass-based energy products, while those with a potentially lower future supply (the EU) are the predominant biomass importers.

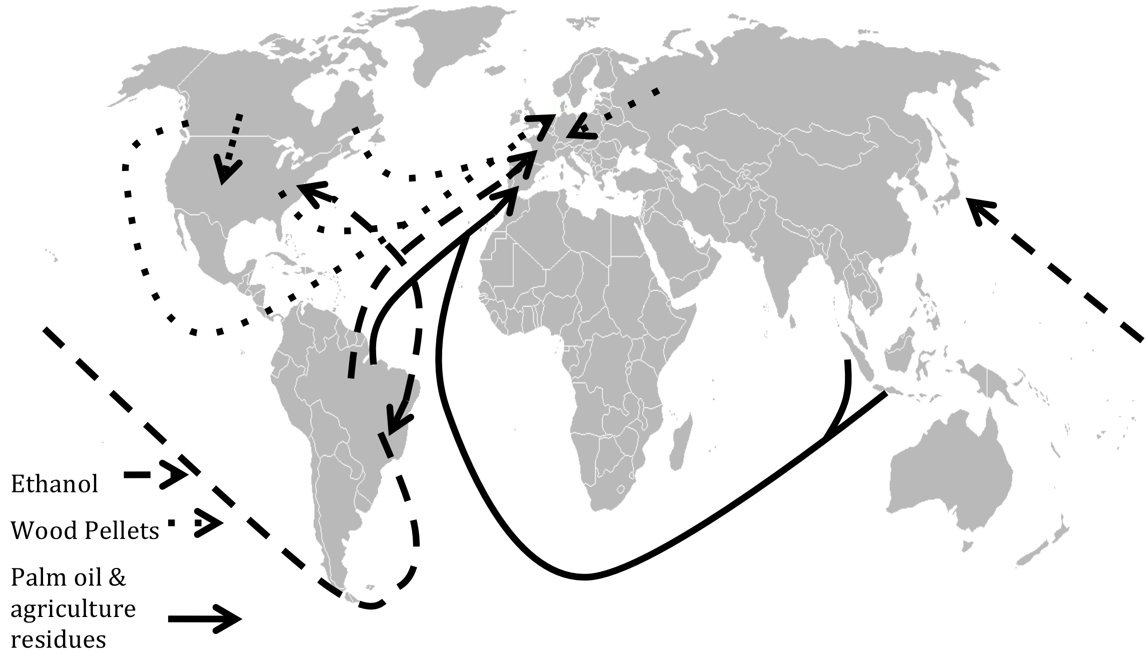

Figure 4: Trade routes for commonly traded biomass-based energy products (adapted from IEA, 2009).

Currently, international trade volumes of solid bioenergy products such as wood pellets and chips are more than double the global trade in biofuels (300 petajoules (PJ) vs 120 PJ in 2010). However, this may change as trade volumes of biomass products increase (Lamers et al. 2011; Lamers et al. 2012). Some biomass products, such as liquid biofuels or wood pellets, are more easily transported over long distances (across the Pacific Ocean for example) than electricity, (which cannot be easily transported beyond the reaches of an electricity grid) (Lamers et al. 2011). The relative ease with which biofuels can be transported may result in the preferential allocation of some sources of biomass to biofuel production for export as it can be produced in regions with ample feedstock supply and consumed where biofuel demand is high. This circumstance has been observed in Brazil which, until recently, exported ethanol to the U.S. (MME, 2012).

In contrast to the limited overall trade in biomass and biofuels, coal and oil are globally traded in large volumes (900 million tonnes (26.4 EJ)) and ((196.8 EJ/d or 34.5

mb/d) in 2011 respectively) (IEA, 2012b). Although biomass-based energy products such as wood pellets and biofuels are traded internationally, the total global markets for these products (13.5 Mt and 1.3 mb/d in 2011 respectively) represent only a fraction of total global biomass derived energy demand (IEA, 2013a).

1.5 Competition for biomass

Globally, sustainable biomass supply is projected to remain greater than total global biomass demand, suggesting that any potential competition between bioenergy and biofuels for feedstock is not likely at the international level. However, as shown in figures 3 and 4, biomass supply varies regionally and global biomass trade is a very small proportion of the total global biomass market. Thus biomass is predominantly produced and consumed domestically or locally. When this is taken into account against the broader context of projected increases in biomass demand outlined by the IEA, supply shortages can be expected in some regions while other jurisdictions will have a surplus supply. In countries where domestic biomass supply may be limited, regional competition for feedstock is anticipated to occur between bioenergy and biofuel applications. This could result in competition for biomass for either bioenergy or biofuel production in those countries which have significant bioenergy/biofuels markets such as Brazil, Denmark, Sweden and the US. This study will assess regional biomass supply and demand data in an attempt to discern if competition is occurring in each of these countries.

The so-called "food versus fuel" debate might help illustrate this potential biomass competition scenario. In 2007, agriculture commodity prices increased nearly 40% with some individuals suggesting that increased production of corn-derived ethanol, creating competition for food and fuel, was the primary reason for this increase in food prices (Rosegrant, 2008; von Braun, 2008). However, the majority of the recent literature suggests that the food vs. fuel competition was minimal and that biofuel production resulted in an increase of less than 1% in agriculture commodity prices (Oladosu et al. 2012; Throstel, 2008; Tyner, 2013). This is to say; the degree to which this competition is actually occurring is a point of contention.

Advanced biofuels, using lignocellulosic feedstocks, have been touted as a more cost competitive and socially acceptable way of producing renewable liquid fuels as it avoids any potential competition between food and fuel. Lignocellulosic biomass, derived from the non-eatable portions of agriculture crops or biomass feedstocks such as wood, is available in greater abundance and has strong potential for higher fuel yields per unit of land than food crops. Lignocellulosic biomass, if grown and harvested sustainably should show improved GHG reductions when compared to conventional feedstocks (Banerjee et al. 2010).

As the push towards production of advanced fuels gains traction, the IEA has predicted that the forest products, agriculture, bioenergy and biofuels sectors will encounter increasing competition for biomass feedstocks (IEA, 2009; IEA, 2012c). As mentioned earlier, forest and agriculture derived biomass can be used for a variety of products including, feed and fodder, lumber, paper and board as well as rayon, nutraceuticals and bio-oil. As the biofuel and bioenergy markets expand, a biorefinery approach, which also involves the production of intermediates and co-products, is expected to increase (IEA, 2009).

Although projected demand for biomass resources is expected to show significant growth through to 2035 (IEA, 2013a), supply of biomass resources will be constrained in some regions, where demand growth outpaces supply, while other countries will remain or become biomass exporters. Although the interdependence of biomass processing industries should ultimately prove beneficial, it is also possible that it will increase competition between traditional and evolving bioenergy/biofuel uses. (IEA, 2009; Chum et al. 2011).

1.6 Drivers for biomass allocation

An ongoing discussion has been underway for some time regarding the major drivers that might be used to promote increased use of renewable energy technologies and bioenergy and biofuels in particular (Montalvo, 2008; Aguilar et al. 2011; Alagappan et al. 2011; Gan and Smith, 2011; Timilsina and Shrestha, 2011; Hultman et al. 2012). The work reported here has not used models but has rather looked at biomass allocation to bioenergy or biofuels through a qualitative assessment of both general and country-specific drivers.

Energy security and climate change mitigation were identified as important general drivers that have promoted the use of biomass for modern applications at the global level (Aguilar et al. 2011; Hultman et al. 2012).

Through the country profiles, we hoped to determine if these drivers influenced biomass allocation decisions in each of the selected countries. It was apparent that a gap persists with regards to the manner in which energy security and climate change mitigation drivers actually influence allocation of biomass to bioenergy or biofuels (IEA, 2009; Timilsina and Shrestha, 2011) as bioenergy or biofuel development is much more complex than just these two general drivers (Gan and Smith, 2011). Countries are subject to influence by far more than energy security and climate change mitigation. Factors such as prevailing economic interests, the cost-competitiveness of biomass based technologies and the government policy mechanisms must be considered (IEA, 2013a). Government policies are not treated as a stand alone driver as they respond to, and influence energy security, climate change mitigation, prevailing economic interest and cost-competitiveness of energy technologies. Thus, the collective influence of these drivers must be studied to be able to better understand how biomass might be allocated.

1.6.1 Energy security defined

Energy security refers to the degree of energy self-sufficiency in a country or region, i.e. the proportion of total energy demand fulfilled by domestic energy resources. A higher degree of energy self-sufficiency means greater energy security (Yergin, 2006). Issues of energy security affect both the political and economic space due to the importance of energy in maintaining daily societal functions. An uncertain energy supply is unfavourable and can have negative socio-economic impacts on a region.

Energy insecurity results from a heavily reliance on foreign imports with the degree of insecurity contingent upon the relative stability of the energy-exporting nation as well as the ease of substitutability of the energy source (Yergin, 2006). Political instability in major oil exporting regions, such as the Middle East or Venezuela, means the supply of oil from these countries is subject to volatility, as seen in the oil crisis of 1973 and again in the early 2000s (IEA, 2013a). When oil supply from these regions drastically declined it caused spikes in the price of oil that rippled through the global economy.

The ease with which an energy source might be substituted by an alternative should lower the concern of energy security associated with that product. Although there are considerable fossil fuel and renewable energy sources available for stationary energy needs, transportation is reliant on fossil fuels for 90% of its energy demand (see table 1). Thus, energy security concerns are often greater for transportation energy needs than stationary, especially when the politically unstable nature of many oil-exporting countries is considered (Yergin, 2006).

1.6.1.1 How biomass energy products improve energy security

Biomass is a ubiquitous energy source, available in most countries on a renewable basis, either specially grown as energy crop plantations or as a by-product of, forestry and agriculture operations. Consuming domestic biomass resources for bioenergy or biofuel production can diversify a nation's energy mix, thereby reducing its dependence on imported fuel sources and improving energy security. Concerns of energy security are a common precondition for the emergence of bioenergy or biofuels in a country's energy mix. Examining a country's energy trade balance and government documents in national and energy policy spheres can help identify energy security concerns. Evaluating the emergence of biomass utilization in Brazil, Denmark, Sweden and the United States, while concurrently examining the importance of energy security concerns within each country, might help better define the possible role that energy security will play in driving bioenergy or biofuel development.

1.6.2 Climate change mitigation and biomass utilization

Energy security has been a shared global trend among countries that consume biomass for biofuels or bioenergy, although alone it does not explain the divergence in technology choices that have been made. The influence that carbon reduction strategies might play in the development of biofuels or bioenergy is also considered. This section of the thesis weighed the influence of government energy and climate policy on the use of biomass for bioenergy and biofuels.

1.6.2.1 How climate change mitigation impacts biomass allocation to biofuels or bioenergy

Historically it has been perceived that the substitution of fossil fuels with biomass could reduce or even eliminate the negative impacts associated with GHG emissions from fossil fuels (Rogner, 2000). In theory, the use of sustainable biomass is carbon neutral, thus its consumption for energy or conversion to a liquid fuel can act to reduce energy and/or transportation related climate change (Rogner, 2000; IEA, 2013a).

Combustion of biomass for bioenergy provides improved GHG emissions reductions and recovers more of the intrinsic energy of its feedstock than conversion of biomass to biofuels (see section 1.2.1). Thus, if climate change mitigation is a primary goal, biomass will be preferentially used to make bioenergy rather than biofuel (IEA, 2013c). The importance of climate change mitigating strategies in Europe has led governments to develop policies and regulations to try to reduce GHG emissions. These carbon reduction strategies have tended to direct biomass to bioenergy rather than biofuel applications (Hedegaard et al 2008; Campbell et al. 2009; Hveplund, 2011).

Recent carbon accounting work has confused the preconceived notion that all biomass leads to GHG emissions reductions when making and using bioenergy and biofuels (Chum et al. 2011). Although some researchers believe that bioenergy still provides better GHG emissions reductions when compared to biofuels, there is no consensus regarding the levels of GHG abatement associated with either energy product (Campbell et al. 2009; Chum et al. 2011; IEA 2009). The inclusion of direct and indirect land use changes in carbon accounting have further complicated the matter (Gnansounou et al. 2008). Determining the emissions associated with biomass products is contingent not only upon distance and the method of transport but also the harvest and conversion practices used in their region of origin (Chum et al. 2011). Advancements in modern carbon accounting have tried to include as many of these variables as possible to accurately reflect the real carbon emissions of biomass-based energy products. The task remains exceedingly difficult with significant variability observed in GHG emission offsets for comparable products depending upon the metrics of analysis (Gnansounou et al. 2008; Chum et al. 2011; Bright et al. 2012; Popp et al. 2012).

Within the past decade, some countries striving to reduce their carbon emissions have created policies specifically targeting transportation emission reductions. The introduction of these policies adds another layer of complexity in biomass utilization decisions. It is anticipated that such policies do effectively alter biomass allocation away from bioenergy and towards biofuels. Due to the limited energy substitutes for transportation, mandates that strive to increase the penetration of renewables in transport have created growing biofuel demand. Emerging biomass consumption trends suggest transportation specific emission policies might influence biomass allocation differently than general climate policies, resulting in the use of biomass for biofuels as opposed to energy. Examples of this can be seen in Denmark and Sweden and are discussed in detail in the country profiles.

1.6.3 Other drivers beyond energy security and climate change affecting biomass allocation decisions

In addition to energy security and climate change, regional and local variation in geography, climate and natural resource endowment impacts a suite of ancillary drivers and ultimately decisions of biomass appropriation to bioenergy or biofuels. For the purpose of this thesis, discussion of these ancillary drivers is restricted to prevailing economic interests and the cost competitiveness of bioenergy and biofuels. The influence of these “other” drivers on biomass allocation to bioenergy or biofuels is discussed to illustrate a further level of complexity in the decision process.

1.6.3.1 Prevailing economic interests

The energy sector is an important source of revenue in many countries. Countries that are able to foster innovation in biomass based energy systems stand to receive enormous economic benefits in the long term. The advent of a biomass-based energy industry can aid struggling industries, improve rural development, cultivate new industries, and lead to job creation. Emerging biomass dependent markets will also encourage economic competitiveness and improve export potential (Danish Energy Agency (DEA), 2005, Lipp, 2007). The ability of prevailing economic interests to influence government policy support schemes for bioenergy and biofuels is discussed for each country.

In agriculture intensive regions, feedstocks tend to be more suitable for conversion to biofuels than combustion for bioenergy (Karatzos et al. 2014). Crops and their residues that can be directed towards biofuel production will enhance farmer's income. As a result, farmer and forestry lobby groups worldwide (such as the U.S. National Corn Growers Association, Bureau of Nordic Family Forestry and Landbrug & Fødevarer in Denmark) have been vocal supporters of the biofuel industry. In countries where the forest sector is a significant part of the rural economy, such as in Sweden and Finland, the biomass is typically directed to bioenergy. Generation of bioenergy from wood and pulp waste provides additional revenue to forestry companies, increases job production in rural regions, yielding positive rural economic benefits. Some regions, such as Sweden, are better at capitalizing on these economic opportunities than others (Hillring, 2002).

1.6.3.2 Cost competitiveness of bioenergy and biofuels

The cost competitiveness of bioenergy and biofuels relative to conventional fossil fuels and other renewable energy technologies is an essential driver in determining the appropriation of biomass feedstocks. Within the context of this thesis, cost competitiveness is examined with respect to technological advancements in biomass conversion and government policy measures aimed to improving the market competitiveness of biomass-based technologies.

The status of development for technologies to convert biomass to either bioenergy or biofuels affects the cost competitiveness of their production, as pioneer facilities experience much greater processing costs than established technologies. Allocation of biomass to either bioenergy or biofuel production can be driven by the availability of a given cost-competitive technology for conversion. Processes are typically optimized for a single feedstock and the development of a conversion technology is often closely related to the availability of a given feedstock within a particular region. Despite growing international trade of biomass-based energy products, biomass is primarily consumed locally. The economics of bioenergy and biofuel production is greatly improved if the feedstock can be sourced locally (Stephens et al. 2010). Availability of biomass feedstocks can be affected by changes in seemingly unrelated spheres as revealed in the case studies of this thesis.

Economic viability of biomass energy products is contingent not only on bioenergy or biofuel production costs but on fluctuating oil prices. Slow economic recovery in much of the world, combined with the recent advent of unconventional oil and gas, (especially in the United States) have caused the crude oil price to fall from its peak of ~$140US/ barrels (bbl) in 2008 to ~$60US/bbl by the end of 2014 (IEA, 2012b; Nasdaq, 2014). In some regions, falling oil prices have had a significant impact on renewable energy investment as the cost per unit of energy generated has increased relative to fossil fuels. Specifically, both conventional and advanced biofuels have experienced reduced generation, causing production and consumption of biofuel products to decline, the degree of which remains to be seen (IEA, 2014).

Table 2: Estimated pre-tax costs of biofuel and petroleum fuels (U.S. cents/liter). (Demirbas, 2011; IEA, 2013a)

	Present Costs (2011)	Projected Costs (2030)
Bioethanol from sugarcane	25-50	25-35
Bioethanol from corn	60-80	35-55
Bioethanol from lignocellulose	60-130	25-65
Biodiesel from vegetable oil	70-110	40-75
Petroleum products	35-60	50-56

Government policies or regulations have the ability to alter cost competitiveness of bioenergy or biofuels. A broad approach must be taken when considering policies that affect the competitiveness of bioenergy and biofuels, considering not only those that directly target biomass technologies but including government programs or regulations that impact a host of different realms, including (but not limited to): fossil fuels, feedstocks, carbon emissions, alternative renewable technologies and even corporate taxation.

1.6.3.3 Policy drivers

It is essential to examine the role of policy as a driver for biomass allocation to bioenergy or biofuels. Within the context of this thesis, policy drivers are assessed as a key aspect in the framework of: climate change mitigation, energy security, prevailing economic interests, and technological cost-competitiveness due to the intimate integration of policy with these four drivers. A stand-alone analysis quantifying the effectiveness of a given policy mechanism in relation to another is beyond the scope of this thesis project. Alternatively important aspects of government policies and programs are discussed for each of the country profiles. The observed variation illustrates how diverse policy mechanisms that influence biomass allocation can be.

1.7 Problem statement

Although the original focus of the proposed thesis work was to identify, "under what circumstances would biomass be more valuable as a feedstock for biofuels rather than bioenergy?" it became apparent that two preceding questions first had to be addressed. These were, "what is the current status of competition for biomass between bioenergy and biofuels?" and "what conditions might lead to biomass being used to produce biofuels rather than bioenergy?" Thus, the latter two questions became the focus of the thesis. It was recognized that the preferred allocation of biomass to either bioenergy or biofuels might be better discerned by examining the main drivers that spurred the development of these renewable energy applications in selected regions. Thus, the work focused on creating profiles of four countries that were either significant bioenergy or biofuels users, (the USA, Brazil, Sweden and Denmark), first determining their main sources, production and use of biomass and their current and projected bioenergy and biofuels use.

After identifying the predominant biomass-based energy technology and the status of biomass competition in each of the country profiles, the relative importance of four drivers which included, energy security, climate change mitigation, regional economic interests, and the cost-competitiveness of bioenergy/biofuels were each assessed. The interaction of each of the four drivers with policy, and the resulting influence on biomass allocation is examined. A historical approach was taken where the relative importance of each driver was assessed. The goal was to address the central question of the thesis, "under what conditions might biomass be allocated to biofuel production rather than bioenergy generation?"

CHAPTER TWO: METHODS

2.1 Rationale for country selection

Brazil, Denmark, Sweden and the United States use bioenergy and/or biofuels as a significant component of their national energy mix (IEA, 2013a; IEA, 2013b; IEA 2014). These four countries were selected due to their extensive use of biomass for modern energy applications and for their current or potential expanded use of biofuels. The data obtained for each of the four countries required extensive regrouping before it was suitable for cross-country comparisons.

For each country, current biomass applications, major biomass feedstock's, and (when available) the origins of the biomass were assessed to see if there was or might be competition for this biomass. Biomass competition in the context of this thesis refers to a scenario where biomass demand exceeds supply.

The country profiles were performed to determine:

1. The importance of bioenergy and biofuels in the current national energy mixes.
2. The major biomass uses.
3. To what extent does biomass competition already exist in each country?
4. Drivers that shaped the historical and current development of bioenergy and biofuels.
5. How these drivers might influence future biomass competition and utilization.

Recall from the previous background section that the four drivers include:

1. Energy security concerns
2. Climate change mitigation desires
3. Prevailing economic interests
4. Cost-competitiveness of bioenergy/biofuel technologies

2.2 Benefits of exploratory research

Exploratory research is performed when seeking to describe a phenomenon and explore its dynamics (Iacobucci & Churchill, 1999). This research methodology allows broad, high level questions to be addressed that are beyond the narrow focus of experimental or lab based research. The wide research scope permits the inclusion of a number of different countries in the analysis. This is approach was employed in an attempt to capture some of the variability that exists internationally with respect to biomass utilization. Furthermore, exploratory research it helps to illustrate the overall complexity of the drivers involved in biomass allocation decisions (Iacobucci & Churchill, 1999). A very important benefit of the exploratory research approach is by addressing the research questions from a broad perspective, it highlights avenues for future research and is helpful in focusing future research questions (Iacobucci & Churchill, 1999).

2.3 Limitations of exploratory research

The exploratory approach created some limitations for this research project. Although the assessment of several countries was valuable to illustrate the diversity of biomass utilization practices, it prevented a thorough examination of every driver for each of the countries. The system of drivers for biomass allocation is too complex within a country to be fully explained within the span of an MSc thesis project. Additionally the importance of a single driver cannot be quantified, nor can the importance of drivers be compared.

The nature of this research project required that bounds be drawn on the products considered in the competition for biomass, restricting the analysis to only bioenergy and biofuels. By doing so, the influence of alternative markets such as wood products, and agriculture were intentionally over looked. Inclusion of these markets in future research may yield different findings regarding the status of biomass competition both globally and regionally.

A final limitation, although it does not pertain to the methods, stems from the limited availability of data concerning newly commercial advanced biofuel technologies. The recent maturity of cellulosic biofuel technologies and the high level of secrecy regarding the proprietary processes make it difficult to discern their potential impact on future competition for biomass.

CHAPTER THREE: COUNTRY COMPARISONS

3.1 Brazil

As a developing country, Brazil experiences different demands on its energy market than the developed nations examined in this thesis as it is faced with the task of expanding access to electricity, supporting a rapidly growing economy and maintaining affordable energy and fuel prices for a large impoverished segment of the population. Ensuring a stable, reliable and affordable energy supply is problematic for a rapidly expanding economy with burgeoning energy demands. In Brazil, the situation is further complicated as the energy mix, with strong hydropower and biomass components, is affected by policies that aim to preserve biodiversity and control land/water resource management. Additionally, the supply of these energy sources is subject to climatic conditions. Droughts in 2001 and early 2014, impacted hydropower inflows, lowering assured energy levels while high rainfall in 2011-2012 negatively affected sugarcane harvests and resulting ethanol production (The Economist, 2014; USDA, 2013). Furthermore, government policies with respect to gasoline price controls effectively undermine national biofuel policies. Such Brazilian specific conditions must be considered in order to assess the status of biomass competition in the country. These nationally specific circumstances also influence the drivers and must be examined in conjunction with general drivers to fully understand biomass allocation decisions in the country.

3.1.1 The Brazilian energy mix

Total energy consumption (2011) in Brazil, 9.6 EJ, is comparable to that of the Scandinavian countries examined in this exploratory research, and is several orders of magnitude smaller than United States energy consumption (MME, 2012). Oil products are the single largest source of energy, accounting for 40% of TEC. Despite this, Brazil has one of the least carbon intensive energy mixes in the world with 46% of domestic energy supply met by renewable energy sources in 2011 (MME, 2012). In comparison, the average among OECD nations is 8% (USDA, 2013). Brazil's high proportion of renewables in its energy mix is the product of limited known domestic oil and gas resources prior to the discovery of the "pre-salt" in the late 1970s. Since this discovery of large oil and gas deposits, the economy of the country is transforming as Brazil emerges as a major global oil and gas producer, although a strong reliance on hydropower for electricity generation and biofuels in transportation maintain the low emissions intensity of Brazil's energy mix (USDA, 2013; IEA, 2013).

Figure 5 illustrates the final energy consumption by source for Brazil in 2011. As experienced in each of the other profiles, variation exists between the classifications of different energy sources. The following figure illustrates the significant diversity that exists within the Brazilian energy mix.

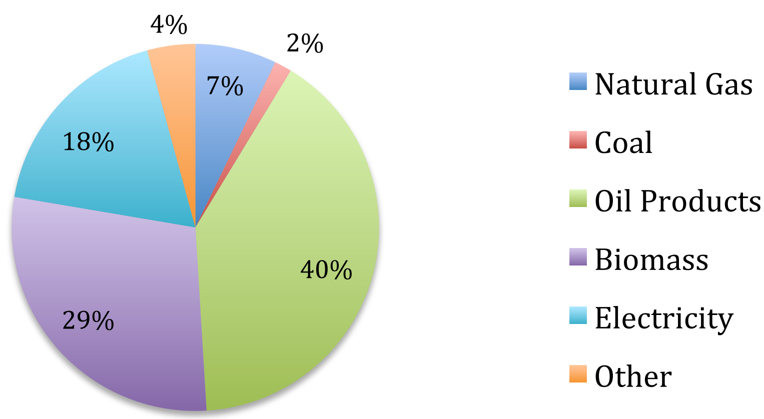

Figure 5: Final energy consumption in 2011 by source in Brazil. Other represents the sum of coke oven gas, coal coke, and tar (original figure, data source MME, 2012).

Industry (3.7EJ) and transportation (3.1 EJ) are the two largest energy-consuming sectors in Brazil while the remainder of consumption is used in the energy sector (0.93 EJ), residential, commercial and public energy demand (1.4 EJ) and agriculture and livestock (0.41 EJ) (MME, 2012). The transportation sector is the most oil intensive sector of the Brazilian economy, accounting for 55% of total oil consumption. Although biofuels have made significant inroads for use in personal and light duty vehicle, large volumes of diesel fuel are consumed for long haul transport (MME, 2012).

3.1.1.1 Renewable energy in Brazil

Brazil has a long history of renewable energy development, investing heavily in renewable technologies in the early 1970s after the OPEC oil crisis sent their trade balance into a serious deficit. Today, Brazil is one of the largest proportional users of renewable energy in the world (46% in 2011) (MME, 2012). Major renewable energy sources are a reflection of the country's domestic resources and major industries as both biomass and hydroelectricity play a prominent role in the renewable energy supply.

The domestic renewable energy supply in Brazil is derived from hydro/renewable electricity, (33%), biomass (58%) and the remaining (9%) denoted as "other" (no clear definition is provided by MME) (MME, 2012). The breakdown of domestic renewable energy supply is provided in figure 6. For the purpose of this figure, biomass is separated into sugarcane products and firewood/charcoal.

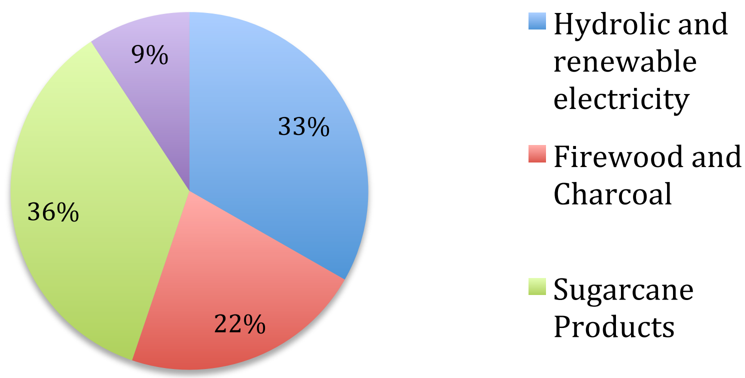

Figure 6: Domestic renewable energy supply by source in Brazil for 2011 (original figure, data source MME, 2012).

In Brazil, hydro reservoirs play an important role in energy generation, acting as power reserves. Reservoirs are held full in case the price of energy imports increases, if this occurs the water is released to enhance the generation of electricity. Recently, droughts in Brazil have made water flow increasingly unpredictable, exposing this type of reserve system to risk.

In 2001-2002 a large power crisis arose in Brazil due to long periods of drought. Energy was rationed for 8 months to cope with the decreased electricity generating capacity; at the time Brazil depended on hydropower for 88% of electricity generation (The Economist, 2014; MME, 2012). Since then the electricity mix has been expanded to include coal, gas and oil-fired power stations, yet Brazil still relies on domestic hydroelectric dams for 74% of its electricity, leaving the country exposed to energy shortages (MME, 2012).

This exposure was made evident in early 2014 when Brazil was faced with the driest rainy season since 2001, and reservoirs were at a mere 37% capacity. Meanwhile, energy consumption has soared, with peak demand reaching an all time high of 86GW in February (The Economist, 2014). Increasing demand came in the wake of new government policies designed to cut household electricity prices and heightened energy consumption leading up to the FIFA World Cup of Soccer, as Brazil was hosting. Low electricity supply combined with heightened demand caused significant shortages across Brazil. Further expansion of Brazil's hydroelectricity production was not a possible solution. Unutilized hydropower potential is severely limited by the location of suitable rivers within the Amazon, making industrial development politically and environmentally sensitive.

Since the energy crisis earlier this year, energy security and diversification of renewables has gained significant political traction prior to the upcoming Presidential election in October of 2014 (The Economist, 2014). Wind, solar and bioenergy based power systems are all being heralded as supplemental energy sources. Biomass, unlike wind and solar holds great promise as it is the only non-intermittent source of renewable energy, allowing for on-demand energy generation. The ability of biomass to act as stored energy, favorably positions bioenergy as a potentially significant renewable energy source in Brazil. A greater discussion of biomass for energy in Brazil occurs in the subsequent section.

3.1.2 Brazilian biomass

Biomass is the largest source of renewable energy in Brazil, accounting for nearly 60% (2.9 EJ) of total renewable energy production or ~30% of final energy production. Biomass is defined as sugarcane products, firewood, charcoal, alcohol and other renewable primary sources (it is unclear from the Ministry of Mines and Energy (MME) if black liquor and biodiesel are included within this definition) (MME, 2012). Sugarcane is the predominant biomass feedstock, contributing ~17% to primary energy production. Firewood and charcoal use is declining in Brazil as access to electricity expands but still accounts for 9% of primary energy demand in 2011 (MME, 2012). Figure 7 depicts the use of biomass for both biofuels and bioenergy in petajoules. From the figure it is apparent that bioenergy generation greatly exceeds biofuel production and that currently biomass is allocated towards bioenergy generation than biofuel production.

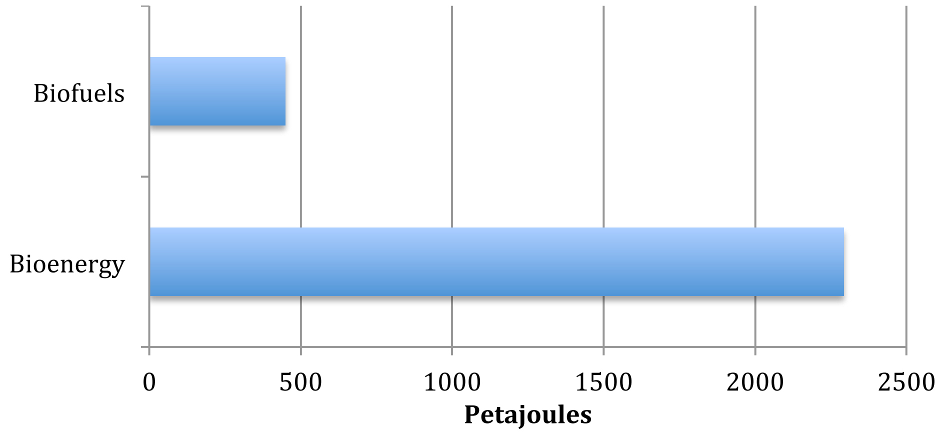

Figure 7: Brazilian 2011 consumption of biofuels (450 PJ) and bioenergy (2,292 PJ), expressed in petajoules (original figure, data source MME, 2012).

Brazilian biomass is nearly all domestically sourced either from; energy specific agriculture or forestry operations, harvest residues and process residues. The only biomass imports are bioethanol, 25 PJ of which were imported in 2011 (MME, 2012). Brazilian government data regarding the origins of these imports was not readily available, however it is previously known that the U.S. and Brazil have an established ethanol exchange where the Americans ship corn-ethanol to Brazil in exchange for sugarcane-ethanol. This exchange occurs due to the U.S. Environmental Protection Agency's favourable classification of Brazilian sugar-derived bioethanol as an advanced biofuel under the Renewable Fuels Standard (Schnepf & Yacobucci, 2013).

How biomass is employed in transportation, electricity and heating/cooling is examined in the subsequent sections to illustrate how biomass feedstocks are consumed in Brazil and the major conversion technologies employed.

3.1.2.1 Biomass for heat and power

Although the Brazilian biofuel program is recognized worldwide, bioenergy is the predominant biomass-based energy technology in Brazil (as highlighted in figure 7) accounting for almost 25% of primary energy demand in 2011 (MME, 2012). The use of bioenergy within industrial, residential, commercial and electricity applications is shown in figure 8.

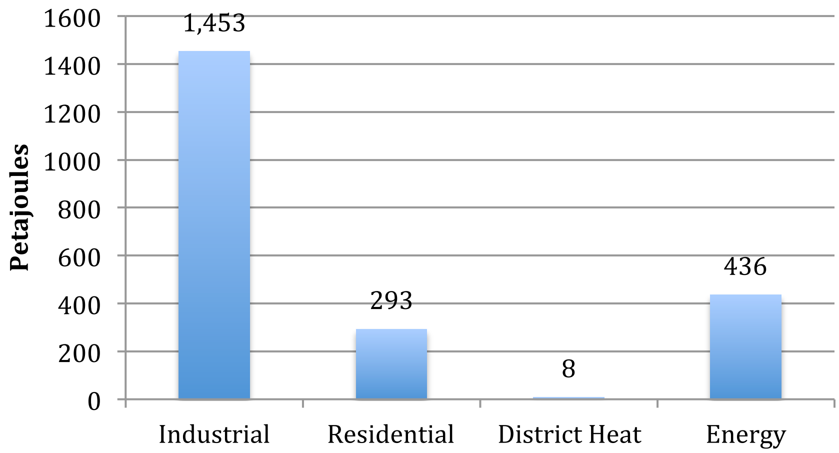

Figure 8: Use of biomass for energy generation by sector for 2011 in Brazil expressed in petajoules (original figure, data source MME, 2012).

Unlike other developing countries where traditional bioenergy accounts for an average of 35% of the final energy demand (or as high as 60% in sub-Saharan Africa), bioenergy generation in Brazil is dominated by modern bioenergy applications (MME, 2012). In figure 8, only the "residential" category includes traditional bioenergy applications. Information regarding the applications of biomass, either traditional or modern, within the residential sector is unavailable, however even if all 293 PJ were consumed traditionally this amounts to only 11% of total bioenergy generation, well below the 35% global average (MME, 2012).

It is apparent from figure 8 that industrial applications dominate bioenergy use in Brazil. Industrial applications of bioenergy include combustion of sugarcane bagasse for heat and power production (1.1 EJ), black liquor combustion in pulp mills (0.2 EJ) and the use of firewood and charcoal for industrial energy generation (MME, 2012; IEA, 2013a). Industries in Brazil rely heavily on biomass as an energy source as many large sugar and pulp mills are situated in remote locations, often not connected to the power grid. Combustion of biomass for heat and power generation allows industrial facilities to be largely energy self-sufficient, preventing the need to install capital-intensive grid connections.

In 2011, sugarcane bagasse, the only biomass feedstock employed by the energy sector, was responsible for 46.5% (436 PJ) of the sector's total energy consumption (MME, 2012). It should be noted that electricity generation is awarded its own category by the Brazilian MME, and thus these figures do not include electricity production (MME, 2012). Limited information exists regarding the types of conversion facilities that employ bagasse.

3.1.2.2 Transportation biofuels

Brazil was one of the first countries to commercialize the fermentation of sugar to fuel grade ethanol and was the world's largest ethanol producer until 2005 when it was surpassed by the United States (MME, 2012). Brazil's biofuel success can be attributed to their widely available and easily fermentable, sugarcane feedstock. Brazil produced 588 million tons of sugarcane in 2012/2013, making it the leading global producer (UNICA, 2014).

Today, Brazil is the second largest producer and consumer of biofuels in the world, the vast majority of which is sugar-derived bioethanol. Bioethanol production is estimated to reach 28.9 BL in 2014, while total exports are forecast at 3.65 BL (USDA, 2013). In 2011 Brazil imported 25 PJ (1.1 BL) of ethanol. Domestic biofuel production is supported by the large fuel-ethanol market existing within the country, stimulated by government blend mandates of 20-25% ethanol in conventional gasoline (the blend is known as gashol in Brazil) and up to 100% blends for flex-fuel vehicles. The high percentage of flex-fuel vehicles is a unique aspect of the Brazilian case. This significantly impacts the country's biofuel markets and it is discussed in more detail in section 3.3.3.

In comparison to ethanol, biodiesel production and consumption is less prolific, 2.8 BL in 2013 (USDA, 2013). Biodiesel blend mandates have recently been approved for increases up to 7% by the end of 2014. As a result, biodiesel consumption is anticipated to exceed its 2.9 BL estimate for the end of that year (USDA, 2013). The notable government programs supporting the emergence of the Brazilian biofuel industry are reviewed in greater detail in a subsequent section of this case.

Brazil, with the US, is emerging as a leader in advanced biofuel production from agriculture residues. The GranBio facility was opened in 2014 and is located in Alagoas, Brazil has a production capacity of 82 million liters of cellulosic ethanol per year, making it the largest-known project of its kind and the first in the Southern Hemisphere. The facility will process 400,000 tons of sugarcane bagasse for biofuel, heat and power production. The integrated CHP facility will produce ~0.5 PJ of surplus electricity (GranBio, 2014).

3.1.3 Drivers for biomass allocation in Brazil

Although biomass competition in Brazil has currently not precipitated any significant competition between bioenergy and biofuels the increasing use of bagasse to generate heat and power within sugar mills and the increasing transfer of generated electricity into the grid implies that this might occur in the future. The sugar from sugarcane, the predominant biofuel feedstock, is used to make ethanol and is not used to make bioenergy. However, competition for sugarcane bagasse, a byproduct of sugar production, is expected to intensify. Many of the newer mils exporting electricity into the grid. Companies such as Raizen and Granbio are also assessing bagasse's potential as a cellulosic ethanol feedstock. However, the domestic supply of bagasse currently dwarfs any potential competition for bagasse in the near future (IEA, 2013a). Although technologies for converting biomass to liquid biofuels are approaching commercialization, competition for biomass feedstock for bioenergy and biofuels is unlikely to occur in the near term.

3.1.3.1 Energy security and the emergence of biomass-based energy

The allocation of biomass to bioenergy or biofuels in an attempt to mitigate energy security concerns has been an essential and reoccurring energy strategy in Brazil. During the Second World War, ethanol production from sugar took off as a way to offset gasoline consumption. Ethanol blending with gasoline peaked at 50 percent when oil was scarce, but this quickly decreased after the war ended as the country was inundated with low cost oil (Kovarik, 2006).

Several decades later, skyrocketing oil prices drove import payments for oil from 500 million to 4 billion dollars annually as a result of the OPEC oil crisis (Hultman et al. 2012). The Pró-Álcool program was a national initiative developed during this period of heightened energy security concerns. The program aimed to stimulate domestic production of ethanol to replace imported gasoline. Details of the policies initiated under the Pró-Álcool program, and its' influence on the allocation of biomass towards biofuels is discussed in section 3.2.2. The expansion phase of Pró-Álcool ended around 1986 as global oil prices fell and domestic oil resources were discovered. Together these events ended energy security concerns thus reducing government support for ethanol (Hultman et al. 2012).

Energy security concerns, although usually driven by oil and petroleum supply, demand and costs, can occur in other energy systems, depending on the energy mix of a given region. Brazil's large reliance on hydroelectricity leaves the country highly susceptible to climate variations that influence water flow. Severe droughts in 2001 and early 2014, impacted hydropower inflows, lowering electricity generation and creating energy security issues with regards to electricity supply. (USDA, 2013) In these instances, combustion of biomass, particularly sugarcane bagasse, for electricity generation has been seen as a suitable complementary renewable energy source. Combustion of bagasse for energy generation increased by 56% from 2002-2011 (calculated from MME, 2012 dataset).

However, it is unlikely that as a driver, energy security is sufficient to explain the total increase in bagasse combustion for energy generation observed over the past decade. Other drivers that have potentially influenced bagasse allocation to bioenergy must be considered.

3.1.3.2 Energy related climate change concerns and biomass allocation

In Brazil, climate change has held a prominent place in government policy since 2008, after a series of extreme weather events lead to the formation of the National Plan on Climate Change (NPCC) (Government of Brazil, 2008). The NPCC set voluntary goals that aimed to increase energy efficiency, encourage increased biofuels and decrease deforestation. In 2010 the voluntary goals outlined by the NPCC were made law. Included in this law was a landmark mandate for GHG emissions reductions. However, a provision within the law calling for a gradual decline in fossil fuel consumption was vetoed by the President at the time and was not included with the passage of the NPCC (Government of Brazil, 2008). Despite Brazilian climate change initiatives, it is unlikely that these voluntary emissions reduction targets had any influence on the allocation of biomass to either bioenergy or biofuels. The lack of punitive measures for non-compliance in the Brazilian system leaves the NPCC policies of low impact (Government of Brazil, 2008). The importance of government mandates and punitive measures in biomass allocation is discussed in reference to Danish and U.S. biofuels policy in each of those respective case studies.

3.1.3.3 Prevailing economic interests

As seen in figure 8, industry is an essential consumer of biomass for energy generation in Brazil thus this section focuses on how major Brazilian industries and government policies sway biomass allocation in the country.

Agriculture, predominantly sugar production, is a major player in the Brazilian economy, accounting for 25% of GDP and employing 35% of the labour force in 2008 (Morgera et al. 2009). Together with forestry operations, these industries are key players in biomass allocation decisions. The sugar industry is of particular importance as Brazil is the world's leading producer of sugar (IEA, 2013a). The significance of the sugarcane industry to the Brazilian economy situates it as a dominant lobby group in the country and a powerful driver making key biomass allocation decisions. Sugar is both a global commodity, traded at an established world price, and the major domestic feedstock for biofuels. This makes biofuels and sugar production in Brazil competing industries. When world sugar prices are low biofuel production from sugarcane acts to supplement the industry. As a consequence, when world sugar prices are high, the sugar industry maximizes revenue by preferentially producing sugar (De Freitas & Kaneko, 2011). Although competition, beyond bioenergy and biofuels is not discussed in other case studies, as it is beyond the scope of the thesis, competition between sugar and biofuels production cannot be overlooked in the Brazilian case. This competition is responsible for significant annual variation in biofuel production over the last decade (MME, 2012; IEA, 2013a).

Sugar extraction from raw sugarcane is an energy intensive process, requiring significant mechanical attrition to remove the sugar from the stalk and subsequent boiling to purify the sugar. Large energy demands, combined with the remote locations of many sugar mills, means the more modern facilities are designed to be principally self-sufficient in energy generation. Combustion of bagasse in co-generation facilities is required to meet energy demand. If grid connections are available, surplus energy is often sold back to the grid. Bagasse represents ~80% (1.1 EJ in 2011) of industrial energy consumption from biomass and provides more than five times the energy than the next largest biomass feedstock, black liquor (0.2 EJ in 2011) (MME, 2012; IEA, 2013a). The institutionalized use of bagasse as an energy source integrated within sugar production facilities means competition for this feedstock will intensify as advanced biofuel production increases.

Forest operations, although not as economically significant as sugar production, are a notable consumer of biomass in Brazil and must be considered when discussing biomass allocation decisions. The Brazilian forest industry is based heavily on the production of pulp and paper from fast growing hardwoods such as eucalyptus. Combustion of pulp and paper biomass waste, including black liquor, amounts to 0.2 EJ of industrial energy consumption (2011) (MME, 2012). Similar to sugarcane mills, modern pulp mills are largely energy self-sufficient by combusting their waste streams for energy generation, and where connections to the grid exist; any surplus energy is sold (IEA, 2013a). The widespread combustion of wood and pulp waste for energy is an important driver allocating biomass towards bioenergy generation.

The second coming of the modern Brazilian ethanol industry emerged out of the manufacturing sector with limited government incentives for ethanol producers (Hultman et al. 2012). Domestic car manufactures were given policy support in the form of tax breaks to produce flex-fuel vehicles with additional purchase incentives passed onto the buyers (Hultman et al. 2012). As a result of these incentives, in 2003 flex-fuel vehicles entered the Brazilian car market. Capable of accepting pure gasoline, pure bioethanol or any proportional mixture of the fuels, these vehicles created a renewed consumer enthusiasm for ethanol (Matsukoa et al. 2009). Introduction of flex-fuel cars was sufficient to stimulate consumption of pure, unblended (hydrated) bioethanol and created opportunities for an expansion of the domestic sugar industry. Flex-fuel vehicles rapidly gained popularity, becoming the predominant passenger vehicle in Brazil, accounting for over 50% of total passenger vehicles and 90% of annual new car sales (IEA, 2013a). Adoption of flex-fuel vehicles, combined with the existing E100 vehicle stock, caused more bioethanol to be sold at the pump than gasoline in 2008 and 2009 (Matsukoa et al. 2009; IEA, 2013).

In recent years the consumption of bioethanol in road transport, specifically hydrous bioethanol, has dropped off significantly, as can be observed in figure 9. Although not included in the figure below, the consumption of both anhydrous and hydrous fuel ethanol experienced an upswing in 2013 and early 2014 (Brazilian Sugarcane Industry Association (UNICA), 2014). Cost competitiveness is a major factor influencing the consumption of biofuels and gasoline in Brazil and are contingent upon a number of variables, explored in further detail in the subsequent section.

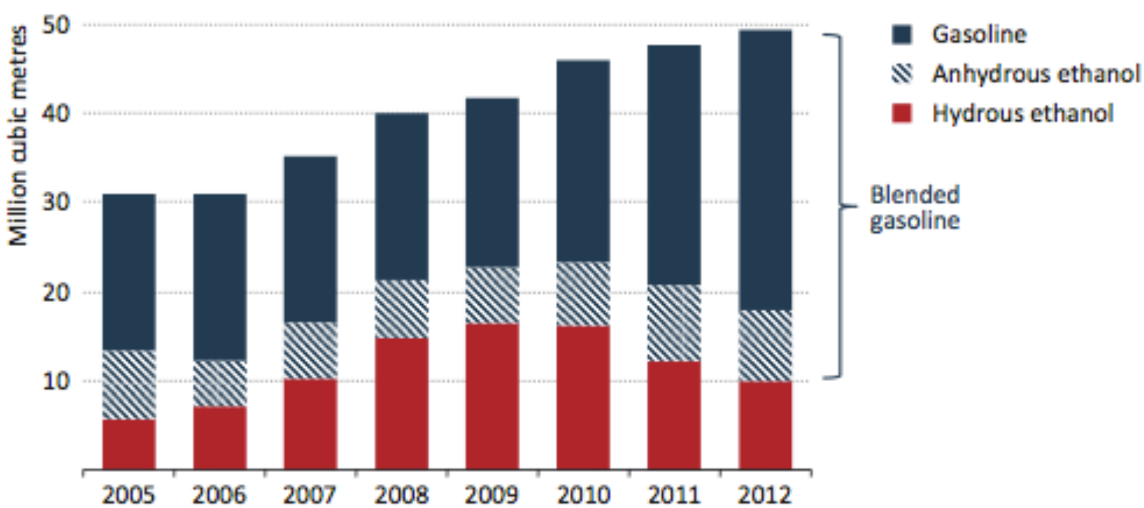

Figure 9: Brazilian consumption of gasoline and bioethanol in road transport from 2005-2012 in million cubic meters (IEA, 2013a).

3.1.3.4 Cost competitiveness of Brazilian bioenergy and biofuels

Biomass allocation in Brazil is less dependent upon the cost competitiveness of biomass-based energy production with existing energy technologies than the Danish, or Swedish profiles examined in this thesis. The Brazilian case experiences advantages compared to the other country profiles due to the simplicity of technologies to convert the nation's available sugarcane to biofuels. However, the allocation of sugarcane, to sugar or biofuel production is a factor of both global sugar prices, and world oil prices as discussed further below. Cost competitiveness is important to consider within this context.

3.1.3.4.1 Technological advancements in biomass-based energy

In Brazil, sugar, not starch or biomass is used to make bioethanol, a biofuel. The ease with which sugar can be fermented to biofuels proves advantageous when compared to starch or lignocellulosic biomass. This technological advantage is unique to the Brazilian case. At the time of the oil crisis, technologies to ferment sugar into biofuels were commercially available and in the mid-to-late, 1970's, the product was cost competitive with oil and gas prices. This cost competitiveness of Brazilian biofuels with gasoline was a major driver for the rapid expansion of ethanol production by the sugar industry (Hultman et al. 2012). The low cost of bioethanol resulted in the increased production of a 100% ethanol (E100) fueled cars (Rosillo-Calle and Cortez, 1998). Today, Brazilian bioethanol benefits from the lowest pre-tax cost of all biofuels, approximately 25-50 cents US/L, nearly half the cost of U.S. corn-based biofuels (Demirbas, 2011; IEA, 2013a).

As discussed in section 3.2.2, Brazil is emerging as a pioneer in advanced biofuel production from lignocellulosic materials. The nature of the widely available, low cost, sugarcane bagasse feedstock makes it more easily convertible to biofuels than more recalcitrant woody biomass feedstocks available in other parts of the world. It is also likely that the relative ease by which agriculture feedstocks can be converted to biofuels when compared to woody residues helps to improve the cost competitiveness of bagasse based advanced biofuels.

Despite the potential logistical advantages of cellulosic derived biofuels being able to be integrated with sugar-derived ethanol, cellulosic biomass is still preferentially allocated to bioenergy. Newer sugar cane processing facilities rely heavily on the energy generated by their waste recycling systems to ensure the cost-competitiveness of their energy intensive operations. Additionally, the geographical location of many sugar and pulp mills in Brazil often means they are not connected to the electricity grid, and thus would have to burn expensive fossil fuels as an alternative to biomass for energy generation.

3.1.3.4.2 Policies affecting cost competitiveness of biofuels and bioenergy

As introduced in section 3.3.2, Brazil's climate policy is outlined in the National Plan on Climate Change. The NPCC set voluntary goals that aim to increase energy efficiency, encourage increased biofuels and decrease deforestation. However, the President vetoed the provision within the law calling for a gradual decline in fossil fuel consumption (Government of Brazil, 2008). The lack of punitive measures for those not reducing their use of fossil fuels leaves the NPCC policies ineffective.

The Pró-Álcool program was the key Brazilian biofuel policy that provided incentives to replace traditional oil based transportation fuels with domestically produced sugarcane ethanol. By doing so, Brazil moved closer to achieving energy independence, improve rural income and maintained economic growth by providing an alternative energy source to oil, although domestic energy security and the reactionary policy mechanisms were imperative to biofuel development (Rosillo-Calle and Cortez, 1998). Support was derived from a bank of policies including: quotas, price floors and ceilings, tax incentives to produce E100 cars, blend mandates, preferential financing, higher taxes on gasoline cars and subsidies for transporting ethanol (Rosillo-Calle and Cortez, 1998).

During the 1970s ethanol use increased dramatically as the relatively low ethanol blend mandate (below 20%) meant that the current vehicle stock could, without any modification, use ethanol-gasoline blends in the existing infrastructure. By 1978, sugar capacity was fully employed and ethanol blends were approaching the 20% target. Subsequently the government began to investigate replacing gasoline with pure alcohol. This required a new transportation fleet and fueling infrastructure and significant funding commitments from the government to support their development. It wasn't until 1979 that the Brazilian government announced new ethanol production targets of 10.6 BL by 1985, up from the goal of 2.9 BL for 1980 (Hira and de Oliveira, 2009). Additionally the government announced it would invest $5 billion over the next 6 years to support fuel production and distribution centers. Government departments were formed to oversee ethanol production and monitor a variety of support policies that included: higher minimum ethanol blends (progressive increase to 25%), capped ethanol price at 65% of gasoline price, price floor for bioethanol producers, improving lines of credit for sugar mill expansions, ethanol required at all gas stations and the maintenance of reserves to stabilize supply (BNDES and CGEE, 2008). A number of policies were set up to specifically push production of alcohol-based cars (known as E100): registration taxes were reduced relative to gasoline cars and easier payment plans introduced with lower down payments and longer payment periods. The programs were a wild success as E100 car sales increased from 1% of total car sales in January of 1980 to 73% by December of that year and 85% by 1985 (BNDES and CGEE, 2008; Hira and de Oliveira, 2009).

The Pró-Álcool program was highly successful in making sugarcane-derived biofuels highly cost-competitive with gasoline during this period of high oil prices. Yet, in the subsequent decades, Pró-Álcool became ineffective at supporting bioethanol due to a number of changing variables. As a result, the Brazilian biofuel industry experienced a decline.

The mid 1980s marked the end of the expansion phase of Pró-Álcool as global oil prices fell and domestic oil resources were discovered, together ending energy security concerns and with that came reduced government support for ethanol. Concurrently, world sugar prices began to rise due to several years of poor sugar harvest and sugarcane mills began to direct more of their crop towards sugar production than ethanol to maximize revenue (Hira and de Oliveira, 2009; Hultman et al. 2012). By 1989 suppliers were faced with unpredictable biofuel supplies, this enraged consumers and the market saw a move away from E100 vehicles. By 1990 E100 represented only 11.4% of new vehicle sales, by 2000 they were available by special request only (BNDES and CGEE, 2008; Hultman et al. 2012). Simultaneously the government was restructuring their support for ethanol. Beginning in 1991, the government systematically removed ethanol subsidies and price controls to move towards free-market pricing. It took until 1999 for this to be completed but effectively signaled the end of the Pró-Álcool program (BNDES and CGEE, 2008).

The ability of flex-fuel vehicles to accept either pure bioethanol or gasoline blends means consumers are very responsive to fuel prices, drivers regularly select the cheaper option since bioethanol and gasoline are essentially perfect substitutes (Matsukoa et al. 2009). The ability of drivers to select fuel based on price helps to explain the transportation fuel trends observed in figure 9, however understanding price competition between biofuels and gasoline in Brazil is complex. Technological advancements in ethanol production have made the fuel cost-competitive with gasoline, despite the country's discounted gas prices (Hultman et al. 2012). However the price of ethanol fluctuates, regularly between 50-70% of gasoline prices (Matsukoa et al. 2009). Price fluctuations are a factor of sugar harvest, world sugar prices and the controlled gasoline price.

Petrobras, the largest oil and gas company in Brazil, is a semi-public company that controls the price of gasoline on behalf of the Brazilian government. Imported gasoline, purchased at world prices, has been subsidized and sold at a loss in Brazil since 2011 in an attempt by the government to curb inflation (Romero and Thomas Jr., 2014; Valle, 2014). This practice has made Petrobras the most indebted publically traded oil company in the world, 2013 losses amounted to $U.S. 8 billion (Romero and Thomas Jr., 2014; Valle, 2014). As Petrobras looks to lower gas subsidies, there-by increasing prices, ethanol consumption can be expected to increase. However, as hopefully revealed by this chapter, factors affecting ethanol demand extend beyond just gasoline prices.

3.1.4 Brazilian conclusions

Renewable energy contributes to 46% of the Brazilian energy mix with biomass being the predominant renewable energy source. Ethanol derived sugar and bagasse that has been combusted are the predominant resources of this energy, accounting for 58% of Brazil's bioenergy production. Although Brazil is the world's second largest producer and consumer of biofuels five times more energy is derived from the combustion of biomass, primarily bagasse, than is derived from bioethanol and biodiesel (figure 8). If there ever is to be a Brazilian biomass competition, it is likely that bioenergy will remain the preferred use of biomass resources.

The main driver behind early biofuel development was concerns of energy security, and the government support mechanisms and policies including but not limited to: ethanol mandates, -subsidies, and the development of the flex-fuel vehicle industry to address this were imperative for biofuel advancement. Compared to energy security, climate change mitigation desires have played a limited role in biomass allocation decisions in Brazil.

Historically, there has been no competition for biomass between bioenergy and biofuels in Brazil. However, this trend might change as bioenergy and cellulosic ethanol can be produced from sugarcane bagasse, which is currently combusted for bioenergy generation at sugar mills. Despite this possibility, it is unlikely that competition will occur, due to ample domestic feedstock availability. It is more likely that bioenergy and biofuels will become co-products with power contracts providing a more assured source of income for biofuels producers, help offsetting the cost of making the biofuel, thus improving its' cost competitiveness with gasoline. This notion is supported by examining the end products of several of the commercial scale cellulosic ethanol facilities operating world-wide, including GranBio's plant in Brazil. Surplus bioenergy generation in this facility amounts to 17MWe per year (GranBio, 2014).

Woody biomass in Brazil is currently used for bioenergy generation and is of particular importance in industrial operations where black liquor, firewood and charcoal are combusted for heat and power generation. Although technologies exist at the pilot scale to transform woody biomass to liquid biofuels, it is unlikely that this feedstock will be allocated towards biofuel production in the near future in Brazil.

3.2 Denmark

In the 1980s Denmark was reliant on fossil fuels for nearly 90% of its total energy needs. Today, Denmark begun a transition to renewable energy technologies, which now provide 22% of the country's energy demand, biomass being the predominant source (Nikolaisen, 2012; Danish Energy Agency (DEA), 2012) Historically the country has predominantly combusted biomass (wheat straw and wood) in DH and CHP facilities with these technologies being a focal point of Danish energy policy since the 1980s (Hvelplund, 2011). The past and current use of biomass for biofuels production is insignificant compared with its use to generate bioenergy. This section looks at the conditions that have and might influence biomass utilization decisions regarding their possible use to produce biofuels or bioenergy.

3.2.1 The Danish energy mix

In Denmark, the national energy portfolio includes almost exclusively fossil fuels and renewable energy (RE), as nuclear power was banned by the government in 1985 (Hvelplund, 2011). In 2011, total energy consumption (TEC) was 0.80 EJ, of which 0.17 EJ (22%) was from renewable energy (DEA, 2012). Figure 10 below illustrates the 2011 Danish energy mix.

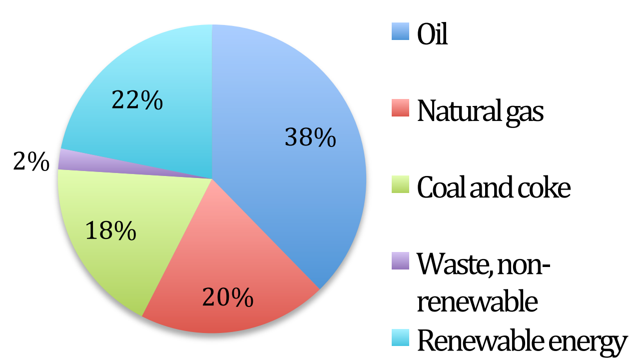

Figure 10: Denmark's 2011 energy mix (original figure, data Source: DEA, 2012).

Despite the mounting use of renewables, Denmark is still reliant on fossil fuels for energy. In 2011, oil (0.30 EJ), natural gas (0.15 EJ) and coal (0.13 EJ) represented 38%, 20%

and 18% respectively of the country's final energy consumption (DEA, 2012). Transportation accounted for the largest share of fossil fuel use, 0.2 EJ (69%) of total oil consumption that year, followed by industry 0.04 EJ (14%) and households 0.02 EJ (6%). As recently as the 1970s, the majority (90%) of Danish fossil fuel resources were imported. However, the discovery of domestic oil and gas deposits in the North Sea in the 1980s transformed Denmark from a major fossil fuel importer to a net exporter (Meyer, 2004).

3.2.1.1 Renewable energy in Denmark

When the oil crisis of 1973 occurred, Denmark's economy experienced a significant downturn as no known domestic fossil fuel resources were available. This, combined with a strong stance against nuclear power left the country in an energy shortage. Concerns of energy security arose out of the crisis, sparking a transformation of the Danish energy system, with an introduction of clear national energy policies spurring the move to renewable energy and energy efficient technologies (Meyer, 2004). Success of these measures has facilitated the increased penetration of renewables, improved energy efficiency, shifted the balance of trade and decoupled economic growth from energy consumption (IEA, 2013b). Figure 11 below illustrates the growth of renewable energy from 1990-2011. By 1997 Denmark was energy self-sufficient and in 2000, emerged as a net-energy exporter (IEA Task 40 Report, 2012). Since 1990, energy consumption has remained constant and CO_2 emissions have declined 7.2%, all while the economy expanded 35% (IEA, 2011).

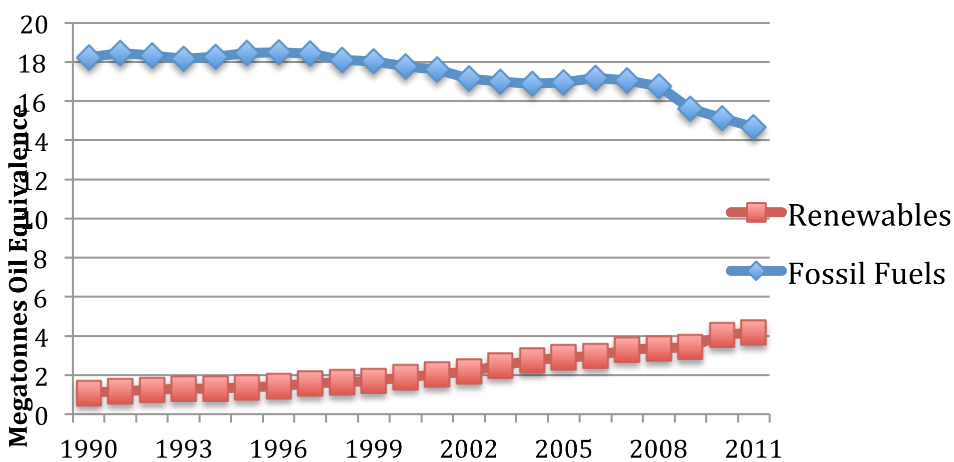

Figure 11: Denmark's energy matrix for 1990-2011 (original figure, data source: DEA, 2012).

Biomass is the largest source of renewable energy in Denmark, accounting for 68% of all renewables or 15% of the total energy supply in 2011. Wind power is the second largest renewable source and contributes 20% to renewable energy generation in Denmark. Biofuels were absent from the Danish energy mix until 2006, but have experienced significant growth as they accounted for ~4% of renewables by 2011, the vast majority of which is imported. Solar and hydroelectric capacity in Denmark is negligible. A detailed breakdown of renewable energy sources is available in figure 12.

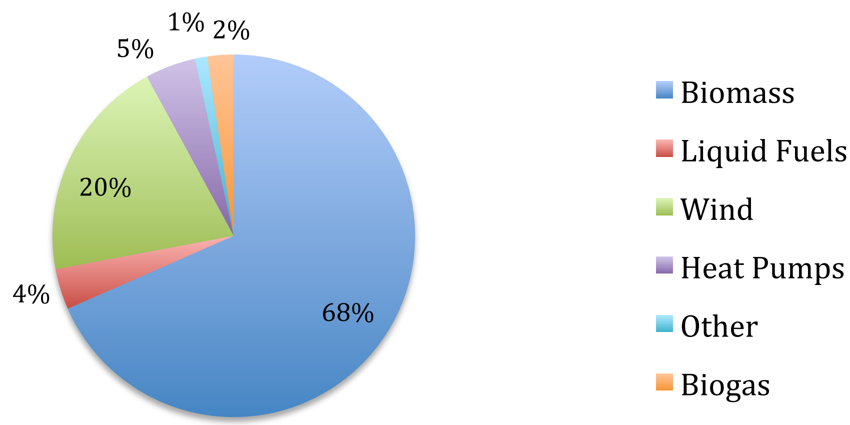

Figure 12: Renewable energy by source in Denmark in 2011. Liquid fuel denotes bioethanol and biodiesel. Heat pumps are classified as renewable by the DEA. Other denotes the sum of geothermal and solar power generation (original figure, data source: DEA, 2012)

3.2.2. Danish biomass

For the purpose of this case, the DEA's (2012) definition of biomass is used, where biomass refers to solid biomass combusted for bioenergy generation. The DEA provides separate categories for biofuels (bioethanol, and biodiesel), bio-oil and biogas (DEA, 2012). Within biomass, wood is the principal feedstock (61% of biomass) although straw, and renewable waste provide significant contributions (16% and 17% respectively). Figure 13 outlines the breakdown of feedstock consumption in Denmark. The wide array of feedstocks available imparts flexibility in potential energy products from biomass.

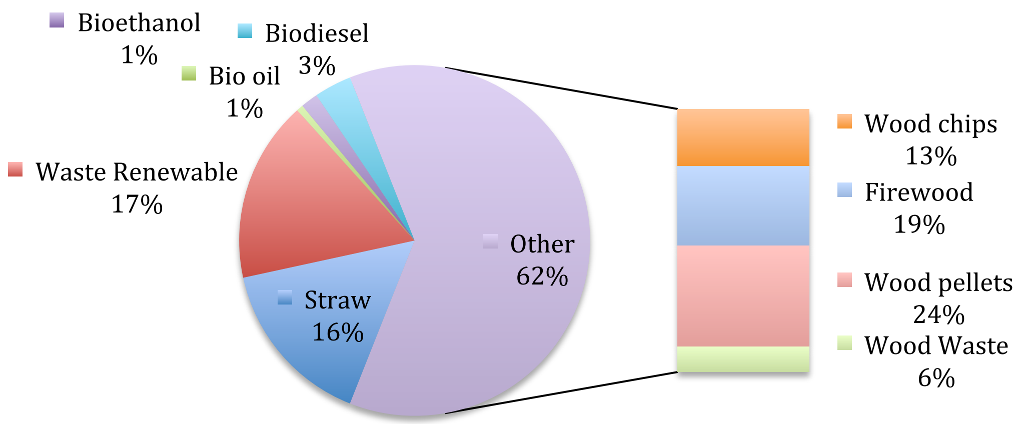

Figure 13: Danish 2011 biomass consumption by feedstock, wood (62%) is further categorized into chips, firewood, pellets and waste (original figure, data source DEA, 2012).

In contrast to the U.S. and Brazil where biomass resources exceed demand, Denmark's domestic biomass supply is limited. Both domestic forest and agriculture derived biomass contribute to meeting Denmark's biomass based energy demand. The total annual production from agriculture and forestry amounts to approximately 18 million tonnes of dry matter. Only a fraction of this (less than 3 Mt) is available for bioenergy production, and even less is suitable for biofuels (Gylling et al. 2012). This limited domestic supply means Denmark relies on imports for large quantities of biomass. Table 1 outlines the domestic production, import and export of different biomass feedstocks in Denmark in 2011 (DEA, 2012).

Bio-mass Source (PJ)	Straw	Wood chips	Fire-wood	Wood pellets	Wood waste	Bio-gas	Waste	Bio-diesel	Bio-ethanol	Total biomass
Produ-ction	19.75	11.29	20.47	2.41	7.52	4.1	21.20	2.96	0	89.7
Import	0	5.81	2.1	27.73	0	0	0	3.42	2.10	41.16
Export	0	0	0	0	0	0	0	1.99	0.96	2.95
Total	19.75	17.1	22.57	30.14	7.52	4.1	21.20	4.39	1.14	127.91
Percent Imported	0	34%	9%	92%	0	0	0	78%	100%	32%

Table 3: Danish domestic production, import and export of different biomass sources in 2011 displayed in petajoules (calculations based on data source DEA, 2012).

Contributions of biomass to electricity, heating/cooling and transportation are examined in the subsequent sections to provide a better understanding of how biomass feedstocks are consumed and which predominant conversion technologies used in Denmark.

3.2.2.1 Biomass for heat and power

The majority of biomass in Denmark is combusted for heat and power production, integrated within industrial operations, in stand-alone heat, power or CHP facilities and residential stoves and boilers. Biomass provided 13% of the country's total electricity generation and 23% of its heating requirements in 2010 (IEA, 2011).

Pellets, firewood, wood chips and wood waste are the predominant biomass feedstocks for bioenergy in Denmark and account for ~62% of total biomass used in the country (figure 13) (DEA, 2012). In 2010, 30.1 PJ of pellets were consumed, representing nearly a quarter of all biomass used that year in Denmark (Nikolaisen, 2012), and thus it relies on imports to satisfy part of its national biomass demand. As outlined in table 3, some firewood (9%) is imported, a significant proportion of wood chips (34%) and nearly all of its wood pellets (92%). Almost half of the pellets that are combusted in Denmark are used in large power plants (15.2 PJ), residential pellet stoves consume 10 PJ of pellets and district heating plants consume 2.9 PJ (Nikolaisen, 2012). Firewood is used exclusively in private households to produce 22.5 PJ of energy, while 17 PJ of wood chips are combusted predominantly in large power plants, CHP and DH facilities (Nikolaisen, 2012). Wood waste generated 7.5 PJ of energy, 60% of which was used by industry (Nikolaisen, 2012).

Unlike the other jurisdictions examined in this thesis (with the exception of Brazil), combustion of agriculture residues is common in Denmark. Large volumes of straw are burnt for bioenergy annually (23.6 PJ in 2010) (IEA, 2012 Task 40) with most combusted for heat and power services in large power (10.3 PJ), DH (4.9 PJ) and CHP (3.6 PJ) facilities, although straw is also used in private households and farms for heat production (2.9 and 1.9 PJ respectively) (Nikolaisen, 2012). Straw, not wood was Denmark's original bioenergy feedstock and the role of straw in helping establish the Danish bioenergy industry is discussed further in section 4.3.2.

Widespread district heating infrastructure is the key aspect of the Danish bioenergy market and an important component contributing to its success in the national energy mix. District heating supplies 60% of domestic household heating services (45% of total heating requirements) with 75% of this heat generated in CHP facilities, improving the overall efficiency of conversion (IEA, 2013b). Unlike Sweden where DH and CHP are dominated by biomass, Denmark relies on both fossil fuels and biomass (approximately 50/50) feedstocks. Over 200 district heating plants, and 15 CHP facilities rely on solid biomass as fuel, while 30 bio-gas fired CHP plants are in operation (IEA, 2011). Together, straw, wood and bio-gas produced 56.63 PJ of electricity and district heat in 2011 (DEA, 2012).

The industrial use of biomass in Denmark is not as common as in the other profiles examined in this thesis. In 2010, biomass contributed approximately 10 PJ of energy, mainly for heating purposes on farms and within the forest sector (Nikolaisen, 2012). The minimal contributions of biomass to industrial energy generation is a factor of Denmark's prevailing economic interests, how these interests influence biomass allocation is covered in detail in section 4.3.3.

3.2.2.2 Transportation biofuels

As outlined in figure 14, biodiesel and bioethanol are the two biofuels consumed commercially for transportation in Denmark (DEA, 2012). No transportation biofuels were consumed in Denmark until 2006 when gasoline blending with bioethanol began, and even then, bioethanol has seen slow expansion when compared to Brazil, the U.S. and Sweden. Consumption only reached 2 PJ in 2011. It took until 2008 for biodiesel to be consumed in Denmark, since then it has emerged as the principal biofuel with 4.4 PJ consumed in 2011 (figure 14).

Today, Denmark has one of the smallest shares of renewable energy in transportation in all of Scandinavia (Larsen, et al. 2012). Compared to bioenergy that amounts to 68% of renewables, biofuels account for only 4% (figure 12). As a proportion of transportation fuel demand, biofuels accounted for only 0.3% in 2011 (IEA, 2013b). Nearly all biofuels consumed in Denmark are imported (table 1). Meanwhile, Danes rely on road transportation more than their European neighbors, with final energy consumption per capita in transport sitting 30% above the EU average (Larsen et al. 2012).

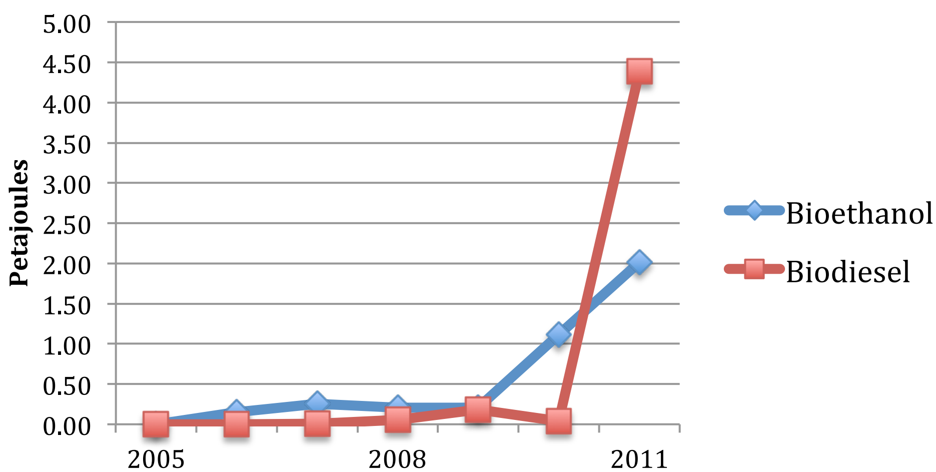

Figure 14: Danish bioethanol and biodiesel demand from 2005-2011. No biofuels were consumed prior to 2006 in Denmark (original figure, data source DEA, 2012).

Bioethanol is only available in low, E5, blends in Denmark, as opposed to the higher blends available in most countries examined in this thesis (Cansino et al. 2012). By comparing total demand volumes of gasoline to demand volumes of ethanol for 2011 as presented by the DEA, it can be noted that the lack of higher blends is not limiting ethanol consumption in Denmark. Not all gasoline sold is consumed as an E5 blend. (DEA, 2012). Currently all of the bioethanol consumed in Denmark is imported, but information on the origins of this fuel was not readily available (DEA, 2012). According to the DEA, no domestically produced bioethanol is commercially available in Denmark. However, a cellulosic ethanol demonstration facility has been in operation since 2009 in Kalundborg employing wheat straw as the predominant feedstock (Larsen et al. 2012). It is unclear if this facility is operating at a scale where the biofuels produced are fed into the Danish transportation fuel supply, or if the produced ethanol is not yet commercially available. Further development of cellulosic biofuels in Denmark may cause a shift in biomass allocation trends; the nature of this shift is discussed further in section 4.3.4.

Despite biodiesel not being consumed in Denmark until 2008, it has experienced rapid growth since then, quickly surpassing bioethanol as the predominant biofuel in the country (figure 14). Biodiesel is consumed only in B5 blends in Denmark, although this low blend is not currently limiting biodiesel consumption as no blend wall has been reached. The more rapid growth of biodiesel when compared to bioethanol is likely due to the favourable consumption of diesel fuel over gasoline in Denmark (DEA, 2012). Similar to ethanol, Denmark relies on imports for biodiesel supply (3.4 PJ in 2011), the origins of which are unknown (IEA, 2012 task 40). Interestingly, Denmark exports a comparatively large volume of biodiesel (nearly 2 PJ in 2011). The IEA suggests this is a result of high fuel taxes, although they fail to elaborate as to the mechanism behind this (Nikolaisen, 2012).

3.2.3 Drivers for biomass allocation in Denmark

Biomass utilization trends in Denmark provide a unique case when examined within the context of biomass competition. Given the limited domestic biomass supply, it is no surprise that Denmark is heavily reliant on imports to meet national demand. Despite the country's dependence on imports, current practices of biomass utilization in Denmark, with their strong bioenergy focus, have limited competition for biomass between bioenergy and biofuels. A heightened appetite for lignocellulosic biofuels in Denmark could influence the allocation of biomass and increase competition, particularly for straw and woody biomass, to biofuels or bioenergy.

For the purpose of this thesis I focused on the drivers for both forest and agriculture biomass allocation in an attempt to provide a complete picture of biomass utilization in Denmark. General energy security and climate change mitigation drivers, in addition to the influence of Danish economic interests and the cost competitiveness of biomass-based energy technologies are explored within the context of how they direct biomass allotment.

3.2.3.1 Energy security and the emergence of biomass-based energy

As discussed in section 2.1.1, energy security concerns arising out of the OPEC oil crisis were sufficient to spark investment in renewable energy technologies, however wind turbines emerged as the technology of focus, not biomass-based energy (Lipp, 2007). It wasn't until the early 1980s that biomass-based energy emerged in Denmark, at which point, the importance of fossil fuel related energy security had declined as domestic oil and gas reserves had been discovered in the North Sea (Meyer, 2004). Researchers have postulated that energy security may have opened the door for renewable energy generation, which in turn, provided easier penetration of biomass based-energy in Denmark. However, this type of analysis is beyond the scope of this study (Meyer & Koefoed, 2003; Hvelplund, 2011).

Fossil fuel supply is satisfied by domestic production, thus in the traditional sense energy security is a non-issue in Denmark. However, the country's reliance on imported biomass products creates an energy security issue that is unique to this case. Recall table 1, a significant proportion of wood chips (34%), wood pellets (92%), biodiesel (78%) and bioethanol (100%) are imported. This creates a scenario where energy security of these biomass-products is low. How secure the imported biomass supply is in Denmark is uncertain, as clear information regarding the origins of the biomass is unavailable. Problems could be expected to arise if this biomass is sourced from politically unstable regions, such as Russia, or from neighboring European countries whose biomass exports may dwindle as they too increase the use of biomass for energy production.

3.2.3.2 Energy related climate change concerns and biomass allocation

Combustion of biomass for energy began in Denmark during the late 1980s. At this time, mounting concerns regarding air quality and emissions problems associated with burning excess straw in farmer's fields had the Danish Government searching for alternative methods of removing this waste (Schwarz et al. 2012). Concurrently, adoption of new renewable energy technologies in Denmark was underway due to the emergence of concerns regarding energy related emissions and their negative impact on the climate (Hvelplund, 2011). Conversion of coal-fired heat plants to straw fueled co-generation facilities emerged as an appropriate solution (Meyer and Koefoed, 2003; Mendoca et al. 2009 and Hvelplund, 2011). Acceptance of CHP was quick in Denmark, by 1988, all Danish cities with populations greater than 60,000 inhabitants were employing CHP facilities (Hvelplund, 2011). It is important to understand however that the volumes of biomass consumed remained limited as other drivers were eliciting their influence on biomass allocation decisions. These drivers are discussed in more detail in section 3.3.3 and 3.3.4.

Experts suggest that despite the additional GHG emissions associated with transportation, the combustion of imported bioenergy products (namely wood pellets) still achieves emissions reductions compared to fossil fuel alternatives (Dwivedi et al. 2014).

However a flaw exists within many of these GHG emission analyses as they fail to recognize the emissions associated with direct or indirect land use changes and the depletion of the carbon stock. A further discussion of these facets of biomass-associated emissions can be found in Schulze et al. 2012. As reviewed in further detail in section 3.3.4, current Danish policies have outlined ambitious emissions targets of a carbon-neutral economy by 2050 (IEA, 2013b).

3.2.3.3 Prevailing economic interests

Agriculture is the major industry within Denmark in contrast to Sweden where the forest based industries predominate. This puts the agriculture industry as a dominant lobby group in the Danish case. As seen in these two profiles, industry has a significant impact on feedstock availability, bioenergy conversion technologies and applications. Only 10 PJ of biomass-derived energy was consumed in the Danish industrial sector, compared to 220 PJ in Sweden (DEA, 2012; SEA, 2013). The absence of a large forest sector helps explain why Danish industry is not a major biomass consumer, as waste burning is not as prevalent within agriculture as it is in forestry or pulp and paper (Nikolaisen, 2012). The differing energy demands of agriculture operations when compared to pulp and paper inhibit waste recycling from making headway into the agriculture industry.

The Danish biotechnology industry had a key role in the emergence of biofuels within Denmark. During the early 2000s, two prominent Danish biotech companies, Novozymes and Danisco (now a subsidiary of DuPont) voiced their concern that the country may fall behind the rest of Europe in moving towards a bioeconomy should they not act on developing biofuels. It was argued that moving towards a more diverse bioeconomy aligned well with the innovative capacity of the country. The collaboration of Novozymes and Danisco with DONG Energy (the largest energy provider in Denmark) and Landbrug & Fødevarer, (an agriculture and food trade association representing Danish farmers and food companies) lead to successful lobbying of the government (Teknologirådet, 2006). The results of this lobbying effort were realized in 2005 as the DEA set in motion legislation to develop liquid biofuels in Denmark (Teknologirådet, 2006). The legislation provided energy and carbon tax exemptions for all biofuels, sufficient incentives to commence the blending of bioethanol with gasoline, as observed in. The meager blend volumes achieved as a result of the tax incentives were not enough to stifle criticism from the scientific and industrial communities. Many groups claimed biased preference for existing biomass applications were stifling innovation and Danish competitiveness within the emerging EU bioeconomy, demanding more be done to aid biofuel development (Teknologirådet, 2006). Eventually, Denmark adopted the biofuel mandates as outlined by the EU Biofuel Directive, creating binding volumetric mandates for biofuel consumption. The specifics of these policies and how they directed biomass allocation in Denmark is covered in the subsequent section.

3.2.3.4 Cost competitiveness of Danish bioenergy and biofuels

This section considers how technologies and policies for bioenergy/biofuels influence cost competitiveness and ultimately biomass allocation decisions in Denmark. In Denmark, the lignocellulosic nature of the first feedstocks employed restricted conversion feasibility to bioenergy generation, largely influencing biomass allocation. As advanced biofuel technologies commercialize, this may change. The presence of district heating infrastructure, combined with the absence of a forest sector comparable in scale to Sweden or the United States, has caused bioenergy generation to be largely restricted to residential and commercial heat and power applications, rather than industrial energy generation. Furthermore, strong policies favoring biomass allocation to bioenergy have largely influenced biomass competition in Denmark.

3.2.3.4.1 Technological advancements in biomass-based energy

In Denmark, straw was the first major biomass feedstock employed for modern energy generation. When the straw emerged as a suitable bioenergy feedstock in the 1980s, a lack of available conversion technologies restricted the use of straw to combustion, as its conversion to biofuels was not yet possible. Combustion was considered suitable as district-heating infrastructure was prominent in Denmark, and the substitution of coal for straw in district heating was an attractive option (Hvelplund, 2011).

By the 1990s strong government mandates set targets for volumes of biomass to be combusted. However, biomass consumption did not grow as quickly as the government outlined (Schwarz et al. 2012). Part of latent growth in biomass consumption stems from the properties of straw biomass, as the combustion of straw creates more ash when compared to wood (Biedermann & Obernberger, 2005). High ash content can increase levels of particulate emission (an expensive gas scrubber is required to reduce emissions), cause corrosion, and decrease thermal efficiency (Biedermann & Obernberger, 2005). These negative consequences associated with straw combustion delayed the expansion of bioenergy in Denmark.

When the Danish government first explored the use of biomass as an energy source, production of biofuels from the domestically available straw and wood residues were not yet technologically feasible. The lack of domestic sugar or starch feedstocks, whose conversion to biofuels was possible in the 1980s, meant biofuels were not considered as a renewable energy option. Today, cellulosic ethanol technologies that employ agriculture residues as a feedstock are operating at the commercial scale in countries around the globe, including the United States, Italy and Brazil. The technological limitations in terms of lignocellulosic biofuels are no longer an impediment to biofuel development in Denmark. Commercialization of lignocellulosic biofuels in Denmark may create competition for limited domestic agriculture residues. Production of advanced biofuels from wood-based biomass remains at the pilot scale worldwide. If commercialization of woody-based biofuels were to occur in Denmark, the country would continue to rely on imports for biomass supply, increasing the feedstock cost and decreasing the GHG emissions reduction. This predicament has driven major biofuel producing companies based in Denmark to set their sights on other more favourable countries to build commercial scale facilities such as the U.S. and Brazil.

3.2.3.4.2 Policies affecting cost competitiveness of biofuels and bioenergy

As a member of the European Union, Denmark is subject to both EU Commission and national energy and climate policies that have an influence on the cost competitiveness of biofuels and bioenergy, thus directing biomass allocation. For the purpose of this thesis Danish national policies alone are considered as they either contradicted or exceeded EU policy and can be considered a more dominating force than EU sanctioned policies. Danish national policies include: complex combinations of renewable energy mandates, carbon, energy, sulfur and environment taxes and tax exemptions (IEA, 2013b). Deciphering exactly how these policies affect the cost competitiveness of biomass-based energy technologies is essential to understanding the complete picture of drivers for biomass allocation decisions in Denmark.

As reviewed in section 3.3.2, co-combustion of straw with coal began in the 1980's in response to concerns of climate change and policies that aimed to reduce emissions related to the open burning of straw. In 1990 the Heating Supply Law passed by Danish parliament further supported biomass-based energy generation by providing the Minister for Energy with the regulatory authority to dictate fuel choices for DH and CHP facilities. The policy increased integration of biomass (particularly straw) co-firing with coal in large-scale heating facilities, and total conversion to biomass combustion facilities for smaller district heating plants (Skott, 2011).

The Biomass Agreement ratification in 1993 strengthened government policy support of bioenergy. It was the first policy agreement on biomass and marked the start of large-scale use of bioenergy in Denmark by mandating 1.2 million tons of straw and 0.2

million tons of wood to be combusted annually by 2000 (Schwarz et al. 2012). However, a disconnect occurred between mandates and the actual implementation and consumption of biomass. Despite the government's mandates for straw and wood combustion, in early 2000 only half of the planned volumes of biomass were being consumed (Meyer & Koefoed, 2003). Following this realization, the Biomass Agreement was amended in 2000, extending the target year to 2005. Changes also included increased support for wood chip combustion by building new CHP facilities engineered specifically for burning wood (Schwarz et al. 2012). Expanding support for woody biomass was a result of a major storm that destroyed large areas of forest, creating another waste feedstock in need of use (Meyer & Koefoed, 2003; Schwarz et al. 2012).

In the same year as the ratification of the original Biomass Agreement, Danish parliament implemented a carbon tax originally valued at DKK 50/tonne CO2 (present value). The tax has risen steadily, and has been marked at DKK 150/tonnes CO2 since 2008 (approximately 26 USD/tonne present value) (IEA, 2013b). The carbon tax was an important driver for the use of biomass in electricity generation as electricity generated from biomass was exempt from the carbon tax, increasing its cost competitiveness when compared to oil, coal or natural gas. In 1996, the addition of a sulfur tax in Denmark further encouraged a transition from sulfur-rich fuels such as coal, and natural gas to low-sulfur fuels like biomass (IEA, 2013b). Until it expired in 2000, the sulfur tax, in combination with the carbon tax, made fossil fuel energy sources (particularly coal due to its high carbon and sulfur emissions) expensive relative to alternatives. The presence of a tax exemption for biomass made the fuel source attractive for energy producers when compared to fossil fuel alternatives, especially when combined with the government mandates for biomass combustion in DH and CHP. In addition to the carbon and sulfur tax, all energy products are subject to an energy tax (IEA, 2013b). In Denmark this tax is restricted predominantly to fossil fuels for heating purposes and electricity consumption in households and the service sector (IEA, 2013b). These measures provide a significant incentive to both consumers and producers. Energy producers are motivated to use renewable, tax exempt, energy sources for heating, such as biomass. Consumers are driven to purchase electricity from renewable sources, and reduce their energy consumption to avoid high electricity prices (IEA, 2013b).

These policies, when combined with the previously mentioned technological limitations, energy security and climate change drivers effectively directed biomass allocation towards bioenergy generation. Equivalent incentives for transportation biofuel generation were absent in Denmark until the mid-2000s, leaving bioenergy open as the most suitable option for biomass allocation.

In 2003, the European Commission issued the Biofuels Directive to promote biofuels in transportation by introducing blending targets of 2.0% and 5.75% by 2005 and 2010 respectively (Hveplund, 2011). In opposition to the Commission's mandates, the Danish Government had set no targets for biofuels based on the assessment that bioethanol blending was not a cost-effective method of GHG reduction (Hedegaard et al 2008; Hveplund, 2011). It wasn't until 2005 that the Danish Energy Agency put forward a motion to develop liquid biofuels. Transportation biofuel consumption was promoted by exemption from energy and carbon taxes, although no blend mandates were instituted. The corresponding introduction of bioethanol by way of blending with gasoline lead to the consumption of bioethanol from 2006, as observed in figure 14, however all bioethanol consumed in Denmark remains imported.

In 2006 the EU Commission expanded their mandates for renewable fuels in transportation, requiring 5.75% and 10% by 2010 and 2020 respectively (Teknologirådet, 2006). The Danish government did not immediately adopt these mandates as it took until 2009 for Denmark to agree to the EU scheduled mandates (Danish Government, 2011). Agreement came following the passage of the EU Commission's Renewable Energy Directive (RED) as it changed their definition of renewables for transportation, opening it up from biofuels specific to one accepting any renewable energy technology (Directive 2009/28/EC). Despite the passage of RED, expanding renewable transportation beyond biofuels, Danish development of biofuels continued to grow. In lieu of the 2009 RED, the Danish government announced it would keep its 10% biofuels mandate for 2020, choosing not to open the mandate up to include other transportation alternatives until 2020. Blending targets have been slowly introduced so that biofuels account for 0.75% in 2010, 3.3% in 2011 and 5.75% in 2012 and a target of 10% by 2020 (Danish Government, 2011). Unlike the US, it is unclear how these mandates are monitored and whether the Danish government has punitive measures for non-compliance. Without clear policy incentives (or disincentives for compliance failure) it is difficult to see how biomass allocation to biofuels will increase in Denmark. The Danish government has continually failed to meet the outlined government mandates for biofuels. Government mandates such as the U.S. RFS typically operate on the premise that the failure to comply is more costly than compliance, thus driving biofuels production regardless of their cost-competitiveness. In 2011, the government announced an expansion in renewable energy mandates in the Energy Strategy 2050, outlining that Denmark will de-carbonize transportation by 2050. Although, biofuels appear to remain the predominant focus until 2020, at which point the government suggests electric vehicles will become more significant after this date (Danish Government, 2011). However, similar to RED, the latest policies fail to outline any punitive measures for non-compliance. Despite the ambitious mandates, biofuels represented only 0.3% of the Danish transportation fuel mix in 2012 and it is unclear how and if the mandates will be achieved (IEA, 2013b).

3.2.4 Danish conclusions

Renewable energy accounts for 22% of the Danish energy mix, with bioenergy constituting the largest source. Domestic biomass supply is mainly restricted to straw, wood chips and firewood while significant proportions wood pellets and biofuels are imported. Currently, nearly all of the biomass is used to produce bioenergy as it accounted for 70% of total renewable energy in 2011. Thus competition for biomass for use as a biofuel feedstock does not and will not likely occur.

The main drivers behind bioenergy development began as climate change and emissions concerns in the 1980s. In response to this concern, support schemes and policies supporting bioenergy generation expanded, and as a result bioenergy's contribution to total energy grew.

Although targets for biofuels were introduced in Denmark in 2006, the country continues to import nearly all of its biofuels. Although major Danish companies such as Novozymes are involved in the research to commercialize and improve advanced biofuels derived from agriculture residues and wood, domestic production is very limited. If advanced biofuels are ever produced in significant volumes they will likely have to compete for biomass feedstocks with existing bioenergy. Domestic production of oil and gas means energy security is not pushing biomass to be allocated towards transportation fuels. As climate change mitigation is an important driver this reinforces the allocation of biomass to bioenergy based on the premise that greater GHG emissions can be avoided by directing biomass to bioenergy rather than biofuels.

The Danish biofuel policy is structured in such a manner that renders it rather ineffective. National mandates for biofuel consumption lack punitive measures for non-compliance and have been largely unsuccessful at improving the penetration of biofuels, only 0.3% of total transportation fuel demand despite 5.75% mandate. To meet their mandate of emissions free transportation by 2050, the Danish government has strong targets for penetration and promotion of electric vehicles that seem to dominate their renewable transportation portfolio beyond 2020.

Based on this analysis, biomass allocation in Denmark will continue to favour bioenergy rather than seeing it used as a feedstock to produce transportation biofuels.

3.3 Sweden

Sweden is a global leader in renewable energy technologies as nearly half of the country's energy mix is derived from renewable energy sources. Biomass is the most important source of renewable energy in Sweden, accounting for ~34% of the country's total energy consumption (in 2013), the highest proportion of any OECD country. Similar to Denmark, bioenergy is the predominant use of biomass, accounting for 33% of Sweden's final energy mix (0.46 EJ in 2013) (SVEBIO, 2013). The strong forest sector and prevalence of DH and CHP infrastructure in Sweden have influenced the rapid development of bioenergy.

It should also be noted that Sweden has been one of the most successful European countries in promoting the use of renewable transportation fuels. Biofuels accounted for 9.8% of total transportation energy demand in 2013 (SEA, 2014). Although bioethanol and biodiesel dominate the renewable fuels market, Sweden was the first country where biogas is commercially available for transport applications. Agriculture residues remain the principle biofuel feedstocks, but the prominence of the Swedish forest sector means the country is a leader in research and development of technologies to transform forest biomass into transportation fuels. Forest derived biofuels have been on the market since 2011, and have an annual capacity of 1 million liters (Holmgren, 2012).

The goals of this exploratory research remain the same as those covered in the previous section. To better understand why biomass is the largest source of renewable energy, how the resource is being consumed, the status of biomass use in Sweden and what factors influence the allocation of biomass to bioenergy or biofuels. Although Sweden is a major biomass producer, because it uses a lot of biomass, demand surpasses domestic supply. Thus, unlike the US, and Brazil, but just like Denmark, Sweden is reliant on imported biomass to meet demand, especially for biofuels (SEA, 2013).

3.3.1 The Swedish energy mix

Sweden is known for their successful integration of renewable energy technologies in their energy mix. Renewables accounted for 49% of total energy demand in 2013, the highest proportion in the developed world. Biomass is the largest single energy source in Sweden, surpassing even oil (34% of TEC or 468.7 PJ), and a unique feature among the countries examined (SVEBIO, 2013). The emergence of biomass for energy, leading feedstocks and the conversion technologies used are discussed in detail in section 3c.2.

The absence of appreciable domestic fossil fuel resources in Sweden means the country relies on imports for most of it oil supply. During the 1970s, oil accounted for 77% of the country's energy mix and, as in the other countries examined, Sweden reacted to the 1973 OPEC oil crisis by seeking to reduce oil dependence. However, unlike the other profiles, Sweden has continued to steadily reduce its reliance on fossil fuels since the crisis. Today, as well as biomass, Sweden uses hydropower (198.7 PJ or 14%), nuclear (208 PJ or 15%) and oil (369PJ or 26%) for most of their energy demand (figure 15). Together, all of the fossil fuels that are used including coal, oil and natural gas, only account for 34% of Sweden's final energy mix. This is the lowest of any IEA member country, and significantly lower than the IEA average of 81% (IEA, 2013e).

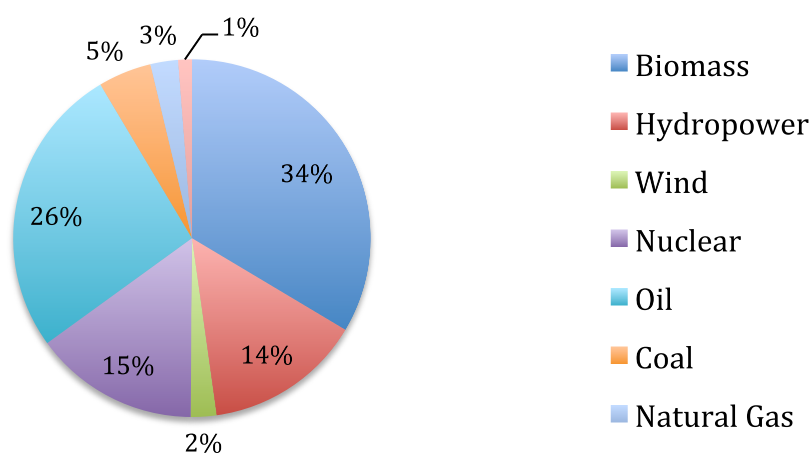

Figure 15: Final domestic energy consumption in Sweden in 2013 (adapted from SVEBIO, 2013).

Nuclear power has been a hotly debated topic in Sweden since the post WWII era when the country began to exploit its uranium reserves, which are some of the largest in Europe (Hultman et al 2012). The first reactor came online in 1971, with 10 more constructed over the following decade (SEA, 2012; Hultman et al. 2012). By the late 1970s however a strong public voice against nuclear emerged, effectively curbing further Swedish development. Government officials called for a total phase out of nuclear by 2010, although little action was instituted as nuclear was responsible for nearly 50% of electricity generation in the 1980s. Finally a moratorium on nuclear capacity expansion was passed and two reactors were closed. However, nuclear power remained a significant proportion of Sweden's energy mix (Hultman et al. 2012; SVEBIO, 2013). In 2010 the moratorium on construction was lifted and in 2011 nuclear power generated over 40% of Sweden's electricity supply (IEA, 2013b).

3.3.1.1 Renewable energy in Sweden

Sweden's renewable energy mix is comprised primarily of biomass (65%) and hydroelectricity (27%) while wind (4.5%) and heat pumps in district heating (3.5%) account for the remainder (SEA, 2013). As stated above, renewable energy investment in Sweden arose predominantly from energy security concerns during the 1970s. Since then reducing oil dependence became a cornerstone of the country's energy policy agenda and has remained such since (Ericsson et al. 2004; SEA, 2013). In the years following the oil crisis, hydroelectricity capacity expanded rapidly and generation nearly doubled between 1970 and 1985 (0.14EJ to 0.26EJ) (SEA, 2013). By this point, Sweden had almost fully exploited their hydropower capacity and it has remained relatively stable over the last two decades. However, generation has fluctuated due to annual hydro-flow variation. At this point the Swedish government realized additional energy alternatives must be considered (Hultman et al. 2012; SEA, 2013).

A research program was launched in 1975 with the ultimate goal of finding durable, domestic energy sources to replace imported fossil fuels (Haegermark, 2001). The program identified both nuclear power and biomass as the two strongest candidates for increasing oil independence in Sweden. At the time, skepticism surrounding nuclear power, and a pending moratorium on reactor construction put additional focus on biomass for energy generation (Haegermark, 2001; Bjorheden, 2006).

Figure 16 outlines renewable energy development by source in Sweden from 1990 to 2011, the date was obtained from the Swedish Energy Agency (2013). Their reporting methods for renewable sources differ slightly from the other organizations employed in this thesis, hence the different categorization. Despite the different categories, it is clear from figure 16 that biomass is the largest source of renewable energy in Sweden, and has experienced the fastest growth in the past two decades.

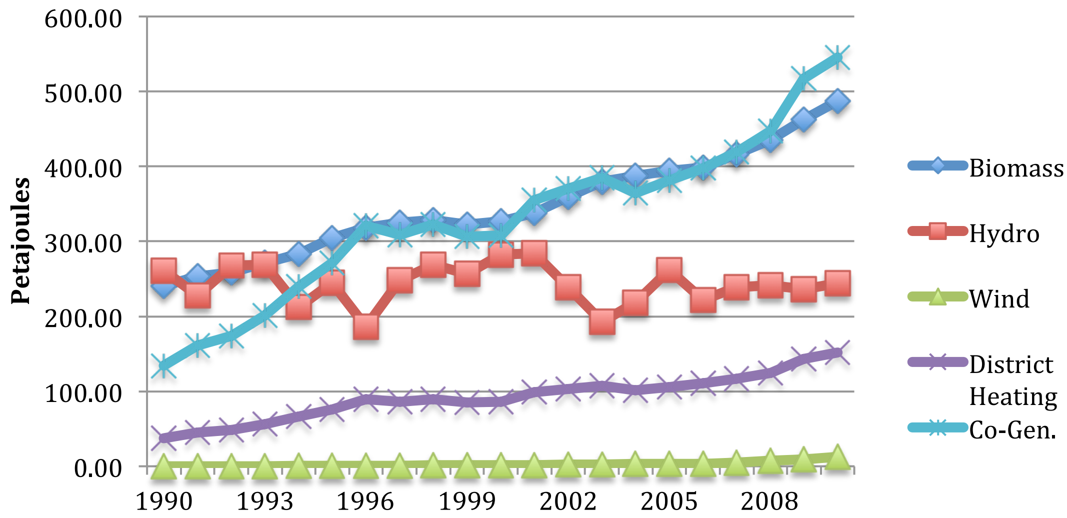

Figure 16: Renewable energy development by source in Sweden from 1990-2011 (original figure, data source Swedish Energy Agency, 2012). Hydropower and wind were not reported separately until 1996.

3.3.2 Swedish biomass

In Sweden, biomass is the predominant energy source, accounting for ~34% of total energy demand in 2013 (SVEBIO, 2013). Forest-derived biomass is the principle biomass feedstock although peat, cereal grains, municipal solid waste and rapeseed oil are widely employed for biomass-based energy products. How these feedstocks are allocated to biofuel or bioenergy generation is explored in further detail in each of the subsequent sections.

3.3.2.1 Biomass for heat and power

Combustion of biomass for heat and power generation accounts for the bulk of biomass based energy consumed in Sweden. Forest biomass, including black liquor, supplies upwards of 90% of the bioenergy feedstock, while peat and agriculture residues make up the balance (Ericsson et al. 2004). Similar to Denmark, bioenergy generation is integrated within industrial operations, in stand-alone heat, power or CHP facilities and in residential stoves and boilers.

District heating systems have been enormously influential in the advancement of bioenergy in Sweden, providing 93% and 83% of heating services in apartment buildings and commercial spaces respectively (SEA, 2013). In 2010 biomass contributed ~0.17 EJ to district heating production, compared to only ~0.03 EJ for electricity production. Unlike Denmark, Sweden's production of electricity from CHP has been underutilized, primarily because of competing, low-cost alternatives such as nuclear and hydropower (SEA, 2013). In 2003 the Swedish government introduced Green Electricity Certificates (GEC) to support the production of renewable energy (Westholm and Lindahl, 2012). The implementation of GEC has helped to spur a transition from district heating to CHP as only electricity qualifies for GECs. By 2015 installed CHP capacity in Sweden is expected to reach 1250 MWe, or ~15% of electricity generation (Salomón et al. 2011). The role of GECs as a driver for biomass allocation will be discussed in further detail in a later section of this exploratory research.

Despite prominence of Swedish forest bioenergy in residential and commercial applications, biomass combustion in industrial facilities generates the majority, 50%, of the country's bioenergy. In 2011, approximately 42% (~0.22 EJ) of total industrial energy demand originated from biomass including black liquor (0.14 EJ), other pulp residues (~0.04 EJ) and sawmill residues (~0.01 EJ) (SEA, 2013). The pulp and paper sector accounts for 90% of industrial bioenergy (~0.18 EJ excluding biomass based electricity from the grid) (SEA, 2013). These trends are easily observed in figure 17 that displays bioenergy generation by source within industry from 1990-2010.

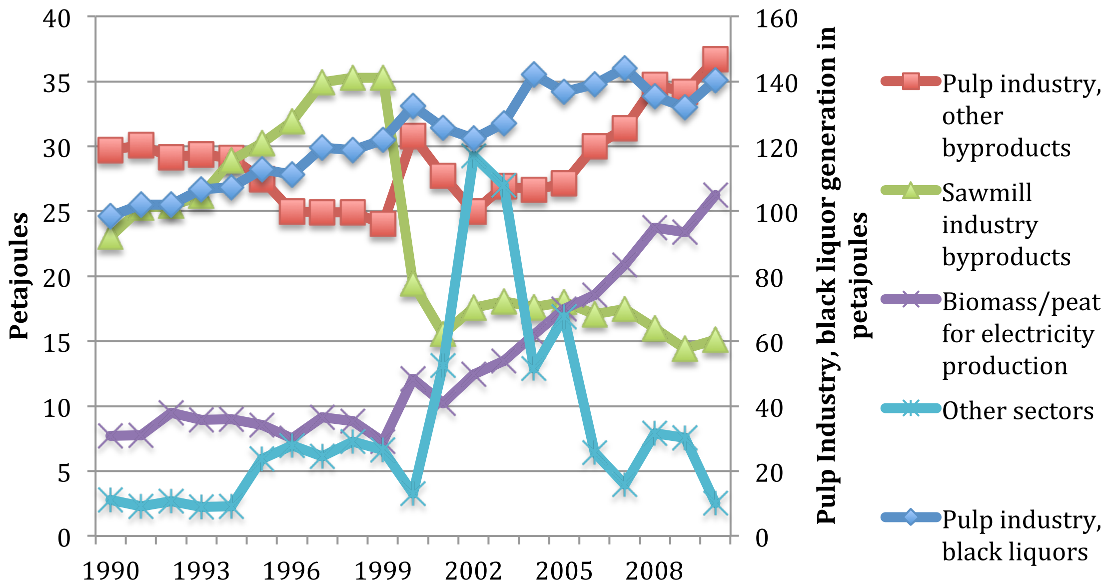

Figure 17: Industrial bioenergy generation in Sweden by source in PJ from 1990-2010 (original figure, data source SEA, 2013). The secondary y-axis on the right represents the energy generation by black liquor in pulp industry only.

3.3.2.2 Transportation biofuels

Sweden has one of the highest proportions of biofuels in their transportation energy mix of any country in Europe, 9.7% of total transportation fuel demand in 2013 (SEA, 2014). The Swedish biofuel market is dominated by bioethanol, biodiesel and biogas, 2011 consumption volumes of which were 8.9 PJ, 11.3 PJ and 2.6 PJ respectively (SEA, 2013). Figure 18 illustrates consumption volumes of these three transportation biofuels in Sweden since 2000. Since 2007 the use of bioethanol has stagnated while consumption of biogas and biodiesel have increased rapidly. Biodiesel is now the predominant transportation biofuel in Sweden, accounting for 49% of biobased motor fuels consumed in 2011 (SEA, 2013).

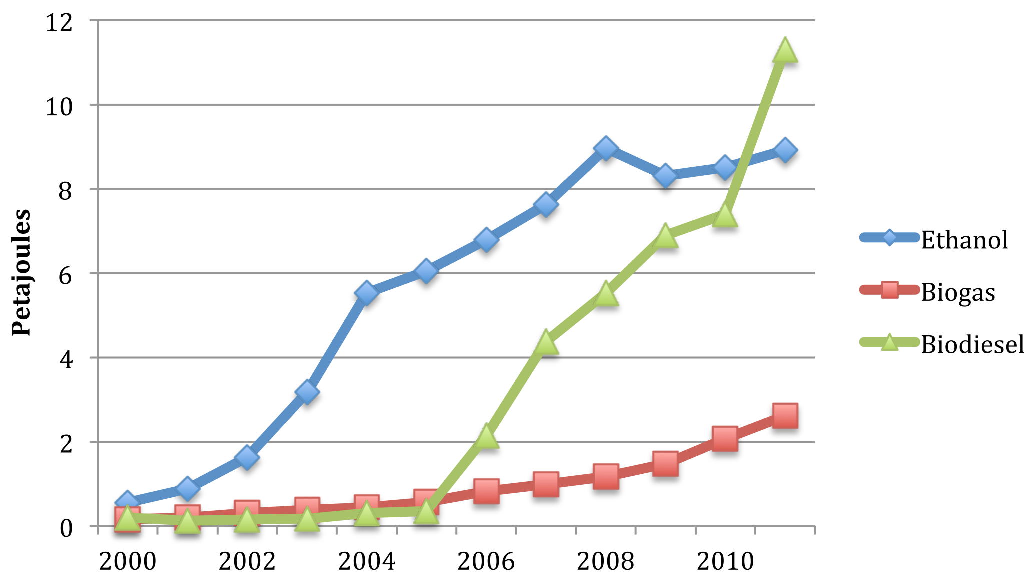

Figure 18: Consumption of transportation biofuels in Sweden from 2000-2011 (original figure, data source SEA, 2013).

Ethanol was the first biofuel to make a significant contribution to the Swedish transportation mix. Bioethanol is consumed blended with gasoline in either a low (5% ethanol, 95% gasoline) or high (85% ethanol, 15% gasoline or E85) blend. Half of total consumed ethanol volume is consumed as E85 while the other half is consumed as a 5% blend (SEA, 2013; Holmgren, 2012). Historically, the majority of bioethanol in Sweden has been imported (nearly 90% in 2009), predominantly from Brazil. However, more recently bioethanol imports have declined as domestic production has increased, although some Swedish producers rely on imported raw bioethanol feedstocks (SEA, 2012). Two major facilities produce bioethanol in Sweden; Agrotanol's 210 ML/yr cereal grain facility and SEKAB's pilot lignocellulosic facility producing 11 ML/yr (Holmgren, 2012). Currently, bioethanol that is imported typically originates from other EU states as opposed to Brazil (Holmgren, 2012; SEA, 2012).

Biodiesel in Sweden is comprised of both fatty acid methyl esters (FAME) and hydrogenated vegetable oil (HVO). FAME is the predominant biodiesel and 5% blends account for 80% of biodiesel consumed within Sweden. Unlike FAME, HVO can be blended up to 100%, a property that has helped HVO to quickly penetrate the Swedish biodiesel market. HVO was only introduced in 2011 but it accounted for 20% of biodiesel consumption that year (Holmgren, 2012). Unlike bioethanol that relies on imports to satisfy demand, 60% of biodiesel consumed in Sweden in 2011 was domestically produced; information on the origins of the feedstock is currently unavailable (SEA, 2011).

Swedish biogas is produced via anaerobic digestion of food waste, sewage sludge, manure energy crops and other organic waste in 230 units located around the country (SEA, 2011). Biogas is primarily consumed locally, often used for municipal transit fleets in regions with digester units, however upgrading is required before the biogas can be employed as a transportation fuel. Current biogas supply is often insufficient to meet demand and natural gas must be substituted. Gasification of woody biomass is being explored to increase the domestic supply of biogas. Construction of a demonstration scale facility at Göteburg was scheduled to be producing 20 MWgas via gasfication of wood pellets or chips in 2013 (Holmgren, 2012; Karatzos et al. 2014). Biogas from the facility is fed into a specialized grid used to service the local fleet of 40,000 gas-powered automobiles (Karatazos et al. 2014).

Although not yet produced at the commercial scale, biojet fuels are experiencing increasing attention and growth in Sweden as integration of biojet production within the pulp and paper industry is possible. Since 2007, Sun Pine's facility in Piteå has produced biojet using woody biomass derived tall oil, current production is 100 ML/yr (Karatzos, et al. 2014). In June of 2014, biofuel powered flights began operation out of the Karlstad Airport on select flights, annual consumption volumes are not yet available. The airport, with their partner Statoil, has installed a permanent biojet storage facility, offering 50% bio-jet blends for sale to all aircraft departing from Karlstad by 2015 (Lane, 2014).

3.3.3 Drivers for biomass allocation in Sweden

Forest derived biomass feedstocks supply nearly all of Sweden's biomass based energy demand. The use of woody biomass for both bioenergy and transportation biofuel production is increasing within the country as domestic production of forest-based biogas, biodiesel and biojet are on the rise (Holmgren, et al. 2012; Karatzos et al. 2014). This scenario positions Sweden as an ideal candidate for biomass competition. However, despite these increases, competition for biomass between bioenergy and biofuels is largely absent, as advanced biofuel production is not yet at commercial scale and current biofuels are largely imported. Imports are also relied upon to satisfy demand of bioenergy demand (SEA, 2013). The following sections assess the importance of individual drivers in biomass allocation decisions in Sweden in an attempt to discern why biomass is largely directed to bioenergy rather than biofuels.

3.3.3.1 Energy security and the emergence of biomass-based energy

Swedish development of modern renewable energy was initially sparked in response to the energy security threats posed by the 1973 OPEC oil crisis. Imported fossil fuels constituted 77% of Swedish energy demand prior to the crisis, leaving the country susceptible to shortages in energy supply (Ericsson et al. 2004). Although two technological pathways emerged to aid Sweden in improving domestic energy sources, nuclear and biomass, biomass was considered favorable due to emerging anti-nuclear sediments within the country.

Research to develop domestic energy sources was launched in 1975 and became the second largest program in Sweden with the main aim to develop durable domestic energy sources (Bjorheden, 2006). In the 1980s and 90s, despite a fall in oil prices and consequently declining salience of energy security concerns, bioenergy continued to experience strong growth in Sweden. Persistent growth of bioenergy in Sweden, despite declining salience of energy security, suggests this driver alone is insufficient to fully explain expanding bioenergy generation.

3.3.3.1 Energy related climate change concerns and biomass allocation

Concerns of energy related carbon emissions and their negative impact on the climate gained salience in the late 1970s in Sweden (Bjorheden, 2006; Hultman et al. 2012). Local environmental initiatives in Växjö resulted in the region’s district heating system transitioning to wood from oil (SEA, 2003). The ease with which this transition could be performed resulted in a widespread move to wood fuels for most of Sweden’s district heating infrastructure. During the early years of the environmental movement in Sweden, biomass experienced favourable allocation to bioenergy, mainly because combustion was a suitable and affordable method of recovering the energy of the available forest feedstock and commercial technologies were unavailable for converting woody biomass to liquid biofuels. As a result, bioenergy was the focus of Swedish biomass-based energy development into the early 2000s, at which point liquid biofuels began to emerge within Sweden (SEA, 2003; SEA, 2011; Hultman et al. 2012).

In 1999, Sweden's energy mix was 38% renewable, however these energy alternatives were restricted to providing green heat and power as renewable fuels had yet to penetrate into the transportation market in the country. Significant transitions had occurred since the 1970s in Sweden to improve energy efficiency in an attempt to curb consumption in stationary energy, while energy consumption in transportation had experienced rapid expansion. From 1970 to 1999, total energy use in transportation grew by nearly 50% from~ 0.25 EJ to ~0.38 EJ (SEA, 2013), all of which was fossil fuel based. This heavy reliance on fossil fuels, and the related poor emissions profile meant transportation emissions became a target for climate change mitigation. Despite their lower GHG emissions reduction potential when compared to bioenergy, biofuels were seen as the most suitable alternative to petroleum fuels and capable of helping Sweden achieve desired emissions reductions within the transportation sector (Silveria, 2005; IEA, 2008; IEA, 2013c).

In 2000, biofuels were introduced in the Swedish transportation sector, although these biofuels were derived from predominantly non-forest feedstocks and thus did not compete with bioenergy for woody biomass (Holmgren, 2012; SEA, 2012). Historically, the large reliance on imported biofuels in Sweden (90% of all biofuels in 2009) meant little competition occurred for the domestic feedstock during early biofuels use. Since 2004, cellulosic ethanol from lignocellulosic material (mostly pulp and paper residues) have been produced in Sweden at the SEKAB's Örnsköldsvik pilot facility while biogas from forest residues has been manufactured in Götenborg at demonstration scale since 2013 (Holmgren, 2012; Karatzos et al. 2014). Production of these cellulosic biofuels in Sweden creates the potential for competition between bioenergy and biofuels for forest feedstocks but decisions for forest biomass allocation to either biofuels or bioenergy since the production of cellulosic biofuels began in the country is subject to more than energy security and climate change concerns.

3.3.3.2 Prevailing economic interests

Forest biomass is the largest single energy feedstock in Sweden, which means the forest sector has a vested interest in decisions regarding biomass allocation to bioenergy and biofuels. The influences of the forest sector in the development of the bioenergy, and later the biofuel sector is imperative to understanding Swedish biomass allocation decisions.

In 1974 the Swedish forest sector was anticipating a shortage of pulpwood and launched a research program aimed at increasing the utilization of small diameter wood and stumps to cope with the impending shortage (Swedish Royal College of Forestry, 1977).

When research interest in bioenergy began in 1975, focus of the Whole Tree Utilization Program shifted to include how bioenergy could be integrated within the forest sector. The early years of bioenergy development in Sweden were very calculated due to the fears of an impending fibre shortage. This concern, combined with the low value of wood fuels, was sufficient to prevent specific harvesting of trees for energy or the widespread utilization of forest harvest residues for energy generation. Alternatively, process residues from sawmills and pulping facilities were the focus of forest and wood energy development research (Ericsson et al. 2004).

Forest ownership in Sweden is comprised predominantly of small private forest owners, who own half of the forests in Sweden, while large forest companies, the state and public organizations own the remaining half (Swedish Wood, 2012). The high proportion of private owners has been a key feature of success for bioenergy and biofuel generation in Sweden, as private owners react differently to drivers than large forest companies. The importance of private forest owners becomes apparent later in this exploratory research when discussing the restructuring or the Swedish energy market and the influence of government policies supporting bioenergy and biofuel production.

Sweden's decentralized system of government means local authorities have significant autonomy in taxations powers and work closely with local businesses to ensure their policies help foster strong economic performance of companies in their jurisdiction (Ericcson et al. 2004; Hultman et al. 2012). Municipalities realized, by teaming up with local forest industries and owners to improve the penetration of bioenergy and biofuels from local feedstocks they would induce job creation and increase revenue in the region. Strategic cooperatives formed between energy service providers, forest sector associations, city planners and the transportation sector facilitating easy transfer of knowledge between groups thus improving the ability for bioenergy and biofuels to enter the energy market (Hultman et al. 2012; Westholm and Lindahl, 2012).

3.3.3.3 Cost competitiveness of Swedish bioenergy and biofuels

This section examines how technologies and policies for bioenergy/biofuels influence cost competitiveness and ultimately biomass allocation decisions in Sweden. I suggest policies (predominantly taxes), increase the costs of traditional, fossil-based, energy technologies, and thus influence biomass allocation decisions. The presence of district heating infrastructure and a strong national forest industry causes competition for biomass between these two energy applications. However, the innovative capacity of the Swedish forest sector has contributed to technological developments for biomass-based energy production and efficiency gains.

3.3.3.3.1 Technological advancements in biomass-based energy

In Sweden, during the 1970s when the notion of using biomass for energy emerged, forest feedstocks were identified the most suitable and readily available feedstock. District heating infrastructure existed in Sweden, but at the time of the oil crisis, these facilities relied predominantly on fossil fuels. Between 1975 and 1980 over 600 large-scale heating systems were converted to biomass feedstocks as the spike in oil prices made combustion of biomass for heat economically attractive. From 1980 to 2008 heating and cooling in Sweden shifted from a system based on 90% fossil fuels to one based 50% on biomass and only 10% on fossil fuels, the remaining 40% of heat demand is supplied by garbage, peat and recycled heat from industrial processes (SEA, 2012). During this time period, conversion of woody biomass to transportation biofuels was not cost competitive with fossil fuels and thus biomass was allocated to combustion for heat, and power generation (SEA, 2012).

As mentioned in section 5.2.2, industrial applications account for 50% of Sweden's modern bioenergy production, concentrated predominantly within the pulp and paper sector (90% of industrial bioenergy generation). Energy recovery technologies were introduced in the late 1930s to early 1940s with the industrial acceptance of the Kraft pulp cooking process (Sixta, 2006). Inclusion of energy recovery systems as an integral step of chemical pulping has made heat and power generated in this manner highly cost competitive with fossil fuels.

An important factor of the cost competitiveness of the bioenergy generated by pulp and paper facilities is the fact that the biomass feedstock is considered waste and has historically had limited value. However traditional applications of forest residues and pulp waste are changing. Energy recovery technologies in chemical pulping have remained relatively unchanged since their original conception and provide a unique opportunity for innovation to create new higher value products, chemicals and biofuels from the waste fractions of forestry operations, a concept known as the biorefinery (Sixta, 2006). As the number of high-value products generated from pulp waste streams increases, biomass available for bioenergy generation may decline as more biomass is directed to these higher valued products.

Although conversion technologies were commercially available to convert sugar, starch and oil rich crops to transportation grade fuels during the 1970s, transformation of lignocellulosic biomass to liquid fuels was not possible. In Sweden this effectively limited biomass allocation to bioenergy generation until the 2004 when SEKAB's Örnsköldsvik demonstration facility began cellulosic ethanol production, yet the feedstock demands of a demonstration scale facility will hardly make an impact on the volumes of wood directed to bioenergy. Since the opening of this facility, several other breakthroughs have made conversion of woody biomass to liquid and gaseous transportation fuels possible from a variety of technologies, as covered in section 1.2.1. Recall crude tall oil is produced from pulping black liquor, and subsequently hydrogenated into HEFA, a diesel like fuel in SunPine's facility in Piteå, producing 100ML annually since 2007 (Holmgren, 2012; Karatzos et al. 2014).

More recently, biogas production via gasification of woody biomass has occurred at the demonstration scale in Göteburg. The emergence of these conversion technologies, capable of transforming forest biomass to transportation fuels, is unlikely to sway the allocation of biomass away from bioenergy in Sweden, however it has caused a restructuring of the Swedish bioenergy and biofuel markets. Most of the new facilities discussed rely on the integration of biofuel and biogas production within the pulp and paper sector, and greater incorporation is anticipated as these technologies reach commercialization. The quantity of biomass waste suitable for the production of these biofuels is comparatively small when considering the volumes of biomass combusted for bioenergy generation, for example tall oil is ~2% of wood feedstocks, effectively limiting the allocation of biomass to biofuel production (Karatzos et al. 2014).

3.3.3.3.2 Policies affecting cost competitiveness of biofuels and bioenergy

Sweden, as an EU member state, is bound by European legislated climate and renewable energy mandates, the country's commitments under the Kyoto Protocol and domestic government policies. Swedish government targets are the focus of this section as in most profiles nationally mandated requirements exceed those of the European Commission, as outlined in the Swedish Renewable Energy Action Plan (2010). How these policies improve the cost competitiveness of bioenergy and biofuels is crucial to understanding biomass allocation decisions in Sweden.

In 1991, a multi-party agreement was reached, embracing sustainable development as the keystone feature of Swedish energy policy. That same year a general carbon tax was applied at a rate of $35 US/t CO_2 and it has been incrementally increased since, reaching

~$148 US/t CO_2 for households and services and ~44 US/t CO_2 for industry (Ministry of the Environment Sweden, 2011). In addition to the carbon tax, Sweden also has an energy tax levied on fuels based on their energy content. The carbon and energy taxes are applied to all energy generated and transportation fuels, making fossil fuels more expensive relative to bioenergy and biofuels.

Within transportation, the Swedish government has a mandate that transportation will be independent of fossil fuel by 2030 (IEA, 2013b). In an effort to meet this mandate, tax exemptions exist for biofuels, where by the energy and carbon taxes are not applied to bioethanol, biogas and biodiesel (SEA, 2013). Energy tax exemptions also exist for natural gas employed as a transportation fuel, however a carbon tax is still applicable (IEA, 2013c). In a 2011 report the Swedish National Audit Office praised the importance of the tax exemptions in the development of a biofuels market in Sweden, as there are currently no blending obligations currently in place. However the audit found the tax exemption is an expensive way to reduce GHG emissions relative to other policy options (SNAO, 2011; IEA, 2013c). In 2014 the government has been considering the introduction of a quota-based system for low-blend fuels requiring a 10% ethanol blend in gasoline and 7% FAME blend in diesel. In conjunction an energy tax would be introduced on low-blends but the energy and carbon tax exemptions will remain for high-blend fuels such as E85 (Holmgren, 2012; IEA, 2013c). This policy would increase the pump price of fuels and it is difficult to discern if it would lead to an increase or decrease in biofuel demand, as consumption of biofuels in a quota-based system is a factor of total transportation fuel demand.

Introduced in 2003, the Green Certificate Market (GCM) promotes production of renewable electricity in a cost-effective manner and in 2012 the market was expanded to include Norway. Electricity suppliers must purchase green certificates based on electricity sales and use from the previous year. Producers of renewable electricity receive certificates for every MWh of electricity they produce, by selling their certificates (currently valued around $30US/MWh) to electricity suppliers the producer gains additional revenue beyond the sale of electricity (IEA, 2013b). The GCM benefits only bioenergy producers generating electricity, as heat production is not covered under the GCM (IEA, 2013c).

3.3.4 Swedish conclusions

Biomass is the largest energy source in Sweden, accounting for 34% of the country's energy mix. Domestic biomass supply is largely forest based, either in the form of wood chips, firewood, pellets and mill residues while significant proportions of wood pellets and biofuels are imported. Currently, biomass is preferentially allocated to bioenergy as it accounts for ~95% of totally biomass based energy generated in Sweden in 2013. The proportion of biofuels in transportation fuels in Sweden is one of the highest rates in the EU at 9.7%. However, compared to the country's bioenergy generation this figure is fleeting, accounting for a mere 5% of total biomass based energy in 2013. Competition between bioenergy and biofuels for biomass is largely absent in the Swedish case as both bioenergy feedstocks (e.g. pellets) and biofuels are imported to meet domestic demand.

The predominant drivers in Sweden are climate and emissions concerns that, when combined with the effective policy mechanisms, such as carbon, emissions and energy taxes make bioenergy and biofuels cost-competitive with alternative energy products.

Sweden currently relies on imports for the vast majority of the country's biofuels. Despite ongoing innovation surrounding advanced biofuels in Sweden, when considering only domestic biomass and the allocation of these largely wood-based feedstocks to bioenergy or biofuels, it is unlikely that these resources will be more valuable as a feedstock for biofuels rather than bioenergy. Despite some of the highest carbon taxes in the world, cost-competitiveness of advanced biofuels remains unattainable in the near-term. Hence the continued dependence on imported biofuels.

Furthermore, the reliance of the Swedish forest sector on the industrial integration of bioenergy generation (~45% of bioenergy generation is within industrial operations) makes the transition away from these technologies very difficult. It is plausible that Swedish advanced biofuel facilities will piggyback on existing forest and pulp sector manufacturing, similar to what has been observed in U.S. and Brazilian facilities.

3.4 United States

The United States is the global leader in energy consumption, consuming 102.6 exajoules (EJ) in 2011, with fossil fuels dominating the energy mix, representing 82% of total energy consumption (TEC) (U.S. EIA, 2012a). Since the mid 2000s, the U.S. has been the largest biofuels producer in the world, dominated by bioethanol from corn, which has received significant government support for decades (Tyner, 2008). Recently, biofuels production in the U.S. has stagnated due to a myriad of factors including but not limited to: declining gasoline consumption creating a blend wall, slower than expected development of advanced biofuels, the expiration of the biodiesel tax credit in December of 2013 and uncertainty surrounding government support policies, principally the Renewable Fuel Standard (RFS).

Although it receives less attention than the U.S. biofuels program, bioenergy generation is widespread in the US. Wood is the primary source of renewable energy (21%) in the U.S. or ~2.1 EJ in 2011, although biomass waste is also combusted for energy generation producing 0.5EJ in 2011 (5% of total renewables) (U.S. EIA, 2012a). Bioenergy production is concentrated predominantly within the wood products industry, where pulping liquors and mill residues are burnt for direct heat and electricity generation. In contrast to Denmark and Sweden, the use of biomass for residential heat and power services is proportionally low, however researchers predict the use of bioenergy outside of industry will increase within the coming years (Aguilar et al. 2011; Song et al. 2012).

The situation regarding biomass allocation in the U.S. is one of the most interesting and exciting, albeit complex, in the world. Of all the profiles examined, the U.S. is the most diverse, in its: populous, major industries, powerful interest groups and political opinions. Within the US, unlike the Scandinavian profiles, domestic biomass supply far exceeds biomass demand (Perlack et al. 2011). In this U.S. case however, it will be important to consider how global demand for biomass, bioenergy and biofuels as well as the rapidly changing domestic energy industry, will influence biomass competition and resource allocation decisions.

3.4.1 The U. S. energy mix

Fossil fuels dominate the U.S. energy mix, representing 82% of total energy consumption (TEC) in 2011, as illustrated in figure 19. Importance of different fossil fuel energy sources is radically changing in America; consumption of petroleum and coal is declining while natural gas is increasing. Petroleum consumption falls as vehicle efficiencies increase and slow economic recovery is altering consumer behaviour, lowering gasoline use. Since 1990, 77% of new electricity generation capacity is natural gas fired, as opposed to the traditional coal. The recent increase in domestic unconventional oil and gas since 2009 has driven the price of natural gas down, reaching historic lows in 2012. Low gas prices, combined with the benefits of higher electricity generation efficiency in gas power plants, have prompted a transition from coal to natural gas in existing electricity generation facilities nationwide (U.S. EIA, 2013).

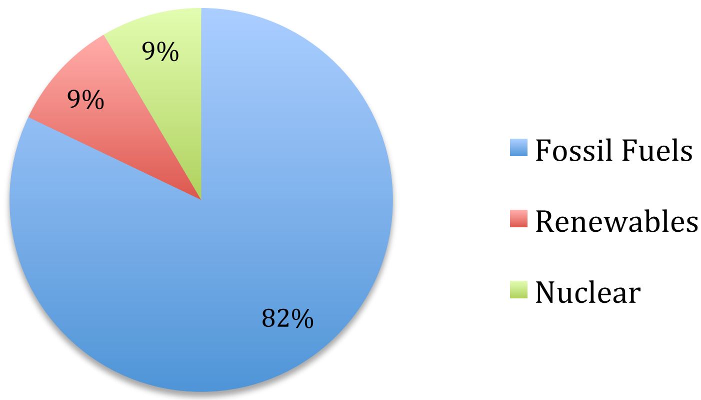

Figure 19: U.S. energy mix in 2011 (original figure, data source U.S. EIA, 2012a).

Trends in the fossil fuel energy market are important to consider within the context of biomass competition as competition between fossil fuels and alternatives is an important driver for biomass allocation, as discussed in chapter 2. Unlike Denmark and Sweden, the proportion of renewable energy in the U.S. energy mix is small, 9% of TEC (9638 PJ) and has experienced comparatively slow growth, increasing by only 2% of TEC since 1990. Understanding renewable generation technologies and their impact on the U.S. energy market is necessary as they too vie with biomass, more directly than fossil fuels, for government funding and support.

3.4.1.1 Renewable energy in the U.S.

The United States has a diverse renewable energy portfolio including: hydro, solar (PV and thermal), wind, geothermal and biomass. . In 2011, renewables generated 9638 PJ or 9% of U.S. total energy consumption (U.S. EIA, 2012a). Figure 20 provides a breakdown of the U.S. renewable energy mix by source. The diversity of technologies widely employed in the U.S. is noticeable when compared to the other countries examined in this case. The greater number of renewable energy technologies means a fight occurs between renewable sources for government policy support and funding. Despite this, biomass was the largest renewable energy source, accounting for 48% of consumed renewables or 4.5% of TEC (U.S. EIA, 2011).

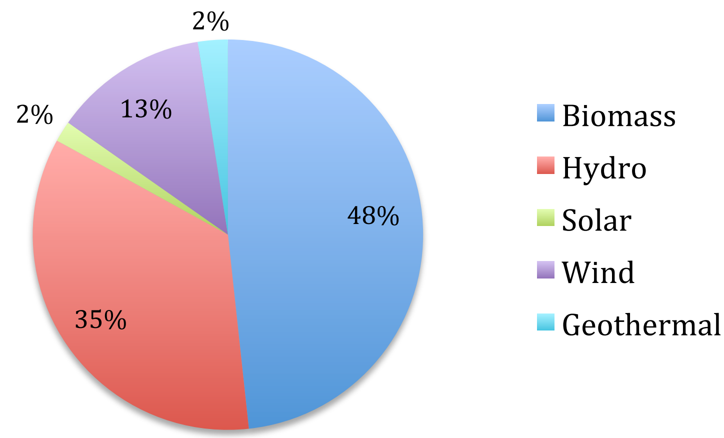

Figure 20: The proportional contribution of renewable technologies in the U.S. 2011 renewable energy mix (original figure, data source U.S. EIA, 2012a).

3.4.2 U.S. biomass

Biomass is the largest source of renewable energy in the country, accounting for 48% of total renewables or 4.5% of TEC in 2011. The U.S. Energy Information Administration (EIA) classifies biomass as wood, waste and biofuels, which includes bioethanol, biodiesel and production co-products (U.S. EIA, 2012a). Of these biomass resources, wood is most widely consumed, followed closely by biofuels. Biomass consumption by source for 2011 is summarized in table 1. The U.S. EIA does not provide as detailed a breakdown of biomass as the Danish Energy Agency, but that is not to say that the same products are not consumed. Although not reflected in the table below, there are a number of biomass feedstocks available for energy production in the US, imparting flexibility in potential biomass-based energy products.

Table 4: United States 2011 consumption of biomass sources in petajoules. Their percent contributions to total biomass consumption are included (calculations based on data source U.S. EIA, 2012a).

Biomass	Wood	Waste	Biofuels
Petajoules	2096.57	503.52	2053.93
% Biomass	45.0	10.8	44.2

3.4.2.1 Biomass for heat and power

According to the U.S. EIA, wood and biomass waste in the United States is used principally for heat and power production in residential, industrial and commercial operations and electricity production in stand alone facilities (U.S. EIA, 2012). Estimates for wood and biomass waste consumption by sector are presented in table 2. Biomass waste includes municipal solid waste, landfill gas, sludge waste, agricultural byproducts and other biomass (U.S. EIA, 2011).

Table 5: EIA estimates of 2011 U.S. wood and biomass waste consumption by sector (calculations based on data source U.S. EIA, 2012a).

	Residential	Commercial	Industrial	Electric Power
Petajoules	474.77	227.84	1554.73	460.74
% Total	18.2	4.5	59.6	17.7

As apparent from table 2, industrial operations consumed the most wood and biomass waste in 2011. Industrial utilization of biomass for energy is closely associated with wood, pulp and paper production levels (Nicholls et al. 2008). The use of wood, wood waste and black liquor available for on-site energy generation rises and falls with the levels of wood product production. At the time of writing, available data for industrial biomass energy consumption by industry and source shows that the pulp and paper manufacturing was the largest single consumer of biomass in 2009, (1039.14 PJ of total energy, 879.39 PJ thermal and 159.75 PJ electricity) (U.S. EIA, 2009). The downward trend in U.S. pulp and paper production is heavily responsible for the decline in wood based energy generation in the United States observed since 2003-2004 and seen in figure 21.

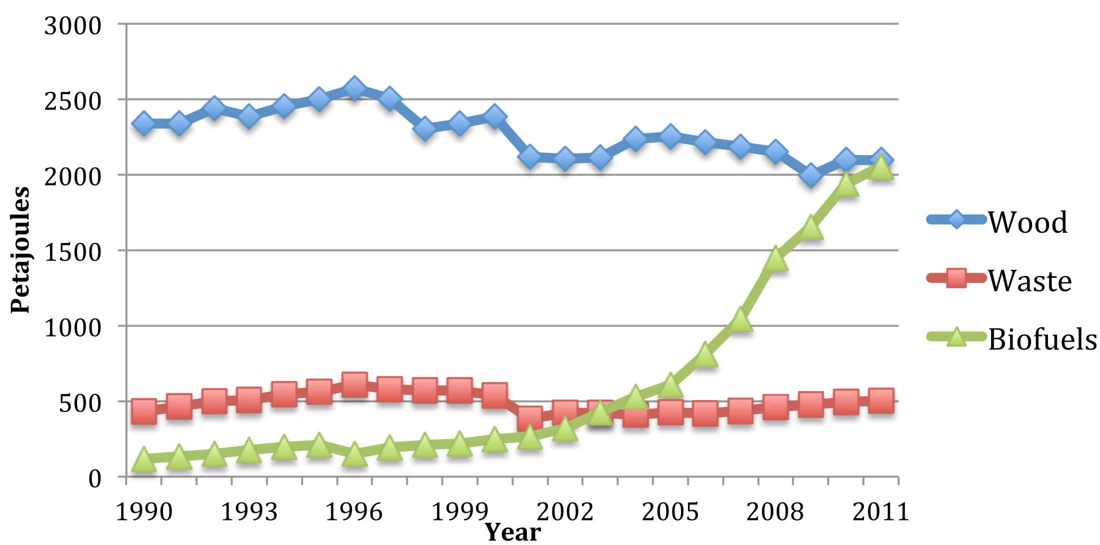

Figure 21: Biomass use in the United States between 1990-2011 (original figure, data source U.S. EIA, 2012a).

The residential sector is the 2nd largest consumer of wood for energy in the US. Combustion of wood for energy in residential settings typically occurs in traditional open fireplaces for heating applications. Residential wood-based bioenergy competes with other home heating alternatives such as natural gas, electricity and heating oil. A study performed by Aguilar and colleagues in 2011 explored the influence of alternative energy prices and public policy on wood energy consumption. They concluded that, utilization of wood in the residential sector is affected more by the price of alternative energy sources than government policies to promote bioenergy. Furthermore levels of wood combustion are positively correlated to the price of heating alternatives (Aguilar et al. 2011).

Stand-alone biomass burning for electricity generation in CHP facilities makes up a small proportion of the U.S. renewable energy mix, 4.7%, when compared to the Scandinavian countries examined in this thesis. Recall in Denmark, biomass provides 13% of total electricity generation and 23% of heating requirements. The use of these facilities in the U.S. is restricted primarily to institutional settings such as heating in hospitals and schools. Interest exists in the U.S. in capturing the efficiency advantages of employing CHP for biomass energy generation, however technology diffusion is limited by the lack of centralized heating infrastructure in the country (White, 2010). Of all electricity producing capacity in the United States in 2012 (1.13 TW) total CHP capacity was a mere 3.5% (0.39 TW) (U.S. EIA, 2013).

3.4.1.2 Transportation biofuels

The United States is the largest producer of biofuels in the world (56.16 billion liters in 2011), making predominantly conventional bioethanol from corn (52.9 billion liters), although biodiesel and cellulosic biofuels also contribute to the U.S. market. Growth in biofuels since the early 2000s is responsible for the majority of the observed increase in renewable energy generation in the US. During this period, biofuels experienced exponential growth thanks to the establishment of the Renewable Fuels Standard (RFS) in 2005 as part of the Energy Policy Act, (for more information on the RFS and biofuel classifications see section 6.3.4.b). The data in figure 22 illustrates biofuel consumption in the United States between 1990 and 2011. Notice bioethanol consumption has plateaued since 2010, the causes of which are explored in further detail below.

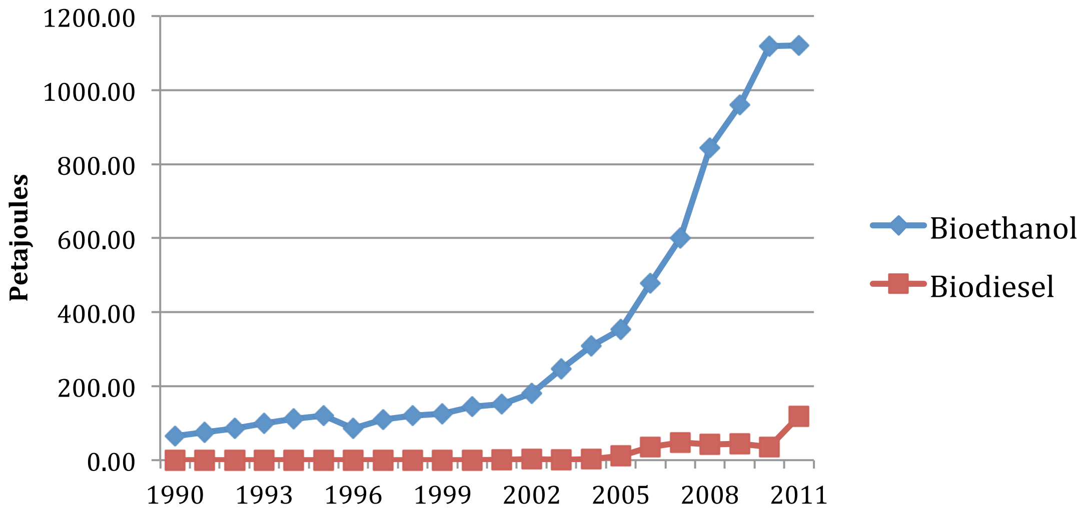

Figure 22: Consumption of biofuels in the United States from 1990-2011 (original figure, data source U.S. EIA, 2012a)

Ethanol is the original biofuel of the American industry, its production as a transportation fuel dating back to the early 20th century (Hultman et al. 2012). Bioethanol is consumed in a low (10% ethanol 90% gasoline) blend known as E10 and a high (85% ethanol 15% gasoline) blend, or E85. Bioethanol was responsible for 1.1EJ of energy, 99% of which is consumed as E10 and effectively all gasoline in the country is consumed at an E10 blend. This creates a situation where gasoline consumption is limiting ethanol consumption in America (U.S. EIA, 2012a; Tyner and Viteri, 2010). Projected gasoline consumption in an E10 market has resulted in ethanol demand that falls short of that mandated by the RFS. This results in two opposing realities, the RFS requires higher volumes of biofuels to be blended each year until 2022, while the physical blend wall may result in declining ethanol consumption as gasoline consumption falls in the US, impart due to poor economic conditions and improving fuel efficiencies (Tyner and Viteri, 2010). Assuming all ethanol continues to be consumed as E10 only, current gasoline consumption only allows for ~13 billion gallons of ethanol to be consumed, less than the RFS2 mandates for 2013-2022. The "blend wall" is why ethanol consumption has plateaued since 2010, as observed in figure 22. The "blend wall" refers to the maximum volume of ethanol that can be blended with gasoline according to currently approved blend levels. A further discussion of the effects of the blend wall on biomass allocation is discussed in section 6.3.3.

Biodiesel consumption in the U.S. began in 2001 and by 2011 amounted to ~0.12 EJ of energy. Blends of B2 (2% biodiesel, 98% petroleum diesel) B5 (5% biodiesel, 95%

petroleum diesel), B20 (20% biodiesel, 80% petroleum diesel) and B100 (100% biodiesel) are all available in America, however B20 is currently the most popular within the country (U.S. DOE, 2014). The popularity of B20 is derived from the balance of cost, emissions, cold weather performance and engine compatibility, while B100 is limited by a lack of regulatory incentives, high pricing and the requirement for special handling and equipment modifications (U.S. DOE, 2014). U.S. biodiesel is predominantly FAME, derived from vegetable oils, yellow grease, spent cooking oils and tallow although soybean oil as the leading biodiesel feedstock (U.S. EIA, 2013).

As a potential solution to the blend wall, research interest surrounding development of drop-in biofuels is expanding in the United States. Unlike Sweden where biogas is commercially available and bio-jet has been produced in demonstration facilities since 2007, drop-in biofuels are currently at the research and development stage, with some pilot and demonstration facilities under construction (U.S. DOE, 2014). Although, the U.S. has recently reported that ~18.2 million gallons of cellulosic biofuels were produced from January-October of 2014, 80% of which was generated in September and October alone. This makes it appear as though advanced biofuels are experiencing a period of growth in the United States, however this is misleading as the overnight expansion has transpired thanks to a new definition of cellulosic biofuels that includes compressed natural gas and other fuels under the cellulosic biofuel umbrella (U.S. EPA, 2014). This new definition may harm advanced biofuel development by undermining the existing mandates.

3.4.3 Drivers for biomass allocation in the U.S.

Competition between bioenergy and biofuels for biomass feedstock is unlikely to occur in near future in the United States. Differing predominant feedstocks for bioenergy and biofuel generation, combined with an ongoing underutilization of biomass resources creates a supply surplus. Therefore, at present, competition between biomass-based energy products is limited. The U.S. DOE has identified that the country holds the potential to produce greater than 1 billion tons of biomass for bioenergy or biofuel production annually by 2030 (Perlack et al. 2011). Despite a lack of current competition for biomass feedstocks, it has been suggested that competition for forest-based feedstocks between bioenergy and biofuels might occur as both domestic advanced biofuel demand, and international pellet/biofuel markets develop.

Instead of domestic competition for the end use of biomass feedstocks, it is likely that competition will occur between domestic and international markets as the U.S.

continues to grow as an important exporter of biomass-based energy products. Reallocation of bioenergy products from U.S. domestic to the international markets is also occurring. The United States is increasing production capacity of pellet mills, notably in the South East, primed for export to European markets. Pellets command a price premium in Europe compared to the United States, enough that it is economically viable to ship pellets 1000s of kilometers via boat to Europe and Scandinavia. As demand for pellets is expected to increase in Europe to meet the EU Commission mandates of 20% renewables by 2020, imports are expected to play an essential role in satisfying demand (IEA, 2013b). Increasing pellet demand in these markets may effectively out compete domestic bioenergy solutions in the absence of U.S. policies specifically promoting bioenergy generation (IEA, 2012c).

The "blend wall" is limiting the consumption of renewable fuels in America, and has sparked a growing trend in research focusing on drop-in biofuels. Interest surrounding the use of woody biomass for drop-in biofuels will certainly increase demand for suitable low-cost feedstocks. However, based on the DOE estimates, competition is unlikely to result in the reallocation of biomass from one energy product to another.

In analyzing the drivers for biomass allocation in the United States, it was apparent that both general and U.S. focused drivers influenced the allocation of biomass. The absence of strong climate change mitigation desires in the U.S. means that energy security has been the leading general driver. As with the other profiles, biomass allocation is subject to pressure from economic interests and the cost-competitiveness of biomass-based energy technologies.

3.4.3.1 Energy security and the emergence of biomass-based energy

An ethanol powered transportation fleet has been considered by the U.S. since the early 20th century, although the early movement was largely thwarted by the Prohibition-era regulations on alcohol. The first instance of energy security influencing biomass allocation in the U.S. was during the Second World War. To help reduce fuel scarcity issues ethanol production rose to 600 million gallons annually. After the war production dwindled rapidly as the world entered a period of oil abundance (Hultman et al. 2012).

It wasn't until 1978, in the shadow of the 1973 OPEC oil crisis, with the passage of the Energy Tax Act, that the ethanol industry re-emerged in the United States. Designed to bolster national energy security, through the creation of a domestic ethanol industry, the Energy Tax Act created a tax incentive for ethanol blenders equal to $0.40 per gallon effectively re-launching the ethanol industry. By 1980, 100 commercial bioethanol plants were operating in the U.S. (Hultman et al. 2012). Throughout the 1980s growth in the ethanol industry was slow, despite the persistence of government subsidies. Subsidies for ethanol production were in place from 1978 until December 31st, 2011. Over the 33 years the tax credit price ranged from $0.40 to $0.60 cents U.S. per gallon (Tyner, 2008). Originally, incentives were applied as an excise tax exemption, until the 2004 Job Creations Act when the government transitioned to the Volumetric Ethanol Excise Tax Credit (VEETC), a blender tax credit (Keeney & Hertel, 2009; Tyner, 2008). It was anticipated that altering the tax from an excise tax exemption to a blender tax credit would further encourage the creation of a transportation biofuel industry separate from the petroleum industry (Tyner, 2007; Tyner, 2008). The biodiesel tax incentive, introduced in 2004, expired with the ethanol incentive in December of 2011, but was recently revised by U.S. Congress on January 1st of 2013 to expire the end of that year. The tax incentive mechanism has been criticized due to its exorbitant costs and ineffectiveness as a stand-alone policy to promote biofuel production. In 2006 the program cost the federal government $U.S. 2.4 billion and $U.S. 5 billion in 2010 for ethanol, and almost 1.4 billion for biodiesel in 2008. In comparison, the Brazilian ethanol tax incentive program costs are estimated at less than $U.S. 1 billion per year (Koplow, 2006). The stark contrast in payouts between Brazil and the U.S. is due primarily to the introduction of volumetric blend mandates in the U.S. that persisted concurrently with the tax incentives that were originally conceived for an oil price of $U.S. 20/bbl (Tyner, 2008)

Renewable energy development in the United States arose, as it did in many of the other profiles, from energy security concerns. In the 1940s, the United States became a net energy importer, and by 1973 the country accounted for nearly one quarter of total global oil trade. Unlike Brazil, Sweden and Denmark, where the OPEC oil crisis of the 1980s was a catalyst for widespread renewable energy development, a similar paradigm shift was absent in America. The oil crisis of the 1980s did help spur growth in the use of geothermal, biofuels and waste biomass for energy, however renewables in the U.S. failed to displace fossil fuels at the same rate as they did in Scandinavia (U.S. EIA, 2012; Klass, 2003).

Subsequent decades saw steady growth in energy imports, energy consumption, and a corresponding decline in energy self-sufficiency. Figure 23 depicts U.S. energy consumption, imports and self-sufficiency from 1942-2011. Energy self-sufficiency bottomed out in 2006 but the trend line has since reversed as TEC and energy imports fell during the economic recession. Presently, the U.S. energy landscape is in a transitional period. As of 2008, domestic fossil fuel production has experienced resurgence thanks to growing accessibility of unconventional oil and gas. In addition, bolstered policies supporting electricity production from renewable sources and federal mandates for biofuels have increased domestic energy production consequently improving national energy self sufficiency. In their World Energy Outlook 2012, the International Energy Agency (IEA) projects U.S. daily oil imports will fall from 9.5 million barrels per day (mb/d) in 2011 to 3.4 mb/d in 2035, representing an improvement in energy self sufficiency of 97%, suggesting the trend line of increasing energy self-sufficiency will continue (IEA, 2012e).

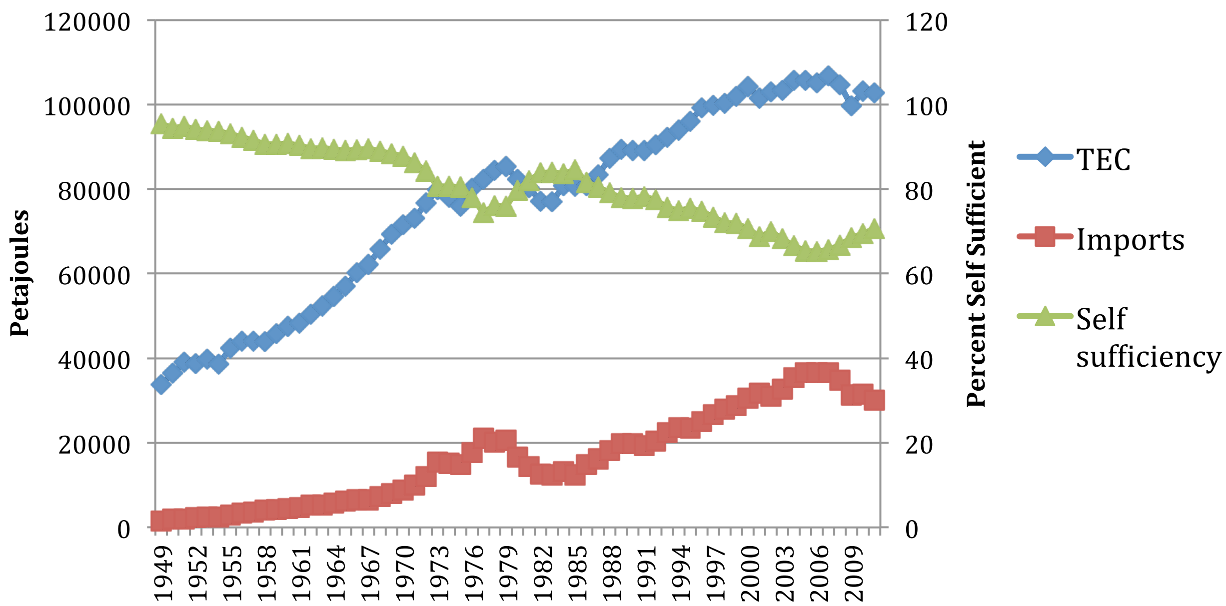

Figure 23: U.S. total energy consumption (TEC), energy imports and the degree of energy self-sufficiency (original figure, data source U.S. EIA, 2012a).

In the early 2000s, diversification and deployment of renewable energy technologies experienced rapid and sustained growth. Figure 24 outlines renewable energy generation by source in the U.S. from 1990-2011. From this figure it is evident that biomass, wind, geothermal and solar technologies have experienced expansion since the early 2000s. Hydroelectric generation has remained relatively stable over the same period, as further growth in this industry is limited as significant expansion faces severe opposition from environmental groups and most sites suitable for hydropower capacity are already utilized (Klass, 2003).

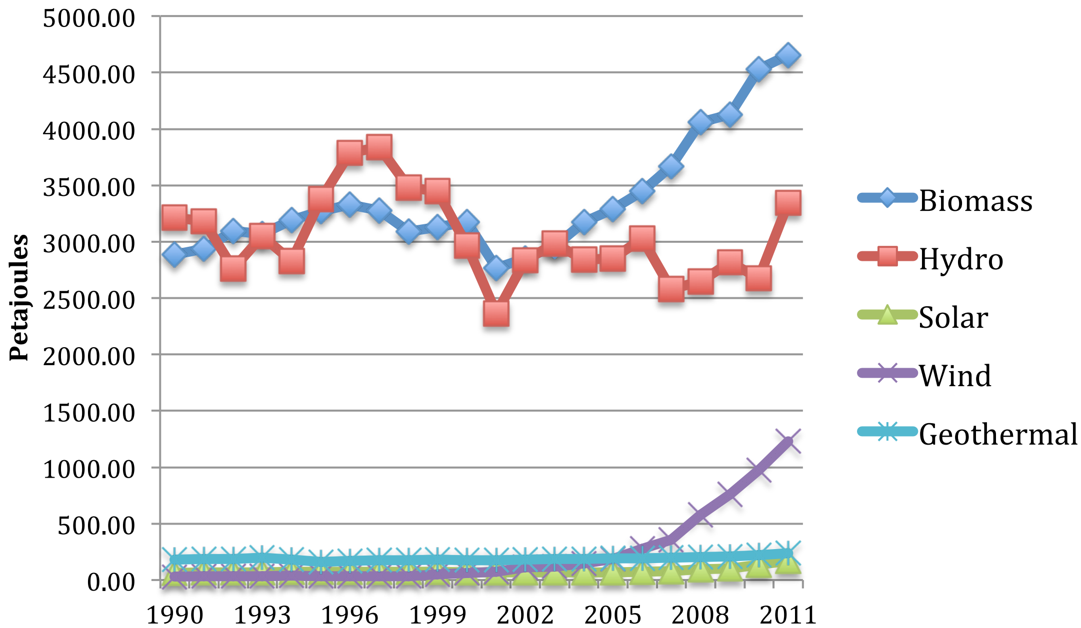

Figure 24: The U.S. renewable energy mix from 1990-2011 by source (original figure, data source U.S. EIA, 2012a).

3.4.3.2 Energy related climate change concerns and biomass allocation

Climate change concerns in the U.S. manifest themselves in different forms than those observed in Denmark and Sweden. Federal renewable energy and GHG emissions reduction mandates do not exist to the same extent as the Scandinavia profiles, although state and county renewable mandates and GHG emission targets are becoming more widespread. A detailed review of state-by-state targets is beyond the scope of this thesis. For more information, monthly updates are available on the Database of State Incentives for Renewables & Efficiency (DSIRE) website (DSIRE, 2014).

American climate change mitigation attempts are often marketed as environmental protection policies and initiatives (Rinebole, 1996). Despite the different packaging, these programs hold influence in biomass allocation decisions in the America. The vast number of policies and programs of this variety in the U.S. means that only a select number of policies that have been previously recognized to influence biomass allocation in the U.S. are discussed in section 6.3.4.

3.4.3.3 Prevailing economic interests

Feedstocks for biomass-based energy generation in the U.S. are predominantly corn and wood based, and the respective forest sector and corn growers associations have a vested interest in decisions regarding the allocation of this biomass to bioenergy and biofuels. Desires of both interest groups are reflected in biomass allocation decisions observed in the United States. Unique to the U.S. case, oil companies have been effective at directing biomass allocation in the biofuels industry.

The first response to the "blend wall" was the EPA's move to increase the blend limit to 15%. In 2010, after substantial vehicle testing, the EPA approved the consumption of E15 gasoline in light-duty vehicles produced since 2001. These vehicles accounted for 62% of passenger vehicles on U.S. roads in 2010 (Schnepf and Yacobucci, 2013). However, as of mid 2012, only 13 stations concentrated in three states offered E15 for sale and thus has been an unsuccessful solution to the "blend wall". The resistance of oil companies and distribution centers to the proposed E15 blends has been enormously influential at inhibiting the penetration of the higher blend. After the failure of the E15 expansion, the EPA announced its' latest solution to the "blend wall". A proposal was put forward last month to cut the mandated volumes of all four categories of biofuels for 2014. The largest reduction is proposed for ethanol, 3 billion gallons below what RFS2 currently mandates, 1.4 of which will come from corn-ethanol. Although the EPA has been issuing waivers of compliance for cellulosic biofuel mandates since 2010, this proposal is the first time corn-ethanol mandates have been a target for reduction in U.S. history.

3.4.3.4 Cost competitiveness of U.S. bioenergy and biofuels

This section considers how technologies and policies for bioenergy/biofuels influence cost competitiveness and ultimately biomass allocation decisions. I suggest competing energy technologies play a more important role in biomass allocation decisions in the US, due to the diverse nature of the energy mix. The absence of key district heating infrastructure in America has impeded the widespread adoption of bioenergy generation in large-scale facilities outside of the forest industry. Furthermore, the differences between the US, largely quota-based, policy approach to biofuels and bioenergy is essential to understanding the country's current and future biomass utilization.

3.4.3.4.1 Technological advancements in biomass-based energy

Compared to the Scandinavian countries examined in this thesis, the United States benefits from an abundance and diversity of feedstocks, ranging from vegetable oil crops, starch rich crops and woody biomass (Perlack, et al. 2011). During the original inception of biofuels in America, technologies to ferment starch rich crops into ethanol were widely available. As energy security concerns came and went in a cyclical fashion, bioethanol was the low-hanging fruit, as the technological feasibility of the process from corn made it an ideal candidate to replace imported fossil fuels.

Despite the enormous forest resources in the United States, the combustion of woody biomass to bioenergy failed to take off when energy security concerns increased. The nature of domestically available energy alternatives for energy generation and the type of available heat and power infrastructure in America played a key role in this latent development. It is likely that bioenergy failed to take off in the United States in a similar manner as experienced Denmark or Sweden due to availability of large U.S. coal and hydro-electricity supply. The availability of these domestic alternatives reduced the energy security concerns facing the heat and power sector, and limited the need for bioenergy generation. Furthermore, unlike Scandinavia, the U.S. lacked the preexisting district heating infrastructure that helped to make the biomass combustion such an attractive alternative.

Technological availability and advancements is obviously important at establishing biomass allocation to one technology or another at the point of emergence for biomass-based energy technologies. However, technological innovation alone is insufficient to explain how biomass allocation changes over time, and the policies affection biofuels and bioenergy must also be considered.

3.4.3.4.2 Policies affecting cost competitiveness of biofuels and bioenergy

A myriad of policies influencing the cost competitiveness of bioenergy and biofuels in the United States are present at the county, state and federal level, although for the purpose of this thesis, only federal level policies are considered. Unlike Denmark and Sweden, the U.S. has not ratified the Kyoto Protocol and thus is not bound by any multi-national climate policies. How federal policies improve the cost competitiveness of bioenergy and biofuels is essential to fully comprehending biomass allocation in the United States.

Despite the long history of biofuel production in the US, dating back to the early years of the automobile, the biofuel industry has experienced a number of false starts. One such period occurred in 1990 with the introduction of the Clean Air Act Amendments that created new regulations for gasoline formulations. Methyl tert-butyl ether, a common gasoline additive at the time, faced a de facto ban due to detrimental environmental effects associated with the toxicity of the substance. As a result, refiners switched to blending with ethanol, effectively stimulating the industry, as reflected in expanded production of 900 million gallons in 1990 to 1.4 billion gallons in 1995 (Hultman et al. 2012).

The Energy Policy Act was Congress' response to volatile petroleum prices as a result of conflict in the Middle East. Initially the RFS program (known as RFS1) required 7.5 billion gallons of biofuel to be blended with gasoline by 2012. The RFS1 was the first renewable fuel volume mandate within America and effectively guaranteed a long-term domestic market for ethanol. The policy generated such a positive response that in 2007, the Energy independence and Security Act expanded the RFS program (now known as RFS2) increasing the volume of mandated renewable fuels to 36 billion gallons by 2022, of which, 16 billion gallons must come from cellulosic biofuels and corn-starch ethanol is capped at 15 billion gallons. In it's current form, the Renewable Fuels Standard (RFS2), is the keystone policy dictating development of biofuels in transportation.

The passage of RFS2 into law established four nested renewable fuel categories in the United States: total renewable fuels, advanced biofuels, cellulosic and agricultural waste biofuels (henceforth cellulosic biofuels) and biomass-based biodiesel (henceforth biodiesel). Each category has separate volume requirements and applied lifecycle and greenhouse gas performance standards. Lifecycle greenhouse gas reductions are compared to conventional fossil fuels as a baseline. The RFS2 was the first transportation biofuel policy in the world to include a lifecycle sustainability requirement. (Schnepf and Yacobucci, 2013). Table 3 below outlines the main features of each of the four fuel categories. It is important to note that due to delayed commercialization of cellulosic biofuels, the EPA has issued mandate waivers since 2010, effectively removing required blending of cellulosics. The current 2013 cellulosic biofuels mandate is 0.014 billion gallons (bgal), down from the 1 bgal outlined by RFS2 (Schnepf and Yacobucci, 2013).

The nested nature of fuel categorization means that any fuel that meets the requirement for cellulosic biofuels or biodiesel also meets the advanced biofuels requirement. Therefore, if production of either of these fuels were to exceed the volumetric mandate, any surplus could be counted towards advanced fuels. Furthermore, any fuel that meets the requirement for advanced biofuels is also able to meet the overall total renewable fuel requirement. Therefore any individual category where there is surplus volume would reduce the need for corn-starch based ethanol for total renewable fuel mandate compliance and imported Brazilian ethanol (1.456 bgal in 2013) for advanced fuel mandate compliance (Schnepf and Yacobucci, 2013).

Table 6: Renewable fuels categories as outlined by RFS2 (adapted from Schnepf and Yacobucci, 2013).

Fuel Category	Emissions Reduction	Fuel Type	2013 Mandate
Total renewable fuels	20% GHG reduction	Corn-starch ethanol and all other biofuels	16.55 bgal (13.8 bgal cap on corn ethanol)
Advanced biofuels	50% GHG reduction	Non-corn feedstock such as: sorghum and wheat ethanol, imported Brazilian ethanol, CAWB and BBD	2.75 bgal
Biodiesel	50% GHG reduction	Any diesel-like fuel from biomass: algal biofuels, mono-alkyl esters, cellulosic diesel	1.28 bgal (adjusted from 1.0 bgal)
Cellulosic biofuels	60% GHG reduction	Cellulosic bioethanol and any biomass-to-liquid such as cellulosic gasoline or diesel	0.014 bgal (adjusted from 1.0 bgal)

The Environmental Protection Agency (EPA) is responsible for implementing and monitoring mandated renewable fuel volumes under the RFS. To do so, the EPA calculates annual percentage requirements for each biofuel category of RFS2. Percentages are used to determine an individual company's renewable volume obligation (RVO). Renewable identification numbers (RINs) were created as a tracking system, issued to the producer or importer at the point of production or importation. When the producer or importer sells biofuels to a blender the RINs are transferred. By blending the renewable fuel with gasoline for retail sale or export the RINs are separated from the fuel and are used by the blender for compliance with their RVO or traded (Schnepf and Yacobucci, 2013). Tradability of RINs has created a market for them, as availability and price of different biofuel products varies from state to state. Blenders unable to meet their RVO purchase RINs from those who have blended beyond their RVO.

Additional federal and state subsidies exist beyond the blended fuel tax credits and RFS2. Complicated combinations of producer incentives, renewable fuel standards, state subsidies, feedstock incentives and more exist, varying from state to state, however experts consider these supplementary to RFS2 (Tyner, 2008). It is apparent that biofuels, especially ethanol, have had substantial, long-term incentives in the United States.

More recently, the U.S. biofuels industry is facing yet another period of stalled growth. Since 2008, consumption of biofuels in the U.S. has slowed significantly as bioethanol consumption has plateaued. This situation is directly attributed to the emergence of the "blend wall". Presently, ethanol is be blended with gasoline in two different volumes, E10, and E85. Gasoline E10 blends can be consumed in all vehicles and E85 is for use in special flexi-fuel vehicles only. However, 99% of all ethanol in the U.S. is consumed as E10, therefore the U.S. is faced with a situation where gasoline consumption is limiting ethanol consumption. Projected gasoline consumption in an E10 market has resulted in ethanol demand that falls short of that mandated by RFS2. This results in two opposing realities, the RFS2 requires higher volumes of biofuels to be blended each year until 2022, while the physical blend wall may result in declining ethanol consumption as gasoline consumption falls in the US, impart due to poor economic conditions and improving fuel efficiencies (Tyner and Viteri, 2010). Assuming all ethanol is consumed as E10, current gasoline consumption only allows for ~13 billion gallons of ethanol to be consumed, less than the RFS2 mandates for 2013-2022.

Government support for the combustion of bioenergy in modern application emerged amid high oil prices in the shadow of the 1973 OPEC oil crisis. A component of the National Energy Act of 1978, known as the Public Utility Regulatory Policies Act (PURA), required that all utility providers purchase electricity at fixed price from qualified facilities employing renewable fuels (Abel, 2006). Although the PURA mandate was open to all renewable energy sources, not solely bioenergy, it resulted in favourable conditions for increasing bioenergy production, as the combustion of biomass to generate electricity was cost competitive compared to other renewable energy sources at this time. Many bioenergy facilities were built as a result of PURA, two thirds of the 35 bioenergy facilities built in California at this time were participating in the fixed price agreement (Morris, 2002). The policy was successful at created burgeoning demand for woody biomass from 1980- early 2000s (Aguilar et al. 2011). In 2005, the Energy Policy Act signaled an end to the purchase requirements (Energy Policy Act, 2005). Following enactment of the Energy Policy Act, a slight decline was seen in the use of woody biomass for energy, however it is difficult to discern if this was a result of the act alone or a number of other external factors, namely declining domestic paper production.

In addition to renewable energy mandates of PURA, the U.S. government has provided significant tax incentives and grants for bioenergy since the 1990s. The Energy Policy Act of 1992 created a tax credit for the production of bioenergy in a closed-loop system. Under the act, a closed-loop system referred to facilities that combusted biomass for energy in which the feedstock employed was energy crops (Energy Policy Act, 1992). In 2004, the American Jobs Creation Act expanded the production tax credit to include open-loop bioenergy generation, which includes the combustion of forest and pulp-related biomass, effectively ensuring all bioenergy systems now qualified for the credit. The tax-credit provided for open-loop biomass ($10/MWh) was less than that for closed-loop ($21/MWh) bioenergy production (American Jobs Creation Act, 2004). Eligibility for open-loop facilities was restricted to a five-year period, expiring by 2010.

After the passage of the U.S. Highway Act of 2005, owners of U.S. Kraft pulp mills began exploiting the Alternative Fuel Provision tax credit put in place by the act, originally designed to promote renewable fuels in the transport sector. By mixing 0.1% diesel fuel with the black liquor, prior to combustion in the recovery boiler, the black liquor/diesel mixture was considered a biofuel and qualified for a USD$0.50/gallon tax credit. Pulp mills in the U.S. that took part in the program experienced significant financial payouts to the tune of USD$6 billion in 2009 alone, effectively subsidizing the U.S. pulp industry. The policy was seen as a failure as it awarded the pulp and paper industry handsomely for increasing their consumption of fossil fuels as diesel is not traditionally blended with black liquor, effectively increasing the GHG emissions associated with the mills. Despite the generous subsidy payout, bioenergy generation within industry fell in the final quarter of 2008 (Aguilar et al. 2011).

The American Recovery and Reinvestment Act of 2009 is regarded as one of the most effective incentive programs for the U.S. bioenergy sector (Becker et al. 2009). This energy tax credit has successfully stimulated growth in biomass-based CHP and electric power facilities across the commercial and industrial sectors (Aguilar et al. 2011). In the residential sector, the Residential Energy Efficiency Tax Credit of 2006 provided residents with tax credit up to $500 for high-efficiency biomass stoves installed. In 2009 the limit was increased to $1500 and remains a major incentive, increasing residential bioenergy consumption, (DSIRE, 2009).

Combined with the slew of tax credits, the U.S. has provided a number of grants and government bonds to fund renewable energy generation, for which bioenergy qualified. The Renewable Energy Systems and Energy Efficiency Improvements Program of 2003 is one such grant, provided funding for feasibility studies and renewable energy systems in the commercial and electricity sectors. In 2008 the program evolved into the Rural Energy For America Program Grant and was expanded from 23M US$ in 2003 to 70M US$ in 2012 (Aguilar et al. 2011).

Unlike biofuels production, which is dictated by the Renewable Fuels Standard (see section 6.3.4b), no nation wide mandate exists to guarantee required levels of bioenergy generation. In its place, state-level mandates exist as an aspect of the Renewable Portfolio Standards (RPS). The RPS encompasses policies designed to increase production of electricity from renewable sources including; wind, solar, geothermal, biomass and some forms of hydroelectricity (Jeffers et al. 2012). At the time of writing, 30 states had RPS mandates with 7 additional states implementing voluntary goals (U.S. EIA, 2012).

A breadth of policies is included under the RPS umbrella. Typically, an RPS mandates a minimum requirement for a share of electricity to be supplied from qualified renewable energy resources within a particular time frame. The number of policies and their mechanisms vary by state yet a number of renewable electricity credit (REC) trading markets have emerged as a response to state RPS targets. RECs operate in a similar fashion to Renewable Identification Numbers (RINs, see section 6.3.4.b), where renewable electricity producers must generate credits to meet their RPS obligation. A producer that collects surplus RECs may trade or sell them to other electricity suppliers who may not generate enough renewable electricity to meet their RPS requirements. Detailed, up to date information for individual state RPS is produced monthly by the Database for State Incentives for Renewables and Efficiency (DSIRE, 2014).

A lack of specific bioenergy policies and mandates are restricting widespread adoption outside industry. In 2010, results from a U.S. Department of Energy (DOE) workshop suggested a lack of federal RPS targets and no comprehensive carbon price are the greatest barriers facing bioenergy's successful adoption in the United States (U.S. DOE, 2010). In addition general renewable energy policies, such as those outlines by the RPS, means bioenergy is competing against other renewable technologies for access to limited funding and resources. Further hurdles affecting widespread biomass utilization for energy include, transportation and harvesting costs, technological challenges and competition for feedstock end uses (Guo et al. 2007). Despite the impediments outlined, a recent report from the United States Department of Agriculture (USDA) expects wood biomass use to contribute 2637.63 PJ in 2015 and 3059.66PJ in 2030 (White, 2010)

3.4.4 U.S. conclusion

Despite being the world's largest producer and user of both bioenergy and biofuels on an energy basis, there has not been, and it is unlikely that there ever soon will be, any competition for biomass for either bioenergy or biofuel production in the US. Biomass emerged as the largest source of renewable energy in the United States, due to its integration within the forest sector. As U.S. pulp and paper production declined ~2004, in-mill bioenergy generation also decreased. Coincidentally, domestic biofuels increased significantly over this time, expanding exponentially (mainly bioethanol).

The expansion of biofuels in the U.S. is largely thanks to government policies based on improving domestic energy security, as evident from the government support schemes passed over the last 40 years (the names alone are very indicative of this).

Today, significant resistance limiting further consumption of these alternative energy sources hinders further biofuels and bioenergy development. The persistence of the blend wall and increasing domestic oil and gas production has resulted in bioethanol consumption limitations, and lowered the cost competitiveness of bioenergy projects. Growth in the world markets for these products has caused U.S. exports of both wood pellets and biofuels to increase, especially as domestic consumption continues to experience limitations. Without clear, long-term support for bioenergy or biofuels in the United States, exports of these products may continue as international markets develop. An interesting situation may arise in the U.S. in which the country becomes a global supplier for bioenergy and biofuel products, due to their abundance of low-cost biomass, with high global market prices for bioenergy and biofuel products out competing the domestic American market for these products.

CHAPTER FOUR: CONCLUSIONS FROM THE COUNTRY COMPARISONS

As evident from the case studies, variation exist in how biomass is employed within both bioenergy and biofuels in all countries examined. This chapter complies data from the case studies on biomass consumption and allocation to bioenergy and biofuels in an attempt to extrapolate broader patterns with respect to: the importance of biomass in the energy mix, chief biomass applications, the status of competition and the influence of the four identified drivers on biomass allocation.

4.1 The importance of biomass in their current energy mix

Biomass is the largest source of renewable energy in the world and in all of the countries examined. Consumption of biomass for energy and fuels is outlined as a proportion of total energy in figure 25. This figure reveals that it is important to examine both biomass consumption as a proportion of total energy and the total energy generated from biomass when trying to truly discern how important biomass is for energy generation in a country.

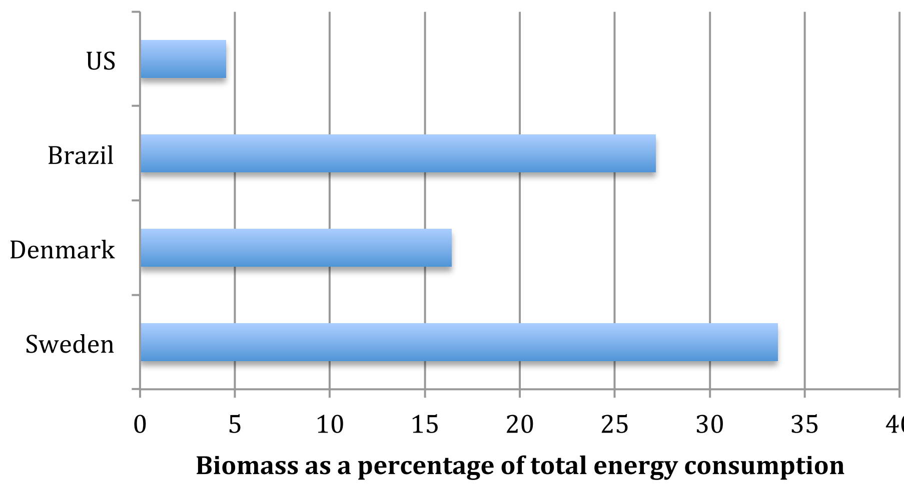

Figure 25: Consumption of biomass as a proportion of total energy demand for the country profiles (original figure data compiled from DEA, 2012; MME, 2012; SVEBIO, 2013; U.S. EIA, 2012).

Despite the United States' dominance as the global leader in biofuel production (2053 PJ in 2011) and bioenergy generation (2600 PJ in 2011) the contribution of biomass to total energy demand is the second lowest of all countries examined at 4.5%. This incongruity is the result of a comparatively high-energy demand (~103 EJ in 2011) of the

U.S. compared to the other country profiles. In contrast, Sweden's biomass consumption accounted for 469 PJ in 2013, an order of magnitude smaller than the US, although it was the largest energy source in the country, accounting for 34%. In Brazil, the high penetration of biomass within the industrial energy mix (over 50% of total bioenergy is within industry) largely explains why biomass forms 27% of the country's final energy mix. Brazil's industrial operations account for the majority of the country's energy demand as private energy demand for heating and transportation is low when compared to Denmark, Sweden or the United States.

The countries examined in this thesis revealed that bioenergy is, by far, the most dominant application for biomass in most countries' energy mixes (figure 26). Biofuels make only a small contribution to biomass consumption, even in Brazil, the second largest biofuel producer in the world. Although, in the United States biofuel consumption is rapidly approaching that of bioenergy and may surpass it in the future with further development of advanced biofuels.

4.2 The state of biomass competition

Relative consumption of bioenergy and biofuels are compared for each country in figure 26. In the countries studies limited competition for biomass occurs between biofuel production and bioenergy generation as different feedstocks are used for these applications. Agriculture products, mainly sugar, starch and oil rich biomass crops, are the predominant biofuel feedstocks and are unsuitable for bioenergy generation; thus competition is mostly absent at present.

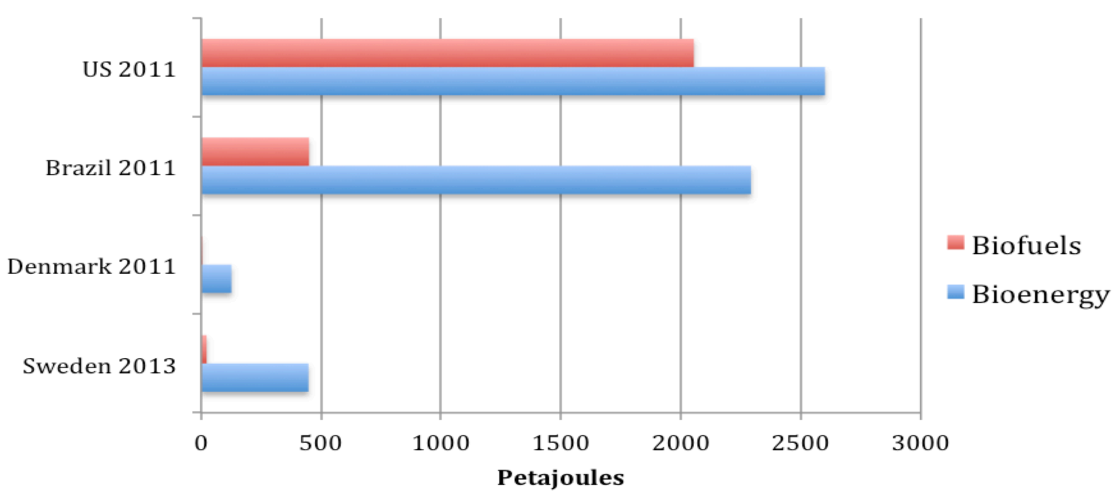

Figure 26: Comparison of bioenergy and biofuel consumption, expressed in petajoules, for

all case countries (original figure data compiled from DEA, 2012; MME, 2012; SVEBIO, 2013; U.S. EIA, 2012).

Increased targets for biofuel blending, heightened sustainability concerns and realized commercial scale lignocellulosic ethanol facilities indicate a growth of advanced biofuels in the future. Under these circumstances it could be anticipated that competition for biomass between biofuels and bioenergy would increase. Yet when several of the current commercial biofuel plants were examined in detail, it became apparent that competition is unlikely to occur, even under circumstances where widespread commercialization of advanced biofuel is realized. All currently commercial cellulosic ethanol plants rely on the co-generation of biofuels and bioenergy to render the processes economically viable. Since the October 2013 opening of Beta Renewable's cellulosic ethanol operation in Crescentino, Italy (83 ML biofuel and 13MWe bioenergy) two other facilities; Abengoa (100 ML biofuel and 22 MWe bioenergy) and GranBio (82 ML biofuel and 17 MWe) have both began the co-production of cellulosic biofuels and bioenergy. The major benefits from co-production are two fold: bioenergy contracts improve cost competitiveness of fuel production and energy generation utilizes waste lignin. The long-term price guarantee of an electricity contract makes bioenergy an attractive co-product as it ensures a fixed income for the facility, helping to improve cost-competitiveness of the biofuel products. Combustion of the energy dense lignin helps to minimize processing waste, however this fraction is only considered a waste stream when enzymatic hydrolysis is employed. Thermochemical conversion of biomass to biofuels will use the lignin fraction thus bioenergy co-generation would be limited. At the time of writing no commercial scale thermochemical advanced biofuel plants were in operation.

4.3 The drivers for biomass allocation

Identifying what factors have influenced biomass distribution in the past, assessing their present contribution to allocation decisions and how they might influence possible competition in the future was one of the objectives of this thesis. Although energy security and climate change were two major drivers, strong regional variation exists in both the cost-competitiveness of biomass based energy and fuels and the prevailing economic interests of each country. The relative importance of these country-specific drivers and their influence on biomass employment for bioenergy or biofuel applications is discussed below.

4.3.1 Energy security

Energy security concerns have been an important driver for the emergence of bioenergy and biofuels in many of the country profiles. The government policies that arose in response to energy security concerns provided a structural base for both bioenergy and biofuels development. Recently, increased access to unconventional oil and gas has changed the energy landscape, lessening the impact of energy security concerns as a driver. Presently, energy security cannot be considered an essential pre-requisite for bioenergy or biofuel development. This may change in the future as fluctuations in global oil prices could make some domestic sources uncompetitive, there by reintroducing energy security concerns.

Furthermore, the incidence of an energy security threat cannot be used to predict biomass allocation to bioenergy or biofuels. Although this issue played a key role in the development of biofuels in both Brazil and the United States, it was also crucial in the development of bioenergy technologies in Denmark and Sweden during the same time period. Salience of energy security does not appear to favour biomass allocation to one conversion technology over another.

Energy security concerns change over time with shifting energy- markets, technologies, supply and demand but this does not necessarily change biomass apportionment decisions. Despite varying levels of energy security and bioenergy and biofuel consumption in all of the country profiles over the last few decades, neither application appears to be correlated to energy security at present. However, transportation fuels are primarily produced from oil, while stationary energy has multiple alternatives; thus in the absence of domestic oil resources, energy security could act as a driver for biofuel development.

4.3.2 Climate change mitigation

As seen in the case studies, support for increasing the contribution of bioenergy and biofuels is often framed within the context of climate change mitigation potential. Desires to avoid the negative externalities associated with fossil fuels have justified investment in bioenergy and/or biofuels. As a driver, climate change mitigation has historically been important in spurring the development of bioenergy and biofuels. Apportionment decisions for biomass are largely dependent upon the perceived sustainability of biomass and the ability of bioenergy or biofuels to achieve GHG emission reduction targets. Diverging perspectives are evident when examining the different approaches to biomass utilization that occurred in Denmark and Sweden in the early 2000s. Swedish adoption of biofuels starkly contrasts the rejection of EU blend mandates in Denmark and illustrates that the presence of climate change mitigation desires is insufficient for discerning how biomass is allocated in a given region.

In some cases, the initial deployment of biofuels and bioenergy was carried out without much emphasis on actual sustainability and climate change mitigation effects. Between 2006 and 2013 stringent sustainability criteria for biofuels in the EU and U.S. means that implementation should have "real" climate benefits (Scarlat & Dallemand, 2011). Similar guidelines are under development for bioenergy feedstocks in the EU and Scandinavia. As sustainability guidelines become more common they should have implications for biomass competition; sustainably harvested lignocellulosic biomass will experience greater climate benefits than current agriculture based biofuel feedstocks (such as corn). It is likely that increased climate change concerns could increase competition for lignocellulosic biomass. Specific targeting of transportation-derived emissions will propel biofuels to be featured prominently in this debate.

To further complicate matters, recent studies have highlighted an increasing uncertainty regarding the GHG emissions reduction potential of bioenergy and conventional biofuel technologies (IEA, 2013b; IRENA, 2014). The origins of this ambiguity arise chiefly from feedstock sustainability and an increasing understanding of environmental costs for both direct and indirect land use (IRENA, 2014). Confusion surrounding actual climate benefits of bioenergy and biofuels, combined with loosened climate targets in the wake of the economic recession, has contributed to slower biofuel and bioenergy growth in the EU. It is difficult to discern what influence climate change may have on the future of bioenergy and biofuel markets, and any suggestions made would be pure speculation and beyond the scope of this thesis.

4.3.3 Prevailing economic interests

The prevailing economic interests within a given country form powerful interest groups. These groups lobby government policy makers in an attempt to advance their own economic interests and have a significant impact on government policies. Historically these groups have been key drivers for both bioenergy and biofuel development in all of the country profiles examined.

Furthermore, the major biomass producing industries in a given country can be used to predict the predominant biomass feedstocks employed, and how these feedstocks are used within the energy sector. The nature of the feedstock be it agricultural or forest based, can be used to further discern how biomass resources will be allocated towards biofuel or bioenergy production. For example in Brazil, where sugarcane is one of the most important agricultural crops in the country, available sugar is best suited for biofuel production. In contrast, Sweden, with abundant forest biomass and strong economic interest groups in this industry will promote the utilization of forest biomass in bioenergy generation.

Currently, the majority of advanced biofuel production is targeting agriculture residues such as straw, corn stover and sugarcane bagasse as feedstocks. As technologies develop that can convert forest biomass to biofuels, a shift in biomass allocation could occur.

Prevailing economic interests outside of biomass producing and handling industries also have the ability to dictate the success of bioenergy and/or biofuels. The diverging reactions of the Brazilian and American automotive industries to biofuel development are an excellent example of this. The widespread acceptance of flex-fuel vehicles and high ethanol blends in Brazil starkly contrasts the ongoing blend-wall situation in the United States.

4.3.4 Cost competitiveness of bioenergy or biofuels

In the competition for biomass, the ability of one technology to contest with another for the same feedstock is very much dependent upon the cost competitiveness, with the more economically viable technology likely to prevail. Traditionally, this notion has seen lignocellulosic biomass favoured for bioenergy generation rather than biofuels, as the technical challenges associated with bioenergy are more surmountable than those associated with biofuel production. However, as identified earlier this is changing as advanced biofuel technologies become commercialized.

Furthermore, trepidations surrounding cost competitiveness can evaporate when other drivers are present and their attention deemed more critical. In these circumstances, technologies often benefit from extensive policy support. This was the case with early biofuel development in the United States and Brazil and the conversion of many CHP and district heating facilities from fossil fuels to biomass in Scandinavia.

4.3.5 Policy and biomass allocation

This thesis has identified a number of drivers involved in the development of bioenergy and/or biofuels. Despite the importance of energy security, climate change mitigation desires, prevailing economic interests, and cost-competitiveness; government policy mechanisms over-ride all other drivers and provide a foundation for bioenergy and/or biofuel development. Policies are necessary to support both the advancement of bioenergy and biofuel technologies.

In each country profiles it was observed that the relative importance of energy security, climate change mitigation, prevailing economic interests, and cost competitiveness are capable of changing overtime. Policies, as a process are unable to change as rapidly as these other drivers (in democratic societies, thus excluding the Brazilian military dictatorship 1964-1985). The slow reactionary capacity of policy means their authority on biomass allocation is more long-standing than the other drivers. In Brazil and the United States, energy security threats existed during the onset of biofuel development and biofuel policies were largely born out of this threat, however when energy security issues waned over time, the policies did not immediately follow. As a result, the presence of strong biofuel policies (RFS and Pró-Álcool) allowed for further expansion of the industry in each country well after a decline in energy security. In Sweden and Denmark, the initial drivers for bioenergy development, have long lost public salience, but the policies implemented during the early inclusion of these technologies within the energy mix, were instrumental in setting the foundation for current biomass apportionment decisions. Interestingly, climate change mitigation and the related policies have experienced muted volatility in Sweden and Denmark, when compared to the United States. Understanding the causes of this phenomenon is outside the scope of this thesis.

Policy support mechanisms such as subsidies, research funding and blend mandates are necessary to support pioneer facilities and allow for process optimization at the commercial scale, eventually driving down production costs. Unfortunately, policies are not always sufficient to promote and maintain production, particularly for biofuels, as seen in all country profiles.

In both the United States and Brazil, binding blend mandates were introduced (in 2005 and 1993 respectively) to create a guaranteed demand for the fuel. The introduction of a 22% blend mandate in Brazil was an effective way to combat cheap oil prices and the presence of mandates concurrently with bioethanol subsidies in the U.S. saw bioethanol consumption increase from ~354 PJ in 2005 to ~1120 PJ in 2010 (U.S. EIA, 2011). In the US, unlike Brazil, mandates are not pegged as a percentage of gasoline consumption; rather the RFS outlines clear volumetric targets to be met by all fossil fuel providers.

In the EU, the 2003 Biofuel Directive introduced blending targets of 2.0% and 5.75% for 2005 and 2010 respectively, although the quota was non-binding (Hveplund, 2011). By 2010 biofuels accounted for only 4.4% of transportation fuel demand, falling short of the mandate. Despite the shortfall, the previous year the EU Commission endorsed a minimum binding target of 10% for biofuels in transport by 2020. In 2012 biofuels reached 5% of transportation fuel demand, however uncertainties regarding the future of EU biofuel policies and slow economic recovery in many of the member states is limiting expansion of biofuels in Europe (IEA, 2014; UN, 2014).

Unfortunately, blend mandates are also subject to unforeseen complications limiting their efficiency. In the US, the blend wall is limiting bioethanol consumption while undermining the RFS mandates, while a flexible bioethanol mandate was introduced in Brazil in an attempt to cope with the fluctuating bioethanol supply due to variability in the annual sugar harvest. Sustainability concerns have changed the EU biofuels climate; especially considering the region relies on imports to meet their current biofuel mandates (UN, 2014). Furthermore, the majority of member countries have failed to meet their targets since the mandates were first introduced in 2003. Globally, blend mandates exist in over 60 countries, however biofuel production and consumption is still concentrated within the U.S. and Brazil as investors may be deterred from other nations with high biomass availability due to the unpredictable political climate of areas such as Russia, China and Africa (IEA, 2014). This further illustrates the fact that, although essential for commercialization, government policies alone are not adequate to increase biofuel use.

In the future, policies will be fundamental for the commercialization of advanced biofuel technologies due to their process complexity and currently high production costs. Clear long-term policy signals will be crucial to stimulate investment in facility construction. In the wake of oil price projections of $US70/bbl by 2015, this will be a demanding task (IEA, 2014). Careful development will be required to avoid the hurdles previously experienced with conventional biofuel policies all while targeting environmental sustainability and limiting the economic cost. Rewarding carbon emissions benefits from these fuels via a carbon tax on fuels could be an effective way to differentiate between conventional and advanced biofuels. The success of similar policies for biofuels has greatly benefited the Swedish biofuel market as the country pays one of the highest prices on carbon in the world and currently leads the EU with 9% biofuels in transportation.

Drop-in biofuels present an opportunity to move beyond road transportation into aviation and marine applications. Furthermore they provide the ability for the U.S. to solve the effective cap on bioethanol consumption currently caused by the blend wall. It will be critical for these fossil-fuel equivalent products to be categorized in a manner that recognizes their potential advantages over both conventional and advanced biofuels.

CHAPTER FIVE: CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

A comprehensive review of current and projected global energy trends, with a focus on biomass-based energy, indicated that there was no competition for biomass between bioenergy or biofuels applications and this was likely to remain the case for the foreseeable future. It became apparent that bioenergy generation is, and will likely remain, the major use for biomass even in jurisdictions such as Brazil and the US where biofuels are produced and used extensively.

This very limited competition is primarily due to the differing feedstock's employed to make bioenergy and biofuels. The vast majority of biofuel production uses conventional, sugar, starch and oil rich feedstocks, while bioenergy production is derived predominantly from woody biomass. Brazil is likely to be the only region where biomass competition might occur in the near future as sugarcane bagasse is increasingly used to generated heat and power at the mill site (sometimes exporting excess electricity into the grid), while companies such as Granbio and Raizen are assessing the potential of using bagasse as a feedstock for cellulosic ethanol production. However, rather than creating competition for cellulosic feedstocks, these facilities are more likely to co-produce biofuels and bioenergy from these residues to achieve improved economic viability.

It is evident from the exploratory research that, although there are a number of drivers involved in the development of bioenergy and/or biofuels, government policies predominate by providing a more stable structure for bioenergy and/or biofuel development. For both Brazil and the United States, although the energy security threats that originally catalyzed biofuel development have somewhat dissipated, the development of strong biofuel policies (RFS and Pró-Álcool) enhanced the expansion of the industry in each country. For Sweden and Denmark, policies such as those initially used to better use their forest and agriculture derived residues to produce bioenergy and, more latterly, to reduce their fossil fuel derived carbon emission, will continue to motivate ongoing bioenergy, and to a lesser extent, biofuels, development.

5.2 Future research

The importance of policy in the development of biofuels and bioenergy suggests that future research would benefit from a cross-country comparison. Unlike this study where numerous drivers were considered, focusing specifically on government support policies employed for biofuels and bioenergy would have significant merit. Comparisons between policy mechanisms allow governments to evaluate the effectiveness of their stimulus methods to those employed by other countries or regions.

The country comparison highlighted the importance of cost-competitiveness of biofuels for their penetration within the energy mix of a given country or region. Over the latter half of 2014, global oil prices declined significantly from ~110$/bbl in June to ~60$/bbl in December (Nasdaq. 2014). This has created an increasingly difficult environment for renewable fuels, which hope to compete with fossil fuels in the transportation sector. Many of the current government policies and programs were designed when long-term oil-price projections were in the $120/bbl range (IEA, 2014). The structure of these support policies will have to be reassessed if oil and fossil fuel prices remain at their current levels. Particular topics of interest include evaluating the effectiveness of specific policy mechanisms such as feed-in tariffs, carbon pricing, fuel taxes or emissions based vehicle registration tax.

It is recognized that the world's biomass supply, demand and trade will expand, if predictions by groups such as the IEA are to be anywhere close to realistic. However, a review of the international and domestically generated data regarding biomass utilization for energy generation revealed that there is significant variation in the projections that have been published by different organizations. For example, the vast majority of biomass supply projections show heavy reliance on biomass derived from dedicated energy crops. However, currently, these crops provide very limited volumes of biomass. Biomass-based energy projections, especially those for biofuels, have a long history of being very optimistic. The IEA's World Energy Outlook 2013 projections and the cellulosic biofuel mandates of the U.S. RFS2 serve as just two examples. Future work must consider how to develop more realistic projections for bioenergy and biofuels as continued over-estimation will have a negative influence on investors and policy makers, affecting the potential success of a given technology in the long-run.

REFERENCES

Abel A. (2006). CRS report for Congress, energy policy Act of 2005. Accessed 13 December 2014. <http://www.circleofblue.org/waternews/wp-content/uploads/2010/08/CRS-Summary-of-Energy-Policy-Act-of-2005.pdf>.

Aguilar, F. X., Song, N., & Shifley, S. (2011). Review of consumption trends and public policies promoting woody biomass as an energy feedstock in the US. biomass and bioenergy, 35(8), 3708-3718.

Alagappan, L., Orans, R., & Woo, C. K. (2011). What drives renewable energy development?. Energy policy, 39(9), 5099-5104.

American Jobs creation Act of 2004. (2004). Pub. L. 108e357, 118 Stat. 1418. Accessed 9 February 2013.<http://www.gpo.gov/fdsys/pkg/PLAW-108publ357/pdf/PLAW-108publ357.pdf>.

Auld, D. (2012). Accountability Denied: The Global Biofuel Blunder. Friesen Press.

Banerjee, S., Mudliar, S., Sen, R., Giri, B., Satpute, D., Chakrabarti, T., & Pandey, R. A. (2010). Commercializing lignocellulosic bioethanol: technology bottlenecks and possible remedies. Biofuels, Bioproducts and Biorefining, 4(1), 77-93.

Becker DR, Moseley C, Lee C. (2011). Supply chain analysis framework for assessing state-level forest biomass utilization policies in the United States. Biomass Bioenerg;35:1429e39.

Berndes, G., Hoogwijk, M., & van den Broek, R. (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy, 25(1), 1-28.

Björheden, R. (2006). Drivers behind the development of forest energy in Sweden. Biomass and Bioenergy, 30(4), 289-295.

Bierdermann, F. and Obernberger, I. (2005). Ash related problems during biomass combustion and possibilities for a sustainable ash utilization. Accessed <http://www.bios-bioenergy.at/uploads/media/Paper-Biedermann-AshRelated-2005-10-11.pdf>.

BNDES and CGEE. (2008). Sugarcane-Based Bioethanol Energy for Sustainable Development. Accessed 8 March 2013 <http://sugarcane.org/resource-library/studies/BNDES%20-%20Sugarcane%20Based%20Bioethanol.pdf>.

Bright, R. M., Cherubini, F., & Strømman, A. H. (2012). Climate impacts of bioenergy: Inclusion of carbon cycle and albedo dynamics in life cycle impact assessment. Environmental Impact Assessment Review, 37, 2-11.

Cansino, J. M., Pablo-Romero, M. D. P., Román, R., & Yñiguez, R. (2012). Promotion of biofuel consumption in the transport sector: An EU-27 perspective.Renewable and Sustainable Energy Reviews, 16(8), 6013-6021.

Campbell, J. E., Lobell, D. B., & Field, C. B. (2009). Greater transportation energy and GHG offsets from bioelectricity than ethanol. Science, 324(5930), 1055-1057.

Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht, M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud. (2011). Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Damartzis, T., & Zabaniotou, A. (2011). Thermochemical conversion of biomass to second generation biofuels through integrated process design—A review. Renewable and Sustainable Energy Reviews, 15(1), 366-378.
Danish Energy Agency (DEA), (2005). Energy Strategy 2025. Danish Energy Authority, Copenhagen, Denmark.
Danish Energy Agency (DEA), (2012). Energy Statistics 2011. Copenhagen, Denmark.
Danish Government. (2011). Energy Strategy 2050. Accessed 22 July 2014. <http://www.kebmin.dk/sites/kebmin.dk/files/news/from-coal-oil-and-gas-to-green-energy/Energy%20Strategy%202050%20web.pdf>.
Database of State Incentives for Renewables & Efficiency (DSIRE). (2014). Accessed 24 July 2014. <http://www.dsireusa.org/rpsdata/index.cfm>.
De Freitas, L. C., & Kaneko, S. (2011). Ethanol demand under the flex-fuel technology regime in Brazil. Energy Economics, 33(6), 1146-1154.
Demirbas, A. (2011). Competitive liquid biofuels from biomass. Applied Energy, 88(1), 17-28.
Dornburg, V., & Faaij, A. P. (2001). Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass and Bioenergy, 21(2), 91-108.
Dwivedi, P., Khanna, M., Bailis, R., & Ghilardi, A. (2014). Potential greenhouse gas benefits of transatlantic wood pellet trade. Environmental Research Letters,9(2), 024007.
Energy policy Act of 1992. (1992). Pub. L. No. 102e486, 106 Stat. 2776. Accessed 22 July 2014. <http://www.usbr.gov/power/legislation/epa92.pdf>.
Energy policy Act of 2005. (2005). Pub. L. No. 109e58, 119 Stat. 594 . Accessed 22 July 2014. <http://www1.eere.energy.gov/femp/pdfs/epact_2005.pdf>.
Environmental Protection Agency (EPA). (2014). RIN Generation and Renewable Volume Production by Month. Accessed 22 July 2014. <http://www.epa.gov/otaq/fuels/rfsdata/2014emts.htm>.
EPE (National Energy Research Company), (2010). National Energy Balance 2010, Base year 2009. EPE, Rio de Janeiro.
Ericsson, K., Huttunen, S., Nilsson, L. J., & Svenningsson, P. (2004). Bioenergy policy and market development in finland and sweden. Energy Policy, 32(15), 1707-1721. European Commission, (2012) Accessed 14 August 2014. <http://ec.europa.eu/energy/renewables /biofuels/doc/biofuels/ com_2012_0595_en.pdf>.
Gan, J., & Smith, C. T. (2011). Drivers for renewable energy: A comparison among OECD countries. Biomass and Bioenergy, 35(11), 4497-4503.
Gnansounou, E., Panichelli, L., Dauriat, A., & Villegas, J. D. (2008). Accounting for indirect land-use changes in GHG balances of biofuels. École Polytechnique Fédérale de Lausanne Working Paper Ref, 437.
Government of Brazil. (2008). Executive Summary National Plan on Climate Change Decree No. 6263 of November 21, 2007. Interministerial Committee on Climate Change, Brazil.
Guo, Z., Sun, C., & Grebner, D. L. (2007). Utilization of forest derived biomass for energy production in the USA: status, challenges, and public policies.International Forestry Review, 9(3), 748-758.
GranBio, (2014). About GranBio. Accessed 13 December 2014. <http://www.granbio.com.br/en/who-whe-are/about-granbio/>.
Gylling M, Jørgensen U, Bentsen NS. The + 10 Million ton plan [In Danish: +10 mio. tons planen].University of Copenhagen 2012.

Haegermark, H. (2001). Priorities of energy research in Sweden. Swedish National Energy Administration, Building Sustainable Energy Systems. Swedish National Energy Administration (STEM) and Svensk Byggtjänst, Stockholm.

Hall, M. (2014). EU diplomats agree to 7% biofuels cap. Accessed 27 December 2014. <http://www.euractiv.com/sections/energy/eu-diplomats-agree-7-biofuels-cap-302499>.

Hedegaard, K., Thyø, K. and Wenzel, H., (2008). Life cycle assessment of an advanced bioethanol technology in the perspective of constrained biomass availability, Environmental Science and Technology, 42(21), pp. 7992–7999.

Heinimö, J., & Junginger, M. (2009). Production and trading of biomass for energy–an overview of the global status. Biomass and Bioenergy, 33(9), 1310-1320.

Hillring, B. (2002). Rural development and bioenergy—experiences from 20years of development in Sweden. Biomass and Bioenergy, 23(6), 443-451.

Hira, A., & De Oliveira, L. G. (2009). No substitute for oil? How Brazil developed its ethanol industry. Energy Policy, 37(6), 2450-2456.

Holmgren, K. (2012). Policies Promoting Biofuels in Sweden- An f3 synthesis report. Chalmers University of Technology. Accessed 3 September 2014. <http://www.f3centre.se/sites/default/files/f3_2012_3_report_biofuels_and_policies_121123.pdf>.

Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D., & Turkenburg, W. (2003). Exploration of the ranges of the global potential of biomass for energy. Biomass and Bioenergy, 25(2), 119–133.

Hultman, N. E., Malone, E. L., Runci, P., Carlock, G., & Anderson, K. L. (2012). Factors in low-carbon energy transformations: Comparing nuclear and bioenergy in Brazil, Sweden, and the United States. Energy Policy, 40, 131-146.

Hvelplund, F., (2001a.) Renewable Energy Governance Systems. Institute for Development and Planning, Aalborg University, Aalborg, Denmark.

Hvelplund, F., (2001b). Political prices or political quantities? New Energy 5, 18–23.

Hvelplund, F. (2011). Energy, Policy, and the Environment. (M. Järvelä & S. Juhola, Eds.), 6.

Iacobucci, D., & Churchill, G. (2009). Marketing research: methodological foundations. Cengage Learning.

International Energy Agency (IEA). (2009). Bioenergy – a Sustainable and Reliable Energy Source. Paris, France.

International Energy Agency (IEA). (2011). Energy Policies of IEA Countries Denmark 2011 Review. Paris, France

International Energy Agency (IEA). (2012a). 2012 Key World Energy Statistics. Paris, France.

International Energy Agency (IEA). (2012b). Oil Medium-Term Market Report 2012 . Paris, France.

International Energy Agency (IEA). (2012c). Global Wood Pellet Industry Market and Trade Study. Paris, France.

International Energy Agency (IEA). (2012d). Technology Roadmap Bioenergy for Heat and Power. Paris, France.

International Eneryg Agency (IEA). (2012e). World Energy Outlook 2012. Paris, France

International Energy Agency (IEA). (2013a). World Energy Outlook 2013. Paris, France.

International Energy Agency (IEA). (2013b). Nordic Energy Technology Perspectives. Paris, France.

International Energy Agency (IEA). (2013c). Renewable Energy Medium-Term Market Report 2013. Paris, France.

International Energy Agency (IEA). (2013d). Bioenergy Task 40. Large Industrial Users of Energy Biomass. Lappennranta, Finland.
International Energy Agency (IEA). (2013e). Energy Policies of IEA countries; Sweden 2013 Review. Paris, France.
International Energy Agency (IEA). (2014). World Energy Outlook 2014. Paris, France.
International Renewable Energy Agency (IRENA). (2014). Global Bioenergy Supply and Demand Projections: A working paper for Remap 2030. Accessed 11 December 2014. <http://www.irena.org/remap/IRENA_REmap_2030_Biomass_paper_2014.pdf>.
Kander, A. (2002). Economic growth, energy consumption and CO2 emissions in Sweden. PhD thesis. Department of Economic History, Lund University, Sweden.
Karatzos, S., McMillan, J.D., & Saddler J.N. (2014). The Potential and Challenges of Drop-in Biofuels. IEA Bioenergy.
Keeney, R., & Hertel, T. W. (2009). The indirect land use impacts of United States biofuel policies: the importance of acreage, yield, and bilateral trade responses. American Journal of Agricultural Economics, 91(4), 895-909.
Klass, D. L. (2003). A critical assessment of renewable energy usage in the USA. Energy Policy, 31(4), 353-367.
Koplow, D., Steenblik, R. (2008). Subsidies to ethanol in the United States. In: Pimentel, David (Ed.), Biofuels, Solar and Wind as Renewable Energy Systems. Springer (Chapter 4).
Kovarik, W. (2006). Ethanol's first century: fuel blending and substitution programs in Europe, Asia, Africa and Latin America. In Proceedings XVI International Symposium on Alcohol Fuels.
Laird, D. A., Brown, R. C., Amonette, J. E., & Lehmann, J. (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. Biofuels, Bioproducts and Biorefining, 3(5), 547-562.
Lamers, P., Hamelinck, C., Junginger, M., & Faaij, A. (2011). International bioenergy trade—A review of past developments in the liquid biofuel market.Renewable and Sustainable Energy Reviews, 15(6), 2655-2676.
Lamers, P., Junginger, M., Hamelinck, C., & Faaij, A. (2012). Developments in international solid biofuel trade—An analysis of volumes, policies, and market factors. Renewable and Sustainable Energy Reviews, 16(5), 3176-3199.
Larsen, J., Haven, M. Ø., & Thirup, L. (2012). Inbicon makes lignocellulosic ethanol a commercial reality. Biomass and Bioenergy, 46, 36-45.
Larsen, L. E., Jepsen, M. R., & Frederiksen, P. (2013). Scenarios for biofuel demands, biomass production and land use–The case of Denmark. Biomass and Bioenergy, 55, 27-40.
Lindahl, K. B., & Westholm, E. (2012). Future forests: Perceptions and strategies of key actors. Scandinavian Journal of Forest Research, 27(2), 154-163.
Lipp, J., (2007). Lessons for effective renewable electricity policy from Denmark, Germany and the United Kingdom. Energy policy, 35(11), 5481-5495.
Lund, H. 2007. Renewable energy strategies for sustainable development.Energy, 32(6), 912-919.
Mabee, W.E., Fraser, E.D.G., McFarlane, P.N., Saddler, J.N., (2006). Canadian biomass reserves for biorefining. Appl. Biochem. Biotechnol. 129, 22–40.
Mathiesen, B. V., Lund, H., & Karlsson, K. (2011). 100% Renewable energy systems, climate mitigation and economic growth. Applied Energy, 88(2), 488-501.
Matsuoka, S., Ferro, J., & Arruda, P. (2011). The Brazilian experience of sugarcane ethanol industry. In Biofuels (pp. 157-172). Springer New York.
McKendry, P. (2002). Energy production from biomass (part 2): conversion

technologies. Bioresource technology, 83(1), 47-54.
Mendonca, M., Lacey, S., & Hvelplund, F. (2009). Stability, participation and transparency in renewable energy policy: Lessons from Denmark and the United States. Policy and Society, 27(4), 379-398.
Metcalfe, J. S. (1988). The diffusion of innovations: an interpretive study. G. Dosi, C. Freeman, R. Nelson, G. Silverberg, and L. Soete (Eds.), Technical Change and Economic Theory. London: Pinter.
Meyer, N. I., & Koefoed, A. L. (2003). Danish energy reform: policy implications for renewables. Energy Policy, 31(7), 597-607.
Ministry of Mines and Energy (MME). (2012). Brazilian Energy Balance 2012. Rio de Janeiro, Brazil.
Ministry of the Environment Sweden. (2011). 20 Years of carbon pricing in Sweden 1991-2011; History current policy and the future. Accessed 14 March 2013. <http://www.ceps.eu/files/MinistrySweden.pdf>.
Miranowski, J., & Rosburg, A. (2012). Long-term biofuel projections under different oil price scenarios. AgBioForum, 16(1), 79-87
Montalvo, C. (2008). General wisdom concerning the factors affecting the adoption of cleaner technologies: a survey 1990–2007. Journal of Cleaner Production, 16(1), S7-S1
Morgera, E., Kulovesi, K., Gobena A., 2009. Case Studies on Bioenergy Policy and Law: Options for Sustainably. FAO Legislative Study 102. FAO, Rome ,Italy. Accessed 16 March 2014. <http://www.fao.org/docrep/012/i1285e/ i1285e00.htm>.
Morris G. (2002). Biomass energy production in California 2002: update of the California biomass Database. National renewable energy Laboratory Subcontractor report. NREL/ SR-510e33111; Dec. 2002.
Naqvi, M., Yan, J., & Dahlquist, E. (2010). Black liquor gasification integrated in pulp and paper mills: A critical review. Bioresource Technology, 101(21), 8001-8015. doi: 10.1016/j.biortech.2010.05.013
Nasdaq. (2014). Accessed 30 December 2014. <http://www.nasdaq.com/markets/crude-oil-brent.aspx>.
NDRC. (2007). Medium and Long-Term Development Plan for Renewable Energy in China, the National Development and Reform Commission. Accessed 6 July 2013. <http://www.china.com.cn/policy/txt/2007-09/04/content_ 8800358.htm>.
Nicholls, D.L., Monserud, R.A. and Dykstra, D.P. (2008). A Synthesis of Biomass Utilization for Bioenergy Production in the Western United States. USDA.
Nikolaisen, L. (2012). IEA Bioenergy Task 40 Country report 2011 for Denmark. Danish Technological Institute Renewable Energy & Transport. Sønder Stenderup, Denmark.
Ohlrogge, J., Allen, D., Berguson, B., DellaPenna, D., Shachar-Hill, Y., & Stymne, S. (2009). Driving on biomass. Science, 324(5930), 1019.
Oladosu, G., Kline, K., Leiby, P., Uria-Martinez, R., Davis, M., Downing, M., & Eaton, L. (2012). Global economic effects of U.S. biofuel policy and the potential contribution from advanced biofuels. Biofuels, 3(6), 703-723.
Perlack, R. D., Eaton, L. M., Turhollow Jr, A. F., Langholtz, M. H., Brandt, C. C., Downing, M. E., ... & Lightle, D. (2011). U.S. billion-ton update: biomass supply for a bioenergy and bioproducts industry.
Popp, A., Krause, M., Dietrich, J. P., Lotze-Campen, H., Leimbach, M., Beringer, T., & Bauer, N. (2012). Additional CO 2 emissions from land use change—forest conservation as a precondition for sustainable production of second generation bioenergy. Ecological Economics, 74, 64-70.

Pöyry, (2011). Pelets- Becoming a global commodity?- Perspective on the global pellet market to 2020. Pöyry, Vantaa, Finland.
Qiu, H., Sun, L., Huang, J., & Rozelle, S. (2012). Liquid biofuels in china: Current status, government policies, and future opportunities and challenges. Renewable and Sustainable Energy Reviews, 16(5), 3095-3104. doi: 10.1016/j.rser.2012.02.036
Richardson, B. (2012). From a fossil-fuel to a biobased economy: The politics of industrial biotechnology. Environment and Planning C: Government and Policy, 30(2), 282-296.
Rinebolt, D. C. (1996). The potential for using wood for energy and
the implications for climate change. Forests and global change: forest management opportunities for mitigating carbon emissions. Washington, DC: American Forests, 117-130.
Rogner, H., (2000). Energy Resources (chapter 5), in Goldemberg, J., Baker, J., Khatib, H., Ba-N'Daw, S., Propescu, A. and Viray, F. World Energy Assessment; energy and the challenge of sustainability (pp135-171). New York, NY, USA: United Nations Development Programme UNDP.
Raomero, S. and Thomas, L. Jr. (2014). Brazil's Star, Petrobras, Is Hobbled by Scandal and Stagnation. Accessed 2 January 2015. <http://www.nytimes.com/2014/04/16/business/International/brazils-star-petrobras-is-hobbled-by-scandal-and-stagnation.html>.
Rosegrant, M. W. (2008). Biofuels and grain prices: impacts and policy responses. Washington DC, USA: International Food Policy Research Institute.
Rosillo-Calle, F., & Cortez, L. A. (1998). Towards ProAlcool II—a review of the Brazilian bioethanol programme. Biomass and Bioenergy, 14(2), 115-124.
Salomón, M., Savola, T., Martin, A., Fogelholm, C. J., & Fransson, T. (2011). Small-scale biomass CHP plants in Sweden and Finland. Renewable and Sustainable Energy Reviews, 15(9), 4451-4465.
Scarlat, N. & Dallemand, J. (2011). Recent developments of biofuels/bioenergy sustainability certification: A global overview. Energy Policy, 39(3), p. 1630 1646.
Schnepf, R., & Yacobucci, B. D. (2013). Renewable Fuel Standard (RFS): Overview and Issues. Congressional Research Service, Washington, DC, USA.
Schulze, E. D., Körner, C., Law, B. E., Haberl, H., & Luyssaert, S. (2012). Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. GCB Bioenergy, 4(6), 611-616.
Schwarz, G., Noe, E., & Saggau, V. (2012). Rethinking Agricultural Policy Regimes, 18(2012), 235–262. doi:10.1108/S1057-1922(2012)0000018013
Silveira, S. (Ed.). (2005). Bioenergy-realizing the potential. Elsevier. Accessed 16 March 2013. <http://books.google.ca/books?hl=en&lr=&id=qTDgf1o8weEC&oi=fnd &pg=PA31&dq=bioenergy+in+Sweden%E2%80%94an+evolving+market,&ots=ck-A9PQL6e&sig=NaRkgeheQt3It_l3i18uzgFMa3E#v=onepage&q=bioenergy%20in%20Sweden%E2%80%94an%20evolving%20market%2C&f=false>.
Skott, T. (2011). Straw to Energy: Status, techologies and innovation in Denmark 2011. Agro Business Park, Tjele, Denmark.
Song, N., Aguilar, F. X., Shifley, S. R., & Goerndt, M. E. (2012). Analysis of U.S. residential wood energy consumption: 1967–2009. Energy Economics, 34(6), 2116-2124.
Stephen, J. D., Mabee, W. E., & Saddler, J. N. (2010). Biomass logistics as a determinant of second-generation biofuel facility scale, location and technology selection. Biofuels, Bioproducts and Biorefining, 4(5), 503-518.
Swedish Bioenergy Association (SVEBIO). (2013). Bioenergy Facts. Accessed 7 January 2014. <http://www.svebio.se/english/bioenergy-facts>.

Swedish Energy Agency (SEA). (2003). Va¨xande energi. Bioenergin i Sverige—en marknad i utveckling. (Growing energy bioenergy in Sweden—an evolving market). Eskilstuna, Sweden
Swedish Energy Agency (SEA). (2011). Energiläget 2011. Swedish Energy Agency, ET 2011:42.Eskilstuna, Sweden.
Swedish Energy Agency (SEA). (2013). Energy in Sweden 2012. Accessed 11 January 2014. <http://www.energimyndigheten.se/Global/Engelska/Facts%20and%20figures/Energy_in_sweden_2012.pdf>.
Swedish Energy Agency (SEA). 2014. Transportsektorns energianvändning 2013. Eskilstuna, Sweden.
Swedish National Audit Office (SNAO). (2011). Biofuels for a Better Climate – How does the tax relief work? RiR 2011:10. Swedish National Audit Office. Accessed 14 January 2014.<http://www.riksrevisionen.se/PageFiles/13896/Summary%20%20RiR%202011_10.pdf>.
Taheripour, F., & Tyner, W. E. (2008). Ethanol policy analysis—what have we learned so far?. Choices, 23(3), 6-11.
Teknologirådet. (2006) Grøn transport—kan vi, og vil vi? Copenhagen, Denmark.
The Economist. (2014). Brazilian energy- Rain Checked. Accessed 9 January 2015. <http://www.economist.com/news/americas/21596530-parched-southern-summer-may-cause-electricity-crisis-rain-checked>
Timilsina, G. R., & Shrestha, A. (2011). How much hope should we have for biofuels?. Energy, 36(4), 2055-2069.
Trostle, R. (2008). Global Agricultural Supply and Demand: Factors Contributing to the Recent Increase in Food Commodity Prices, ERS, USDA, Washington, D.C.
Tyner, W. E. (2008). The U.S. ethanol and biofuels boom: its origins, current status, and future prospects. BioScience, 58(7), 646-653.
Tyner, W. E. (2013). Policy Update: Pity the poor biofuels policymaker.Biofuels, 4(3), 259-261.
Tyner, W. E., & Viteri, D. (2010). Policy Update: Implications of blending limits on the U.S. ethanol and biofuels markets. Biofuels, 1(2), 251-253.
Brazilian Sugarcane Industry Association (UNICA). (2014). Brazilian Sugarcane Harvest. Accessed 6 January 2015. <http://sugarcane.org/internal/images/brazilian-sugarcane-harvest>.
United Nations (UN), (2014). The state of the biofuels market. Accessed 9 January 2015. <http://unctad.org/meetings/en/Miscellaneous%20Documents/Biofuels_draft_2_SmWithCover.pdf>.
U.S. Department of Agriculture (USDA). (2013). Brazil Biofuels Annual- Annual Report 2013. Accessed 11 March 2014. <http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_9-12-2013.pdf>.
U.S. Department of Energy (DOE), (2010). Biopower Technical Strategy Workshop, December 2009. Office of the Biomass Program, EERE/DOE. Washington, D.C.
U.S. Department Of Energy (DOE). (2014). Biodiesel Blends. Accessed 30 December 2014. <http://www.afdc.energy.gov/fuels/biodiesel_blends.html>.
U.S. Department Of Energy (DOE). (2014). Drop-in Biofuels. Accessed 30 December 2014. <http://www.afdc.energy.gov/fuels/emerging_dropin_biofuels.html>.
U.S. Energy Information Administration (EIA). (2009). Industrial biomass energy consumption and electricity net generation by industry and energy source, 2009. Accessed 6 March 2014. <http://www.eia.gov/renewable/annual/trends/pdf/table1_8.pdf>.

U.S. Energy Information Administration (EIA). (2012a). Annual Energy Review 2011. Washington, D.C.
U.S. Energy Information Administration (EIA). (2012b). Table 10.1 Renewable Energy Production and Consumption by Primary Energy Source, 1949-2011. Accessed 6 March 2014.<http://www.eia.gov/renewable/data.cfm#summary>.
U.S. Environmental Protection Agency (EPA). (2013). EPA Proposes 2014 Renewable Fuel Standards, 2015 Biomass-Based Diesel Volume. Accessed 9 January 2015. <http://www.epa.gov/otaq/fuels/renewablefuels/documents/420f13048.pdf>.
U.S. Energy Information Administration. (2014). Country Analysis Note Germany. Accessed 24 June 2014. <http://www.eia.gov/countries/country-data.cfm?fips=GM>.
Valle, S. (2014). Brazil said to reject petrobras gasoline price requests. Accessed 13 October 2014. <http://www.businessweek.com/news/2014-06-04/brazil-said-to-reject-petrobras-gasoline-price-requests>.
Von Braun, J. (2008). Food and financial crises: Implications for agriculture and the poor (Vol. 20). Intl Food Policy Res Inst.
Walton, A. (2009) Provincial-level projection of the current Mountain Pine Beetle outbreak: update of the infestation projection based on the 2008 Provincial aerial overview of forest health and revisions to the model BCMPB v6. British Columbia Forest Service: Victoria, BC.
Weber, C., Farwick, A., Benisch, F., Brat, D., Dietz, H., Subtil, T., & Boles, E. (2010). Trends and challenges in the microbial production of lignocellulosic bioalcohol fuels. Applied microbiology and biotechnology, 87(4), 1303–15. doi:10.1007/s00253-010-2707-z
Westholm, E., & Beland Lindahl, K. (2012). The Nordic welfare model providing energy transition? A political geography approach to the EU RES directive.Energy Policy, 50, 328-335.
White, E. (2010). Woody Biomass for Bioenergy and Biofuels in the United States- A Briefing Paper. Oregon State University, Corvallis, Oregon, US.
Wood, S.M., Layzell, D.B. (2003). A Canadian Biomass Inventory: Feedstocks for a Bio- based Economy. BIOCAP Canada Foundation, Kingston, ON, Canada.
Yang, H., Zhou, Y., & Liu, J. (2009). Land and water requirements of biofuel and implications for food supply and the environment in China. Energy Policy,37(5), 1876-1885.
Yergin, D. (2006). Ensuring energy security. Foreign affairs, 69-82.