Bioenergy Production and Utilization in Different Sectors in Sweden: A State of the Art Review

Stephen O. Amiandamhen,[a] Anuj Kumar,[b] Stergios Adamopoulos,[a,]* Dennis Jones,[c, d] and Bengt Nilsson [a]

In the continual desire to reduce the environmental footprints of human activities, research efforts to provide cleaner energy is increasingly becoming vital. The effect of climate change on present and future existence, sustainable processes, and utilizations of renewable resources have been active topics within international discourse. In order to reduce the greenhouse gases emissions from traditional materials and processes, there has been a shift to more environmental friendly alternatives. The conversion of biomass to bioenergy, including biofuels has been considered to contribute to the future of climate change mitigation, although there are concerns about carbon balance from forest utilization. Bioenergy accounts for more than one-third of all energy used in Sweden and biomass has provided about 60% of the fuel for district heating. Apart from heat and electricity supply, the transport sector, with about 30% of global energy use, has a significant role in a sustainable bioenergy system. This review presents the state of the art in the Swedish bioenergy sector based on literature and Swedish Energy Agency's current statistics. The review also discusses the overall bioenergy production and utilization in different sectors in Sweden. The current potential, challenges, and environmental considerations of bioenergy production are also discussed.

Keywords: Bioenergy; Biofuels; Biomass; Climate change; Greenhouse gases; Sweden

*Contact information: a: Department of Forestry and Wood Technology, Faculty of Technology, Linnaeus University, Lückligs Plats 1, Växjö 35195 Sweden; b: Natural Resources Institute Finland (Luke), Production Systems, Tietotie 2, Espoo 02150 Finland; c: Luleå University of Technology, Department of Engineering Sciences and Mathematics, Wood Science and Engineering, Skellefteå 93187, Sweden; d: Faculty of Forestry and Wood Sciences, Czech University of Life sciences Prague, Kamýcká 129, 165 21 Praha 6 – Suchdol, Czech Republic; *Corresponding author: stergios.adamopoulos@lnu.se*

INTRODUCTION

Bioenergy is an important part of the energy economy, accounting for about 70% of all renewable energy supplies (Reid *et al.* 2020). The world's bioenergy sector has been growing steadily over time. According to the International Energy Agency (IEA), bioenergy is projected to grow by 37 GW over the period 2018 to 2023 to reach 158 GW. This projected growth is 10% lower than the deployment over the 2012 to 2017 period (IEA 2018). Global additions remain relatively stable at between 5 GW and 8 GW per year throughout the forecast period, with China, the Asia-Pacific region, and Brazil making key contributions (IEA 2018). In the European Union (EU), the United Kingdom and The Netherlands are major markets for bioenergy. In a bid to mitigate climate change, while providing energy for an increasingly growing population, the EU has set objectives to ensure an increase in share of renewable sources of energy generation in Europe. The target is to reach 10% and 14% of renewable energy in the transport sector by 2020 and 2030 respectively (Jåstad *et al.* 2020). This will result in a 20% reduction in greenhouse gas

(GHG) emissions by 2020, as well reductions in the overall dependency on fossil fuels (Lund 2007; Buonocore *et al*. 2012). These measures will intensify further, with the EU's intention of being climate-neutral by 2050. Although renewable energy is important going forward in meeting the EU's objectives, the renewable energy supply chain alone cannot meet the world's energy requirements (Swedish Energy Agency, SEA 2009). Consequently, local efforts should ensure that energy production and use have a reduced impact on global climate. Sweden's efforts on energy research and development (R&D) has been an important contributor to the growth of the economy. Originally, the aim of the R&D programme was to reduce national dependency on imported oil. However, over the last three decades, energy efficiency and renewable energy have been the subject of many research efforts (SEA 2009). In 2009, the Swedish government introduced a cohesive climate and energy policy, which targeted a 40% reduction in climate gas emissions and an energy supply consisting of at least 50% renewable energy. The vision was to achieve zero net emissions of GHGs by 2050 (in line with EU aspirations) and target a fossil-free vehicle fleet by 2030. In addition, the use of fossil fuels for heating is planned to be phased out by 2020 and efforts on renewable energy production, including bioenergy, intensified (SEA 2009). Subsequently, the share of energy from renewable sources was increased to 55% in 2017 compared to 38% in 1999 (SEA 2019). To mitigate the effect of climate change and other environmental concerns, as well as increase energy security, it is important to increase the share of bioenergy in the energy system (Buonocore *et al*. 2012).

Bioenergy generation in Sweden has steadily grown over the past few decades, with a significant increase in production between 2005 and 2017. Supported by strong legislative driving forces, the Swedish energy sector has become a vehicle for a fossil-free market approach in bioenergy production and utilizations. The bioenergy generated is utilized in a variety of sectors including transport, industry, and district heating, with the industry and district heating being the biggest sectors. The transport sector mainly utilized biofuel products such as bioethanol, biodiesel, and biogas. Börjesson *et al.* (2015) analyzed the future of bioenergy in Sweden and its effect on the reduction of CO_2 and other GHGs. The analysis was based on the bottom-up, optimized MARKet and ALlocation (MARKAL) model, which included a comprehensive representation of the national energy system. According to their results, the total bioenergy use will be significantly increased by 63% by 2050 compared to 2010. On the other hand, the CO_2 emission will reduce by 80% by 2050. The largest increase will occur in the transport sector, which is anticipated to account for 43% of the total primary bioenergy use by 2050.

In line with this projected increase and a production target to meet the bioenergy needs in Sweden, it is imperative to have a sustainable supply of materials for bioenergy production. Biomass for energy production can be obtained from different bio-based materials, as well as municipal biodegradable waste. Various lignocellulosic materials including forest biomass (logging residues and sawmill side streams) and agriculture biomass (non-food energy crops and food residues) are predominately explored for bioenergy production. However, forest biomass remains the oldest source for bioenergy production (Björheden 2017). Forest biomass, energy crops, and agricultural residues are the main biomass types available in Sweden. More than half the land area of Sweden, about 57% or 23 million hectares is covered in forest, making forest biomass a sustainable base for a substantial increase in bioenergy production. The Swedish agricultural sector also contributes to biomass production, not only with residues but especially in energy crops to supplement forest-based biomass.

There are several studies on Swedish bioenergy production focused on raw materials including energy crops (Nordborg *et al*. 2018a, b), agricultural residues (Waldenström *et al*. 2016; Bentsen *et al*. 2018), forest biomass (Bryngemark 2019), stump harvesting (Persson and Egnell 2018), and marine biomass (Hackl *et al*. 2018; Wollak *et al*. 2018). Some studies have addressed certain developments in the bioenergy sectors concerning district heating (Amiri and Weinberger 2018; Sernhed *et al*. 2018; Brinkley 2018), biofuels for transport (Ouraich *et al.* 2018; Mutter 2019), energy policies (Börjesson *et al*. 2015; Hansen and Berlina 2018), and climate impacts of bioenergy production and consumption (Ortiz *et al*. 2016; Hammar *et al.* 2019; Schmidt *et al*. 2019). One of the major considerations in forest biomass utilization is the increasing demand for bioenergy, and this is expected to result in conflict with other economic interests. The aim of this study is to review and characterize bioenergy production and utilization in different sectors in Sweden. The prospects and challenges in the bioenergy sector for forest raw materials are also discussed.

BIOMASS AVAILABILITY

Forest Biomass

Forest biomass is a renewable component of the natural carbon cycle, thus representing an important factor in national, regional, and local supply of raw materials. Forest biomass includes energy crops, woody stems, and other parts of the tree, which are regarded as logging residues. Apart from the traditional use of wood, forest biomass is used as fuel for heating and power generation, and in the production of liquid and gaseous biofuels (Lundmark *et al*. 2015). Recycled waste wood, sawmill residues, and woody pellets are classified as secondary forest biomass, which is also used as fuel (Ericsson *et al*. 2004). Forest biomass is one of the most important sources of bioenergy, accounting for approximately half of the EU's total renewable energy consumption (Jonsson *et al*. 2018). However, about 35% of the annual forest harvest in Sweden is left in the forest as residues. This represents about 138 TWh of bioenergy, which will eventually decompose and release CO_2 into the atmosphere (IRENA 2019b). In recent years, the demand for forest fuel has declined, partly due to mild winters and consequently lower than usual fuel demands from heating plants (Nilsson 2016). It is expected that demand for forest fuel in Sweden will increase by 30 TWh in 2030, and an additional 35 to 40 TWh in 2050 (Börjesson *et al*. 2017). This is comparable to current annual biomass use at 130 TWh. In 2005, forest fuel accounted for about 20 TWh of biofuel use, from which logging residues accounted for about 5 to 6 TWh (Anon 2006). According to de Jong *et al*. (2012), about 6% of biofuel used in Sweden is processed from logging residues. It is estimated that about 60 TWh of potential energy will be generated annually from logging residues in the 2020s; however, this estimate can be reduced by about 25% due to ecological limitations (Fridh and Christiansen 2015).

The supply of wood-based materials to the energy sector is an important contributor to sustainable energy security and meeting the targets of a fossil-free economy in Sweden. Table 1 presents the production, export, and import data of wood-based materials in Sweden between 2014 and 2018. Wood residues during the last decade have become the leading raw material in bioenergy sector. However, much still depends on the importation of this material. The import of wood residues increased to 816,261 m^3 in 2018 compared to 676,270 m^3 in 2014.

Table 1. Wood Based Materials for Energy Sector: Production, Export and Import in Sweden compared with Europe between 2014 and 2018. Table republished from FAO (2019) with permission from FAO

Wood materials	Value (m^3)	Region	2014	2015	2016	2017	2018
Wood residues (m^3)	Production	Sweden Europe	8,600,000 72,784,087	10,175,000 74,152,848	8,799,000 60,091,158	9,151,000 61,283,124	9,151,000 62,563,494
	Export	Sweden Europe	71,450 8,460,800	121,672 7,916,958	97,222 6,303,226	59,490 5,660,178	69,221 5,671,641
	Import	Sweden Europe	676,270 11,170,023	667,410 10,383,364	957,274 7,648,161	780,793 6,201,983	816,261 7,593,094
Wood pellets (tons)	Production	Sweden Europe	1,577,000 15,240,295	1,660,000 16,415,888	1,738,000 16,976,197	1,741,000 18,999,782	1,835,000 20,567,938
	Export	Sweden Europe	252,790 8,109,078	245,000 8,556,760	228,316 8,530,329	199,650 10,079,348	154,276 11,067,620
	Import	Sweden Europe	521,630 12,364,143	354,942 13,680,839	267,977 13,972,453	272,260 15,437,745	379,955 17,332,175
Wood charcoal (tons)	Production	Sweden Europe	500 578,340	500 609,966	500 670,630	1,000 711,377	1,000 713,613
	Export	Sweden Europe	1,820 438,647	1,975 510,900	1,478 609,411	1,756 650,203	1,542 716,254
	Import	Sweden Europe	39,150 991,485	24,761 1,044,261	35,893 1,029,125	31,363 1,059,961	28,346 1,183,205
Wood chips and particles (m^3)	Production	Sweden Europe	10,300,000 73,005,261	9,965,000 73,142,932	11,344,000 80,650,004	11,368,000 84,120,280	11,368,000 86,459,020
	Export	Sweden Europe	161,540 12,294,801	206,751 11,579,166	266,115 12,407,301	259,372 14,604,806	226,994 15,762,715
	Import	Sweden Europe	1,132,260 14,049,682	1,082,911 13,222,143	1,530,204 14,902,805	1,988,728 16,435,815	2,112,059 17,120,249
Wood fuel (all species, m^3)	Production	Sweden Europe	- -	- -	- -	- -	- -
	Export	Sweden Europe	14,850 8,263,712	62,918 8,376,396	26,544 7,821,308	- -	- -
	Import	Sweden Europe	377,470 5,895,892	271,830 5,063,152	188,183 4,902,525	- -	- -
Recovered waste wood (tons)	Production	Sweden Europe	- -	- -	- -	1,502,000 26,166,537	1,502,000 26,357,139
	Export	Sweden Europe	- -	- -	- -	- 1,943,946	- 2,025,765
	Import	Sweden Europe	- -	- -	- -	- 3,035,327	- 2,918,729

In the European market, there has been a relatively steady decline in import and export of wood residues, whilst the production has been unstable but currently at 62,563,494 m^3 in 2018. The domestic production of wood residues also increased to 9,151,000 m^3 in 2018 from 8,600,000 in 2014. Solid fuels from forest biomass such as wood pellets have established a strong hold in the Swedish bioenergy sector. The production of wood pellets increased annually, reaching 1.835 million tons in 2018 from 1.577 million tons in 2014. Wood charcoal also contributes to the bioenergy sector in terms of utilization, but wood charcoal is mostly imported to Sweden, with imports reaching 28,346 tons in 2018. Wood chips and particles also have big potential for the energy sector, with a stable production of wood chips and particles for some time. In 2011, the production of wood chips reached an all-time high of 16 million m^3. Thereafter, production decreased annually due to competition from other sectors, especially from wood-based panels, which use these materials in its production. In 2017, IKEA started a new particleboard production plant in Sweden, thereby putting further restraint on the availability of wood chips and particles for bioenergy production. The wood chips production appears to be levelling-off at 11,368,000 in 2018. However, the situation in Europe has been unaffected by market forces, with a significant increase in wood chips production from 73 million m^3 in 2014 to 86.4 million m^3 in 2018.

Energy Crops and Agricultural Residues

Energy crops cultivated on agricultural and/or marginal land are herbaceous or woody crops. Stands of woody crops are usually referred to as short rotation coppice plantations. Traditionally, the herbaceous crops are grown for food or fodder production. Short rotation woody crops (SRWC) have the potential to provide a sustainable source of biomass, especially on contaminated land of limited use (Djomo *et al*. 2011). Energy crops are useful for energy generation and biogas production. To ensure bioenergy supply sustainability, the realizable energy from biomass must be greater than the energy used in production and transport (Bentsen *et al*. 2016). The potential of energy crops for biogas production varies from region to region. Some of the criteria used to compare this potential include land area for agriculture, arable land and arable land per capita. Sweden's potential for energy crop was estimated as 0.36 ha arable land per capita, which is lower than the European average of 0.41 (Holm-Nielsen and Oleskowicz-Popiel 2007). However, there is considerable potential to generate biogas from energy crops in Sweden, which can surpass 4 TWh in the midterm. It was assumed that 25% of the energy crops can be used for biogas generation out of 10% available arable land (Holm-Nielsen and Oleskowicz-Popiel 2007). Energy crops are also useful in crop rotation to improve soil quality on fallow land (Lönnqvist *et al*. 2013).

Agricultural residues cover both primary residues, *i.e.* harvesting residues and secondary residues (Rettenmaier *et al.* 2010). Currently, agricultural residues are also used for bioenergy generation, as well as biofuel production. The bioenergy production from agricultural biomass is estimated at 6 to 8 TWh by 2020, comprising about 1% of total energy supply (Waldenström *et al.* 2016). The potential for agricultural residues in the bioenergy system is due to the versatility of bioenergy, compared to other renewable sources. To meet the target of sustainable energy for all, about 13 to 30 EJ yr^{-1} of agricultural residues must be used by 2030. This target requires that the share of renewable energy is doubled in the global energy assessment before 2030 by extensive utilization of agricultural residues (Bentsen *et al*. 2016). Currently, the biomass potential of primary agricultural residues is approximately 3.7 billion metric tons of dry matter annually, which corresponds to approximately 65 EJ yr^{-1}. This represents the global theoretically potential of cereals and sugar cane, which accounts for 80% of the total residue production (Bentsen *et al*. 2016). Despite the potential of agricultural residues, a certain share must be recycled to the ecosystem to avoid loss of soil nutrients. Biomass residues are important ecosystem components, and their extraction should comply with ecological restrictions (Manolis *et al*. 2019).

CURRENT BIOENERGY SITUATION IN SWEDEN

Traditionally, energy use in Sweden is largely based on renewables and nuclear energy, which is about two-third of the primary energy supply (IEA Bioenergy 2018). Fossil fuels including oil products, coal, natural gas, and peat make up about 30% of the energy supply (Fig. 1). The use of nuclear power increased since the oil crises of 1973. However, the disasters at Three Mile Island (1979) and Chernobyl (1986), and the zero nuclear power target by 2010 resulted in increased searches for alternative energy sources (Bentsen *et al.* 2016). The use of fossil oil in the Swedish energy supplies is currently about 24% compared to 75% in 1970. This significant decline could be due to utilization of alternative energy source for residential heating, which was almost totally dependent on fossil oil. The total primary energy supply of Sweden in 2016 amounted to 2,061 petajoule (PJ) with an export surplus of electricity of 42 PJ. In 2017, about 66% of total renewable resources was used in electricity generation.

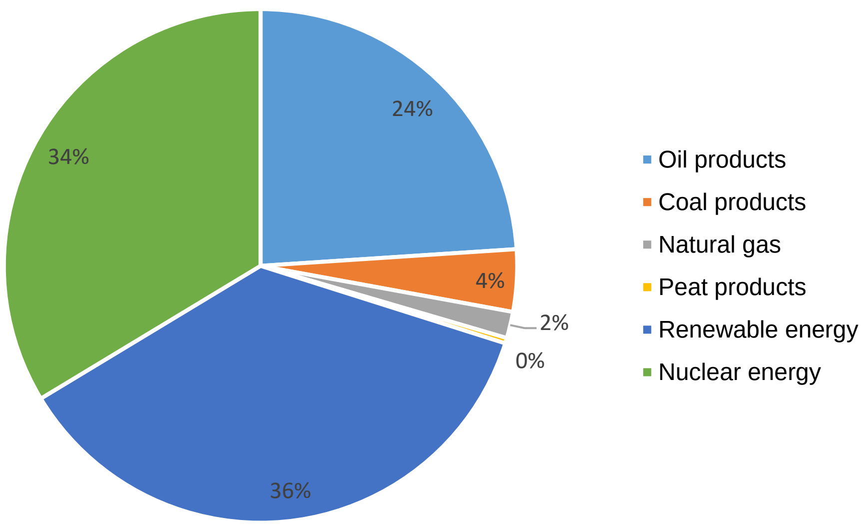

Fig. 1. Total primary energy supply in Sweden. Figure republished from IEA Bioenergy (2018) with permission from the International Energy Agency

In Sweden, the bioenergy sector covers biomass utilization for energy generation and production of biofuels including biogas, biodiesel, and bioethanol. The bioenergy sector also covers bioenergy use in different sectors, including residential and services, industrial, and transportation sectors. According to the Swedish Commission on Oil Independence, it was predicted that Sweden will be using 228 TWh of bioenergy annually by 2050 (Anon 2006). The Swedish bioenergy sector uses different biomass including solid and liquid biofuels, wood fuel, vegetable and animal oils, biogas, and municipal biodegradable waste for energy generation. The use of biomass varies among different sectors as illustrated in Fig. 2. The total use of biomass for energy generation shows an increasing trend from 52 TWh in 1983 to 143 TWh in 2017. Industry and district heating were the largest sectors in biomass utilization for energy, and they utilized 56 and 38 TWh, respectively, of biomass energy in 2017. In the industrial sector, pulp and paper mill was the largest user of biomass for energy with a final energy use of 49.7 TWh in 2017, sharing about 88% of total biomass use. Wood products industry shared 9% while non-metallic mineral, food and beverage, and chemical engineering industries shared 1% of biomass use, respectively (Fig. 3). The district heating sector showed a significant increment from 2 to 38 TWh from 1983 to 2017. District heating has been the driving force for use of primary forest fuel in Sweden. The use of biomass for energy in the residential and services sector may decrease by 10% by 2030. This decrease may be caused by increased demand for heat pumps and use of energy efficient buildings (Börjesson *et al.* 2017). The amount of biomass fuel used for electricity production increased from 2 to 15 TWh from 1983 to 2017. The amount of electricity production by biomass increased from 4 TWh in 2003 to 11 TWh in 2010, but it decreased to 5 TWh in 2018 (SEA 2019) owing to the use of alternative sources of renewable energy. The transport sector has also been growing since the year 2002 (Fig. 2). In 2017, about 39% of biomass resources *i.e.* biofuels was used in the transport sector (SEA 2019).

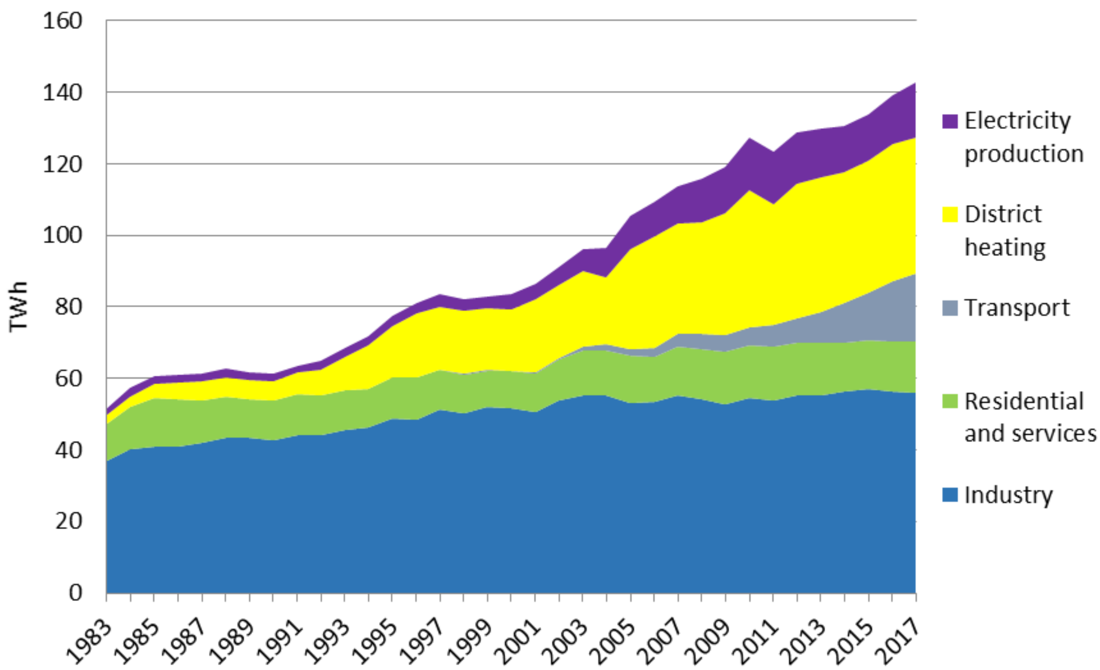

Fig. 2. Use of biomass in different sectors for energy generation (1983 to 2017). Figure republished from SEA (2019) with permission from the Swedish Energy Agency

In the Swedish bioenergy sector, the total biomass energy generated from different biomass increased significantly during the last decade (Fig. 4). Undensified wood fuel and black liquor were the largest contributors with 55,059 and 44,181 GWh respectively in 2017 (SEA 2019). Biodiesel and municipal biodegradable waste also contributed largely to bioenergy production.

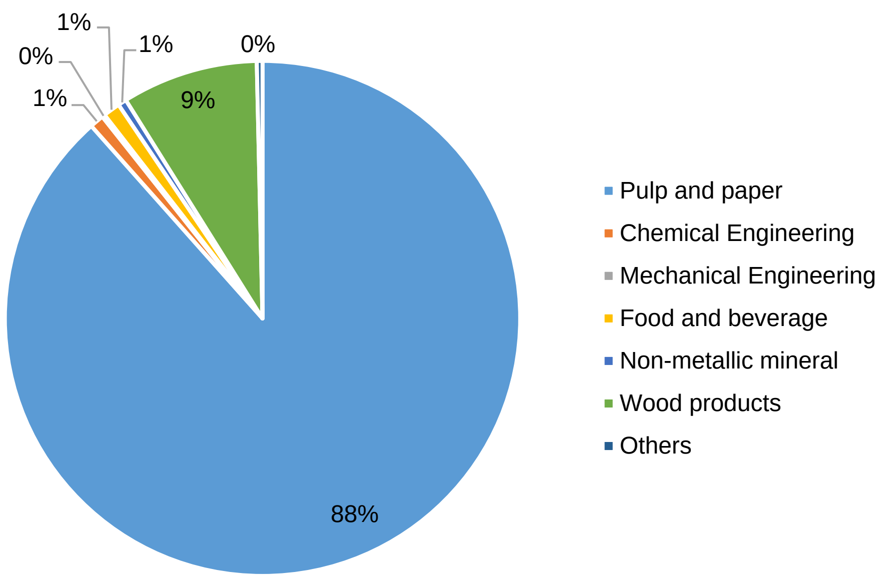

Fig. 3. Use of biomass for energy in the industrial sector (TWh). Figure republished from SEA (2019) with permission from the Swedish Energy Agency

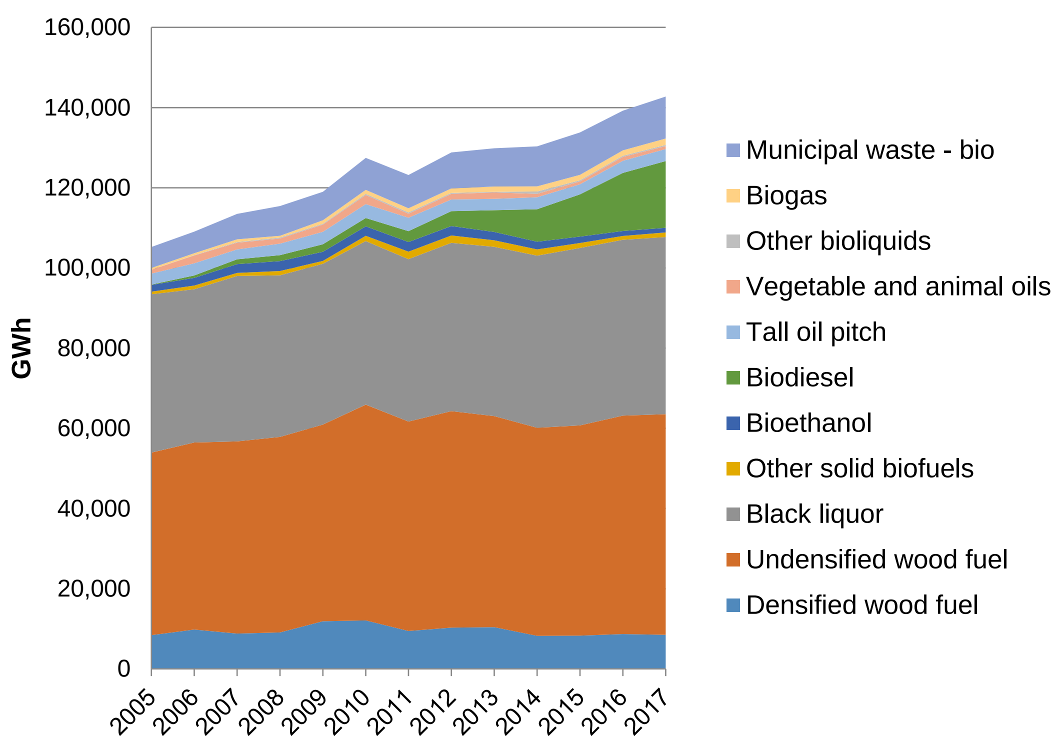

Fig. 4. Use of biomass by fuel category, GWh. Figure republished from SEA (2019) with permission from the Swedish Energy Agency

Figure 5 shows the total energy use by energy carrier in Sweden from 1970 to 2017. Electrical energy consumption, with a share of 33%, has been inconsistent since 1970, whilst energy consumption by district heating has been steady at 50 TWh since 2012. The

Swedish district heating system has adapted to several challenges including market, feedstock, distribution network, and climate benefits (Werner 2017). The consumption of biomass energy showed a linear trend, reaching 89 TWh in 2017 compared to 45 TWh in 1970, thereby accounting to 23% of energy generation. The consumption of petroleum products was reduced to 87 TWh in 2017 from 247 TWh in 1970, and it also shared 23% in the energy sector.

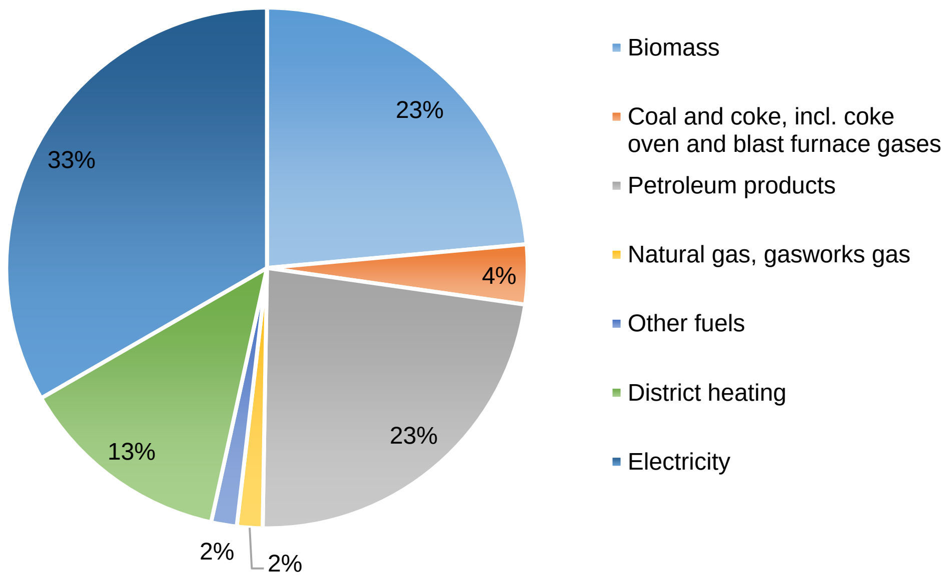

Fig. 5. Sweden's total final energy use, per energy carrier 2017. Figure republished from SEA (2019) with permission from the Swedish Energy Agency

According to SEA (2019), the final biomass energy use in the residential and services sector has been relatively steady for about five decades (1970 to 2017), ranging between 12 to 14 TWh of biomass energy. In the industrial sector, the final energy use by biomass showed an annual fluctuation between 32.7 to 56.1 TWh during the same period. In the transport sector, the final energy use by biofuels ranged from 0 to 19.1 TWh during the period 1996 to 2017 (SEA 2019).

BIOFUELS IN SWEDEN

Biofuels constitute the different fuels produced from conventional processes using biomass. First generation biofuels were produced from existing agricultural crops including sugars, grains, and oilseeds, which are used for food, feed, and industrial purposes (Bentsen *et al*. 2016). In Sweden, the main biofuels produced include bioethanol, biodiesel including fatty acid methyl esters (FAME), hydrotreated vegetable oils (HVO), and biogas. In addition, dimethyl ether (DME) and ethyl tert-butyl ether (ETBE, an ethanol-based octane increasing additive for gasoline) are used in minimal volumes (Grahn and Hansson 2015). Since 2000, biofuel consumption in Sweden has increased significantly. Whilst bioethanol and biodiesel consumption has saturated in recent years, the production and consumption of biogas and HVO has increased (Martin *et al*. 2020).

About 47% of the bioethanol production was used in the manufacture of low blend fuel, while about 90% of the biodiesel in the transport sector was also based on low blend formulations, 70% of which consisted of FAME. The share of biogas of the total gas use for vehicles amounted to about 60% (Grahn and Hansson 2015).

Due to the availability of raw materials for production, liquid biofuels such as bioethanol and HVO are important drivers for a fossil-free road transport in Sweden Bryngemark 2019). To promote the consumption of these biofuels, different tax exemption rates are applied by the Swedish government, which depends on the type of biofuel (bioethanol, FAME, or HVO), and on the content of the biofuel mixture (Climate Chance 2018). Consequently, HVO100 is totally exempt from both carbon tax and energy tax, and its price remains competitive with that of fossil diesel. The consumption of HVO increased significantly between 2015 and 2017, and it had a share of about 73% of liquid biofuel shipments, making HVO the third most consumed fuel in Sweden, following petrol and diesel (Climate Chance 2018). There is a huge potential for these liquid biofuels to replace fossil-based fuels in all types of internal combustion engines that traditionally use gasoline, diesel, or kerosene (IRENA 2019a). According to the renewable energy roadmap, the use of liquid biofuels in freight and shipping have the potential to reduce GHG emission by 80% and increase the market share of transport energy use to 10% by 2030.

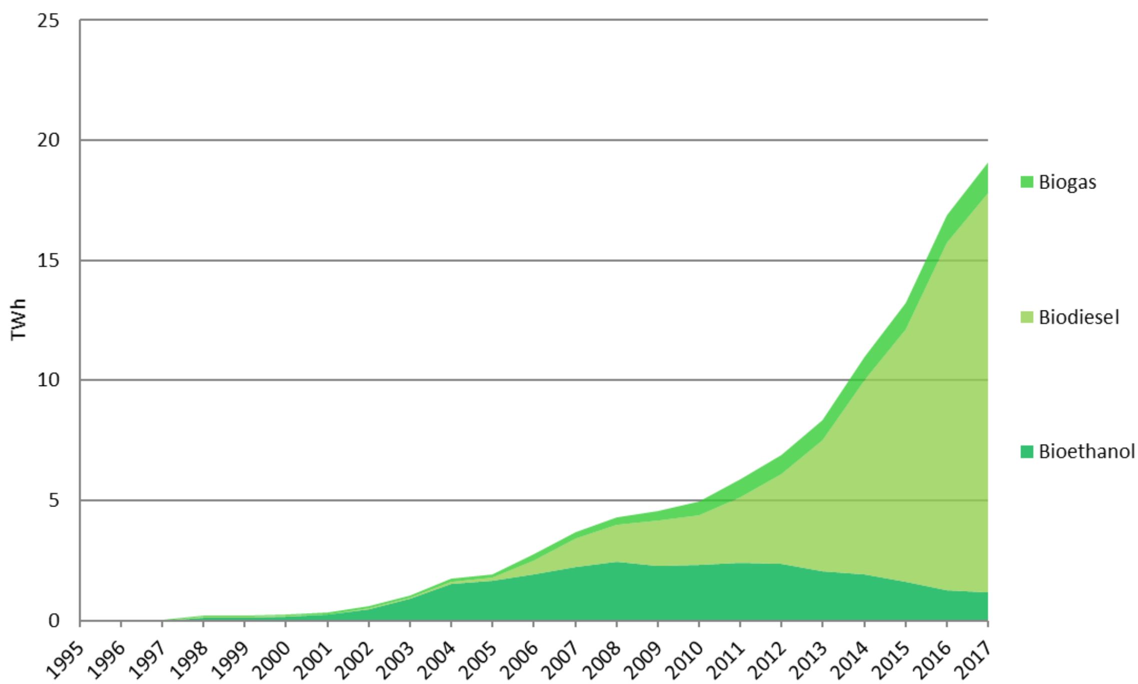

Fig. 6. Biofuels used in the transport sector in Sweden. Figure republished from SEA (2019) with permission from the Swedish Energy Agency

There has been an increased utilization of biofuels, and especially biodiesel, over the past few decades (SEA 2018). These fuels have been mostly used in the transport sector, and amounted to about 19.1 TWh in 2017, which corresponded to about 19% of the transport sector's energy use. According to the International Renewable Energy Agency (IRENA), the use of biofuels in road transport, aviation or shipping has the potential to significantly reduce emission of GHGs (IRENA 2019a). In 2019, Scandinavian Airlines (SAS) announced they were using biofuels derived from forest residues and the camelina plant (*Camelina sativa*), which can be cultivated on marginal land (SAS 2019). Figure 6 shows the trend in the total amount of biofuels used in Swedish transport sector during the last two decades (SEA 2019), though the announcement by SAS related to using aviation biofuel will see a further increase in the coming years. SAS plans to substitute the current volume of aviation fuel for biofuel by 2030. The plant is expected to start operation by the end of 2022 with an initial annual capacity of 300,000 m^3 (SAS 2019).

Biodiesel

Biodiesel represents a range of biofuels produced from vegetable oil or animal fat, which consists of long-chain alkyl (methyl, ethyl, or propyl) esters. Basically biodiesel is made by the chemical reaction of lipids including soybean oil and animal fat with alcohol to produce fatty acid esters. In Sweden, biodiesel components such as FAME, HVO, and DME are often blended with fossil diesel in a low blend, but they can also be high blends that have more or less pure biodiesel (Hult and Mendoza 2014). FAME is produced by the esterification of vegetable oils using methanol as a catalyst, HVO is produced by the reaction of fatty acids with hydrogen, whilst DME is a synthetic gaseous diesel fuel that is produced by the dehydration of methanol. HVO is readily used in Sweden and the feedstock used for production are crude tall oil, vegetable, or animal waste oil, slaughterhouse waste, palm oil, animal fats, *etc*., although palm oil and animal fats are no longer in use due to EU regulations (SEA 2019). Recently, other materials including rapeseed, palm fatty acid distillate (PFAD), and maize are being used for HVO production. HVO can be used in high concentration in diesel engines, or even in pure form (HVO100). Traditionally, biodiesels have been produced from vegetable sources, *i.e.,* first generation biodiesels resulting in competition with the food production sector (Grippi *et al.* 2020). Consequently, the potential of processing lignocellulosic biomass and residues to FAME has been exploited (Hult and Mendoza 2014). Biodiesel can also be produced from tall oil, which is processed from black liquor.

Bioethanol

Bioethanol is produced by the fermentation of simple sugars in food crops, biomass and lignocellulosic feedstock. The main sources of raw materials for bioethanol production in Sweden are wheat, maize, barley, triticale, sugar cane, sugar beet, *etc*. The production process depends on feedstock but it generally involves pretreatment of the raw materials, distillation, conversion, and product purification. Bioethanol is usually blended with gasoline in varying contents from 5 to 100%, representing blends of anhydrous ethanol in gasoline; however, the most common blends are E5, E10, and E85 (Bušić *et al.* 2018). In Sweden, all 95-octane fuel is E5, and it is used in conventional gasoline engines. E85 is also widely available owing to its ability to run flexible-fuel vehicles. Although many countries are now producing E10 for light-duty vehicles, there has been no recent market development from E5 to E10 in Sweden (Ekbom 2018). A blend of 95% ethanol and 5% of the ignition improver ED95, which was developed by Sekab with the aim of improving ignition in modified diesel engines, has been used in Sweden since 1985. In addition E100 is used to a limited extent. Bioethanol consumption in Sweden has been on a decline compared to other transport biofuels, decreasing from 2.4 TWh in 2011 to 1.1 TWh in 2017 (SEA 2019). According to World Data Atlas, ethanol consumption in Sweden was about 5,500 barrels per day, which was higher than the daily production of 3,160 barrels per day in 2016 (Knoema 2019). Most of the ethanol used in Sweden is imported, with United Kingdom and Ukraine currently providing a larger share of the import (SEA 2019). The production of ethanol and its derivatives for transport vehicles have been relatively unstable in many countries due to several factors including feedstock, fluctuating prices, competition with other biofuels, and more significantly government policies. In 2016, the global ethanol production was 100.2 billion litres, and this is expected to increase to 134.5 billion litres by 2024 (Bušić *et al.* 2018). Ethanol production from lignocellulosic biomass such as straw and logging residues have greater potential to reduce GHG emissions and the risk associated with land use changes (Börjesson *et al*. 2012).

Biogas

Biogas is produced by the decomposition of organic matter including lignocellulosic biomass in the absence of oxygen. Biogas can also be produced together with hydrogen from renewable electricity in a power-to-gas process (IRENA 2018). In Europe, Sweden has the highest biogas share in natural gas use at more than 23%, driven by government incentives in the last couple of years.

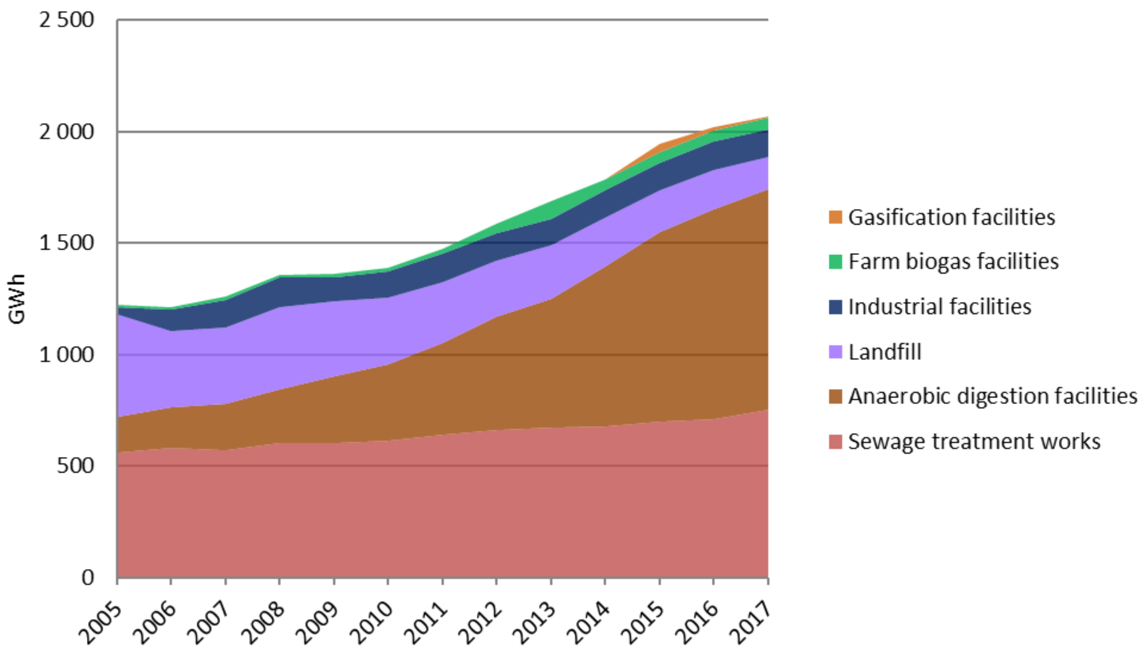

Fig. 7. Production of biogas by facilities. Figure republished from SEA (2019) with permission from the Swedish Energy Agency

In 2015, biogas production in Sweden was approximately 7,009 TJ of primary energy, which represented 195 million m^3 natural gas equivalent (Scarlat *et al*. 2018). Biogas has a greater potential to reduce GHG by 60 to 80% when used as a vehicle fuel compared to gasoline or diesel. The production of biogas generates liquid residues that can be used in other aspects such as fertilizer applications. Using liquid residues as organic fertilizer can contribute to methane (CH_4) reduction, which invariably reduces the overall GHG emissions (IRENA 2019a). Figure 7 shows the production of biogas, from different facilities in Sweden from 2005 to 2017 (SEA 2019). Various raw materials including animal and vegetable byproducts, household and industrial waste, as well as energy crops can be used in biogas production. Lönnqvist *et al.* (2013; 2015) reviewed the Swedish biomass potential for biogas production and they found that the demand for biogas in transport has increased, requiring supplementation with fossil gas. Conventionally, biogas is usually upgraded by blending with natural gas, which is then supplied to the natural gas grid. This upgrading has been necessitated by a shift from heat and electricity production due to emerging opportunities in transport sector and advancement in technology. The biomethane thus produced can be used as vehicle fuel, for electricity generation, or energy supply for district heating or cooling (IRENA 2018). The use of biomethane as transport fuel has been promoted by Swedish government incentives for use in both public and private vehicles.

CURRENT BIOFUEL SITUATION IN SWEDEN

In recent years, there has been a series of recommendations by the Swedish government toward biofuel production and market. The Swedish policy framework has been to reduce fossil dependence and GHG emissions in the transport sector (Martin *et al*. 2020). The recommendations are based on a long-term priority for the transportation sector. Consequently, the Swedish vehicle fleet was proposed to be independent of fossil fuels by 2030. The recommendation also proposes a longer-term vision for 2050, whereby Sweden would have a sustainable resource base and energy security with zero GHG emissions (Holmgren 2012). In line with this advocacy, the Swedish biofuel market has been promoted by several incentives, amongst which are exemption from carbon and energy tax, and the continuous blending of biofuel with fossil fuel. The carbon tax has contributed significantly to the promotion of bioenergy in Sweden by making biofuel more competitive with fossil fuel (IRENA 2019b). These measures have led to developments of new biofuel grades in the Swedish market. For example, the introduction of the pump law in 2006, which requires some filling stations to also provide at least one biofuel option (Holmgren 2012), resulted in the installation of biofuel grade E85. Ethanol E85 was initially introduced to Sweden in 1994 at Örnsköldsvik, where it was used to fuel some imported flexifuel cars. Although at that time, E85 was processed from corncobs and sugarcane, the goal in Sweden was to produce it from forest residues, a process which had been long developed at the biofuel plant in Örnsköldsvik.

In Sweden, the Norwegian utility company Statkraft has developed a method to produce biodiesel from biomass including wood chips and organic waste on marginal land. The process is based on hydrothermal liquefaction and produces a second-generation biofuel, which is carbon neutral. Statkraft formed a joint venture called Silva Green Fuel AS with the Swedish forestry group Södra in 2015. The collaboration was aimed at establishing a €50 to 70 million plant in Tofte, with a capacity of 100 to 150 million litres of biofuel annually. There have also been other developments in the Swedish biofuel industry. Setra Group AB plans to install a new plant to produce pyrolysis oil by a liquefaction process. The plant is expected to produce about 25,000 tons of pyrolysis oil annually, which will be refined into biofuel by Preem. Parallel to this, Preem, RenFuel, and Rottneros are planning to establish a new biofuel plant at the pulp mill in Vallvik, with an annual production capacity of 25,000 to 30,000 tons of lignin. This collaboration will project Preem as the pioneer biofuel producer in Sweden using black liquor derived-lignin. Together with Lignolproduktion AB and other probable plants to be installed, the target is to produce an annual capacity of 300,000 to 500,000 tons of lignin.

According to the Swedish Association of bioenergies (Svebio), the biofuel industry encountered a period of stagnant growth and development. Within this period, only three new ethanol production centres were built by St1, Agroetanol, and Sekab. Bakery waste is currently being used by St1 and Agroetanol for fermentation into ethanol, while Sekab processes wood sugar into biochemicals and biojet (Ekbom 2018). In addition, two new FAME biodiesel units were developed by Perstorp, and some biogas production units by different companies including E.ON, Swedish Biogas, and Strängnäs (Climate Chance 2018). However, waves of pilot and commercial projects for HVO biodiesel production have also been recorded. For example, the Swedish oil company Preem plans a 600% increase in its production capacity to 1.3 million m^3 by 2023. Similarly, St1 plans operation of a 200 kiloton plant for HVO100 by 2020. These projects demonstrate the expansion of the HVO market, and the erosion of the monopoly by major biofuel companies such as Neste, which currently produces about 2.5 million tons and represents more than 50% of world capacity (Climate Chance 2018). In 2018, SunPine invested SEK 250 million in a new production plant for tall diesel fuel. The new line, which is planned to start operation in 2020, is expected to increase capacity by 50%. Crude tall oil (CTO) has been used to produce diesel fuel since 2006 when the process technology was developed. The company is owned by Preem, Sveaskog, Södra, and Kiram AB, and operates a €23 million plant in Piteå. The commercial process involves sulphuric acid esterification with CTO and biomethanol, which builds up the CTO diesel components. Thereafter, the component is distilled into the main product CTO and the by-product, pitch fuel. The CTO is then upgraded to a high-quality diesel fuel whilst the pitch fuel is used as a green fuel oil. It is planned to extract other beneficial substances from the oil including resin acids and sterols in the future. Given the right conditions, SunPine could meet 14% of all renewable diesel requirements in Sweden by 2030 (SunPine 2018).

Sweden is one of the highest consumers of biofuel in Europe (about 32%), primarily due to the general acceptance of E85, and generation of heat and electricity. However, the availability of E85 is being threatened due to its low energy efficiency. This has led to the introduction of other biofuel options in the market with advanced energy and environment profile. In 2018, Circle K launched miles 95 bio, which contains 15% renewable content in gasoline. The product contains a fossil-based gasoline blended with a mixture of 5% ethanol and about 10% HVO gasoline, which is 100% renewable. According to Circle K, the product has the potential to reduce friction and clean diesel engines, thus reducing fuel consumption. The product also reduces GHG emissions by 12.3% compared to fossil fuel (Bioenergy International 2018). The Nordic ecolabelled Preem evolution diesel plus from pine oil also contains at least 50% renewable raw material with a contribution of 89% reduction in GHG emissions (Preem 2018). Biofuels may become much more expensive from 2021 when Sweden’s exemption from EU rules expires, which offers relief in carbon and energy taxes on high blend biofuels. This is expected to cause a decline in demand and force local traffic in Sweden to abandon biofuels. The aim is to support Sweden’s goal of CO_2 emission reduction in the transport sector by 70% by 2030 (Teknikens Värld 2019). The Swedish biofuel market is experiencing some rapid changes, although there has been no viable developments in low blend ethanol fuel, coupled with a stagnant development in some biodiesel grades (Ekbom 2018). Since the approval of HVO100 for most cars and heavy-duty trucks, biofuel companies are now producing more HVO100 biodiesel. Furthermore, electric-charged vehicles are increasingly becoming popular with a target of 200,000 cars and 5000 charging points by the end of 2020.

COMPETITION FOR RAW MATERIALS WITH INCREASED BIOENERGY DEMAND

Bioenergy plays a significant role in reducing carbon emissions, especially in the transport sector. Biofuels from forest raw materials are important to attain the renewable energy targets in the transport sector (Bryngemark 2019). However, there are several industries including furniture and biochemicals that compete with the bioenergy sector for raw materials (Reid *et al*. 2020). Within the bioenergy sector, the heat and power sector also utilize forest raw materials and compete with the biofuel sector. In Sweden, material or energy use of biomass is determined by market actors, and this largely depends on price and availability. The model has consequently favored the principle of cascading, where material use is prioritized prior to energy use (IRENA 2019a). For example, wood residues, which have potential to be burnt for energy, also are important raw materials for the particleboard, biochemical, and biofuel industries. In Sweden, the availability of wood raw materials amongst other factors has affected the wood-based panel industry due to growing competition with the bioenergy sector (Kumar *et al.* 2020). In the Swedish forest model, the production of particleboard and fibreboard ceases due to increased prices of raw materials (Bryngemark 2019). Apart from the panel industry, there is a continuous effort to increase the use of forest biomass for biochemical purposes, thereby putting further strain in the bioenergy sector. Forest biomass can be converted into a variety of green biochemical products including basic constituents such as lignin, celluloses, and enzymes. In an effort to increase biomass utilization potential and mitigate the effect of competition, some Swedish companies have established integrated facilities for producing biochemicals and biofuel. Domsjö Fabriker, which primarily produces ethanol and celluloses from forest biomass also produces biogas as a major product (Kumar *et al.* 2020). Sekab refines ethanol from cellulose-based biomass into different biochemicals, chemical products, and vehicle fuels. Södra Cell Värö, which is one of Sweden's largest forest industry sites, operates a bio-combinate plant that produces sawn wood, pulp, pellets, tall oil, heat, and electricity. The site plans to take a biochemical approach in the future to start producing methanol and lignin.

Other materials used in the bioenergy industry also have applications in the biochemical industry, *e.g.* black liquor and bioethanol. Black liquor is a residual product from the kraft pulp mill containing varying contents of organic and inorganic materials, depending on mill type and raw materials used. The organic content of black liquor comprises dissolved lignin, hemicelluloses, soap, and other organics, whilst the inorganics mainly comprise paper making chemicals (Pettersson *et al.* 2012). Black liquor has been used in the pulp industry for energy generation since the mid-1930s. However, research and development in byproducts processing has resulted in alternative methods of extraction or isolation of the liquor components. This option is increasingly becoming popular with regard to lignin processing in biorefinery and biofuel for diesel engines. However biofuel processing still depends on the market value of the synthetic gas and other fuels produced, compared to the energy value from conventional processing of the liquor (Ekbom *et al.* 2003). The development of black liquor-derived biodiesel fuels could reduce CO_2 emissions by 5.7 million tons. This figure represented 12% of the annual Swedish production levels in 2000 and could contribute significantly to the required savings on GHGs emissions (Ekbom *et al.* 2003). Within the biorefinery concept, a range of biochemicals can be derived from controlled processing of black liquor. Black liquor derived-lignin can be used in value-added applications such as in platform phenolic chemical products (Naron *et al*. 2017). High levels of organic acids such as formic and lactic acids can be processed from black liquor by partial wet oxidation reaction with catalysts including iron activated carbon (Fe/AC), Fe/AC with hydrogen peroxide and iron (III) sulphate (Mishra *et al.* 1995; Muddassar *et al*. 2015).

Crude tall oil (CTO), which is an important chemical by-product in a kraft mill, is obtained from black liquor by thermal acidification of rosin soap. Tall oil rosins obtained after fractional distillation of CTO has been used to produce various chemicals including adhesives, rubbers, cement binder, and emulsifiers. In addition, tall oil has been used to improve the water resistance of cellulosic fibres and as a hydrophobic agent in manufacturing medium density fibreboard panels (Hosseinpourpia *et al*. 2019). In bioenergy, tall oil can be used to produce biodiesel by esterification and distillation. Different methods have been described for producing biodiesel from tall oil using catalysts. Some of the methods include high temperature esterification of tall oil fatty acids with methanol (White *et al*. 2011) and use of HCl-methanol (Demirbas 2008). In other studies, Kocik *et al*. (2017) screened solid catalysts for esterification of tall oil fatty acids with methanol, whilst Mikulec *et al.* (2012) processed diesel oil components from tall oil using atmospheric gas oil on zeolite catalysts.

Bioethanol, which is widely used as a transport fuel, has been a base chemical for many consumer products for more than a century. It is produced from biomass fermentation and has been used in products including cosmetics, household products, food additives, alcoholic beverages, and hand sanitizers. The competition for this material in the biochemical and bioenergy industries continues to affect the market prices of the products and influence global demand. In the outbreak of the corona virus pandemic (COVID-19), the production of ethanol fuel dropped due to the slump in gasoline demand and rise in the demand of hand sanitizers. Fuel demand dropped worldwide by about 30% due to movement restrictions to limit the spread of the virus (Reuters 2020). Subsequently, the rise in global demand of hand sanitizers caused many fuel ethanol companies to produce sanitizers or provide industrial ethyl alcohol to support hand sanitizer production companies. In Sweden, Sekab and other biochemical companies redirected their productions to hand sanitizers to manage the crisis. These companies originally did not have permit to produce sanitizers due to strict EU regulations. It is likely that some companies will stay in the hand sanitizer business even after ethanol fuel demand recovers due to a return of about 5% of income (Kimani 2020).

The use of forest biomass presents several advantages to both panel and bioenergy sectors from the environmental point of view. In terms of emission control, the development of wood panel products utilizing wood residues has helped to reduce carbon dioxide footprint up to about 80% (Reid *et al*. 2020). Increasing the use of wood residues in composite materials could significantly improve global carbon balance (IRENA 2019b). Similarly, production of biofuels has contributed directly to GHG emissions reduction of about 30-90% compared to fossil fuels (Kimani 2020).

ENVIRONMENTAL CONSIDERATIONS

The interest in renewable energy has been increased due to depletion of fossil reserves and the associated environmental concerns of climate change (Rubin *et al*. 1992). In the search for a sustainable source of renewable energy, there has been an increased interest in forest resources. Forests are renewable components of natural carbon and are becoming increasingly important sources of future energy supplies (Cintas *et al*. 2017). In Sweden, forest utilization is based on productive and environmental objectives. Whilst the productive objective deals with sustainable management of forests, the environmental objective focuses on securing biodiversity and genetic variation (IRENA 2019b). According to the Swedish Environmental Protection Agency, the environmental objectives for bioenergy from forests in Sweden should be focused on reduced climate impact, natural acidification only, zero eutrophication, sustainable forests, and non-toxic environment. Swedish forests provided about 60% of bioenergy supplies in 2016. Although biomass extraction and carbon uptake are quite high, there is a potential for forest bioenergy to increase. However, large-scale depletion of forest resources is neither sustainable nor carbon neutral (Egnell *et al*. 2018). Biomass plants tend to release more GHG than fossil-powered plants per MWh; therefore, net emissions from bioenergy could exceed that from fossil oils (Booth 2018). Logging activities cause forest soils to release stored carbon and rotting of roots, which releases CO_2. In addition, combustion of forest residues increases CO_2 emissions, as the carbon stored in biomass is released into the atmosphere (Egnell *et al*. 2018). The removal of forest biomass, which was traditionally left in the forest after logging operations, affects functioning forest ecosystems. Forest residues are needed to support biodiversity by providing habitats for both fauna and flora species. It is stated that forest residue removal has the potential to reduce growth rate in future tree generations as the residues contain more nutrients than stems (IRENA 2019b). There is also an increased risk of available mercury in soil water after clear felling, thereby affecting water quality (Johansson and Ranius 2019). However, other studies have reported rapid carbon benefits from forest harvesting based on various assumptions. Some of the assumptions relate to increased forest planting after harvest and that burning sustainable forest residues can reduce CO_2 emissions as long as the carbon stocks are increasing (Booth 2018).

Other environmental concerns with the increasing bioenergy needs are land use and GHG emissions (Zhou *et al*. 2015). Bioenergy production also has a negative effect on water quality, biodiversity, and soil organic carbon. However, these effects depend on several factors including biomass types and land location (Wu *et al*. 2018). Land transitions from native grassland to first generation energy crops or short rotation woody crops (SRWC) can result in significant increases in GHG emissions. Consequently, an evaluation of the energy crop types and management practices is vital when considering the mitigation of CO_2 emissions (Wu *et al.* 2018). Furthermore the production and utilization of biofuels also cause a shift in the ecosystem balance. For example, biogas has about 12 times more eutrophication potential than fossil fuels, although this effect can be controlled by feedstock types and improved production techniques (Whiting and Azapagic 2014).

Apart from environmental concerns, bioenergy also affects food security and supply. As a result, the EU has supported plans for second generation biofuels, by restricting the use of agricultural products in biofuel production (Climate Chance 2018). Currently many biofuels are produced from agricultural products, but the EU is promoting more use of biomass residues. Consequently the Swedish biofuel industry relies on biomass residues for biofuel production, of which an example is the production of HVO100 from renewable material residues. The industry also uses SRWC for energy generation. SRWC such as willow do not compete with agricultural crops, and they can be grown on marginal land to increase bioenergy production (Hammar *et al*. 2014). SRWC yielded more energy and reduced GHGs emissions up to about 90 to 99% compared to coal (Djomo *et al*. 2011). In a related study, the production and use of willow reduced GHGs emission by about 25 to 103% compared to fossil fuels; however the gains in reduction potential may be due to changes in soil organic carbon (Hammar *et al*. 2014). It is important to address the economic and ecological factors that affect the bioenergy potential of SRWC to fully exploit their environmental benefits.

CONCLUSIONS

Bioenergy provides about a third of Sweden's energy needs, and about half of this energy is used in the forest products industry. The bioenergy sector will continue to play an active role toward meeting the target of a fossil-free society. However, government policies and biomass availability remain the determining factors for a sustainable transition to a bio-based economy. The bioenergy sector in Sweden has developed over the years, and some of the criteria used to evaluate its potentials and market include energy security, reduced carbon footprint, innovation and creation of new value chains.

Forest biomass including recovered wood and energy crops are important sources of sustainable bioenergy and biofuels. Currently about 90% of recovered wood is used for energy generation; however, recent policies focus more on secondary and tertiary uses of wood. Although the shift to bioenergy is a way of reducing human dependence on fossil fuels and mitigate climate change impacts, clear felling of forests and excessive exploitation of forest biomass for bioenergy production has been challenged due to environmental concerns. The main environmental considerations with bioenergy are land use and GHG emissions. The amount of GHG emissions from burning of forest biomass has been argued to be more than that from burning conventional fossil-based fuels. In addition, land transitions to support short rotation coppice may result in increased GHG emissions.

In Sweden, the main biofuels used in the transport sector include bioethanol, HVO, and biogas, and recently more biofuel derivatives are being developed. Carbon accounting related to biofuel consumption will be vital in the years to come. If Sweden wants to demonstrate the sustainability of its biofuel strategy, changes to raw materials supply and relocation of production will be essential for emission reduction. Currently, this strategy appears to be a temporary solution, which only applies locally. The future development of this trend and the global applicability of the strategy will determine whether Sweden will be the future example for fossil-free road transport.

ACKNOWLEDGMENTS

The authors acknowledge funding provided by the Swedish Research Council Formas (Project 942-2016-2, 2017-21) and by the Kamprad Family Foundation (Project Grant No. 20160052, 2017-19). The authors also wish to thank Växjö Energi (VEAB), Växjö for constructive discussions. The involvement of Dennis Jones within this collaborative paper was as a result of a sub-contractual agreement with RISE, Stockholm for which DJ is extremely grateful.

REFERENCES CITED

Amiri, S., and Weinberger, G. (2018). "Increased cogeneration of renewable electricity through energy cooperation in a Swedish district heating system – A case study," *Renewable Energy* 116, 866-877. DOI: 10.1016/j.renene.2017.10.003

Anon. (2006). *Making Sweden an Oil-free Society*, The Swedish Commission on Oil Independence, Government Offices of Sweden, Stockholm, Sweden.

Bentsen, N. S., Nilsson, D., and Larsen, S. (2018). "Agricultural residues for energy- A case study on the influence of resource availability, economy and policy on the use of straw for energy in Denmark and Sweden," *Biomass Bioenergy* 108, 278-288. DOI: 10.1016/j.biombioe.2017.11.015

Bentsen, N. S., Nilsson, D., Larsen, S., and Stupak, I. (2016). *Agricultural residues for energy in Sweden and Denmark- Differences and commonalities*, IEA Bioenergy: Task 43: 2016: 05.

Bioenergy International. (2018). "Circle K launches gasoline with up to 15% renewable content in Sweden," Bioenergy International, (https://bioenergyinternational.com/biofuels-oils).

Booth, M. S. (2018). "Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy," *Environmental Research Letters* 13(3), 035001. DOI: 10.1088/1748-9326/aaac88

Börjesson, M., Athanassiadis, D., Lundmark, R., and Ahlgren, E. O. (2015). "Bioenergy futures in Sweden–system effects of CO_2 reduction and fossil fuel phase-out policies," *GCB Bioenergy* 7(5), 1118-1135. DOI: 10.1111/gcbb.12225

Börjesson, P., Ahlgren, S., and Berndes, G. (2012). "The climate benefit of Swedish ethanol: present and prospective performance," *Wiley Interdisciplinary Reviews: Energy and Environment* 1(1), 81-97. DOI: 10.1002/wene.17

Börjesson, P., Hansson, J., and Berndes, G. (2017). "Future demand for forest-based biomass for energy purposes in Sweden," *Forest Ecology and Management* 383, 17-26. DOI: 10.1016/j.foreco.2016.09.018

Björheden, R. (2017). "Development of bioenergy from forest biomass – A case study of Sweden and Finland," *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering* 38(2), 259-268.

Brinkley, C. (2018). "The conundrum of combustible clean energy: Sweden's history of siting district heating smokestacks in residential areas," *Energy Policy* 120, 526-532. DOI: 10.1016/j.enpol.2018.05.059

Bryngemark, E. (2019). *The Competition for Forest Raw Materials in the Presence of Increased Bioenergy Demand: A Partial Equilibrium Analysis of the Swedish Case*, PhD Dissertation, Luleå University of Technology, Luleå, Sweden.

Buonocore, E., Franzese, P. P., and Ulgiati, S. (2012). "Assessing the environmental performance and sustainability of bioenergy production in Sweden: A life cycle assessment perspective," *Energy* 37(1), 69-78. DOI: 10.1016/j.energy.2011.07.032

Bušić, A., Mardetko, N., Kundas, S., Morzak, G., Belskaya, H., Šantek, M. I., Komes, D., Novak, S., and Šantek, B. (2018). "Bioethanol production from renewable raw materials and its separation and purification: A review," *Food Technology and Biotechnology* 56(3), 289-311. DOI: 10.17113/ftb.56.03.18.5546

Cintas, O., Berndes, G., Hansson, J., Poudel, B., Bergh, J., Börjesson, P., Egnell, G., Lundmark, T., and Nordin, A. (2017). "The potential role of forest management in

Swedish scenarios towards climate neutrality by mid century," *Forest Ecology and Management* 383, 73-84. DOI: 10.1016/j.foreco.2016.07.015
Climate Chance. (2018). *Transport in Sweden- The automotive sector's transformation is taking shape*, 2018 Annual Report, Global Observatory on non-state Climate Action, 1-15.
De Jong, J., Akselsson, C., Berglund, H., Egnell, G., Gerhardt, K., Lönnberg, L., Olsson, B., and von Stedingk, H. (2012). "Konsekvenser av ett ökat uttag av skogsbränsle," En syntes från Energimyndighetens Bränsleprogram 2007–2011; *Consequences of an Increased Forest Fuel Withdrawal*, Composite Report from the Swedish Energy Agency's R & D Programme 2007–2011, (Report No. 8), Swedish Energy Agency, Eskilstuna, Sweden.
Demirbas, A. (2008). "Production of biodiesel from tall oil," *Energy Sources, Part A*, 30(20), 1896-1902. DOI: 10.1080/15567030701468050
Djomo, S. N, Kasmioui, O. E., and Ceulemans, R. (2011). "Energy and greenhouse gas balance of bioenergy production from poplar and willow: A review," *GCB Bioenergy* 3(3), 181-197. DOI: 10.1111/j.1757-1707.2010.01073.x
Egnell, G., Ahlgren, S., and Berndes, G. (2018). *Bioenergy systems in Sweden - Climate Impacts, Market Implications, and Overall Sustainability*, Swedish Energy Agency, 2018:23.
Ekbom, T. (2018). *Country Update Sweden*. IEA Bioenergy Task 39 Business Meeting, April 2018, Beijing, China.
Ekbom, T., Lindblom, M., Berglin, N., and Ahlvik, P. (2003). "Technical and commercial feasibility study of black liquor gasification with methanol/DME production as motor fuels for automotive uses - BLGMF," Stockholm, Sweden.
Ericsson, K., Huttunen, S., Nilsson, L. J., and Svenningsson, P. (2004). "Bioenergy policy and market development in Finland and Sweden," *Energy Policy* 32(15), 1707-1721. DOI: 10.1016/S0301-4215(03)00161-7
FAO. (2019). "Global forest products fact and figures," 2019, Forest Products Statistics, Rome, Italy, Food and Agriculture Organization of the United Nations, (http://www.fao.org/faostat/en/#data/FO).
Fridh, M., and Christiansen, L. (2015). *Rundvirkes- och Skogsbränslebalanser för År 2013 – SKA* 15; *Wood balances and forest fuel balances for the year 2013 in Sweden* (Report No. 3), Swedish Forest Agency, Jönköping, Sweden.
Grahn, M., and Hansson, J. (2015). "Prospects for domestic biofuels for transport in Sweden 2030 based on current production and future plans," *Energy and Environment* 4(3), 290-306. DOI: 10.1002/wene.138
Grippi, D., Clemente, R., and Bernal, M. P. (2020). "Chemical and bioenergetic characterization of biofuels from plant biomass: Perspectives for Southern Europe," *Applied Sciences* 10(10), 3571. DOI: 10.3390/app10103571
Hackl, R., Hansson, J., Norén, F., Stenberg, O., and Olshammar, M. (2018). "Cultivating *Ciona intestinalis* to counteract marine eutrophication: Environmental assessment of a marine biomass based bioenergy and biofertilizer production system," *Renewable Energy* 124,103-113. DOI: 10.1016/j.renene.2017.07.053
Hammar, T., Ericsson, N., Sundberg, C., and Hansson, P. (2014). "Climate impact of willow grown for bioenergy in Sweden," *BioEnergy Research* 7(4), 1529-1540. DOI: 10.1007/s12155-014-9490-0
Hammar, T., Stendahl, J., Sundberg, C., Holmström, H., and Hansson, P. (2019). "Climate impact and energy efficiency of woody bioenergy systems from a landscape

perspective," *Biomass Bioenergy* 120, 189-199. DOI: 10.1016/j.biombioe.2018.11.026
Hansen, A. C., and Berlina, A. (2018). "Bioenergy development in Sweden - Frameworks for success," in: *Towards a Sustainable Bioeconomy: Principles, Challenges and Perspectives*, W. Leal Filho *et al.* (eds.), Springer, Cham, Switzerland, pp. 457-481. DOI: 10.1007/978-3-319-73028-8_23
Holmgren, K. (2012). *Policies Promoting Biofuels in Sweden*, The Swedish Knowledge Centre for Renewable Transportation Fuels, F3 Synthesis Report, f3 2012:3.
Holm-Nielsen, J. B., and Oleskowicz-Popiel, P. (2007). *The Future of Biogas in Europe: Visions and Targets 2020*, European Biogas Workshop and Study Trip, June 2007, Esbjerg, Denmark.
Hosseinpourpia, R., Adamopoulos, S., and Parsland, C. (2019). "Utilization of different tall oils for improving the water resistance of cellulosic fibers," *Journal of Applied Polymer Science* 136(13), 47303. DOI: 10.1002/app.47303
Hult, C., and Mendoza, D. (2014). *Biodiesel fuels in Sweden: Drivers, Barriers, Networks and Key Stakeholders*, (Report No. 2014:06), Challenge Lab 2014: Sustainable Transport and Mobility Solutions, Master's Thesis, Chalmers University of Technology, Gothenburg, Sweden.
IEA. (2018). "Renewables 2018: Market analysis and forecast from 2018 to 2023," International Energy Agency, (https://www.iea.org/renewables2018/power/).
IEA Bioenergy. (2018). *Sweden – 2018 Update: Bioenergy Policies and Status of Implementation* (Country Reports), International Energy Agency Bioenergy, 09 2018.
IRENA. (2018). "Biogas for road vehicles: Technology brief," International Renewable Energy Agency, (https://www.irena.org/).
IRENA. (2019a). "Liquid biofuels," International Renewable Energy Agency, (https://www.irena.org/transport/Liquid-Biofuels).
IRENA. (2019b). "Bioenergy from boreal forests: Swedish approach to sustainable wood use," International Renewable Energy Agency, Abu Dhabi.
Jåstad, E. O., Bolkesjø, T. F., and Rørstad, P. K. (2020). "Modelling effects of policies for increased production of forest-based liquid biofuel in the Nordic countries," *Forest Policy and Economics* 113, 102091. DOI: 10.1016/j.forpol.2020.102091
Johansson, J., and Ranius, T. (2019). "Biomass outtake and bioenergy development in Sweden: the role of policy and economic presumptions," *Scandinavian Journal of Forest Research* 34(8), 771-778. DOI: 10.1080/02827581.2019.1691645
Jonsson, R., Blujdea, V. N. B., Fiorese, G., Pilli, R., Rinaldi, F., Baranzelli, C., and Camia, A. (2018). "Outlook of the European forest-based sector: Forest growth, harvest demand, wood-product markets, and forest carbon dynamics implications," *IForest.* 11(2), 315-328. DOI: 10.3832/ifor2636-011
Kimani, A. (2020). "Hand sanitizer boom could save the ethanol industry," (https://oilprice.com/Alternative-Energy/Biofuels.html).
Knoema. (2019). "Fuel ethanol consumption by country," (https://knoema.com/).
Kocík, J., Samikannu, A., Bourajoini, H., Pham, T. N., Mikkola, J., Hájek, M., and Capek, L. (2017). "Screening of active solid catalysts for esterification of tall oil fatty acids with methanol," *J Clean Prod* 155, 34-38. DOI: 10.1016/j.jclepro.2016.09.174
Kumar, A., Adamopoulos, S., Jones, D., and Amiandamhen, S. O. (2020). "Forest biomass availability and utilization potential in Sweden: A review," *Waste and Biomass Valorization*. DOI: 10.1007/s12649-020-00947-0

Lönnqvist, T., Sanches-Pereira, A., and Sandberg, T. (2015). "Biogas potential for sustainable transport – A Swedish regional case," *J Clean Prod* 108, 1105-1114. DOI: 10.1016/j.jclepro.2015.07.036

Lönnqvist, T., Silveira, S., and Sanches-Pereira, A. (2013). "Swedish resource potential from residues and energy crops to enhance biogas generation," *Renewable and Sustainable Energy Reviews* 21, 298-314. DOI: 10.1016/j.rser.2012.12.024

Lund, H. (2007). "Renewable energy strategies for sustainable development," *Energy* 32(6), 912-919. DOI: 10.1016/j.energy.2006.10.017

Lundmark, R., Athanassiadis, D., and Wetterlund, E. (2015). "Supply assessment of forest biomass–a bottom-up approach for Sweden," *Biomass Bioenergy* 75, 213-226. DOI: 10.1016/j.biombioe.2015.02.022

Manolis, E. N., Zagas, T. D., Karetsos, G. K., and Poravou, C. A. (2019). "Ecological restrictions in forest biomass extraction for a sustainable renewable energy production," *Renewable and Sustainable Energy Reviews* 110, 290-297. DOI: 10.1016/j.rser.2019.04.078

Martin, M., Larsson, M., Oliveira, F., and Rydberg, T. (2020). "Reviewing the environmental implications of increased consumption and trade of biofuels for transportation in Sweden," *Biofuels* 11(2), 175-189. DOI: 10.1080/17597269.2017.1345363

Mikulec, J., Kleinová, A., Cvengroš, J., Joríková, L., and Banič, M. (2012). "Catalytic transformation of tall oil into biocomponent of diesel fuel," *International Journal of Chemical Engineering* 1-9. DOI: 10.1155/2012/215258).

Mishra, V. S., Mahajani, V. V., and Joshi, J. B. (1995). "Wet air oxidation," *Ind Eng Chem Res* 34(1), 2-48. DOI: 10.1021/ie00040a001

Muddassar, H. R., Melin, K., de Villalba, K. D., Riera, G. V., Golam, S., and Koskinen, J. (2015). "Green chemicals from pulp production black liquor by partial wet oxidation," *Waste Manage Res* 33(11), 1015-1021. DOI: 10.1177/0734242X15602807

Mutter, A. (2019). "Mobilizing sociotechnical imaginaries of fossil-free futures–Electricity and biogas in public transport in Linköping, Sweden," *Energy Research & Social Science* 49, 1-9. DOI: 10.1016/j.erss.2018.10.025

Naron, D. R., Collard, F., Tyhoda, L., and Görgens, J. F. (2017). "Characterisation of lignins from different sources by appropriate analytical methods: Introducing thermogravimetric analysis-thermal desorption-gas chromatography – mass spectroscopy," *Industrial Crops & Products* 101, 61-74. DOI: 10.1016/j.indcrop.2017.02.041

Nilsson, B. (2016). "Extraction of logging residues for bioenergy- Effects of operational methods on fuel quality and biomass losses in the forest," Ph.D. Dissertation, Linnaeus University, Växjö, Sweden, (http://lnu.diva-portal.org/smash/get/diva2:1049815/FULLTEXT01.pdf).

Nordborg, M., Berndes, G., Dimitriou, I., Henriksson, A., Mola-Yudego, B., and Rosenqvist, H. (2018a). "Energy analysis of willow production for bioenergy in Sweden," *Renewable and Sustainable Energy Reviews* 93, 473-482. DOI: 10.1016/j.rser.2018.05.045

Nordborg, M., Berndes, G., Dimitriou, I., Henriksson, A., Mola-Yudego, B., and Rosenqvist, H. (2018b). "Energy analysis of poplar production for bioenergy in Sweden," *Biomass Bioenergy* 112, 110-120. DOI: 10.1016/j.biombioe.2018.01.021

Ortiz, C. A., Hammar, T., Ahlgren, S., Hansson, P., and Stendahl, J. (2016). "Time-dependent global warming impact of tree stump bioenergy in Sweden," *For Ecol Manage* 371, 5-14. DOI: 10.1016/j.foreco.2016.02.014
Ouraich, I., Wetterlund, E., Forsell, N., and Lundmark, R. (2018). "A spatial-explicit price impact analysis of increased biofuel production on forest feedstock markets: A scenario analysis for Sweden," *Biomass Bioenergy* 119, 364-380. DOI: 10.1016/j.biombioe.2018.09.029
Persson, T., and Egnell, G. (2018). "Stump harvesting for bioenergy: A review of climatic and environmental impacts in northern Europe and America," *Wiley Interdisciplinary Reviews: Energy and Environment* 7(6), e307. DOI: 10.1002/wene.307
Pettersson, K., Mahmoudkhani, M., and von Schenck, A. (2012). "Opportunities for biorefineries in the pulping industry," in: *Systems Perspectives on Biorefineries*, A. S. Björn (ed.), Chalmars, pp. 48-58.
Preem. (2018). "Preem evolution diesel," (https://www.preem.se/om-preem/hallbarhet/).
Reid, W. V., Ali, M. K., and Field, C. B. (2020). "The future of bioenergy," *Global Change Biology* 26(1), 274-286. DOI: 10.1111/gcb.14883
Rettenmaier, N., Schorb, A., Köppen, S., Berndes, G., Christou, M., Dees, M., Domac, J., Eleftheriadis, I., Goltsev, V., Kaiba, D., Kunikowski, G., Lakyda, P., Lethonen, A., Lindner, M., Pekkanen, J., Röder, J., Torén, J., Vasylyshyn, R., Veijonen, K., Vesterinen, P., Wirsenius, S., Zheliezna, T., and Zibtsev, S. (2010). "Status of biomass resource assessments," Version 3 (Project report), Biomass Energy Europe (BEE), FP 7 Grant Agreement 213417, University of Freiburg, Germany.
Reuters. (2020). "U.S. calls ingredients in some ethanol-based hand sanitizers unsafe," (https://www.reuters.com/article/).
SAS. (2019). "SAS starts using biofuel in aircrafts," (https://scandinaviantraveler.com/en/aviation/).
Scarlat, N., Dallemand, J.-F., and Fahl, F. (2018). "Biogas: Developments and perspectives in Europe," *Renewable Energy* 129 (Part A), 457-472. DOI: 10.1016/j.renene.2018.03.006
Schmidt, S., Södersten, C., Wiebe, K., Simas, M., Palm, V., and Wood, R. (2019). "Understanding GHG emissions from Swedish consumption - Current challenges in reaching the generational goal," *J Clean Prod* 212, 428-437. DOI: 10.1016/j.jclepro.2018.11.060
SEA. (2019). "Energy in Sweden - Facts and figures 2019," Swedish Energy Agency, (http://www.energimyndigheten.se/en/news/2019/).
SEA. (2018). "Energy in Sweden 2018: An overview," Swedish Energy Agency, (https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=5774).
SEA. (2009). "The Swedish energy research programme," Swedish Energy Agency, (http://www.energimyndigheten.se/en/).
Sernhed, K., Lygnerud, K., and Werner, S. (2018). "Synthesis of recent Swedish district heating research," *Energy* 151, 126-132. DOI: 10.1016/j.energy.2018.03.028
SunPine. (2018). "SunPine to invest SEK 250 million in new plant," (https://www.sunpine.se/en/pressmeddelanden/).
Teknikens Värld. (2019). "HVO100 and E85 can be extremely expensive in Sweden," (https://teknikensvarld.se/hvo100-och-e85-kan-bli-extremt-dyra-i-sverige/).
Waldenström, C., Ferguson, R., Sundberg, C., Tidåker, P., Westholm, E., and Åkerskog, A. (2016). "Bioenergy from agriculture: Challenges for the rural development

program in Sweden," *Society and Natural Resources* 29(12), 1467-1482. DOI: 10.1080/08941920.2016.1150538
Werner, S. (2017). "District heating and cooling in Sweden," *Energy* 126, 419-429. DOI: 10.1016/j.energy.2017.03.052
White, K., Lorenz, N., Potts, T., Penney, W. R., Babcock, R., Hardison, A., Canuel, E. A., and Hestekin, J. A. (2011). "Production of biodiesel fuel from tall oil fatty acids *via* high temperature methanol reaction," *Fuel* 90(11), 3193-3199. DOI: 10.1016/j.fuel.2011.06.017
Whiting, A., and Azapagic, A. (2014). "Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion," *Energy* 70, 181–193. DOI: 10.1016/j.energy.2014.03.103
Wollak, B., Forss, J., and Welander, U. (2018). "Evaluation of blue mussels (*Mytilus edulis*) as substrate for biogas production in Kalmar County (Sweden)," *Biomass Bioenergy* 111, 96-102. DOI: 10.1016/j.biombioe.2018.02.008
Wu, Y., Zhao, F., Liu, S., Wang, L., Qiu, L., Alexandrov, G., and Jothiprakash, V. (2018). "Bioenergy production and environmental impacts," *Geoscience Letters* 5, 14. DOI: 10.1186/s40562-018-0114-y
Zhou, S., Yong, Y.-C., Cao, B., Tao, H.-C., and Zhuang, L. (2015). "Bioenergy and its environmental impacts," *The Scientific World Journal* 508037. DOI: 10.1155/2015/508037.

Article submitted: January 23, 2020; Peer review completed: May 24, 2020; Revised version received and accepted: September 11, 2020; Published: September 18, 2020.
DOI: 10.15376/biores.15.4.Amiandamhen