AGRICULTURAL RESIDUES FOR ENERGY IN SWEDEN AND DENMARK – DIFFERENCES AND COMMONALITIES

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AGRICULTURAL RESIDUES FOR ENERGY IN SWEDEN AND DENMARK – DIFFERENCES AND COMMONALITIES

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Table of Contents

1.OBJECTIVE

The objective of this study was to review differences and commonalities in the conditions for the production, supply and use of agricultural residues for energy between Denmark and Sweden. The investigation focus on cereal straw as this is the most important residue resource in both countries. The study includes policy frameworks as well as production and harvesting conditions, and market and fuel consumer premisses.

More in depth regional analyses are carried out for Eastern Denmark and Scania in southern Sweden. These regions have several commonalities including the type of landscape and crop farming conditions, but are separated by a narrow strait (Öresund), which also constitute the border between Denmark and Sweden.

The study was inspired by the IEA Bioenergy Inter-Task project on mobilising sustainable biomass resources for energy (Smith et al. 2015).

2.INTRODUCTION

Bioenergy has potential to contribute substantially to the future global renewable energy mix. Accelerating production and use of environmentally sound, socially accepted and cost-competitive bioenergy may help to increase security of energy supplies while at the same time reducing greenhouse gas emissions from energy consumption. Currently close to 56 EJ of biomass is used for energy generation worldwide. About 60% is used for traditional heating and cooking while the remainder is used in modern conversion technologies for the production of heat, transport fuels, and electricity (REN21 2014). Modern use of agricultural residues for energy is so far limited to large-scale power and heat production and to a lesser extent transport biofuel production. In Europe, the Renewable Energy Directive (EU-RED) (European Parliament and the Council 2009) sets a target of 10% renewable transportation fuels by 2020, and in the US, the Renewable Fuel Standard (RFS2) set a target of 46 billion gallons yr^{-1} of biofuels. This has created a significant demand for biofuels in the EU and North America. Bioenergy targets are not exclusive to Europe and North America, a large number of South American, Asian, African and Oceanian countries have policies and targets on bioenergy deployment. A global overview is provided by the Renewable Energy Policy Network (REN21 2014).

First generation biofuels are to a large extent based on existing agricultural crops – sugars, grains and oilseeds that have traditionally been used for food, animal feed and some industrial uses, and can be readily converted into liquid biofuels. Public concerns over rising food prices and the perceived risk that further growth in the demand for first generation biofuels will increase food prices, has led the European Commission (EC) to propose a limit of 7% for the amount of first generation transportation biofuels that can be counted towards the 10% renewables RED target. Similarly the U.S. has capped biofuel production from corn grain at 15 billion gallons yr^{-1}. Direct and indirect land use changes resulting from the conversion of forest and grassland into crop production can lead to loss of biodiversity and carbon stocks, and have also been identified as a public concern particularly as the population continues to grow. This has resulted in a greater focus on the use of biological wastes and residues, including agricultural crop residues, for the production of bioenergy and non-food bio-products.

Various bioenergy targets are set to meet different goals on energy security and climate change mitigation, and some include targets on straw use. The International Renewable Energy Agency (IRENA), estimates that 13-30 EJ yr^{-1} of agricultural residues must be used by 2030 to meet the Sustainable Energy for all (SE4All) target of doubling the share of renewable energy in the global energy mix before 2030 (Nakada et al. 2014). Meeting the targets set by the Global Energy Assessment (GEA 2012) requires extensive use of agricultural residues, with an estimated technical potential of 49 EJ yr^{-1}.

Bentsen et al. (2014) estimates the current global theoretical potential of primary agricultural residues from cereals and sugar cane to be approximately 3.7 billion metric tonnes of dry matter annually, corresponding to ~65 EJ yr^{-1}. Earlier studies find the theoretical potential of cereals and sugar cane residues to be 2.7 – 3.5 billion metric tons yr-1 (Smil 1999, Lal 2005, Krausmann et al. 2008, Hakala et al. 2009), corresponding to 47-61 EJ yr-1. Cereals and sugar cane may account for 80% of the total residue production (Lal 2005) and constitute the part easiest to harvest.

The technical and sustainable potential of agricultural residues is significantly less. A certain amount of residues must be left onsite to protect soil productivity. Scarlat et al. (2010) summarise research on sustainable removal rates for a number of crops, and report rates between 15 and 60% for most crops. the actual current use of crop resides is poorly known (Bentsen et al. 2014) as very few countries collect data on residue production and use. A number of modelling studies find, on a global level, the current appropriation (incl. for energy) to 2.9 billion tonnes yr-1 (66% of total residue production) (Krausmann et al. 2008, Rogner et al. 2012). A somewhat contradictory estimate is provided by Wirsenius (2003), who estimated the fraction of agricultural residues appropriated by humans to 41% of the global production. The IPCC special report on renewable energy (Chum et al. 2011) reviewed the vast body of literature on bioenergy resources and reports the technical potential1 of agricultural residues, including processing waste (secondary residues) by 2050 to be 15-70 EJ yr-1, i.e. enough to meet the SE4All target, but not necessarily enough to meet the GEA target.

3. POLICY FRAMEWORKS TO PROMOTE BIOENERGY AND THE USE OF AGRICULTURAL RESIDUES

3.1. Denmark

The oil crisis in 1973-74 is often considered the starting point of Denmark's political interest in renewable energy. Prior to the crisis Denmark, as many other Western countries, was totally dependent on oil imports to drive the energy sector (Lund 2009). The earliest political moves to focus on biomass for energy is found in the 1985 'Windmill agreement' between the ministry of energy and the utility sector, which acknowledged the need for further talks on the use of straw for energy (Ministry of Energy 1985). In the 1986 'Electricity agreement' that stipulated the installation of 80-100 MW_e combined heat and power production based on domestic fuels such as natural gas, straw, wood chips or biogas (Ministry of Energy 1986). At the time of the adoption of the Climate Convention in 1992, new CO_2-taxes were introduced with the aim of reducing greenhouse gas emissions, and energy policies shifted to take account of environmental concerns around fossil fuel use. The first targets specifically for straw-based energy were set in the 'Biomass agreement' of 1993 (Danish Government 1993). The agreement mandated the use of 1.2 million tonnes of straw and 0.2 million tonnes wood chips for energy by 2000 (**Figure 1)**

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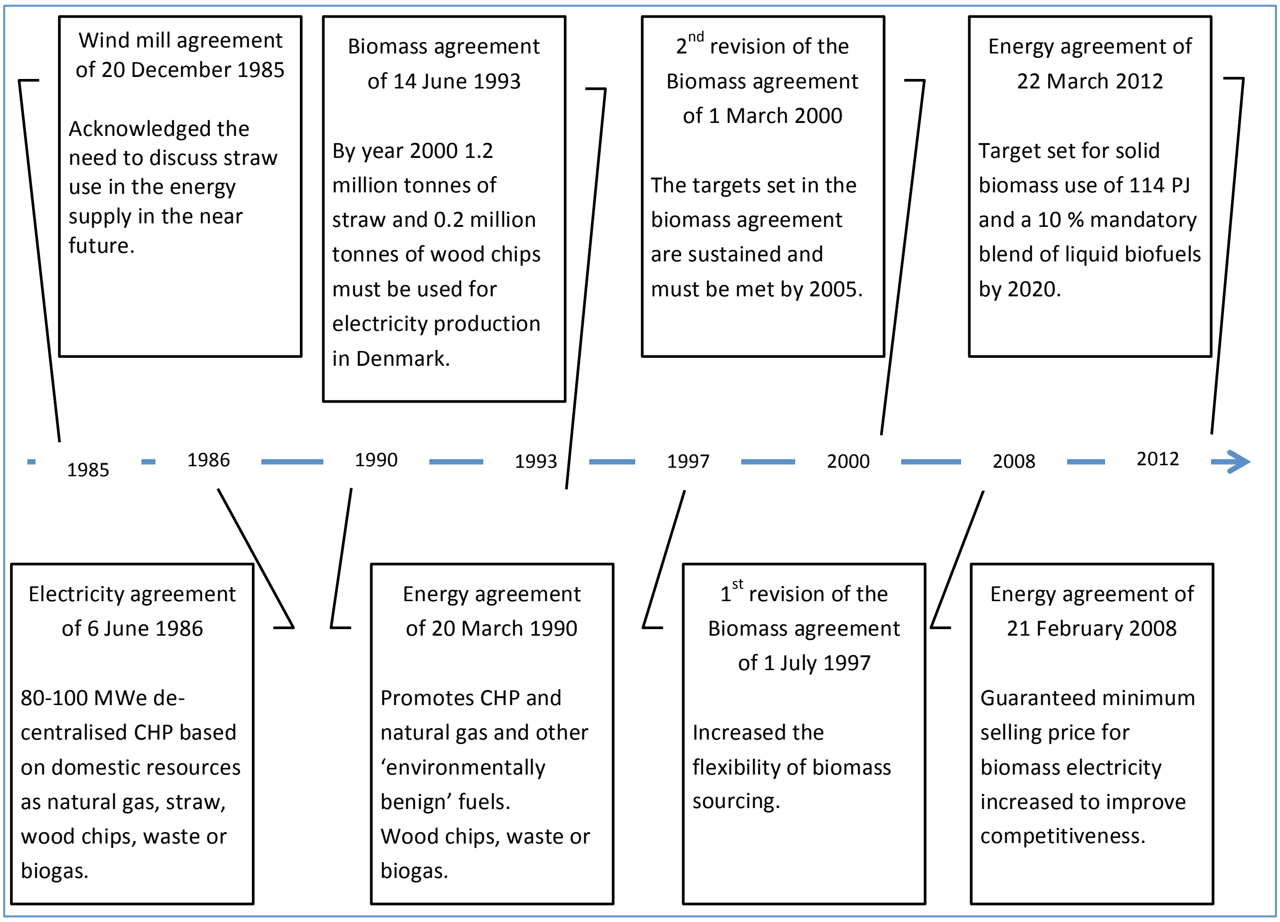
[1] Technical potential is a fraction of the theoretical potential and considers the limitations of the biomass production practices assumed to be



Wind mill agreement of 20 December 1985

Acknowledged the need to discuss straw use in the energy supply in the near future.

Electricity agreement of 6 June 1986

80-100 MWe de-centralised CHP based on domestic resources as natural gas, straw, wood chips, waste or biogas.

Energy agreement of 20 March 1990

Promotes CHP and natural gas and other ‘environmentally benign’ fuels.
Wood chips, waste or biogas.

Biomass agreement of 14 June 1993

By year 2000 1.2 million tonnes of straw and 0.2 million tonnes of wood chips must be used for electricity production in Denmark.

1st revision of the Biomass agreement of 1 July 1997

Increased the flexibility of biomass sourcing.

2nd revision of the Biomass agreement of 1 March 2000

The targets set in the biomass agreement are sustained and must be met by 2005.

Energy agreement of 21 February 2008

Guaranteed minimum selling price for biomass electricity increased to improve competitiveness.

Energy agreement of 22 March 2012

Target set for solid biomass use of 114 PJ and a 10 % mandatory blend of liquid biofuels by 2020.

Figure 1. Time line of political agreements and incentives to support the development of bioenergy in Denmark.

The ‘Biomass agreement’ was revised in 1997 and 2000. In 1997 the overall target for biomass use was maintained, but straw now had to make up at least 1.0 million tonnes instead of the mandated 1.2 million tonnes. As the biomass target was not met by 2000 the second revision of the ‘Biomass agreement’ extended the deadline to 2005. The biomass target was finally met in 2009. After a period in the mid-2000s with energy policy focusing on economic growth and liberalization of the electricity market, focus shifted again in the late 2000s to create a fossil free future (Nygård 2011). The Danish feed-in tariffs for renewables were increased. Another policy driver was the European Union’s Renewable Energy Directive , which was adopted in 2009 (European Parliament and the Council 2009). EU-RED sets targets for the deployment of renewable energy by 2020 for each member state and for the EU as a whole, and mandated blending of biofuels in gasoline and diesel in all member states. The targets are implemented in national strategies and legislation as described in EU-RED mandated national renewable energy action plans (NREAP). According to the Danish NREAP a slight increase in the use of straw for energy is required to meet the targets; an additional 500TJ (34,000 tonnes) by 2015 (compared to the use in 2006) increasing to an additional 1000 TJ (69,000 tonnes) by 2020 (Klima og Energiministeriet 2010).

The increased flexibility of fuel choice together with conversion of co-fired plants to entirely wood pellets and wood chips firing has decreased use of straw for heat and electricity since 2010. This may, however be compensated by new capacity under construction to supply Aarhus, the second largest city in Denmark with heat. What is going to be the largest straw fired plant in Denmark has the capacity to use 240,000 tonnes per year (Tougaard 2015). It is expected that in the longer run straw will be used increasingly for production of bioethanol and bio-oil, but energy utilities are holding back investments due to uncertainty on long-term policy commitments for second generation biofuels

3.2. Sweden

From World War II to the oil crisis in 1973, imported cheap oil had become the predominating fuel also in Sweden. After the oil crisis, however, increasing oil prices and a wish to break the dependency on imported fuels led to the search for domestically produced energy carriers. Nuclear power is such an example, and its use increased considerably in the 1970s and 1980s. The accidents at Harrisburg (1979) and Chernobyl (1986), and the decision to phase out nuclear power by 2010 after a referendum in 1980, resulted in a search for new alternatives. For example, economic support was introduced to convert boilers from oil to peat, coal and wood fuels. The awakening awareness in the 1980s and 1990s of the influence of greenhouse gas emissions on climate led to new turns in the energy policy with movement towards energy-savings and the use of renewable energy sources, mainly bioenergy.

There has been a wide range of ‘policy milestones’ regarding the use of bioenergy in Sweden, such as governmental commissions and public inquiries, and energy policy agreements and decisions (SOU 2007). Examples of governmental commissions and investigations are the Energy Commission (Energikommissionen) in 1977, Environmental tax inquiry (Miljöavgiftsutredningen) in 1989, the Biofuel Commission (Biobränslekommissionen) in 1992, the Energy Commission (Energikommissionen) in 1994 and the enquiry on agriculture as a bioenergy producer (Utredningen om jordbruket som bioenergiproducent) in 2007 (SOU 2007). A third Energy Commission was appointed in 2015.

Political agreements and decisions can be implemented in various ways. The instruments used by the Swedish government to promote the production and use of bioenergy include: administrative policy instruments (regulations), support to research, development, demonstration, dissemination of information, and economic incentives (monetary or non-monetary) (Hillring 1998).

Regulations

Two examples of important acts in the historical development of biofuels in Sweden were the Solid Fuel Act and the Wood Fibre Act. The Solid Fuel Act from 1982 prescribed that newly built heating plants were obliged to have a boiler using solid fuels and that this type of boiler must remain atthe facility during its lifetime. A main reason was a goal to phase out plants using liquid fuels (oil) in preference of the use of solid fuels (biomass and coal). The act was revoked in 1994 due to a greater focus on greenhouse gases, instead of decreased dependency on imported fuels. The newly introduced carbon dioxide tax, for example, was also easier to administer (Hillring 1998).

Before the large expansion of the use of biomass energy in Sweden, there was a fear that the wood fibre resources were not enough to meet the demand from both the important wood fibre industry and the nascent bioenergy sector (Hillring 1998). Consequently, the wood fibre use was regulated in the Wood Fibre Act (SEA 2009). The wood chip market was deregulated in 1991 when this act was partially revoked after several investigations showed that there were sufficient raw materials for both sectors. For sawdust and wood shavings, however, the act remained in use until 1993 in order to secure the availability of these raw materials for the fibreboard industry. The deregulation of this market after 1993 is one reason for the dramatic increase in the use of wood pellets and wood briquettes in Sweden in the following decades. Initially, woodpellets were mainly used in large-scale boilers, that had been converted from coal powder. More recently wood pellets have replaced oil in small-scale district heating systems as well as domestic heating systems, which are now the dominant sectors in the use of wood pellets (Nilsson and Bernesson 2008).

Support programmes

An important support programme was the Oil Replacement Programme (1981-1986), which, among other, provided support to prototype and demonstration for biofuel and peat fired plants. The financial support by the Oil Replacement Fund was financed by a fee on oil product use. In 1988, this programme was replaced by the Energy Technology Fund, which was used to finance several large research and development projects (Hillring 1998, SOU 2007). The Fabel government development programme of 1993 - 1997 (Främjande av biobränsle) was aimed at promoting the production of electricity from solid biomass.

Examples of government investment support programmes that have had an important impact on the use of biofuels are the peat combustion investment support (1981-1986), the investment support to combined heat and power production (1991-1997) and the investment support to district heating (1991-1996). LIP (Lokalt investeringsprogram) (1998-2002) and KLIMP (Klimatinvesteringsprogrammet) (2002-2012) were locally specific programs aimed at supporting the transition from fossil fuels to renewables and to reduce greenhouse gas emissions. Billions of Euros have been spent in these programmes with varying, but in many cases positive, results. For example, the support to CHP plants resulted in about 20 new CHP plants using bioenergy (SEA 2009). There is a risk with some support schemes however, that the industry's own investment in research and development is lowered as the governmental support may shoulder such financial burdens (Hillring 1998).

Taxes

In Sweden, the energy tax, the sulphur tax, the nitrogen oxide fee and the carbon tax are used as monetary incentives for moving towards a more sustainable use of fuels. For bioenergy, conditions changed for the heating sector, when the carbon dioxide tax on fossil fuels was introduced 1 January 1991 as a result of political decisions after the environmental charges investigation. For example, heating oil accounted for 31% for space heating and hot water in dwellings and non-residential premises in 1990, but only for 2% in 2013. During the same period, the total use of biomass has increased from 220 to 460 PJ yr^{-1}. In 2013, the total use of petroleum products, natural gas and coal (incl. coke) was 460 PJ yr^{-1} (Energimyndigheten 2015).

Initially, the carbon tax was 0.027 € kg^{-1} CO_2 [2] and it was equal for all sectors (Andersson 2012). Since then the tax has increased progressively to the current level of 0.12 € kg^{-1} CO_2 (SEA 2015b). The introduction of this tax led to protests from industry, which claimed that the tax would impair their competitiveness on international markets. These protests were considered by the government, and industry was allowed a reduced rate. From 2011 industry had to pay 30% of the full carbon tax, from 2015 60% and from 2018 they will have to pay 100% of the full carbon tax (Andersson 2012, Melin 2015, Swedish Tax Agency 2015).

There is a general opinion that the carbon tax is now one of the main reasons for the rapid decline in the use of fossil fuels in Sweden (Hillring 1998, Andersson 2012). The tax is directly proportional to the carbon dioxide emissions from fossil fuels and it follows the "polluter pays principle" (PPP). The tax is also easy to administer and sets a long-term trajectory towards a more sustainable society (OECD 2013, Svebio 2015).

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[2] An exchange rate of € 1.00 = 9.27 SEK (2016-01-11) was used throughout the report.

Green electricity certificates

A key determinant for the increased production of electricity from biofuels in Sweden is green electricity certificates, which were introduced on 1 May 2003. In 2002, about 250 PJ of electricity were produced from renewable energy sources, mainly from large-scale hydropower plants (90%) (Energimyndigheten 2012). The initial aim of the certificate system was to increase the annual electricity production from renewable sources by 36 PJ yr^{-1} between 2002 and 2020. In 2010, this target was increased to 90 PJ yr^{-1}. Between 2003 and 2012, renewable electricity production increased by 48 PJ yr^{-1} (SEA and Norwegian Water Resources and Energy Directorate 2015). Of the total increase in energy production capacity from 2003, the share of wind power is 53% and of biopower 39% (SEA 2015a).

From 1 January 2012, Norway is included in a joint certificate market with Sweden. The target is to increase the annual electricity production from renewable sources by a total of 95 PJ yr^{-1} between 2012 to the end of 2020. In 2012-2013, a new production capacity of 22.3 PJ yr^{-1} was deployed on the Norwegian-Swedish market (SEA and Norwegian Water Resources and Energy Directorate 2015).

The electricity certificate system replaced earlier governmental system based on direct support. It is market-based as the prices of the certificates depend on supply and demand. The sellers are the electricity production companies, which get the certificates for free from the state. Buyers are the electricity traders, which are obliged to buy a certain number of certificates according to a quota system. The average spot market price in 2013 was 20.8 € per certificate corresponding to a production of one MWh_e) (SEA and Norwegian Water Resources and Energy Directorate 2015). The certificate system is neutral with regard to technology and energy sources. Biofuels, peat (in CHP plants in Sweden), geothermal energy, solar energy, hydropower, wind, and wave power are approved renewable energy sources. This neutrality promotes investment in the most cost-effective technologies (Swedenergy 2015b). The certificate system is financed by an extra fee paid to the electricity traders by the final consumers. This extra cost was 0.84 € GJ^{-1} (excl. VAT) in 2014 (Swedenergy 2015a).

It is a general perception that the certificate system has been successful and that the extra costs for the consumers are modest from a European perspective (SEA 2015a, Swedenergy 2015a). Regular follow-ups and checkpoint evaluations ensure that e.g. the quota system works as intended (Energimyndigheten 2014). The Swedish Bioenergy Association (Svebio) is currently proposing that the system should focus more on ensuring e.g. frequency balancing capacity, and not only on the production of electric energy (Melin 2015).

Development of the use of bioenergy

As stated earlier, the Swedish energy system has for many decades relied on fossil fuels, nuclear power and hydropower. However, with a steady increase since the oil crises in 1970s, the total supply of bioenergy is now about the same as the total supply of crude oil and petroleum products, i.e. about 460-470 PJ yr^{-1} (Figure 2).

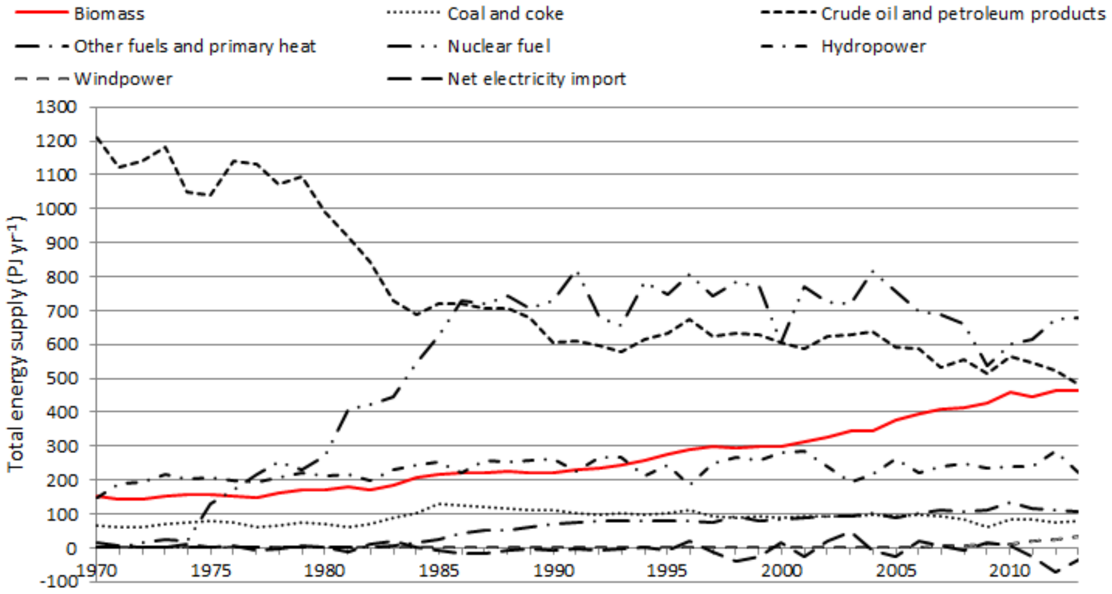

Figure 2. Trajectories of energy supplies in Sweden from 1970 to 2013 (Energimyndigheten 2015). Nuclear fuel is reported gross, i.e. as supplied nuclear fuel. Other fuels and primary heat include natural gas, gasworks gas and primary heat from heat pumps in district heating plants.

The most important user of bioenergy is the forest industry, mainly the pulp and paper industry, which to a large extent use their biomass residues internally. The use of bioenergy in the district heating sector has had increased during last few decades, due to its improved economic competitiveness. The use of bioenergy for electricity production and in the transport sector also had an increasing trend.

Forest-based fuels are the predominant biomass used in Sweden. Some important reasons are the vast resources, a tradition of using wood as fuel, well-established and cost-effective harvest and logistics systems, extensive forest industry producing by-products suitable for energy purposes, satisfactory combustion properties (*e.g*. comparatively low ash contents and comparatively low risks of slagging) and competitive prices relative to other biofuels. The current use of solid forest-based fuels (harvest residues, small trees from thinnings, stumps and wood of low value) in Sweden is about 270 PJ yr^{-1}, and has the potential to increase to 450 PJ yr^{-1} (Andersson 2012). The current use of black liquor from the pulp and paper industry is about 130 PJ yr^{-1} and has the potential to increase to 160 PJ yr^{-1} (Andersson 2012).

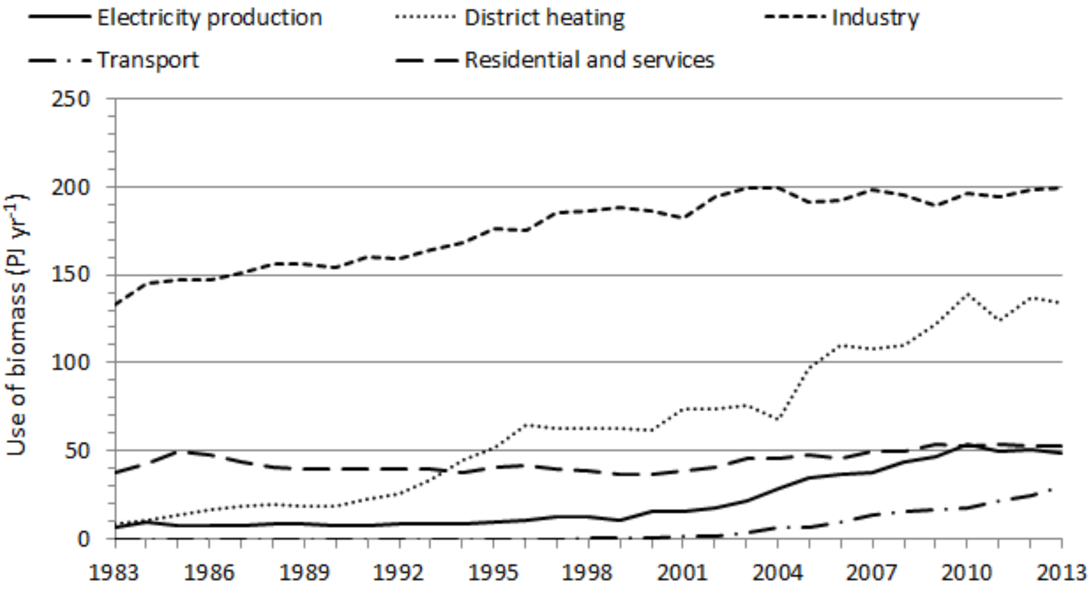

Figure 3. Use of bioenergy in Sweden (SEA and Norwegian Water Resources and Energy Directorate 2015).

4.USE OF STRAW FOR ENERGY

Straw fuel users can be divided into four different categories depending on organisational and structural levels (Voytenko and Peck 2012). The *small scale local heat producers* typically produce grain on their farms and have a substantial heat demand in their own buildings and for grain drying. They often have a batch-fired boiler (normally < 0.6 MW_{th}). The main reason for installing the boiler is economic. Expensive fossil oil is replaced by cheaper straw from the farm, even if the monetary value of own labour associated with straw firing may be undervalued. (Aldrich and Fiol 1994, Voytenko and Peck 2012).

The *medium scale local heat producers* often have a continuously-fed boiler (often 1-1.5 MW_{th}) with straw shredder. Besides own needs, they also sell excess heat to neighbours or to a local district heating network. The activities can be viewed as being at an intra-industrial level. The farmer saves money by replacing fossil oil with cheap straw from own or neighbouring fields, and also has an opportunity to get an extra income from heat sales (Voytenko and Peck 2012).

A third category, *medium scale boilers* produce heat for district heating. Larger plants in this category (up to 6 MW_{th}) can be owned privately or by the municipality, farmers or cooperatives. The supply of straw is often regulated by written contracts, and there is an intra-industrial level of relationship within this category, involving farmers, straw suppliers, boiler owners, municipalities, heat buyers, etc. The main reasons for establishing such plants are economic, legislative and/or political. For example, there may be a municipal policy to phase out the use of fossil fuels (Voytenko and Peck 2012).

The *large scale power or CHP producer* category is the most complex. Sophisticated technology is used for receiving and feeding the fuel into the boiler and for the production of process steam or district heating and electricity. The plants are often owned and financed by big energy companies. Boilers are constructed to combust straw, but can take in alternative fuels *e.g*. herbaceous crops or wood chips to supplement the straw feedstock. The straw price is determined by the market, depending on supply and demand. The relationship between the plant owner and other stakeholders in the supply chain are often established at an inter-industrial level characterized by competition and negotiations. Several specialist operators are involved in the whole chain from recovery of straw from the fields to selling of electricity and heat, and to the final disposal of combustion ash. Acceptance by general public is often an important issue. The main reasons for establishing such plants are economic, legislative and political (Voytenko and Peck 2012).

The use of straw for the production of vehicle fuels may be a fifth category. Two examples are the production of ethanol from lignocellulosic raw materials (Ekman et al. 2013) and the production of gaseous fuel via anaerobic digestion (Xavier et al. 2015) or thermal gasification (Thomsen et al. 2015, Zhu et al. 2015).

4.1. Current use

The number and type of energy providers in Sweden and Denmark is presented in **Table 1**. There are no commercial plants producing vehicle fuels in either Sweden or Denmark. Sweden has no CHP plants using straw in contrast to Denmark with 27 CHP plants in operation and one under construction (Tougaard 2015). There are at least four district heating plants in Sweden (Skurup, Såtenäs, Trelleborg, Löderup), with a total installed output of about 12 MW_{th} and a total straw demand of about 12,000 tonnes straw yr^{-1} (Paulrud and Eriksson 2014). The number of medium-scale plants on farms selling excess heat may amount to 25 in Skåne (Johnsson, 2006). Some examples are Jordberga (3 MW_{th}), Högestad-Christinehof (1.4 MW_{th}), Björnstorp, Barsebäck, Svenstorp and Skabersjö (Bernesson and Nilsson 2005, Mattsson 2006, Paulrud and Eriksson 2014). The total number of such plants in Sweden may be around 40. The number of small-scale plants, which have an installed output of typically 0.5 MW_{th}, may be around one hundred (Bernesson and Nilsson 2005), with an estimated use of 50,000 tonnes straw yr^{-1}. Hence, the estimated total use of straw for energy in Sweden is about 0.1 million tonnes yr^{-1} compared to 1.4 million tonnes yr^{-1} in Denmark.

Table 1. Number of plants and estimated use (1000 tonnes yr^{-1}) of fuel straw.

	Small-scale local heat production	Medium scale local heat provision with excess for sale	Medium scale conversion and district heating[1)]	Large scale power or CHP production	Production of vehicle fuels	Total use
Sweden						
No. of plants	100[2)]	40[2)]	4	0	0	
Estimated use	50[2)]	50[2)]	12	0	0	112
Denmark						
No. of plants	-	-	58	27	0[3)]	
Estimated use	339[4)]	2	390	592	-	1,323

[1)] Incl. non-residential and industrial heating.

[2)] Uncertain, estimated value.

[3)] A demonstration scale plant for converting straw to ethanol is placed in Kalundborg in the Zealand region. It has a capacity of 4 tons of straw per hour, but doesn't operate regularly.

[4)] Includes residential use and use in the agricultural sector.

According to a survey in 2012, straw was harvested on 40% of the total area planted with cereals (1.02 million ha) in Sweden (SCB 2013). Of the straw from this area, 73% was used for litter/bedding and 13% for feed purposes, while 9% (*i.e.* 3.6% of the total area or 36,000 ha) was used for heating (Figure 4). Fuel straw was also harvested on about 5,000 ha with rapeseed crops. Assuming an average straw yield of 3 tonnes ha^{-1} , the total quantity of harvested fuel straw in Sweden will be about 0.12 million tonnes yr^{-1}, which is of the same order of magnitude as indicated in **Table 1**.

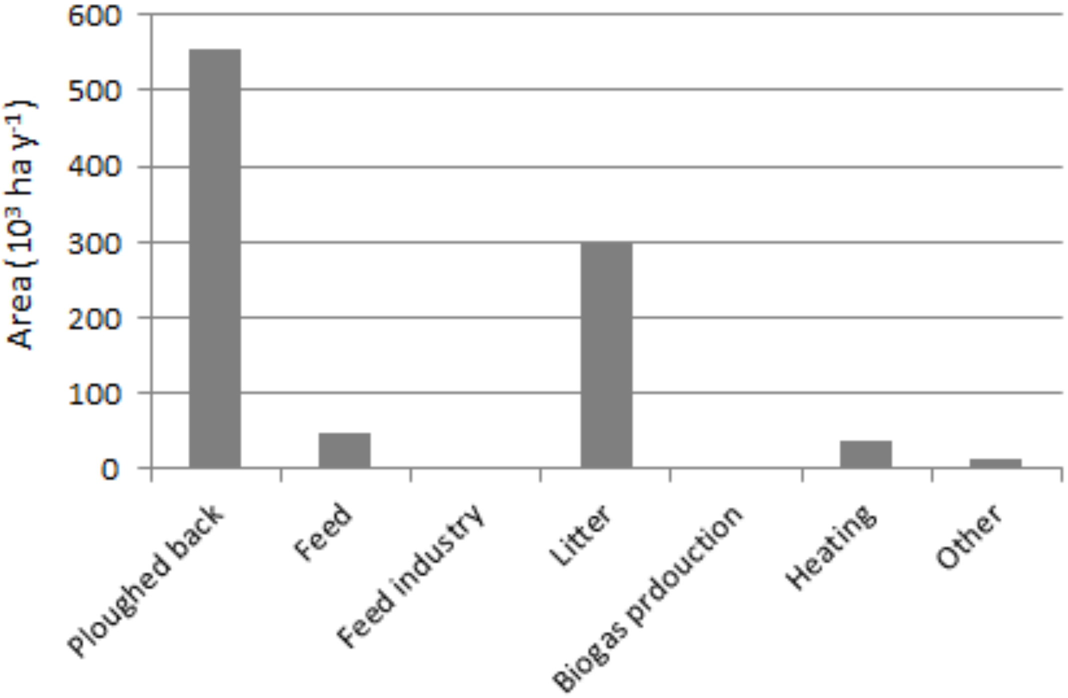

Figure 4. Use of cereal straw in Sweden according to a survey by Statistics Sweden (SCB 2013).

In Denmark straw has been used as a source of energy for many years, but before the mid-1980s predominantly for heating in individual households, farmhouses and in agricultural production (**Figure 5**).

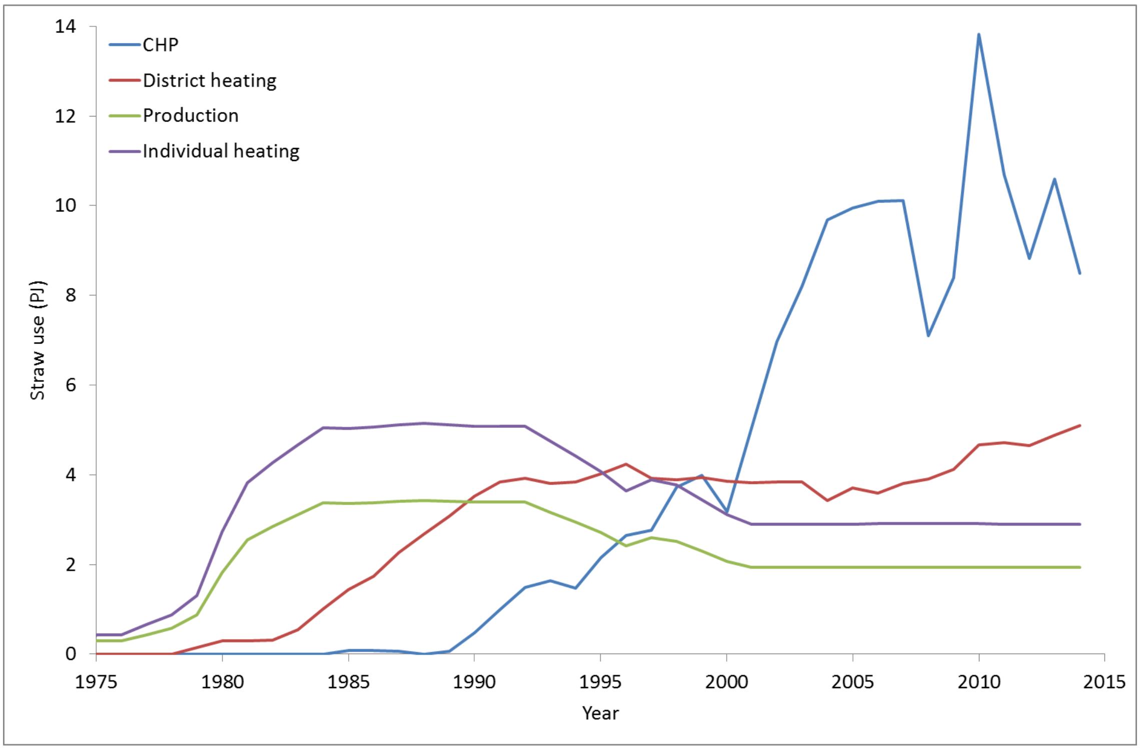

Figure 5. Straw used for energy and its allocation to different energy sectors in Denmark from 1975 to 2012. Data on CHP, district and individual heating (including housholds and farm production purposes) are derived from the Danish energy statistics (DEA 2015).

The use of straw for energy has increased over time and peaked in 2010 at 1.6 million tonnes. In 2015, the consumption was 1.3 million tonnes with 1 million tonnes used for CHP and district heating. This accounts for 12 % of the renewable energy production in Denmark or 2.8 % of the consumption of primary energy resources. While the amount of straw produced in Danish agriculture has decreased slightly over the last 15 years, the fraction collected and utilized in particular for energy purposes has increased. Currently around 50% of the straw is collected and of this fraction almost 45-50 % is used for energy generation. In parallel with the use of straw for heat and electricity, Danish companies have, in the last 10-12 years, worked intensively on developing technologies for converting straw/agricultural biomass into liquid fuels. The Inbicon project has, since 2003, been operating a pilot scale and since 2009 as a demonstration scale plant (Larsen et al. 2012, Bolwig and Amer 2013). The demonstration plant has a capacity of 4 tonnes straw input per hour and is integrated with a power plant which supplies excess steam for process heat. Inbicon sees their technology as part of a more general biorefinery concept, producing not only energy but also bio-chemicals and bio-materials. Straw has also been tested as feedstock for low temperature gasification in the Pyroneer project with the aim of producing syngas for stationary applications. Although promising results were achieved in the initial stages (Thomsen et al. 2015), the pilot scale gasifier, initially operated by Dong Energy has since been decommissioned. A pilot scale plant for hydro thermal liquefaction (HTL) of straw and other biomass fractions was built and operated by Aarhus University in May 2015. HTL converts biomass to a crude biooil (Zhu et al. 2015).

4.2. Future potential

The Danish market for primary crop residues is dominated by cereal (wheat, barley) straw. The annual total production of agricultural residues is around 6 million tonnes with cereal straw accounting for 90% or more. Rape seed straw accounts for the bulk of the remainder with a marginal contribution of residues from pulses (0.1 – 0.3% of the annual crop residue production).

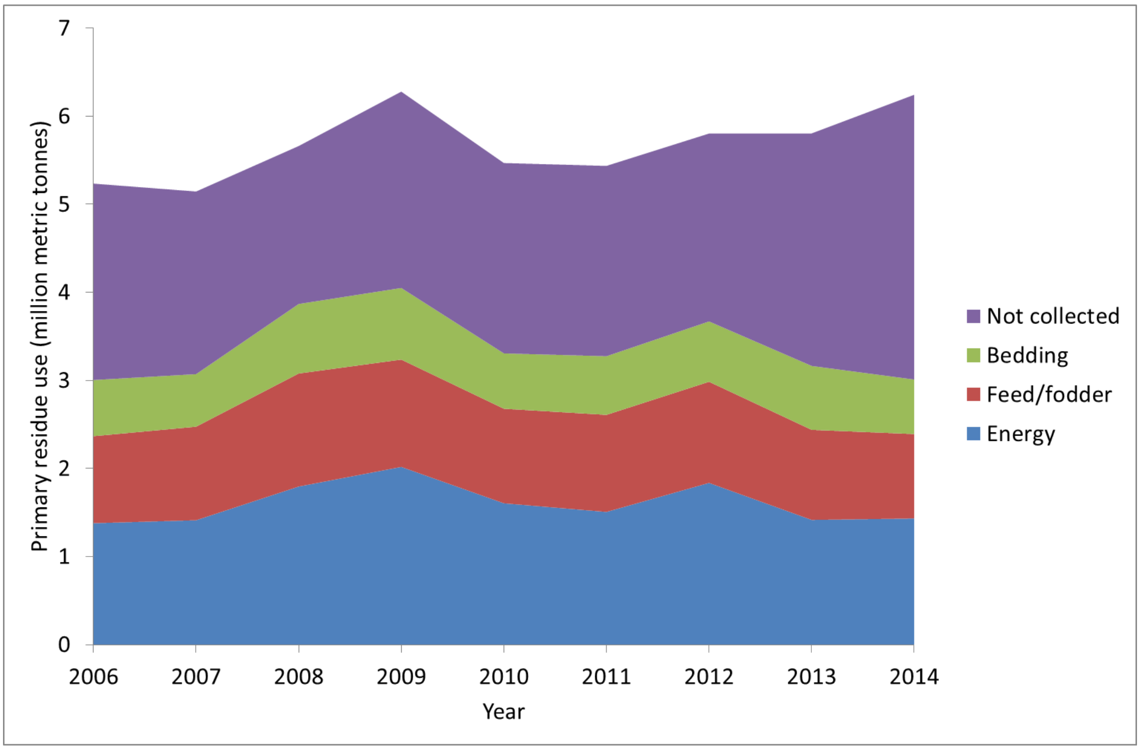

Figure 6. Annual production and use of primary crop residues from Danish agriculture (Statsitics Denmark 2015). Mass is measured as fresh weight, i.e. with 15% water.

The use of residues in different markets varies from year to year. In the period from 2006 to 2014 around 50% of the production was harvested, with 45-50% of the harvested amount being used for energy production. The '+10 million tonnes study' (Gylling et al. 2013) analysed a number of scenarios for increased biomass production in Denmark and found that the amount of straw sustainably available for biorefinery or energy purposes could be increased to 2.5-3.0 million tonnes yr^{-1} dry matter (43-51 PJ yr^{-1}) by 2020 through increased mobilisation and/or increased production. Increased mobilisation requires a larger demand for straw from district heating, CHP or advanced biofuel production and can be achieved through harvesting of larger areas and modifying harvest technology to harvest a larger part of the crop residues. Increased production can be achieved by a shift to more straw rich cereal varieties (Gylling et al. 2013).

In Sweden, a governmental investigation from 2007 ("Bioenergi från jordbruket – en växande resurs"), reviewed different potentials for the use of straw as fuel in Sweden (SOU 2007): the Bioenergy Commission (Biobränslekommissionen) (from 1992) 40 PJ yr^{-1}, the Federation of Swedish Farmers (LRF) 25 PJ yr^{-1} and the Swedish Bioenergy Association (Svebio) 18-25 PJ yr^{-1}. Some estimations on an EU level have also been presented showing that Sweden may have a potential of about 14 PJ yr^{-1} (Panoutsou et al. 2009, de Wit and Faaij 2010, Scarlat et al. 2010, Bentsen and Felby 2012, Elbersen et al. 2012).In Sweden the demand for straw for animal bedding and feed is often prioritized before other uses, and the price of this straw is in many cases higher than the price of straw for energy purposes. Thus, the quantities of straw that could be used as fuel are strongly dependent on the alternative demands for straw in this sector.

Nilsson and Bernesson (2009) estimated the physical potential for straw to 2.9 million tonnes, the practically harvestable potential to 2.0 million tonnes and the quantity harvested for bedding and feed to 1.1 million tonnes. The physical potential did not include chaff and the stubble; the practically harvestable potential took into account the requirement for straw to maintain soil organic matter content. Although the number of different animals was known, the actual average straw requirement per animal was uncertain. Nevertheless, the total straw quantity that could be used as fuel was estimated to 0.8-0.9 million tonnes yr^{-1}, corresponding to about 13 PJ yr^{-1}.

Removal of straw from agricultural fields implies removal of organic matter, which may contain up ot 60% organic carbon (Bertilsson 2010). In terms of climate change mitigation some studies indicate that it is preferable to harvest the straw and use it for the replacement of fossil fuels rather than ploughing it down to increase the soil carbon storage. The reason is that the net soil carbon sequestration is negligible in a 100-year-perspective (Powlson et al. 2008, Monteleone et al. 2015). However, from a soil fertility perspective, ploughing down the straw is beneficial, as it maintains the soil's structural stability, infiltration capacity and microbiological activity (Powlson et al. 2011). Recommendation have been made that straw should not be harvested where the soil organic matter content is below 3.5% (Bertilsson 2010), although there are controversies regarding the exact threshold (Loveland and Webb 2003).

The future potentials of straw may be influenced by thresholds for soil organic matter content as the content in some plain agricultural areas in Sweden, e.g. southeast Scania, is near or even below this threshold. A typical crop rotation in the plain areas in Scania is: sugar beet, spring barley, winter rape, winter wheat and triticale (Tjell and Aronsson 2000). In such rotations, two straw harvests are typically carried out. There are, however, no regulations as to how often straw can be harvested.

Similar discussions on the sustainability of continued straw removal exist in Denmark. In the eastern part of the country, straw has been harvested over many years. There are fewer ruminants and grasslands, and less animal manure to sustain the carbon content of soils compared to the western part of the country. As in Sweden no regulation is in place to control the extent and frequency of straw harvest but the Dexter ratio[3] (Dexter 2004, Dexter et al. 2008) has been suggested as an indicator to monitor and quantify the problem. A Dexter ratio of 10 or above is considered the critical limit for maintaining physical and mechanical sustainability of soils (Schjønning et al. 2009). Particularly soils in eastern Denmark, with their moraine origin and a history of intensive management, exhibit Dexter ratios close to or above 10.

5. STRAW FOR ENERGY LANDSCAPES IN SOUTHERN SWEDEN AND EASTERN DENMARK

This section describes differences and commonalities between the Scania region in Southern Sweden and the Capital and Zealand region in East Denmark (Figure 7) and assesses the potential influence on straw use for energy.

Scania in southern Sweden has the most abundant straw resources (Nilsson and Bernesson 2009). The harvest conditions regarding geographical density, straw yields per hectare, weather, etc. are among the best in the country. At the same time, the availability of woody fuel resources is limited

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[3] The Dexter ratio calculates the topsoil ratio between clay content and organic carbon content.

in comparison to most other regions in Sweden. Of the total area of cereals in Scania, straw is ploughed down on about 50% of farms in the region or 110,000 ha (SCB 2013). Straw is harvested for bedding on about 60,000 ha, for feed on 14,000 ha and for heating purposes on 18,000 ha.

The physical potential of straw production in Scania was estimated by Nilsson and Bernesson (2009) to 773,000 tonnes yr^{-1}. Taking restrictions regarding soil organic content and weather conditions during harvest into account, the practically harvestable quantity was approximated to 540,000 tonnes yr^{-1}. To estimate the use for bedding and feed, the number of different animals was multiplied by their approximated average need for straw per year. The resulting sum was 232,000 tonnes yr^{-1}, or 43% of the total harvestable quantity. This use is indeed an important competitor to energy straw in Scania, especially in areas with extensive animal farming.

Eastern Denmark has, in many respects, similar conditions for straw harvest; a high proportion of agricultural land in rotation (~60%) and a high proportion of cereal production.

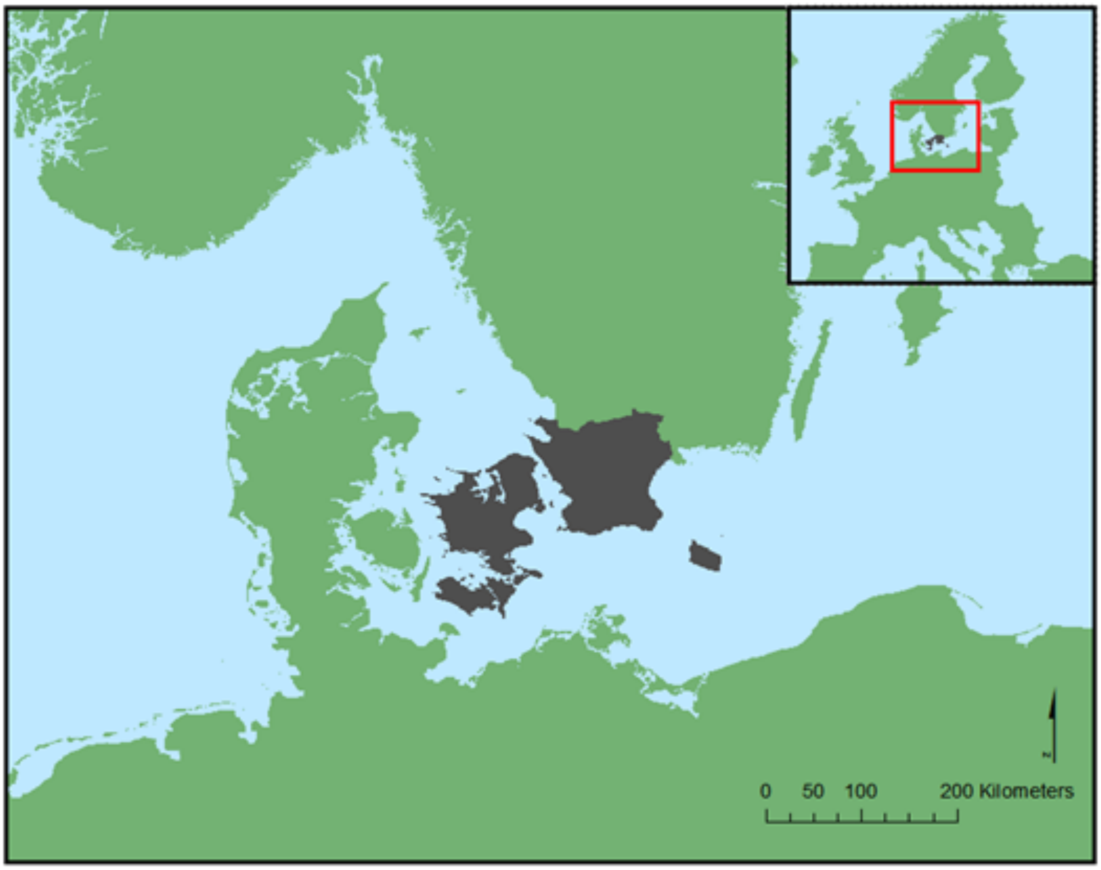


Figure 7. Geographical scope of the analysis. The Capital and Zealand region in eastern Denmark and the Scania Region in southern Sweden.

5.1. Geographical density of straw resources

Straw is a low bulk density fuel. Thus, the costs are sensitive to handling and transport over long distances. Eastern Denmark has a much higher geographical density of cereal and oil crop cultivation than Scania (**Table 2**). About 40% of the total land area is covered by these crops in Eastern Denmark, whereas the coverage in Scania is 23%. The total grain and oilseed production of these crops is 264 tonnes km^{-2} in Eastern Denmark compared to 136 tonnes km^{-2} in Scania.

It should be noted that the *local* geographical straw density may differ considerably within the areas studied. In the southwestern part of Scania, the density is much higher than in the north-eastern part. Consequently, more detailed studies are needed when analysing possible locations of energy conversion plants.

Table 2. A comparison of the area density of cereal crops in Scania and Eastern Denmark (Capital and Zealand region).

	Scania	East Denmark
Total land area (km^2)	10,939	9,782
Area with cereals and oil crops (ha)[a]	250,200	393,911
Share of total land area with cereals and oil crops (%)	22.9	40.3
Area with winter wheat (ha)[a]	91,990	180,125
Share of total land area with winter wheat (%)	8.4	18.4
Total production of cereals and oil crops (1000 tonnes yr^{-1})[a]	1,487	2,584
Production of cereals and oil crops per total land area (tonnes km^{-2})	136	264

[a] average of the years 2006-2014.

5.2. Straw yield per hectare

The straw yield has an important influence on total costs. The baler machines are expensive and their capacity, expressed in tonnes of straw baled per hour, must be high in order to reduce costs. Low yields also result in higher proportions of transfer and transport costs. The straw yield depends on type of crops and varieties and their corresponding straw to grain ratios, on the use of straw-shortening chemicals, on whether organic or non-organic farming is practised.

In both Scania and Eastern Denmark, winter wheat and spring barley are among the most common straw-producing crops (Figure 8). In Scania they account for about 22% and 19%, respectively, and in Denmark for 34% and 24%, respectively. The proportions of winter wheat, winter barley, spring barley and winter rape are higher in Denmark, whereas the proportions of spring wheat, rye, triticale and oats are slightly higher in Scania.

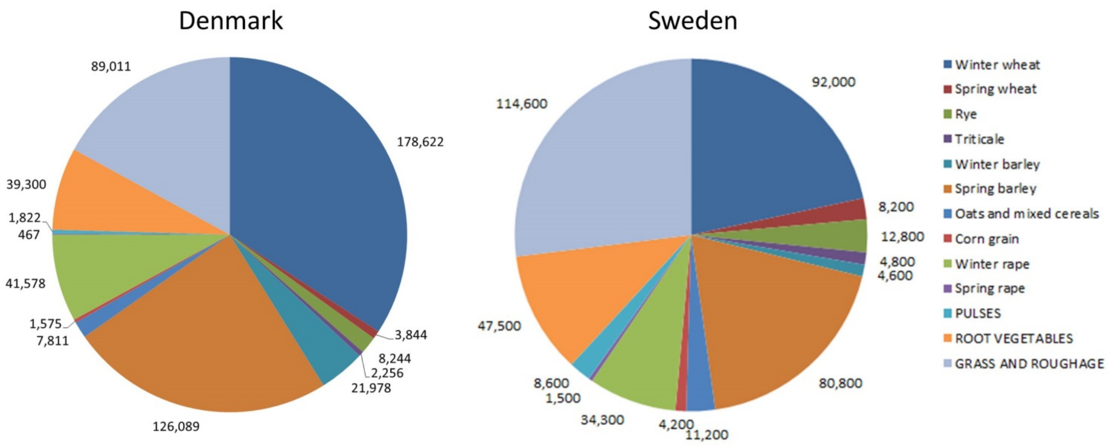


Figure 8. Allocation of arable land (ha) for various crops in eastern Denmark (left) and Scania (right), presented as averages over the period 2006-2014. Categories in capital letters are aggregates of several species. (Danmarks Statistik 2015, Jordbruksverket 2015b).

Average crop yields are not unambiguously higher in either Scania or eastern Denmark (Table 3). However, with winter wheat and spring barley being the dominant crops in both eastern Denmark and Scania, the yield is slightly higher in eastern Denmark.

Table 3. Average crop yields, calculated as the average total yield divided by the average total area for the years 2006-2014 (Danmarks Statistik 2015, Jordbruksverket 2015b). The Swedish straw-to-grain ratios were obtained from a study by Nilsson and Bernesson (2009) carried out under Swedish conditions. The Danish straw to grain ratios are the ratios applied by Statistics Denmark for agricultural statistics (Larsen and Haastrup 2009).

	Scania			East Denmark		
	Straw to grain ratio	Grain/seed yield (tonnes ha^{-1})	Potential straw yield (tonnes ha^{-1})	Straw to grain ratio	Grain/seed yield (tonnes ha^{-1})	Potential straw yield (tonnes ha^{-1})
Winter wheat	0.60	7.5	4.5	0.55	7.9	4.3
Spring wheat	0.66	5.3	3.5	0.50	4.8	2.4
Rye	0.78	6.6	5.1	0.80	6.3	5.0
Winter barley	0.57	6.1	3.5	0.55	6.5	3.6
Spring barley	0.37	5.5	2.0	0.55	5.9	3.2
Oat	0.52	4.6	2.4	0.60	4.7[1]	2.8
Triticale	0.65	5.6	3.6	0.80	5.4	4.3
Winter rape	1.02	3.6	3.7	0.90	3.9	3.3
Spring rape	0.94	2.2	2.1	0.90	2.1	2.6

[1] calculation based on an average total yield including the yield of mixed cereal crops.

[2] calculation based on an average total area including the area of “other” cereal crops.

It should be noted that the straw to grain ratio for a certain crop differs between varieties. The most common winter wheat varieties sown in Sweden in the autumn of 2014 were Julius (35%), Marribos (15%) and Ellvis (11%) (Jordbruksverket 2015a) (Table 4). Their average straw lengths were 83 cm, 81 cm and 80 cm, respectively, according to official tests (Hagman et al. 2015). The most common winter wheat varieties in Denmark sown in the autumn of 2014 were Mariboss (35%) KWS Dacanto (20%) and Hereford (13%), with straw lengths of 85 cm, 90 cm and 84 cm, respectively.

Table 4. Most common winter wheat and spring barley cultivars used in Sweden and Denmark for the 2015 harvest.

	Sweden			Denmark		
	Cultivar	Use (%)	Straw length (cm)	Cultivar	Use (%)	Straw length (cm)
Winter wheat	Julius	35	83	Mariboss	35	85
	Mariboss	15	81	KWS Dacanto	20	90
	Elvis	11	80	Hereford	13	84
	Olivin	9	88	Jensen	9	86
	Brons	8	74	KWS Cleveland	7	77
Spring barley	Propino	26	75	Quench	35	67
	Tamtam	18	73	Evergreen	25	70
	Irina	13	66	KWS Irina	10	61
	Anakin	8	71	Propino	9	71
	Quench	7	70	Odyssey	8	63

5.3. Weather conditions

Prevailing weather conditions during the harvest season determine whether the straw has a sufficiently low moisture content for use as a fuel (a commonly used limit is <20% (wet basis), but <18% is preferable). If the straw is too wet at harvest it will lose dry matter during storage due to microbial activity, and mouldy bales may be difficult to shred and may also represent a health hazard.

There are not significant differences in weather conditions during harvest between eastern Denmark and Scania (Figure 9). The average air temperature is 0.5-1.5 °C higher in eastern Denmark than in Scania in August and September, and the average precipitation is about 5 mm lower per month in eastern Denmark.

The equilibrium moisture content (EMC) of straw can be used as a weather-based indicator of the possibilities to harvest sufficiently dry straw. EMC describes the moisture content of straw when it has come to equilibrium in an environment with specified values of temperature and relative humidity. In this study, EMC was calculated for Malmö (in southeast Scania, with similar weather conditions as Eeastern Denmark, see Figure 9) and for Hörby (in the middle of Scania). The modified Halsey equation (Jayas & Mazza, 1993; ASAE, 2000) was applied to winter wheat straw with parameters developed by (Nilsson & Bernesson, 2009). The 'time windows' in Figure 9 indicate that there are somewhat better weather conditions for straw harvest in Malmö (and thus presumably also in eastern Denmark) than in Hörby, *i.e.* the total period with EMC<18% is longer in Malmö, although the difference is small between the areas.

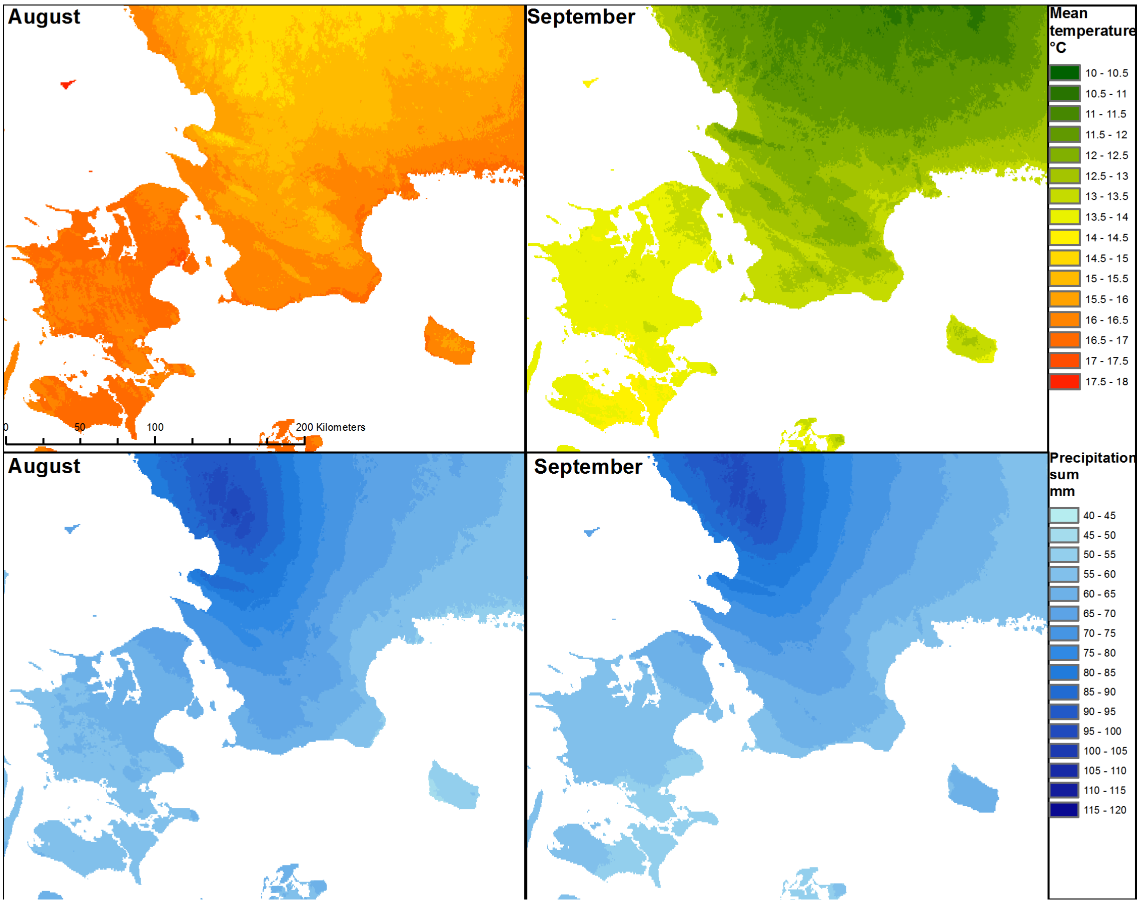
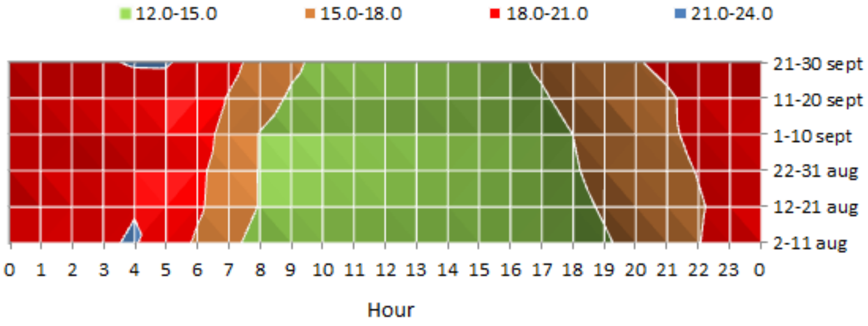


Figure 9. Average air temperature (upper) and average precipitation (lower) in August (left) and September (right) in eastern Denmark and Scania (Hijmans et al 2005).

The earlier the crop is sufficiently ripe for threshing, the higher the possibility of harvesting straw with sufficiently low moisture contents. The time of sowing and the weather conditions during the cultivation period have an impact on the time of ripeness. For the most common winter wheat varieties sown in Sweden in 2014, the average length of the growing seasons were: Julius (35% of the total area) 319 days, Marribos (15%) 320 days, Ellvis (11%) 318 days, Olivin (9%) 318 days and Brons (8%) 320 days, according to official tests (Jordbruksverket, 2015c; Hagman *et al*., 2015). A study on the harvest time for winter wheat in former Malmöhus län (the southwest half of Scania) showed that the threshing, in average, started on 13. August and that half of the fields had been threshed by 21. August (Nilsson and Bernesson 2009). However, there were years when the threshing of winter wheat started as late as 14 September. In such a year it may be difficult to harvest sufficient quantities of dry straw as the weather conditions are poor. The average duration of the harvest of winter wheat in Scania during the years 1985-1992, expressed in workdays, was 14 days, with a standard deviation of 1.4 days (Nilsson and Bernesson 2009). This was the number of possible harvest days, taking maturity and weather conditions into account.

In conclusion, weather conditions seem to be somewhat more favourable for straw harvest in eastern Denmark than in Scania, although the difference is quite small. It should also be noted that the geographical variability in weather conditions is higher in Scania (especially between the southern and the northern parts) than within eastern Denmark (Figure 10). As a result of slightly better weather conditions, the straw producing crops may ripen earlier in eastern Denmark than in Scania, which favours straw harvest.



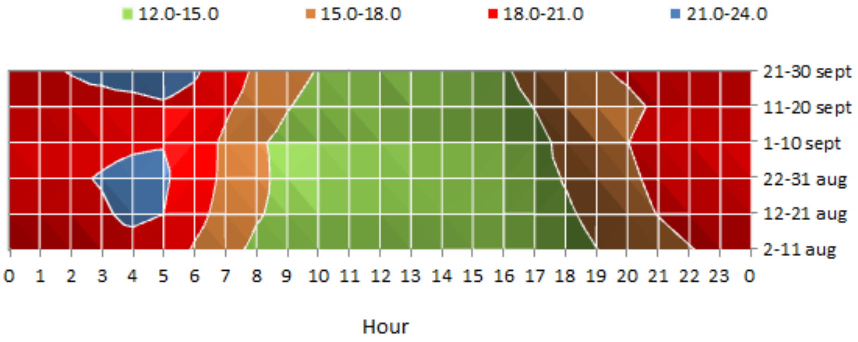


Figure 10. Hourly equilibrium moisture contents (EMC) of winter wheat straw in August and September, calculated with the modified Halsey equation with weather parameters (temperature and relative humidity) from weather stations at Malmö (upper) and Hörby (lower). The EMC has been calculated using average hourly values of temperature and relative humidity from a period of 20 years (1995-2014). The basic weather data were provided by the Swedish Meteorological and Hydrological Institute (SMHI).

5.4. Fuel prices and costs

The price of alternative energy sources determines the competitiveness of straw.

Denmark

The production cost of straw for energy has been estimated €3.4 – 3.9 GJ^{-1} (LHV), profit not included (Fødevareministeriet 2008, Dubgaard et al. 2013). The direct cost of straw production includes field operations (e.g. baling and transport), storage, insurance, administration and road transport (**Figure 11**). The nutrient value of straw that must be replaced when straw is harvested, risk and profit should be added to this. Road transport cost has been estimated to be €1.7 GJ^{-1} for straw delivered to CHP plants (average distance 50 km) and €1.2 GJ^{-1} to district heating plants (average distance 30 km) (Ea Energianalyse and Wazee 2011). Road transport constitutes 25-30% of the total cost. Belbo and Talbot (2014) found similar patterns in production cost for straw handling in Norway with the exemption that longer distance road transport does not take place in the Norwegian farms scale heating supply chains.

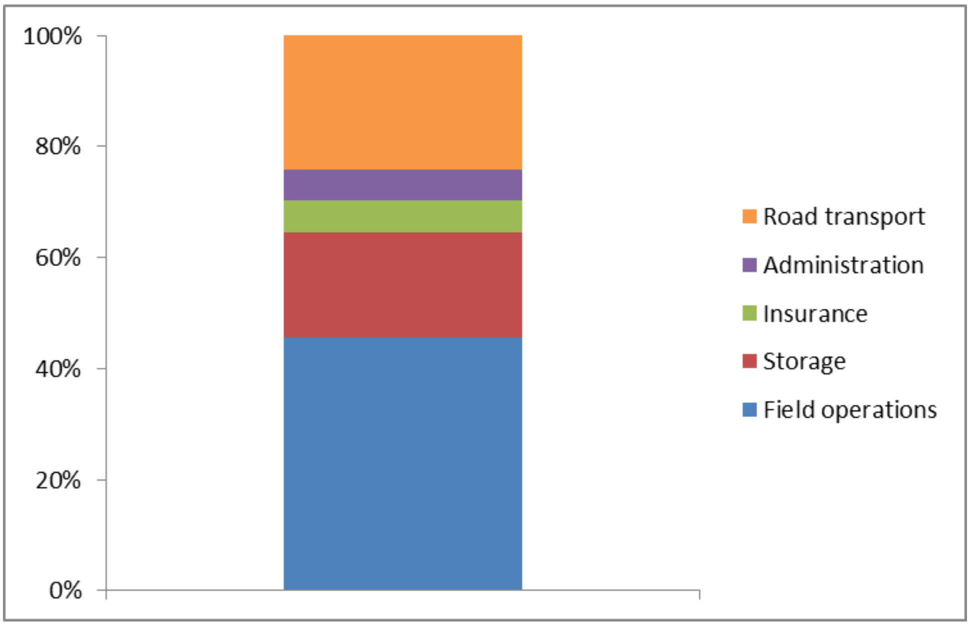


Figure 11. Relative break-down of direct cost associated with production of straw for energy in Denmark. Own calculations based on Fødevareministeriet (2008), Bang et al. (2013), Dubgaard et al. (2013).

The selling price of straw has been stable over time and is currently €5-5.5 GJ^{-1} (Bang et al. 2013) . Straw delivered to decentralized district heating plants is usually assumed to be sold at a slightly lower price (Figure 12) than to large centralised CHP plant because of shorter transportation distances (Bang et al. 2013).

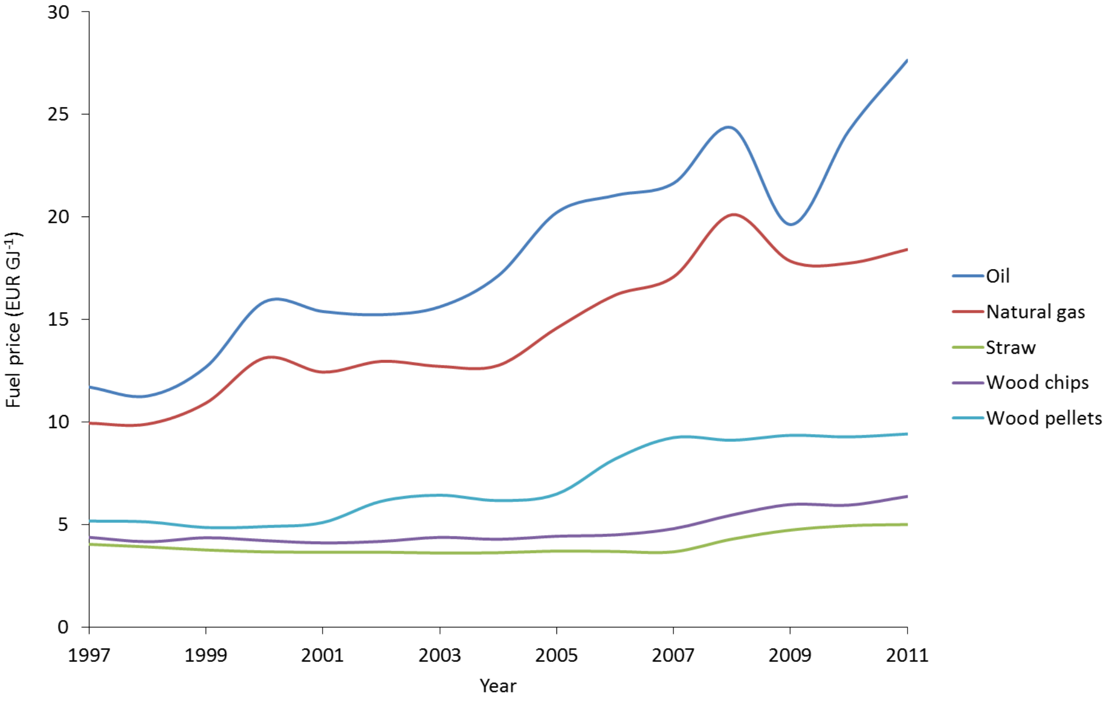


Figure 12. Fuel prices excl. VAT, but incl. other taxes in nominal values in Denmark for fuels delivered to district heating plants (Dansk Fjernvarme 2012). Prices are based on voluntary reporting without external audit.

Historically the price of straw and wood chips has followed each other closely with straw being 5-15 % cheaper than wood chips (Bang et al. 2013). Compared to alternative fuels straw is the cheapest available and the price volatility of straw and other biomass fuels is lower on an energy basis than for natural gas and oil.

Sweden

In the residential and services sector in Sweden, the pricing of district heating has become more competitive in comparison to heating with oil, electricity and natural gas (Figure 13). Wood chips, refined wood fuels (briquettes, pellets, etc.) and recycled wood are the predominant fuels in the Swedish district heating sector. The price of these biofuels has levelled off or even decreased during recent years, after an increasing trend until 2010-11 (Figure 14). The price may differ between different regions depending on variations in supply and demand. In southern Sweden, where the conditions for straw harvesting are most favourable, the average price for wood chips and refined wood fuels has been both higher and lower than the average price for the country as a whole (Figure 15). In 2014, the average price for wood chips was €5.8 GJ^{-1} in Sweden. Statistics for straw prices in Scania are not available.

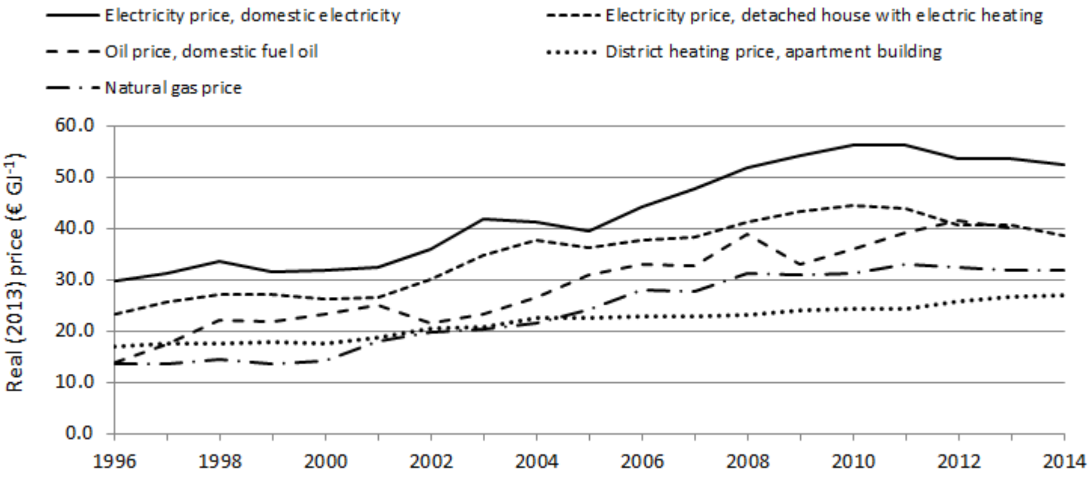


Figure 13. Energy prices for the residential and services sector from 1996 to 2014 (real prices at the 2013 level), (SEA 2015c).

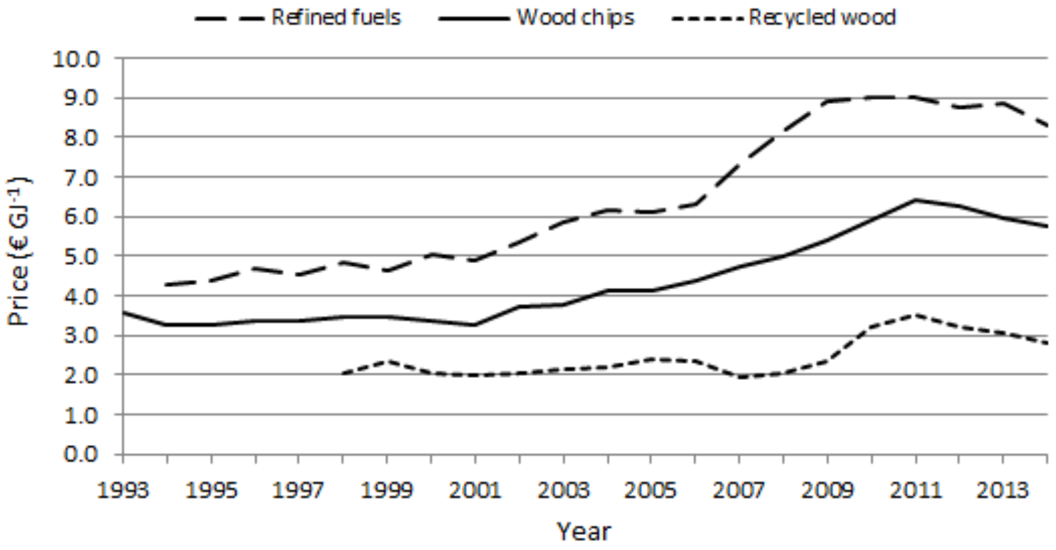


Figure 14. Average fuel prices for district heating plants in Sweden from 1993 to 2014 (current prices, excl. taxes), SEA (2015c).

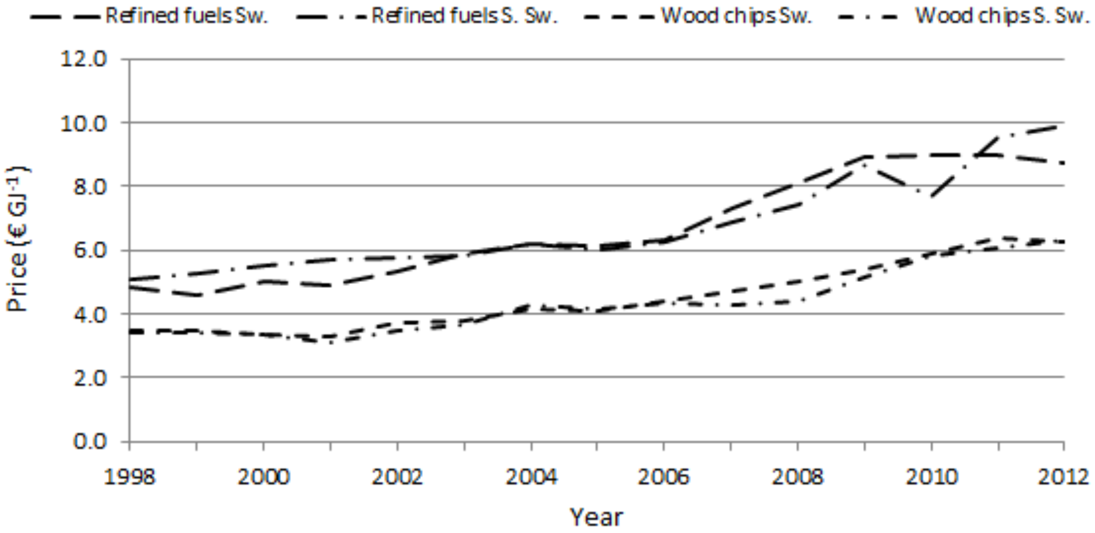


Figure 15. Average fuel prices for district heating plants in Sweden as a whole (dashed line) and in southern Sweden (dash and dot line) from 1998 to 2012 (current prices, excl. taxes), SEA (2015c).

The costs of straw may vary widely depending on payment to farmers for the straw (incl. compensation for removal of nutrients), harvest techniques, transport distances, and storage facilities. Nilsson (2010) calculated the total costs for delivery of straw to a heating plant in western Scania to €4.5-4.8 GJ^{-1}, including a farmer payment of €7.5 tonne^{-1} and indoor storage. Other studies have shown costs from about €3.0 GJ^{-1} (with *e.g.* outdoor storage) to about €5.4 GJ^{-1} (Mattsson 2006, Paulrud 2015). The additional costs of using straw as fuel, e.g. for handling and feeding of straw and ash, in comparison to wood chips, were estimated to €0.4-1.1 GJ^{-1} (Myringer et al. 2009). Although more detailed cost analyses are needed to make firm conclusions, it seems that straw has the potential to be economically competitive with wood chips in Scania.

6.SYNTHESIS AND CONCLUSION

6.1. Resource density

One of the marked differences between Scania and East Denmark is the density of the straw resources. In East Denmark the straw resource is almost double that in Scania (**Table 2** and Table 3). The density directly affects transport distances required to supply a power or heating plant and thus the economics of the operation. Due to the low energy density of straw, transportation between supplier (farmer) and consumer (power/heat plant) is an important cost element. The road transport of baled straw is approximately 25% higher than for wood chips and up to 250% more expensive than wood pellets based on bulk density (Ea Energianalyse and Wazee 2011).

Transport distances required to meet specific supplies for hypothetical supply regions was higher in Scania than in eastern Denmark Figure 16. To supply a given amount of straw in Scania approximately 40% longer transport is required than in eastern Denmark. This means straw is less competitive in Scania than in eastern Denmark, considering that 25-30% of the procurement cost goes to road transport (Figure 11).

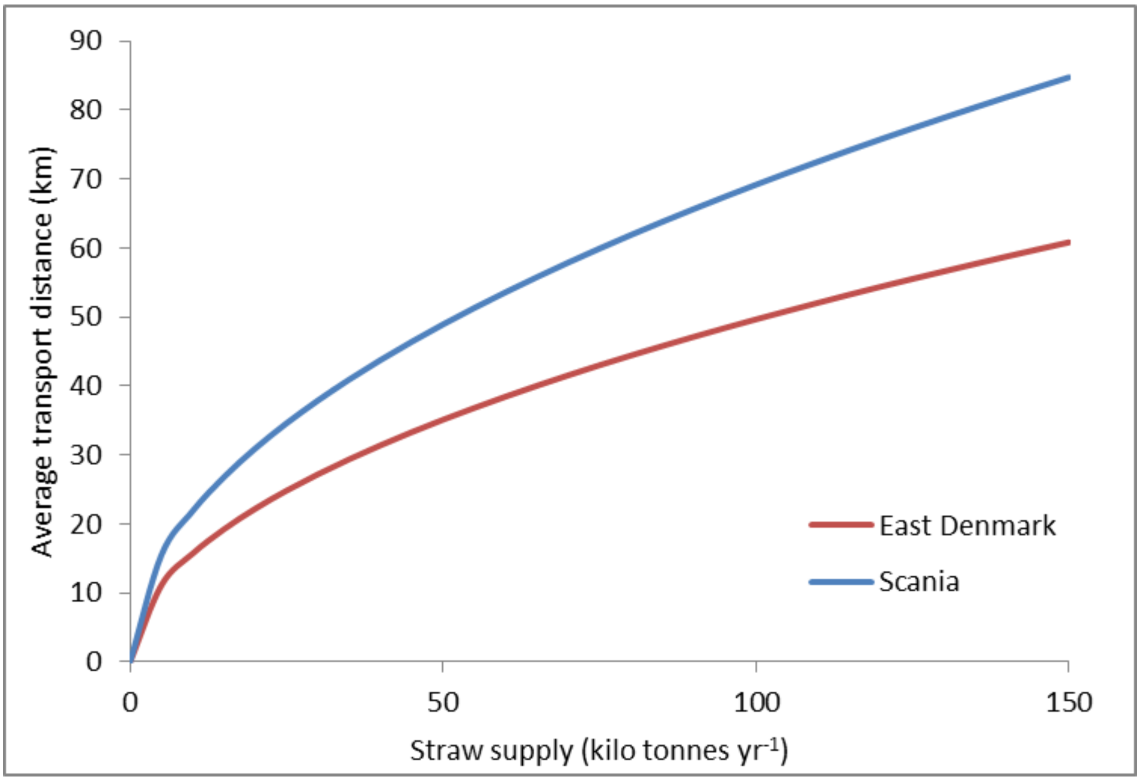


Figure 16. Hypothetical minimum transport distances for straw supply to a plant demanding up to 150,000 tonnes yr^{-1}. A hypothetical supply area is assumed as a concentric circle around the supply destination. The area weighted average transport distance is calculated as $r*0.5^{1/2}$. This is the transport distance that gives access to half the area of a circle with radius r. It is assumed that 40 % of the total straw production is harvested for energy purposes. Road network tortuosity is assumed to 1.5 (Nilsson 2010).

6.2. Policy and organisational framework

Denmark and Sweden has, as does the rest of the European Union, policies in place to support the deployment of renewable energy (Kitzing et al. 2012). CO_2 tax exemption is a common tool in the two countries. Denmark has used different forms of feed-in tariffs (FIT) for renewable electricity as the main incentive since 1993 (Lipp 2007, Kitzing et al. 2012) together with tenders on off-shore wind power with specified capacity (Kitzing et al. 2012). Sweden chose a fundamental different support strategy by implementing tradable green certificates (TGC) in 2003 (Haas et al. 2011). With uniform schemes TGCs promote the cheapest technology for renewable energy generation in contrast to FITs, tenders and quotas that specify not only the quantity of renewable energy generation but also the quality (applied technology) (Kitzing et al. 2012). Attempts to deploy green certificates have been made also in Denmark (IEA 2017), but without lasting success.

The organisational framework differs between Denmark and Sweden. Voytenko and Peck (2012) report that particularly large scale energy producers are instrumental in developing the straw to energy market, which is why the Danish market is established and the Swedish is still developing. In Denmark, also the Danish Straw Suppliers Association has contributed to ensure a transparent market (Voytenko and Peck 2012). In some respect, the organisation of straw to energy supply chains in Scania are more comparable to Norway where straw is used exclusively in small scale heat plants (Belbo and Talbot 2014) and not in large scale operations as in Denmark.

6.3. Fuel prices and competing fuels

In a competitive fuel market, the price is determined by the supply and demand of the fuel. A *perfect* market is characterized by, for example, a sufficient number of suppliers and consumers, open information and homogenous products. In the energy sector, external effects (i.e. taxes), the long-term investments required and the lack of long-term and steady policy frameworks may also influence fuel prices. Due to the large demand of straw in Denmark, a market-like situation, with several buyers and sellers who determine the price, has developed. The main competitors on the solid biofuel market are wood chips and wood pellets. Comparison to straw, the price of wood chips and wood pellets have been about 15-25% and 40-100% higher, respectively, in Denmark.

In Sweden, there are no ’official’ market prices for straw, although local ’market-like’ prices may occur in some areas; e.g. the counties Scania, Västra Götaland, and Östergötland. These prices are mainly set by the demand for straw for animal keeping. The price of wood chips was about €5.5 GJ^{-1} in 2015 in Sweden (Energimyndigheten and Statistiska Centralbyrån 2016). As pointed out earlier, the extra costs for fuel and ash handling of straw, compared to wood chips, has been estimated to €0.4-1.1 GJ^{-1} under Swedish conditions (Myringer et al. 2009). Thus, a price of up to a maximum of €4.4-5.1 GJ^{-1} would make straw competitive with wood chips. Such prices may be possible in flatland regions in southern Sweden.

The price of wood chips has generally been about 10-20% higher in Denmark than in Sweden. The difference in price for wood pellets between Denmark and Sweden has been smaller than for wood chips. This can be explained by, for example, the lower transport costs for these processed fuels. The higher prices of wood fuels in Denmark, and thus the higher economic competitiveness of straw, is one important reason for the continued use of fuel straw in this country. When using straw at a farm-scale level, however, the production costs in relation to fuel prices may be a more relevant for comparison.

In Denmark the difference in prices between straw and wood-based fuels remains fairly constant (Bang et al. 2013). In Sweden, the price of wood chips is not expected to rise dramatically in the nearest future (Energimyndigheten 2015), although several new heating and CHP plants have been built in recent years. One reason for the stable prices may be that the economic potential of wood fuel resources still is large, indicating also that the supply curve is rather flat. The price of refined fuels and recycled wood is more difficult to foresee as they are internationally traded products.

Comparing the prices of wood chips, refined wood fuels and straw, it can be concluded that the economic competitiveness of large-scale use of fuel straw generally has been higher in Denmark than in Sweden. It is difficult, however, to quantify this difference due to for example varying local market situations. Further analysis regarding production costs may give more insights. It should also be noted that the overall attractiveness of a fuel is not only dependent on market prices. Non-economic and non-technical barriers, such as tradition and knowledge, may also play important roles (Eriksson, pers.comm.).

6.4. Production costs

The costs for straw can be divided into payment to farmers for the straw, machinery costs, labour costs, storage costs, administration, insurance and profit. The payment to farmers is intended to compensate for nutrient and soil carbon losses and for the risk of delayed sowing of winter crops due to straw harvest. In reality, however, this payment may also be influenced by the local market situation, i.e. by the supply and demand of straw in the region. This payment, or maybe more correctly price, seems to be about the same in Denmark as in Sweden (Scania), i.e. about €8-15 tonne^{-1} (Mattsson 2006), even if this price may not reflect the current market situation.

There is a common labour market in the so-called Öresundsregionen (eastern Denmark and Scania), and since the opening of the Öresund Bridge in the year 2000, there has been a continuous equalisation of labour and residential costs. For the countries as a whole, the average total labour costs are similar, although the gross wages are higher in Denmark (Ekonomifakta 2016). The total labour cost for a tractor driver in Sweden is typically about €25 hr^{-1} (Rosenqvist, pers. comm.). The investment costs for machines and other technical equipment and storage facilities can also be considered similar for Sweden and Denmark (Rosenqvist, pers.comm.), as is the case for the interest rate. The repo rate was below zero in both Denmark and Sweden in January 2016 (Finansportalen 2016). Sweden has higher diesel fuel prices as a result of higher taxes (Hagberg et al. 2010). However, calculated altogether per tonne of straw, there seems to be small differences when summing up the prices of labour, machines, capital and fuels.

The productivity in harvest and handling of straw is dependent on several factors, for example, straw yield, size and shape of fields, road networks, transport distances and in-field drying conditions (weather) (Nilsson 2000). Small and irregular-shaped fields imply higher costs as the productivity may drop considerably (in particular when <2.0 ha) (Nilsson et al. 2015). For Scania (and most probably also eastern Denmark), small and distant fields with cereals are less common than in many other regions in Sweden (Nilsson et al. 2014). For large-scale harvest of straw, such fields are avoided for economic reasons. The information provided in chapter 4 indicated that the average transport distances may be shorter in eastern Denmark compared to Scania, and that the weather conditions may also be more favourable in eastern Denmark, whereas there were no significant differences in straw yield between Scania and eastern Denmark. The 'time window' for harvest may also be slightly longer in East Denmark because of earlier ripening of straw-producing crops and generally better in-field drying conditions. It should also be noted that the current productivity most probably is higher in Denmark because of the existence of a mature industry for large-scale harvesting and utilisation of energy straw (Hinge 2009).

In conclusion, the total production costs per tonne of energy straw may generally be lower in eastern Denmark than in Scania, mainly as a result of a higher productivity in harvesting and handling. There are some areas in Scania, however, where the conditions are similiar, especially in the most southern parts.

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