Industrial Hemp (*Cannabis sativa* L.) – a High-Yielding Energy Crop

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Cover: Production pathways for biogas (top) and solid biofuel (bottom) from hemp. Photos: T. Prade; except biogas plant and CHP plant: Bioenergiportalen.se.

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Abstract

Bioenergy is currently the fastest growing source of renewable energy. Tighter sustainability criteria for the production of vehicle biofuels and an increasing interest in combined heat and power (CHP) production from biomass have led to a demand for high-yielding energy crops with good conversion efficiencies.

Industrial hemp was studied as an energy crop for production of biogas and solid biofuel. Based on field trials, the development of biomass and energy yield, the specific methane yield and elemental composition of the biomass were studied over the growing and senescence period of the crop, i.e. from autumn to the following spring.

The energy yield of hemp for both solid biofuel and biogas production proved similar or superior to that of most energy crops common in northern Europe. The high energy yield of biogas from hemp is based on a high biomass yield per hectare and good specific methane yield with large potential for increases by pretreatment of the biomass. The methane energy yield per hectare is highest in autumn when hemp biomass yield is highest.

The energy yield per hectare of hemp for use as a solid biofuel is highest in autumn when the biomass yield is highest. However, important combustion-related fuel properties, such as moisture, alkali, chlorine and ash content and ash melting temperature, are significantly improved when industrial hemp is harvested in spring instead of in autumn. Major fuel properties of hemp are not significantly influenced by annual cultivation conditions, latitude or choice of cultivar.

Net energy yields per hectare and energy output-to-input ratios of hemp are above-average in most applications, and are highest for use of hemp as solid biofuel. Use of hemp as a biogas substrate suffers from higher energy inputs and lower conversion efficiencies, but produces a high-quality vehicle fuel.

Advantages over other energy crops are also found outside the energy balance, e.g. low pesticide requirements, good weed competition and suitability as break crop in cereal-oriented crop rotations. Improvements in hemp biomass and energy yields may strengthen its competitive position against maize and sugar beet for biogas production and against perennial energy crops for solid biofuel production.

Keywords: bioenergy, fibre hemp, feedstock, solid biofuel, biogas, substrate, biomass yield, energy yield, energy balance, production

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...the greatest service which can be rendered any country is to add an useful plant to it's culture...

Thomas Jefferson (Memorandum of Services to My Country, after 2 September 1800)

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Prade T, Svensson, S-E, Andersson A, Mattsson, JE (2011). Biomass and energy yield of hemp grown for biogas and solid fuel. *Biomass & Bioenergy* 35(7), 3040-3049.

II Kreuger E, Prade T, Escobar F, Svensson S-E, Englund J-E, Björnsson, L (2011). Anaerobic digestion of industrial hemp – Effect of harvest time on methane energy yield per hectare. *Biomass & Bioenergy* 35(2), 893-900.

III Prade T, Finell M, Svensson S-E, Mattsson JE. Fuel properties of industrial hemp (*Cannabis sativa* L.) at different harvest dates. Submitted to *Fuel*.

IV Prade T, Svensson S-E, Mattsson JE. Energy balances for biogas and solid fuel production from industrial hemp. Submitted to *Biomass & Bioenergy*.

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The contribution of Thomas Prade (TP) to the papers included in this thesis was as follows:

I TP planned and carried out sampling, prepared samples and analysed data. Wrote the manuscript in collaboration with the co-authors.

II TP planned and carried out field trial sampling, prepared samples and analysed data from field trials. Calculated energy yield. Contributed to the data analysis and writing.

III TP planned and carried out sampling and sample preparation of the southern Swedish field trials, analysed data. Wrote the manuscript in collaboration with the co-authors.

IV TP carried out literature data collection and analysed data. Wrote the manuscript in collaboration with the co-authors.

Abbreviations

BEY	Biomass energy yield
BMP	Biochemical methane potential
CEY	Combustion energy yield
CHP	Combined heat and power
DM	Dry matter
DME	Dimethyl ether
FAME	Fatty acid methyl ester
GHG	Greenhouse gas
HHV	Higher heating value
IDT	Initial deformation temperature
LCA	Life cycle assessment
LHV	Lower heating value (d.b. = dry basis; w.b. = wet basis)
MEY	Methane energy yield
MC	Moisture content
MSW	Municipal solid waste
NEY	Net energy yield
PPI	Pulp and paper industry
$R_{O/I}$	Output-to-input ratio
SRC	Short rotation coppice
SSF	Simultaneous saccharification and fermentation
THC	Δ-9-tetrahydrocannabinol
VS	Volatile solids

Why hemp?

Hemp (*Cannabis sativa* L.) is an annual herbaceous crop that has been cultivated by mankind for millennia for its fibres and seeds (Bocsa & Karus, 1998). It originates from western Asia and India and the first evidence of hemp used in northern Europe dates back to the 9th century (Godwin, 1967). Over centuries the fibres were used for the making of ropes, sails, cloth and paper, while the seeds were used for protein-rich food and feed. The import of other fibres such as sisal from Central America and jute from India led to a decline in hemp cultivation in Europe in the 19th century (Bradshaw & Coxon, 1981). It was mainly the use of hemp as a resource for drug production based on its high content of the psychoactive compound tetrahydrocannabinol (THC) led to the prohibition of its cultivation worldwide by the United Nations in 1961. While new cultivars were bred during prohibition, development of harvesting technology for hemp discontinued and knowledge about its cultivation fell into oblivion. When prohibition was revoked in the 1990s in the European Union and Canada, industrially used hemp emerged again as a result of the increasing interest in natural fibres. Although hemp is a crop with many applications and uses and there are varieties available with insignificant THC content, its cultivation is still prohibited in some industrialised countries, e.g. Norway and the USA (Smith-Heisters, 2008; Clarke, 2002).

Originally approved for fibre production, industrial hemp can also be used for production of renewable energy carriers, such as solid biofuel, biogas and bioethanol. With its potentially high biomass yield and its suitability to fit into existing crop rotations, hemp could complement and exceed other available energy crops. Because of the reignited interest in hemp there is now a need for re-establishing knowledge about its cultivation and harvest, but also about its new applications as an energy crop.

1 Introduction

1.1 Renewable energy carrier production[1] and consumption[1]

1.1.1 Overview

Production of renewable energy has become a common phrase when discussing the future energy supply – on global, national, regional and local scale. On a global scale, there are two main reasons why production of renewable energy is desirable.

The first reason is that renewable energy – as the term implies – can be renewed, i.e. the source of the energy is replenished, e.g. by natural cycles or a steady supply. The latter can be seen as endless, at least in the time scale of human existence on earth. Renewability of energy supply is important, since the worldwide demand for energy, e.g. for food production, transportation or production of goods, is still increasing (*Figure 1*). The majority of global energy use is based on fossil fuels (*Figure 2*), which are non-renewable or finite. The biggest share of the supply is covered by mineral oil, followed by coal and natural gas (BP, 2011). Many of the current fossil fuel reserves under exploitation have passed peak production and are in decline (Smil, 2003). However, these reserves will not come to an end soon or at all for economic reasons. Besides easily extractable fossil fuel reserves, there are larger resources[2] that are more difficult and costly to extract.

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1. According to the laws of thermodynamics, only energy carriers, not energy itself, can be 'produced' or 'consumed'. Energy can be converted from one carrier to another or transformed from one state (e.g. chemical, electrical, kinetic, gravitational potential, thermal, radiant, nuclear) to another. However, in colloquial language 'energy production' and 'energy consumption' are accepted terms.

2. Resources represent all deposits of a given fossil fuel that are present in the Earth's crust. However, the part of a resource that is extractable with available techniques at an acceptable cost is called reserve. Reserves are potentially replenished by more advanced extraction technology becoming available or rising fuel prices rendering extraction economically viable (Smil, 2003).

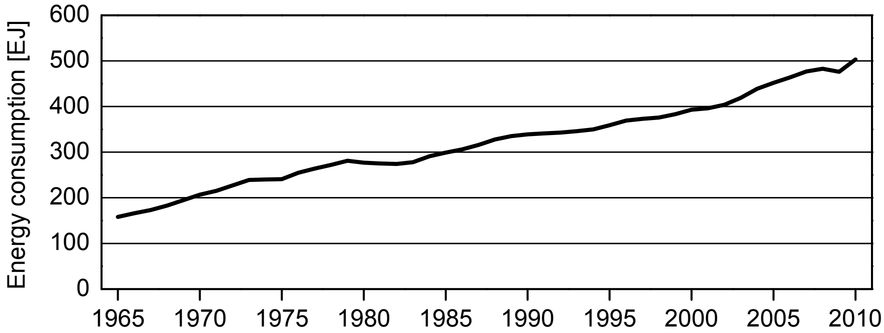

Figure 1. Global primary energy use 1965-2010 (BP, 2011). EJ = 10^{18} J.

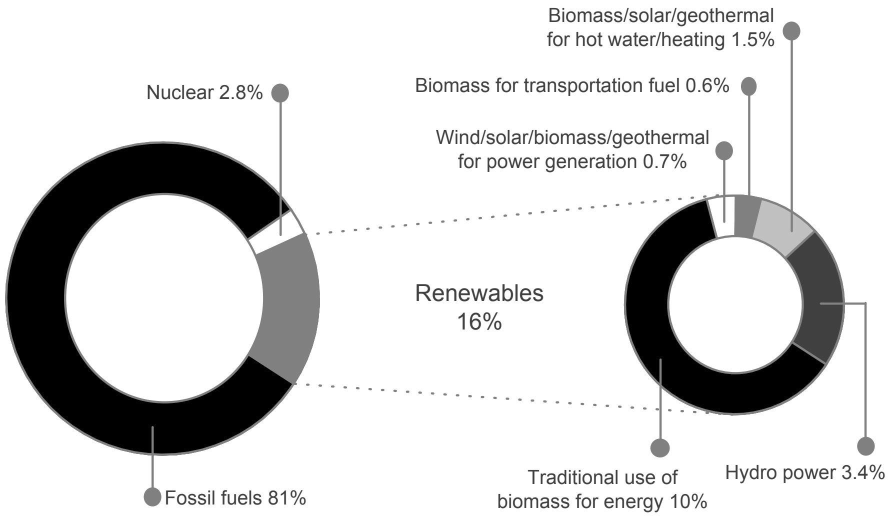

Figure 2. Global final energy use by fuel in 2010 (REN21, 2011).

The second reason is that the greenhouse gas (GHG) effect can potentially be mitigated[3] by replacing fossil energy with renewable energy if production and use of the renewable energy causes less greenhouse gas emissions than those of fossil fuels.

Numbers for the current global share of renewable energy supply vary greatly. Some reports claim that renewables account for only approx. 7.8% of global primary energy carrier consumption (e.g. BP, 2011). However, this number is misleading, since a major proportion of renewable energy is not

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3. Major greenhouses gases are carbon dioxide, methane, nitrous oxides, ozone and water vapour. The gases have different magnitude of effect on the global climate (e.g. the average global temperature), and are therefore accounted for as carbon dioxide equivalents.

accounted for in this statistic, e.g. fire-wood used in Third World countries (Best & Christensen, 2003). When this traditional biomass is accounted for, renewable energy accounts for approx. 16% of the global energy supply[4] (*Figure 2*) (REN21, 2011)

On national level, additional incentives exist for adopting renewable energy sources for many countries. Independence from import of fossil energy carriers is a powerful driver to promote domestic biofuel production (Wiser & Bolinger, 2006), as are socio-economic aspects, such as unemployment and rural depopulation (Domac *et al.*, 2005).

1.1.2 Types of renewable energy sources

There are many types of sources for renewable energy carrier production. They are based on transformation of kinetic energy (e.g. of wind, waves), gravitational potential (tides, rivers), thermal energy (geothermal sources) or chemical energy (bioenergy) to other, often more useful forms of energy, such as electrical energy (power), thermal energy (heat) or chemical energy (fuels[5]). During the past decade, bioenergy was by far the fastest growing renewable energy source (AEBIOM, 2011; BP, 2011), partly due to large-scale implementation of fossil fuel replacements in heat and power production and transportation biofuel production.

1.2 Bioenergy

Bioenergy is derived from biomass, i.e. biological material of organisms living or recently alive[6]. This includes plants, but also animals and microorganisms.

It is estimated that so-called traditional bioenergy, i.e. non-commercial use of e.g. wood and dung in rural areas as fuels for heating and cooking, accounts for 10-14% of global primary energy carrier consumption (REN21, 2011; Best & Christensen, 2003). This is considerably more than the 7.8% for all commercial renewable energy carrier consumption combined and the number

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4. There are three major ways of counting renewable energy flows, which lead to significant variations in the share of renewable energy (REN21, 2007).

5. The term 'fuels' is often used as a synonym for liquid motor fuel, i.e. a transportation fuel or vehicle fuel. However, 'fuel' has a wider meaning, including all substances that store energy that can be extracted to perform e.g. mechanical work. Fuels can be solid (e.g. coal, wood), liquid (e.g. mineral oil, vegetable oil) or gaseous (e.g. natural gas, biogas). Fuels derived from or consisting of biomass are termed 'biofuel'.

6. Peat takes a special position here. The biomass that formed peat is derived from organisms long dead, however, peat can still be seen as a (slowly) renewing source of energy. Exploitation might be sustainable from a carbon balance point of view, if exploitation rates are below those of peat creation. However, this classification is not undisputed (Schilstra, 2001).

gives an impression of the potential of this type of bioenergy. However, the production of bioenergy referred to in this thesis is based on commercial use of biomass.

1.2.1 Biomass for energy carrier production

Biomass available for commercial energy carrier production can be separated into two types. The first type is termed ‘residues’ and includes residual material originating in agricultural and industrial processes, e.g. from the production of food, fuels, building materials, in forestry, e.g. from plantation thinning and harvesting, in maintenance of e.g. parks, roadsides or beaches, or in treatment of waste water. The second type of biomass is cultivated for the sole purpose of energy carrier production, e.g. from agriculture (energy crops), forestry (fire wood, pellets) or marine origin (algae).

The major sources of biomass for energy purposes in Sweden are wood fuel, residues from the pulp and paper industry (PPI), municipal solid waste (MSW), peat and energy crops (*Figure 3*). The pulp and paper industry uses biomass unfit for pulp production as a source of internal energy supply. Wood from forestry and recovered wood is the dominant energy carrier in district heating. However, energy crops are used only to a limited extent so far.

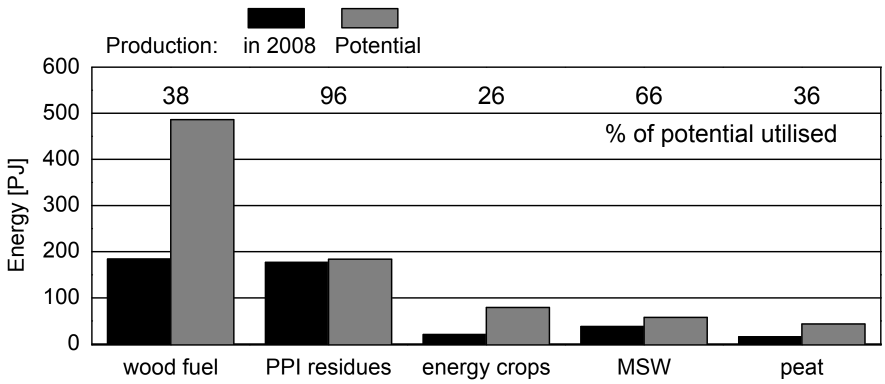

Figure 3. Annual energy carrier production from biomass in Sweden (black columns) and annual potential (grey columns) (Loman, 2010; SCB, 2010; SVEBIO, 2003; current production from energy crops: calculated from *Table 2*). PPI = pulp and paper industry; MSW = municipal solid waste. PJ = 10^{15} J.

1.3 Biomass conversion processes for energy carrier production

1.3.1 Anaerobic digestion

Anaerobic digestion[7] is a process that is based on microbial[8] degradation of biomass (substrate) in a practically oxygen-free environment, e.g. a digester[9]. The process can be carried out wet[10] or dry[10]. Dry fermentation is usually applied for substrates with high DM content, e.g. energy crops. However, energy crops are often co-digested, e.g. with manures, and accordingly wet processes are applied in such cases.

The main energy carrier produced in anaerobic digestion is methane (CH_4). It often comprises the majority of the biogas produced, besides carbon dioxide and a number of trace gases. Raw biogas can e.g. be combusted[11] in gas boilers (for heat production) or engines/turbines for combined heat and power (CHP) production. Upgrading[12] of raw biogas to high methane content results in methane gas utilisable as vehicle fuel. The nutrient-rich remainder of the biomass that is not converted to biogas is called digestate[13] and can be used as a biofertiliser in field crops.

1.3.2 Combustion

Biomass can be combusted in either small-scale (e.g. a household boiler or furnace) or large-scale boilers, e.g. for production of heat, power or CHP. Biomass for combustion usually has a MC around 30-40% for wood fuels[14] and below 20% for straw fuels[15] (Nilsson *et al.*, 2011a; Mattsson, 2006; Nilsson, 1997). In large-scale plants, the combustion heat in the boiler is transferred to water, which can then be used for district heating or steam turbines for power generation. The incombustible, inorganic part of the

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7. An anaerobic digestion is a fermentation process in an oxygen-free or -limited environment.

8. In the digester, an undefined mixed microbial population catalyses biomass degradation to biogas.

9. A digester is also called ‘fermenter’.

10. Wet and dry anaerobic digestion process usually have a dry matter content of 10-15% and 24-40%, respectively (Luning *et al.*, 2003).

11. Often the raw biogas is cleaned from H_2S prior to combustion, in order to avoid corrosion on gas-side engine or boiler surfaces.

12. Upgrading is the removal of carbon dioxide and other trace gases from the raw biogas. Is the biogas to be distributed in a natural gas grid, the heating value is often adjusted to that of the natural gas.

13. Digestate is also called ’digested residue’.

14. Wood fuels are e.g. wood chips, bark and saw dust. Wood fuel is also upgraded to pellets, briquettes and wood powder (MC ~10%), which are used in large CHP plants.

15. Straw fuels are e.g. cereal straw, hemp, miscanthus and reed canary grass.

biomass remains as ash after combustion. Ash from biomass combustion is often used as fertiliser (van Loo & Koppejan, 2008).

1.3.3 Fermentation

Fermentation is a microbial conversion of biomass. In contrast to anaerobic digestion, oxygen may be present and often a defined microbial culture is used[16]. Fermentation of biomass can be applied to produce a large number of products, both for energy and non-energy use[17]. Bioethanol production is probably the oldest application of biomass fermentation and is produced on a large scale from e.g. sugar cane (e.g. Brazil), wheat and triticale (e.g. Sweden) or maize (e.g. USA). In these cases usually only the plant parts containing the easily-converted compounds[18] of the biomass are fermented. After the fermentation, the bioethanol is separated from the fermentation broth by distillation, leaving the stillage (residues from distillation). Bioethanol is used e.g. as vehicle fuel[19] or as additive[19] to fossil fuels.

With adequate pretreatment, even lignocellulosic[20] biomass can be converted to bioethanol. This pretreatment is required in order to increase the enzymatic accessibility of cellulose and to remove hemicellulose and lignin (Sun & Cheng, 2002). Pretreatment methods include physical, physico-chemical, chemical and biological processes (Sipos *et al.*, 2010; Sun & Cheng, 2002). In a subsequent simultaneous saccharification and fermentation (SSF) process, cellulose is enzymatically hydrolysed and the monomeric sugars released are fermented to bioethanol (Olofsson *et al.*, 2008). Residues from the fermentation process can be used as feed, digested anaerobically for biogas production (Kreuger *et al.*, 2011b; Barta *et al.*, 2010) or combusted for heat and power production (Sassner *et al.*, 2008).

1.3.4 Other conversion techniques

Fermentation of biomass can produce energy carriers other than ethanol, e.g. other alcohols (e.g. methanol, butanol) and acetone. Other biomass conversion processes suitable for energy carrier production (*Table 1*) include gasification and pyrolysis of biomass for production of gaseous (syngas), liquid (pyrosylsis oils) and solid (char) energy carriers. Some of the energy carriers produced are refined further to synthetic fuels such as Fischer-Tropsch diesel, biomethanol,

16. E.g. baker's yeast (*Saccharomyces cerevisiae*).
17. Non-energy uses include e.g. food additives, chemicals and pharmaceuticals.
18. E.g. sucrose (sugar) extract from sugar cane and starch from cereal and maize grains.
19. As vehicle fuel, bioethanol is sold pure (e.g. Brazil) or in mixes with petrol (e.g. Sweden: E85 - 85% ethanol, 15% petrol or petrol with e.g. 5-10% additive of ethanol).
20. Lignocellulosic biomass consists mainly of cellulose, hemicelluloses and lignin.

dimethyl ether (DME), synthetic petrol and synthetic diesel. Most of these processes are currently under development and are not available for large-scale production of these fuels.

Table 1. *Biomass conversion processes.*

Process	**Process conditions**	**Energy carriers produced**
Gasification	Thermal conversion, limited air/oxygen supply	Syngas[a]
Pyrolysis	Thermal conversion, exclusion of air/oxygen	Char, pyrolysis oil, syngas[a]
Torrefaction	Thermal conversion, exclusion of air/oxygen	Char
Transesterification	Chemical conversion of biomass-derived oils	FAME[b]
Fermentation	Biochemical conversion	Alcohols, acetone

[a] Syngas consists mainly of hydrogen and carbon monoxide.

[b] FAME = fatty acid methyl ester, used as biodiesel vehicle fuel.

1.4 Energy crops

Biomass from agricultural energy crops has several major advantages over residual biomass. Firstly, the composition of the biomass is relatively well known and constant, while residual biomass may vary strongly in composition, as well as in level of contamination[21]. However, while residual biomass often has no or a minor economic cost for making it available to energy carrier production, costs for biomass production from energy crops have to be covered by the energy carriers produced. This is why energy crops need to be cost-efficient in order to compete with residual biomass sources. Furthermore, energy crops have to be area-efficient[22], since they often share the limited area of arable land available for cultivation with food, feed and other industrial crops.

A large number of crop species are currently used worldwide for energy carrier production. However, cultivation of most of these crops is restricted to certain regions, e.g. by requirements for a certain climate zone. Some examples of the most common energy crops in large-scale cultivation are sugar cane (for bioethanol production in Brazil), maize (for bioethanol in the USA and for

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21. Contamination refers to both content of pathogenic organisms and foreign components, e.g. soil or plastic particles. Technical solutions exist to limit negative effects on e.g. human health, digestion or combustion processes, for both types of contaminations.

22. In order to be area-efficient, an energy crop needs to produce high energy yields per unit area.

biogas in Germany), rapeseed (for FAME[23] in France and Germany), jatropha (for FAME in China and India) and willow[24] (for CHP production in Sweden). Apart from willow, only a limited number of energy crops are cultivated in Sweden (*Table 2*).

Table 2. *Cultivation of energy crops in Sweden 2007 (Rolandsson, 2011; Svensk Växtkraft, 2011; SCB, 2008). Straw used for energy purposes is listed for comparison.*

Energy crop	Application	Cultivated area[a] [ha]	Biomass [Mg]
Hemp	Direct combustion	829	4,700[b]
Reed canary grass	Direct combustion	665	5,000[c]
Ley grass	Vehicle fuel (biogas)	~400	5,000
Cereals[d]	Direct combustion	4,700[e]	21,994
Oil seed rape[f]	Vehicle fuel (biodiesel)	9,400[e]	29,556
Cereals[g]	Vehicle fuel (ethanol)	12,500[e]	70,764
Willow (SRC)[h]	Direct combustion	13,260	148,738
Straw[i]	Direct combustion	107,000[e]	75,381

[a] Cultivated area for energy purposes in Sweden.
[b] Average dry matter yield was assumed to be 5.6 Mg/ha (**Paper I**)
[c] Average dry matter yield was assumed to be 7.5 Mg/ha (Olsson *et al.*, 2001)
[d] Only grains (oats, triticale, rye) are accounted for.
[e] Estimated from total biomass and normal yields (SCB, 2007). For straw, an available amount of 0.7 Mg/ha was assumed (Nilsson & Bernesson, 2009).
[f] Only seeds are used.
[g] Only grains (wheat) are accounted for.
[h] SRC = short rotation coppice = wood chip production from 3-4 year old plants.
[i] Straw from cereals and oil seed rape. Straw is not a dedicated energy crop, but is given here for reference.

1.5 Sustainability of energy crop production and use

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (UN, 1987). Sustainability is based on environmental, social and economic aspects (UN, 2005). The sustainability of production and use of biofuels from energy crops can be divided into two main topics:

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23. FAME = Fatty acid methyl ester, also known as RME (rapeseed methyl ester if produced from rapeseed) or biodiesel. FAME is used as transportation fuel.

24. Willow for energy purposes is cultivated on agricultural land as short rotation coppice, SRC. Plantations are cultivated for a total period of 10-20 years with harvest in approx. 3-4 year intervals.

The first topic is the potential competition between food and fuel for arable land. Large-scale implementation of first generation[25] biofuel production is claimed to increase food prices on global scale (e.g. Hill *et al.*, 2006). It is outside the scope of this thesis to discuss this problem, but the need to avoid the social impact of biofuel production during the course of its large-scale implementation is acknowledged.

The second topic relates to environmental aspects of sustainability. It is claimed that not all pathways for production of biofuels contribute to greenhouse gas (GHG) emission mitigation. Instead, a number of recent studies argue that the production of some biofuels leads to higher fossil energy costs than are replaced (Ulgiati, 2001), more emissions of GHG than if fossil fuels had been used instead (e.g. Crutzen *et al.*, 2008; Scharlemann & Laurance, 2008; Zah *et al.*, 2007) or only modest benefits (Farrell *et al.*, 2006). Most of these studies focus on production of first generation bioethanol from maize or wheat. However, the extent of GHG emissions from biofuel production pathways is often strongly dependent on subsequent utilisation of residual material streams and by-products (Börjesson, 2009). It is therefore important to study energy and GHG balances for complete production pathways, in order to compare energy crops. Furthermore, it is necessary for conversion pathways for production of biofuels from energy crops to be evaluated and compared with each other. As a result, 1) highly efficient, case-specific ‘energy crop-application type’ combinations can potentially be identified and can be promoted subsequently; and 2) the environmental, economical and social costs of bioenergy carrier production can be minimised.

1.6 Industrial hemp – basic characteristics

After revoking the hemp prohibition in the European Union, cultivation of industrial hemp was first approved for fibre production during the 1990s (Steger, 2001), later even for the production of energy (EC, 2003). In the EU, only hemp cultivars approved by the European Commission, i.e. industrial hemp cultivars with THC content[26] below 0.2 wt-%, are allowed in hemp cultivation for industrial purposes.

25. First generation biofuels are based on parts of crops (e.g. grains, seeds) suitable for food and feed production. While a shift to biofuel production results in little change for agriculture, the amounts of food and feed produced might change considerably. In comparison, second generation biofuels use lignocellulosic (i.e. whole-crop) biomass.

26. THC stands for Δ-9-tetrahydrocannabinol, which is the main psychoactive substance found in hemp. Samples for analysing the THC content of hemp must consist of the upper third of a

A subsidy for the cultivation of hemp in the EU is linked to certain conditions, such as use of approved cultivars and certified seed material and requires prior administrative approval (EC, 2004; EC, 2003). The list of hemp cultivars approved for subsidy contains only fibre varieties; the only oil hemp cultivar was removed from the list in 2007 (Callaway, 2008). *Table A1* in the Appendix provides a list of old and recent cultivars used for fibre and seed production.

If hemp is cultivated for fibre production, long fibres suitable for use in production of textiles and other fibre products are the most valuable part of hemp plants, accounting for approx. one third of the total above-ground biomass. The remaining major part is of less value and is used e.g. for paper pulp production or as animal litter (van der Werf, 1994).

1.6.1 Current cultivation and industrial use of hemp

Hemp is cultivated in a number of countries around the world. China has become the largest producer of hemp (*Figure 4*), with focus on fibre production. Hemp in France is primarily used for seed and cigarette paper production, while Canada has built an industry for food and cosmetic use of hemp, with the seeds being the main product of the hemp biomass. Other non-energy uses are e.g. production of building material (e.g. for insulation), textiles and fibre boards.

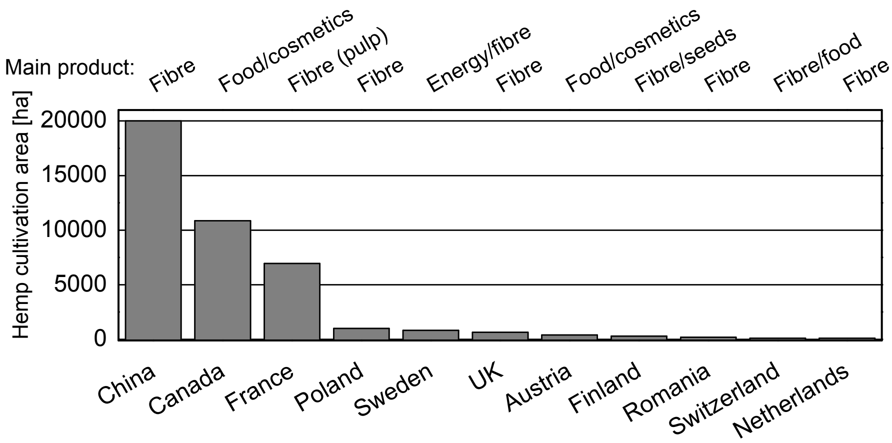

Figure 4. Current cultivation area of industrially used hemp in the world (Atkinson, 2011; Eurostat, 2011; Rolandsson, 2011; Defra, 2009; FAO, 2009; Agreste, 2007; ADAS, 2005; Greslehner, 2005; Karus & Vogt, 2004; Müssig & Martens, 2003; Dreyer *et al.*, 2002; Mediavilla *et al.*, 1999). The figure given for China is only an estimate (FAO, 2009).

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representative number of plants selected at random at the end of their flowering period and with stalks and seeds removed (EC, 2003).

1.6.2 Plant physiology of hemp

Hemp is an annual herbaceous plant that can grow up to 5 m tall (van der Werf, 1994). It has been used for millennia to produce e.g. cloth, feed and food. It is mainly the fibres and seeds that are used for these purposes.

The fibres found in industrial hemp plants are primary and secondary bast fibres (in the bark of the plant) and libriform or short fibres (in the core of the plant), which together constitute approx. 35-38% of the total biomass of hemp plants grown for fibre purposes and harvested in autumn (Svennerstedt, 2001; van der Werf, 1994). Leaves from plants harvested in autumn account for approx. 30% of the total plant biomass of hemp (Svennerstedt, 2001), while seeds account for approx. 1-10% in fibre hemp cultivars (Siritanu & Siritanu, 2009; van der Werf, 1994).

1.6.3 Agronomy of hemp

Hemp requires a well-prepared seedbed[27], i.e. free of perennial weeds and other debris, in order to ensure a good physical environment for the growing plants and sufficient capillarity movement of water to the surface (Ranalli, 1999).

Sowing of hemp is usually carried out by drilling in the prepared seedbed with a grain drill at a depth of 2-3 cm. Deeper sowing affects the yield adversely (Ranalli, 1999).

A high plant density is desired for fibre production in hemp, while a low plant density is desired for seed production (van der Werf, 1994). The economically optimal plant density of hemp grown for energy purposes is lower than the plant density that gives maximum stem quality for fibre production purposes (Ranalli, 1999). The highest biomass yield, as would be desired for energy purposes, therefore requires an amount of approx. 20 kg seeds per hectare, resulting in a plant density of approx. 100 plants per square metre (van der Werf *et al.*, 1995).

Hemp is adapted to the same climate as wheat, i.e. temperate and cool climate conditions. The crop grows best on well-drained, fertile, medium-heavy soils, especially silty loam, clay loam, and silty clays (Ranalli, 1999).

Hemp does not require use of herbicides, as it overshadows the soil quickly after the initial growth phase and therefore suppresses weed growth. Only a few insect species are known pests in hemp (McPartland & Hillig, 2006), but

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27. A stale seedbed, i.e. a seedbed prepared one or several weeks prior to actual seed drilling followed by a mechanical weed treatment (e.g. harrowing), can help free the field from annual weeds. This method is preferred in organically grown hemp (Rasmussen, 2004).

none of these causes economic losses (Ranalli, 1999). Several fungal diseases exist in hemp, but are rare (Ranalli, 1999).

1.7 Hemp biomass as a source of energy

Hemp biomass was used for energy purposes for centuries, if not millennia. However, energy use of hemp traditionally was limited to the use of oil pressed from hemp seed for e.g. lighting purposes. Commercial use of industrial hemp biomass for energy purposes has been suggested in many countries, e.g. in the USA (Castleman, 2006), Ireland (Rice, 2008), Spain (Casas & Rieradevall i Pons, 2005), Germany (Plöchl *et al.*, 2009; Brodersen *et al.*, 2002) and Poland (Burczyk *et al.*, 2008), but no reports on the actual amount used for energy carrier production are available. In Sweden, hemp is already mainly grown for energy purposes (Sundberg & Westlin, 2005). In 2007, hemp was cultivated on approx. 800 ha in Sweden (Rolandsson, 2011). Most of this biomass was processed into briquettes and sold locally as a solid biofuel for heating of private households.

Several options exist for conversion of biomass into useful energy carriers (*Figure 5*). Firstly, production of heat and/or power by direct combustion of the whole-crop biomass can be employed. Secondly conversion of biomass-bound energy into liquid or gaseous transportation biofuels, such as bioethanol and biogas, can be performed.

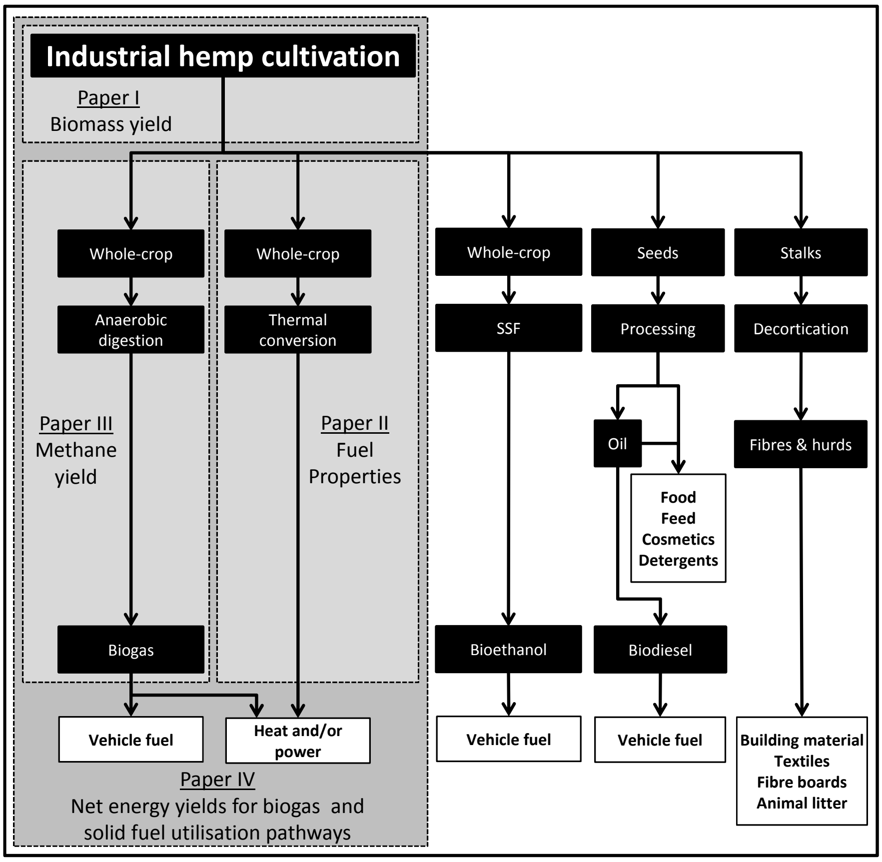

Figure 5. Utilisation pathways for hemp biomass. Grey boxes show aspects investigated in this thesis. SSF = simultaneous saccharification and fermentation.

1.7.1 Hemp as a biogas substrate

Hemp can be used as a substrate in anaerobic digestion in order to produce biogas. The energy yield of methane per unit area is dependent on the biomass yield and the specific methane potential of the biomass. The latter is potentially influenced by the growth stage of the plants, i.e. the chemical composition of the biomass. This composition changes during plant growth. For example, content of structural carbohydrates and lignin increases with later harvest dates (Jones, 1970). While carbohydrates such as cellulose and hemicelluloses are subject to degradation and conversion into methane, lignin is recalcitrant to degradation and energy bound as lignin and other undigested compounds is lost with the digested residue[28] (Ghosh *et al.*, 1985). A lower specific methane yield can therefore be expected if the crop is harvested too late. Use of the nutrient-rich digestate as biofertiliser is an option that potentially improves energy- and environmental efficiency.

The biomass energy yield (BEY)[29] per hectare describes the total amount of energy stored in biomass, i.e. the energy potential. It is calculated from the biomass yield per hectare and the corresponding higher heating value (HHV) of the biomass. The methane energy yield (MEY) per hectare is calculated from the biomass yield per hectare and the corresponding specific methane yield, using the HHV of methane. The ratio of MEY/BEY represents the efficiency of the conversion to biogas.

1.7.2 Hemp as a solid biofuel

Hemp grown in Sweden for direct combustion purposes is left standing in the field during winter, in order to reduce the moisture content (MC). In late September or early October senescence of the plants begins which ultimately leads to the loss of leaves, flowers and seeds. When harvested in spring, only the hemp stems are left to harvest. This concept of spring harvest is generally applied for solid biofuel production from hemp. However, there are no scientific studies showing whether this mode of operation results in the highest energy yield per hectare, due to a lower MC or whether losses of biomass lead to decreased energy yield in spring compared with harvest in autumn.

If hemp is to be harvested in spring, it is therefore necessary to maximise the stem yield in order to maximise the energy yield per hectare. If flowering is delayed, plant assimilates are redirected to seed production later and the period of biomass accumulation is prolonged (van der Werf, 1994). Stem yield can therefore be increased by choice of a late-maturing cultivar such as Futura 75 (van der Werf, 1994). Flowering of hemp plants is also delayed by long days and is reported to start first when the day length is shorter than 14 hours (Lisson *et al.*, 2000; Borthwick & Scully, 1954). This happens around August 18th, August 28th and September 8th on cultivation sites at latitudes of 45, 55 and 65°N, respectively (Giesen, 2010).

If biomass is completely dried before combustion or if all water in the flue gas is condensed and the latent heat in the vapour is utilised, then the biomass energy yield (BEY), based on HHV, is relevant. However, for use of hemp as a solid biofuel, the combustion energy yield (CEY)[29] is also relevant, since this

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28. Thermal conversion of digested residues is possible, but MC is often high. Instead, the residues can better be used as biofertiliser.

29. See section 2.5 on HHV and LHV on page 32.

is usually the basis for fuel price (van Loo & Koppejan, 2008). The CEY is based on the LHV and describes the maximum recoverable energy by combustion, if the energy in the flue gas is not recovered, e.g. in small-scale combustion such as household boilers or fireplaces. The LHV is negatively correlated to the moisture content of the biomass, which is usually high in fresh, green biomass.

Besides the energy yield, the physical and chemical fuel properties of an energy crop influence its suitability and therefore its competitiveness as a solid biofuel. Physical properties, e.g. particle size, bulk density, angle of repose and bridging tendency, can be adjusted by physical treatment, e.g. grinding, milling or compaction. Since chemical fuel properties are inherent and hard to change once the crop is harvested (Mattsson & Briere, 1984), this thesis focused on finding a harvest period in which the risk is at a minimum for problems during combustion due to undesirable chemical fuel properties.

The chemical fuel properties of the biomass play an important role in the combustion process, especially the content of major alkali and earth alkali metals, i.e. sodium (Na), potassium (K), magnesium (Mg) and calcium (Ca), and that of silicon (Si) and chlorine (Cl), aluminium (Al), sulphur (S) and phosphorus (P). These elements and their content in the ash resulting from combustion can cause problems in the combustion chamber, e.g. slagging, fouling and corrosion (Baxter *et al.*, 1998).

Slagging is a high-temperature (>800°C) ash deposition process within the boiler, where ash particles melt, fuse into larger particles and form deposits, e.g. on boiler walls, which can interfere with the combustion process (van Loo & Koppejan, 2008). Fouling is a low-temperature process which involves mostly alkali metals and occurs at cooled surfaces of the boiler, e.g. heat exchangers. Alkali metals deposit on these surfaces and act as a binding agent between the surface and non-volatile ash particles (van Loo & Koppejan, 2008). Growing deposits decrease heat transfer from flue gas to heat exchanger and thereby lower the energy yield. Corrosion is a process whereby metal surfaces in the boiler are destroyed, which decreases the lifetime of a boiler. Corrosion is caused by gaseous or alkali-aided chlorine species (van Loo & Koppejan, 2008)

Alkali-metals and chlorine are the main compounds in the biomass that cause damages to boilers. However, other elements can influence the availability of harmful species, e.g. the content of sulphur strongly influences the amount of chlorine compounds available for causing corrosion. Therefore, it is important to consider the content of groups of elements in order to estimate potential combustion problems. Several indices exist for estimating the risk of slagging, fouling and corrosion. Most of these indices were originally developed for characterising fossil solid fuels such as coal. Only few of them, e.g. the Miles index and the molar S/Cl ratio, have been considered suitable for characterising solid biofuels too (*Table 3*).

Table 3. *Slagging and corrosion indices relevant for use on biomass fuels used in this study.*

Index	**Equation**	**Risk levels**	**Reference**
Miles index	$(K_2O + Na_2O)$ / HHV [kg/GJ]	>0.17 risk for slagging >0.34 almost certain slagging	(Miles *et al.*, 1995)
Molar S/Cl ratio	S / Cl [mol/mol]	<2 risk for corrosion	(Miltner *et al.*, 2006)

1.7.3 Hemp as a bioethanol substrate

Fermentation of hemp biomass for production of bioethanol is a future option for hemp biomass, but is outside the scope of this thesis. Conversion processes for lignocellulosic biomass feedstock, such as hemp, are currently being developed (Kreuger *et al.*, 2011b; Sipos *et al.*, 2010), but are not yet commercially available in large-scale format. However, recent studies show that hemp is an interesting crop even for ethanol production (Kreuger *et al.*, 2011b).

1.8 Objectives

The main aim of this thesis was to contribute to help demonstrate whether hemp (*Cannabis sativa* L.) is suitable as a source for production of renewable energy. Specific objectives of the studies conducted were to:

1. Investigate potential hemp biomass yields per hectare at different harvest dates.
2. Identify application-specific harvest periods for optimal energy yield.
3. Find the potential methane yield per hectare for conversion of hemp biomass to biogas via anaerobic digestion.
4. Characterise hemp biomass as a solid biofuel for direct combustion.
5. Evaluate potential gross and net energy yields from hemp in an energy balance.
6. Compare hemp to other biomass sources in respect to suitability and availability as a source for production of renewable energy.

2 Materials and methods

The main body of this thesis is based on field trials of hemp (**Papers I-III**). Biomass samples were taken over the course of three seasons and at approx. monthly intervals. These samples were used for determination of biomass yield, moisture content, heating value, energy yield, specific methane yield and mineral content of hemp biomass. In order to compare different production pathways of hemp-based energy carriers, scenario assessment techniques were applied in **Paper IV**. The results obtained for hemp in this thesis were compared with reference data on other biomass sources. For details of materials and methods, please refer to descriptions in **Papers I-IV**.

2.1 Field trials

Field trials were carried out at three locations (*Table 4*) in order to measure biomass dry matter (DM) yield (southern trials only), moisture content (MC) on a wet basis and to collect samples for further analysis. Hemp was sown at 20 and 40 kg seeds ha^{-1} in the southern and northern field trials, respectively. Row distance was 12.5 cm and drilling depth was 3 cm in all field trials.

2.2 Sampling

In the southern field trial, sampling was conducted at roughly monthly intervals from July until spring the next year, when MC was found to be below 30%. In the northern field trials, sampling was carried out on three occasions termed autumn, winter and spring. Samples for determination of DM biomass yield (**Paper I**) were taken from 1 m x 1 m squares, i.e. 8 rows of plants in each 1 m row length, from each replicate plot. Plants in these squares were hand-cut close to the ground, resulting in 1-3 cm long stubble. All sampling squares had more than 4 m clearance from the plot border to avoid border effects. The sampling sites for each sampling in the time series were located at randomised points within the plots.

Table 4. *Location and major specifications of the field trials the papers described in Paper I-IV.*

Location	Soil type	Year[a]	Hemp cultivar	Nitrogen fertilisation level/s	Paper
Nöbbelöv	sandy loam	2007	Futura 75	100, 150, 200	I, II, III
N55°43' E13°08'	2.7% humus	2008	Futura 75	100, 150, 200	
(southern Sweden)		2009	Futura 75	0, 50, 125, 200	
Röbäcksdalen	silt loam	2007	Beniko Tiborszállási	100	III
N63°48' E20°14'	5.0 % humus				
(northern Sweden)					
		2008	Beniko Tiborszállási Kompolti Uso 31	80	III
Degernäs	clay loam	2007	Beniko Tiborszállási	100	III
N63°45' E20°15'	3-6% humus				
(northern Sweden)		2008	Kompolti Uso 31	80	III

[a] Year in which the field trial was established

Samples for DM yield determination were taken only in the southern field trial. Similarly, additional biomass samples comprising three hemp plants were taken for determination of MC (**Paper I-III**) and mineral and extended mineral analysis (**Paper III**). For the methane potential assays[30] approx. 25 hemp plants were collected additionally (**Paper II)**.

2.3 Methane potential assays

Biomass samples for determination of the biochemical methane potential (BMP) of hemp were chopped and then digested in a laboratory assay. The inoculum was taken from a commercial anaerobic sewage sludge digester. Pure cellulose with inoculum and pure inoculums were used as controls. The samples were incubated at 50°C for an excess of 30 days and the volume of

30. Sampling was carried out monthly from July to October 2007 for hemp fertilised with 150 kg nitrogen per hectare.

biogas produced was measured daily to once every second day. The methane concentration in the biogas was measured by gas chromatography.

2.4 Sample analyses

Standard methods were used for analysis of biomass samples (*Table 5*). Determination of DM yield and MC were carried out by the author, while further analysis was carried out by accredited commercial laboratories. Concentrations of structural carbohydrates in biomass used for methane potential assays were determined by extraction of non-structural carbohydrates (Sluiter *et al.*, 2006).

Table 5. *List of standard methods used for analysis of hemp biomass samples.*

Analysis	Method	Reference
HHV	ISO 1928:1995	(ISO, 1995)
Sample preparation for content of C, H, O, N, S, Cl	SS 187114:1992	(SIS, 1992)
Content of C, H, N	LECO-1	
Content of Cl	SS 187154:1984	(SIS, 1984a)
Content of S	SS 187177:1991	(SIS, 1991)
Content of O	ISO 1928:1995	(ISO, 1995)
Ash content	SS 187171:1984	(SIS, 1984b)
IDT	ASTM D1857-68	(ANSI, 1968)
Content[a] of Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Na, Ni, P, Pb, Rb, Se, Si, Sn, Sr and Zn	SS 28150:1993	(SIS, 1993)
Content[b] of Al, Fe, K, Mg, Na, and P	BS EN 13656:2002	(BSI, 2002)

[a] Only for samples from the southern field trial in 2007.
[b] Only for samples from the northern field trials.

2.5 Heating value calculations

The energy content of biomass can be calculated by its heating value. The heating value can be determined in a bomb calorimeter, resulting in the so-called higher heating value (HHV), which is a measure of the theoretical maximum energy to be derived from the biomass by any kind of thermal conversion (*Figure 6*).

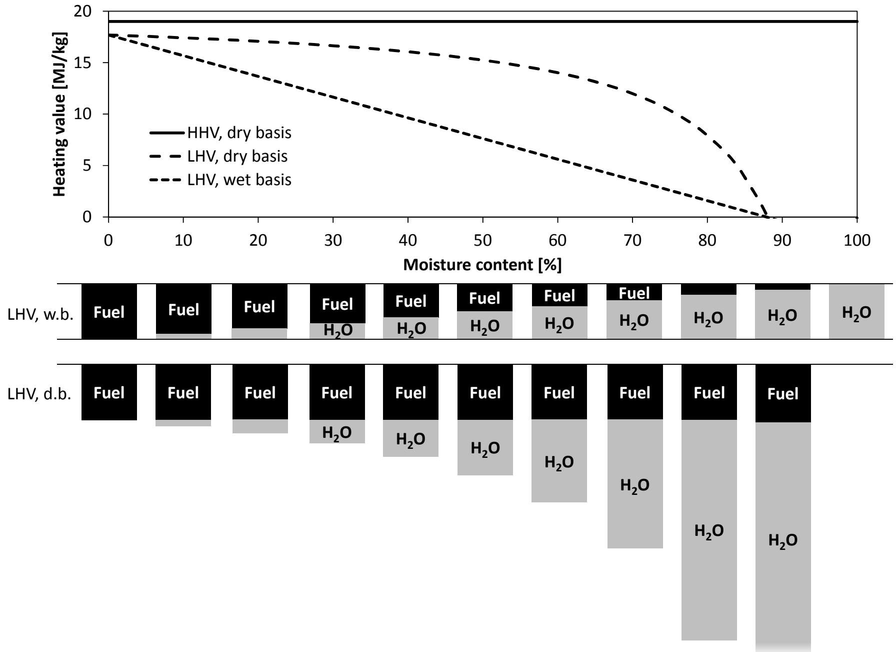

Figure 6. Relationship between higher heating value (HHV) and lower heating value (LHV). The influence of the biomass moisture content on the HHV and LHV is exemplified for a fuel with a HHV of 19 MJ/kg and a hydrogen content of 6% (top). The corresponding ratios of fuel and water content are displayed for the LHV, wet basis (w.b.; centre) and the LHV, dry basis (d.b.; bottom).

The heating value of biomass can also be calculated as lower heating value (LHV) on both a wet and dry basis. LHV on a dry basis (d.b.) shows the maximum energy per mass unit dry matter that can be derived, taking into account the energy needed for vaporisation of water in the biomass and water formed[31] during thermal conversion, e.g. combustion. Vaporisation of water during conversion requires energy, which is lost if the water cannot be condensed and the heat energy it contains recovered. The LHV can also be determined on a wet basis (w.b.), where the maximum energy that can be derived is given per mass unit total weight (= wet weight), i.e. dry matter content plus moisture content in the biomass. Note that for $LHV_{w.b.}$ the dry matter content ('fuel') for a given total weight is different at different moisture contents (*Figure 6*, centre). The $LHV_{d.b.}$ has the same dry matter content irrespective of the moisture content (*Figure 6*, bottom). For a given amount of dry matter, and varying MC, $LHV_{d.b.}$ is preferred for calculations. The values

31. Water is formed by oxidation of organically bound hydrogen, which in plant biomass usually ranges between 4-7% (**Paper IV**).

for the LHV can be calculated from equations 1 and 2 (van Loo & Koppejan, 2008):

$$\mathrm{LHV_{w.b.}} = \mathrm{HHV_{d.b.}} \cdot \left(1 - \frac{\mathrm{MC}}{100}\right) - \mathrm{ED} \cdot \frac{\mathrm{MC}}{100} - \mathrm{ED} \cdot \frac{\mathrm{HC}}{100} \cdot \mathrm{MMR} \cdot \left(1 - \frac{\mathrm{MC}}{100}\right) \quad \text{(Eq. 1)}$$

$$\mathrm{LHV_{d.b.}} = \mathrm{HHV_{d.b.}} - \mathrm{ED} \cdot \left(\frac{\mathrm{MC}}{100 - \mathrm{MC}}\right) - \mathrm{ED} \cdot \frac{\mathrm{HC}}{100} \cdot \mathrm{MMR} \quad \text{(Eq. 2)}$$

Parameter	**Explanation**	**Unit**	**Value**
ED	Enthalpy difference between gaseous and liquid water at 25°C	MJ kg^{-1}	2.444
HC	Content of hydrogen in the biomass	%	
MMR	Molar mass ratio between water (H_2O) and hydrogen (H_2)	-	8.936

Both HHV and LHV have practical applications. Simple, small-scale boilers usually cannot recover heat from the water vapour in the exhaust gases. In such case, the $\mathrm{LHV_{d.b.}}$ shows the maximum theoretical heat energy to be derived from a given fuel. However, large-scale boilers are often equipped with a flue gas condensing unit which will recover the latent heat of the water vapours in the exhaust (flue) gas. The HHV gives the amount of useful thermal energy which can be gained theoretically[32] in such cases.

2.6 Adjustment of biomass yield

2.6.1 Adjustment for average soils

The fields used in the southern field trials of this study have above-average soil quality and are likely to give higher biomass dry matter yields than other field with average soil quality in the region. A fair comparison to yields of other energy crops therefore requires adjustment of the present hemp biomass yields.

For comparison, standard yields from the agricultural region *Götalands södra slättbygder* (*Gss*), which extends over the Swedish west and south coast, up to 35 km inland (55°20´-57°06´N, 12°14´-14°21´E), were used (SCB, 2009). These standard yields are calculated for different regions as 15-year and 10-year averages from annual yield data collected from agricultural enterprises.

In order to find the probable biomass standard yield for hemp in the *Gss* region, the yields of sugar beet, barley and wheat in the years 2007 to 2009 on the same farm as the hemp field trials were compared with the corresponding standard yields in *Gss* (SCB, 2009). For each comparison, the corresponding

32. Energy losses (e.g. heat radiation from the boiler) lead to practically available amounts of useful energy that are less than the theoretical maximum. The ratio of recoverable energy to total energy in the fuel is termed ‘thermal efficiency’.

hemp DM yields for autumn and spring harvest were reduced by the percentage of higher yields on the field trial farm in comparison with the corresponding standard yield. The probable standard yields for hemp in the *Gss* region were found to be on average 24% lower than the yields found in the present field trials, for both autumn and spring harvest (data not shown).

2.6.2 Adjustment for harvest losses

Literature data on standard yields for crops cultivated in the region correspond to the amount of biomass available after harvest, i.e. the amount of biomass in the standing corp in the field minus the losses occurring during harvest[33]. Biomass yield data from field trials in this study represent the amount of biomass standing in the field as crops.

To account for losses during harvest, hemp DM yields were reduced by 10% and 25% for harvesting in autumn and spring, respectively.

2.7 Comparisons of hemp biomass yields with those of other biomass sources

The biomass and energy yields of hemp were compared with those of crops suitable either for biogas or solid biofuel production. For these comparisons, only crops that are potentially grown in the region studied, i.e. southern Sweden, were chosen.

Energy yields of crops used as substrates for biogas production were calculated as maximum potential energy yields from DM yields and the corresponding HHV (SCB, 2009; Amon *et al.*, 2004; Börjesson, 1996; Helsel & Wedin, 1983) (**Paper I**). Energy yields of crops used for solid biofuel production were calculated from DM yields and the corresponding $LHV_{d.b.}$ (SCB, 2009; Börjesson, 1996). Maximum potential energy yields for solid biofuels were calculated from DM yields and the corresponding HHV (SCB, 2009; Börjesson, 1996).

The annual energy yields for other renewable transportation fuels from crops cultivated in southern Sweden were based on literature data (Agriwise, 2009; Schittenhelm, 2008; Börjesson, 2007) (**Paper II**). The energy content of the biomass was calculated from the whole-crop DM yield and the corresponding HHV. The energy yield of the transportation fuel produced was calculated from the DM yield of the plant part used (e.g. grains, seeds) and the corresponding HHV.

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33. Harvest losses include biomass not harvested (e.g. plant stubble) and biomass harvested, but not recovered (e.g plant parts cut, but not picked up by the baling press = left on the soil).

The net energy yield (NEY) and the corresponding output-to-input ratio ($R_{O/I}$) for crops used for comparison with hemp were based on literature data (Börjesson *et al.*, 2010; Caserini *et al.*, 2010; Plöchl *et al.*, 2009; Uellendahl *et al.*, 2008; Berglund & Börjesson, 2006; Hagström, 2006; Heller *et al.*, 2003) (**Paper IV**).

2.8 Statistical analyses

Data in **Papers I-III** were analysed using statistical analysis software packages (*Table 6*). Data were analysed using ANOVA with the Tukey post-hoc test to identify significant differences between means.

Table 6. *Statistical software packages used in Papers I-III.*

Paper	Statistical package	Method	Post-hoc test
I	SAS 9.1, SAS Institute Inc., Cary, USA	ANOVA GLM	Tukey-Kramer
II	R 2.13, R Development Core Team	ANOVA GLM	Tukey
III	Prism 5.0b, Graphpad Software Inc., La Jolla, USA	One-way ANOVA t-test	Tukey

2.9 Scenario assessment

2.9.1 Base scenarios

As shown above, hemp can be used in different ways for the production of renewable energy. The different utilisation pathways for hemp biomass can be grouped in terms of two different biomass harvest dates: Hemp harvested as green plants in autumn if intended for biogas, or as dry plants harvested in spring if intended for solid biofuel production (**Paper I**). Four base scenarios were created in order to compare different utilisation pathways of hemp biomass for production of renewable energy on the basis of their net energy yield (*Figure 7*; **Paper IV**).

- **Scenario I** describes combined heat and power (CHP) production from combustion of spring-harvested baled hemp. In this scenario, hemp would act as a complement to straw fuel in a large-scale CHP plant, e.g. as is common in Denmark (Hinge, 2009). In CHP production, the combustion heat is used for production of both electricity (power) and heat, e.g. for residential and commercial district heating.

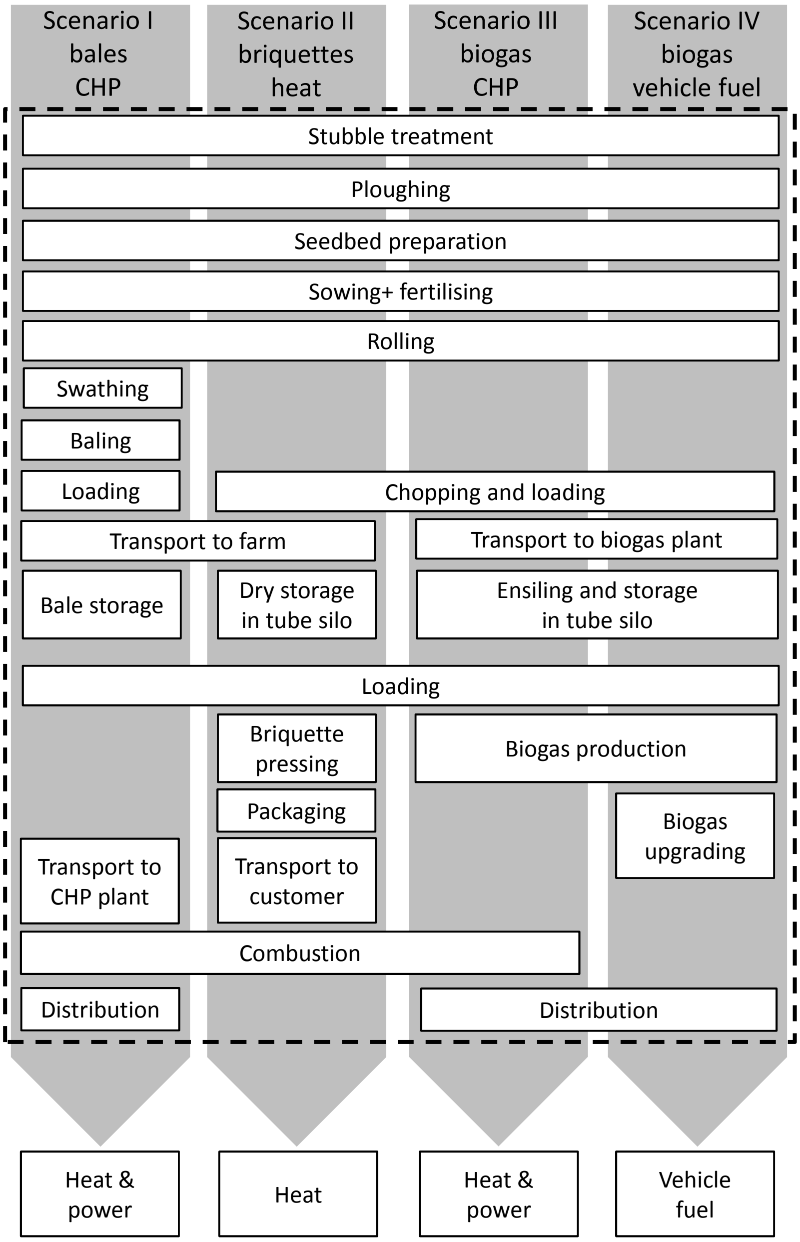

Figure 7. Schematic diagram of the field and transport operations accounted for in CHP production from baled hemp (scenario I), heat production from briquetted hemp biomass (scenario II), CHP production from hemp-derived biogas (scenario III) and vehicle fuel production from hemp-derived biogas (scenario IV).

- **Scenario II** describes the production of heat from combustion of spring-harvested, chopped and briquetted hemp. This scenario illustrates the utilisation currently relevant in parts of Sweden, i.e. combustion in small-scale boilers for heating of private homes (Bioenergiportalen, 2007).
- **Scenario III** describes the production of CHP from biogas derived by anaerobic digestion of autumn-harvested chopped and ensiled hemp. This scenario outlines how biogas (mostly from maize digestion) is commonly used in Germany (Schüsseler, 2009).
- **Scenario IV** describes the production of vehicle fuel from biogas derived by anaerobic digestion of autumn-harvested chopped and ensiled hemp. This scenario depicts the situation of how biogas (of origins other than hemp) is increasingly being used in Sweden, Germany and other European countries as vehicle fuel (Börjesson & Mattiasson, 2008).

2.9.2 Energy balances

For all scenarios, the net energy yield (NEY) was calculated by subtracting the sum of direct and indirect energy inputs from the energy output. The energy output-to-input ratio ($R_{O/I}$) was calculated by dividing the gross energy output by the accumulated energy input of each scenario. Energy input was calculated as the sum of direct and indirect energy inputs (Dalgaard *et al.*, 2001; Hülsbergen *et al.*, 2001; Scholz *et al.*, 1998).

Direct inputs accounting for fuel consumption from field, transport and storage operations were assumed to be based on the use of fossil diesel. Other direct energy inputs were heat energy (e.g. for heating the biogas digester) and electricity (e.g. for operation of the briquette press, digester pumping and mixing).

Indirect energy inputs accounted for the energy use in production of seeds, fertiliser, machinery, diesel fuel and electricity, as well as in maintenance (lubricants, spare parts) of the machinery used (Mikkola & Ahokas, 2009).

The energy output from production of biogas was calculated using the biomass DM yield, the specific methane yield and the corresponding HHV (Plöchl *et al.*, 2009; **Paper III**). The energy output from the use of hemp biomass as solid biofuel was calculated from the hemp DM yield and the corresponding heating value (**Paper IV**): For combustion of bales in a CHP plant equipped with a heat recovery unit, the HHV was used. For combustion of briquettes in a simple boiler or wood stove, the $LHV_{d.b.}$ was used.

3 Summary of results

3.1 Biomass yield of industrial hemp

Above-ground biomass dry matter of hemp in the southern field trials increased significantly during plant growth to peak values around September to October in all three years (*Figure 8*; **Paper I**). Between September and December DM yields decreased significantly in all three years (*Figure 8*). No significant changes occurred thereafter until final sampling in the spring (*Figure 8*).

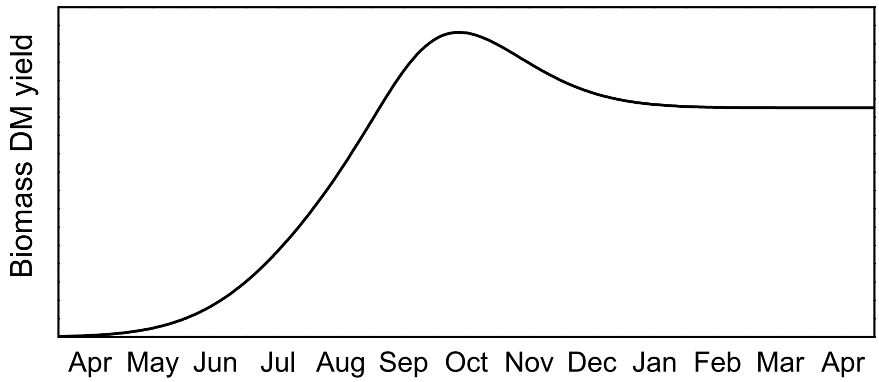

Figure 8. Schematic graph of above-ground biomass dry matter yield of hemp during growth and senescence of the crop. The diagram represents data from the southern field trial.

3.2 Hemp as a substrate for biogas production

3.2.1 Specific methane yield

No significant difference in the specific methane yield was found in samples harvested in July, August, September and October. After approx. 16 and 20 days, 90% and 95%, respectively, of the total methane potential after 30 days was reached (*Figure 9*; **Paper II)**. The average specific methane yield for all samples analysed was 234±35 m^3 Mg^{-1} volatile solids (VS).

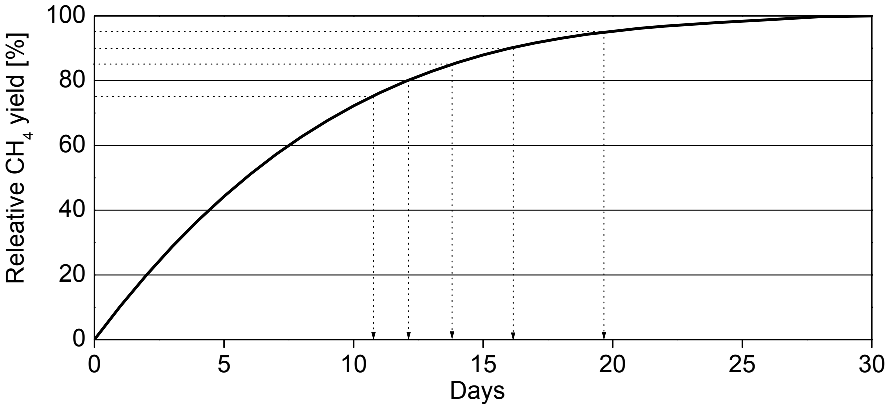

Figure 9. Schematic accumulated specific methane (CH_4) yield for hemp during thermophilic batch digestion expressed as a percentage of the total accumulated methane yield after 30 days. Based on accumulated data from 2006 and 2007 on samples from the southern field trial.

Content of structural carbohydrates and lignin had a tendency to increase from July to October. However, lignin content was relatively low even in October (not shown; **Paper II**).

3.2.2 Methane energy yield per hectare

The average MEY per hectare increased in the samples harvested from July to October (*Figure 10*; **Paper II**). The average MEY per hectare for the two months with highest yield, September and October, was 136±24 GJ ha^{-1}. This can be compared with the BEY of hemp in the same period, 286±27 GJ ha^{-1} based on HHV.

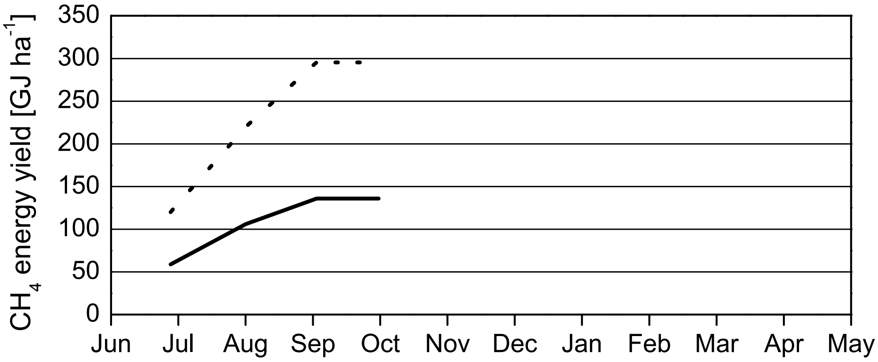

Figure 10. Schematic graph of methane energy yield (MEY) per hectare (solid line) based on the HHV of methane. The dotted line represents the potential biomass energy yield (BEY), based on the HHV of the biomass.

3.2.3 Harvest period

The optimal harvesting period for hemp used as a biogas substrate was found to be September-October, resulting in an average DM yield of 14.4 Mg ha^{-1} for the period 2007-2009. Even within this optimal harvesting period for biogas production, DM yields were significantly different between years (*Figure 17*), resulting in a standard deviation of ±15% in the period investigated.

3.3 Hemp as a solid biofuel

3.3.1 Moisture content

Plant biomass MC decreased from approx. 80% in July to approx. 30% in the period March to April in samples from the southern field trials (*Figure 11*; **Paper I**). However, the moisture in spring-harvested hemp was unevenly distributed between different sections of the plant. The first 20 cm of the stems above the ground had a MC between 52-64%, while >20 cm above the ground the MC was between 12-22% in biomass (*Figure 11*).

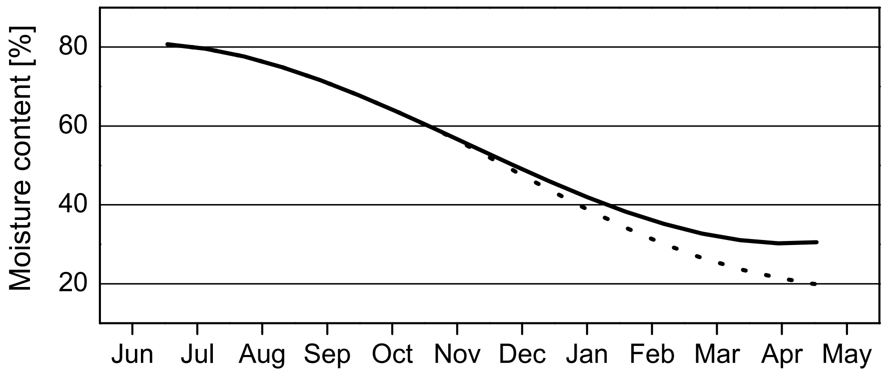

Figure 11. Schematic graph of the moisture content of all aboveground hemp plant biomass (solid line) and of all biomass 20 cm above the ground and higher (dotted line) during growth and senescence. Based on data from samples in the southern field trial in 2007 (**Paper I**).

3.3.2 Heating value

The HHV of the hemp biomass increased significantly from 17.5 MJ kg^{-1} in July to an average of 18.4 MJ kg^{-1} during the period August-December. It further increased significantly to an average of 19.1 MJ kg^{-1} during the period January-April (*Figure 12*; **Paper I**). The $LHV_{d.b.}$ increased significantly from 2.5 MJ kg^{-1} in July 2007 to an average of 11.9 MJ kg^{-1} during the period August-December. It further increased significantly to an average of 15.9 MJ kg^{-1} during the period December-April (*Figure 12*).

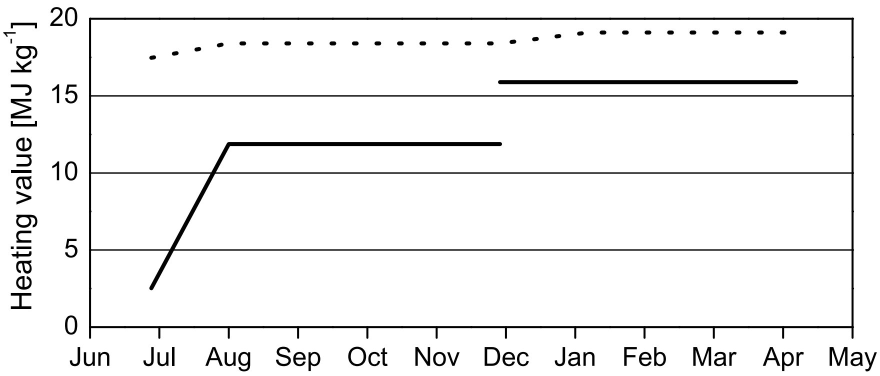

Figure 12. Schematic graph of the higher heating value (HHV; dotted line) and lower heating value ($LHV_{d.b.}$; solid line) of hemp according to samples from the southern field trials.

3.3.3 Potential energy yield

The biomass energy yield (BEY), increased to the significantly highest mean value of 296 GJ ha^{-1} for the period September-November (*Figure 13*; **Paper I**).

From September to December, the BEY decreased significantly, whereas from December to April it did not change significantly and averaged 246 GJ ha^{-1}.

The combustion energy yield (CEY) increased significantly from July to August and from August to September. No further significant changes in CEY occurred between September and final sampling in April and it averaged 201 GJ ha^{-1} (*Figure 13*; **Paper I**).

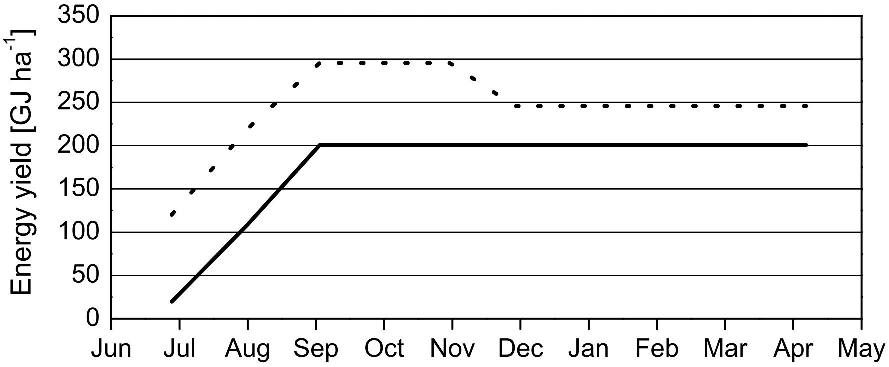

Figure 13. Schematic graph of biomass energy yield (BEY; dotted line; based on the hemp DM yield and the corresponding HHV) and combustion energy yield (CEY; solid line, based on the hemp DM yield and the corresponding $LHV_{d.b.}$), according to samples from the southern field trials.

3.3.4 Chemical fuel properties

Most of the major elements causing ash-related problems during combustion decreased significantly in content, i.e. S (-38%), Cl (-97%), Ca (-41%), K (-86%), Si (-47%), P (-61%) and Mg (-68%) in samples from southern and northern trials (**Paper III**).

The initial deformation temperature (IDT) was found to be 1550±60°C independent of harvest date. The Miles index decreased significantly to 0.14 MJ kg^{-1} in spring samples (*Figure 14*; **Paper III)**. The S/Cl ratio increased significantly to 5.6 in spring samples (*Figure 15*; **Paper III)**.

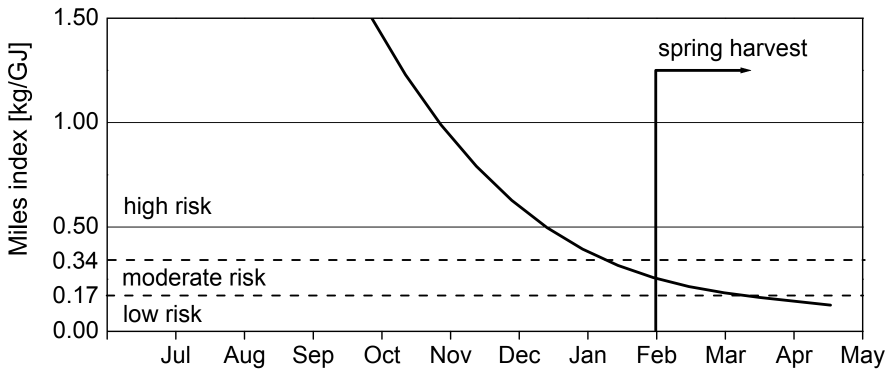

Figure 14. Schematic graph of the Miles index of hemp samples from all field trials. Dotted lines mark boundaries for risk of slagging. Risk of slagging increases above 0.17 kg/GJ and almost certain slagging occurs above 0.34 kg/GJ (Miles *et al.*, 1995).

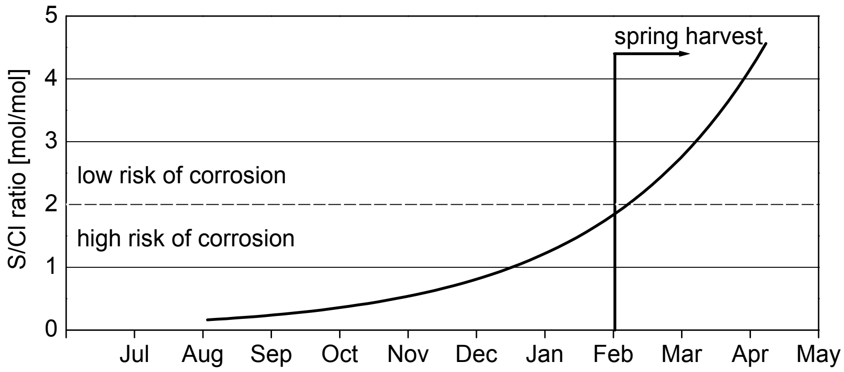

Figure 15. Schematic graph of the S/Cl ratio of hemp samples from all field trials. Biomass with a S/Cl ratio above 2 (dotted line) carries a low risk of corrosion (van Loo & Koppejan, 2008).

For the HHV, IDT and content of ash and the major ash-forming elements, no significant differences were found to originate from variety, location or year.

CaO, MgO, SiO_2, K_2O and Na_2O had a combined share of approx. 60% in the ash of spring-harvested hemp from the northern field trials. In the ternary CaO-SiO_2-K_2O diagram (*Figure 16*; **Paper III)**, hemp samples were clustered together with those of coniferous wood, forestry residues and willow within the area with IDT likely to be over 1200°C (Dahl & Obernberger, 2004).

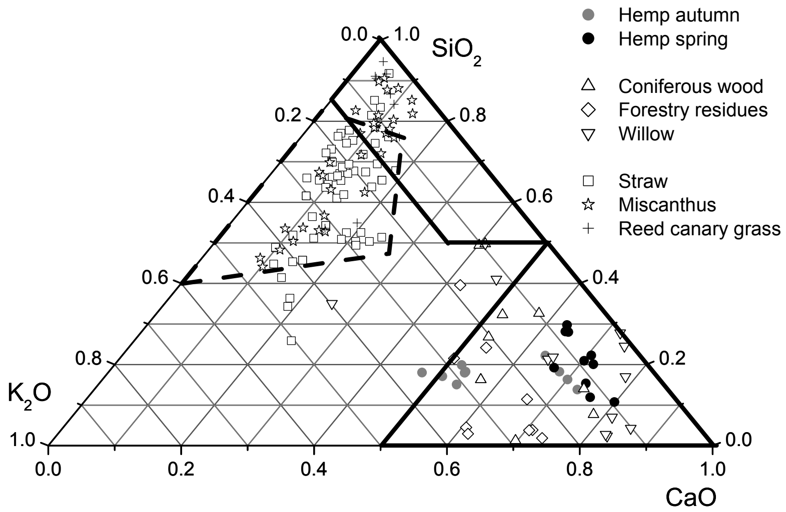

Figure 16. Ternary K_2O-SiO_2-CaO diagram with data on hemp biomass from the northern field trials in the present study compared with literature data (ECN, 2009; Erhardsson *et al.*, 2006; Skrifvars *et al.*, 1999; Miles *et al.*, 1995) for selected solid biofuels. Samples within solid boundary lines have a low risk of showing significant sintering problems (Fernandez Llorente & Carrasco García, 2005). Samples outside dashed lines are likely to have a initial deformation temperature (IDT) higher than 1200°C (Dahl & Obernberger, 2004), which indicates a low risk of slagging and fouling.

3.3.5 Harvest period

The BEY for use of hemp biomass as solid biofuel in large-scale combustion plants[34] with energy recovery from flue gas by condensation is highest for hemp harvested during the period September to November and about 20% lower if harvested in the period December to April (*Figure 13*). If the latent heat in the flue gas cannot be recovered, e.g. in small-scale heating plants and boilers, the CEY from hemp biomass is constant from September onward.

The fuel quality of hemp, i.e. the risk of slagging fouling and corrosion, varies strongly during these harvest periods. The ternary CaO-SiO_2-K_2O diagram (*Figure 16*) shows a decreased risk for sintering problems for samples harvested in spring. Also, the Miles index (*Figure 14*) and the S/Cl ratio (*Figure 15*) show significant improvements for samples harvested from February onward. In February, both Miles index and S/Cl ratio improve beyond critical values. In April, the Miles index is in the zone representing a low risk of slagging and fouling.

34. For example, for heat, power or CHP production.

For applications as solid biofuel, the optimal harvesting period was found to be in spring[35], resulting in an average DM yield of 9.9 Mg ha^{-1}. Even within this harvesting period for solid biofuel production, average DM yields were significantly different between years (*Figure 17*).

3.4 Influence of nitrogen fertilisation

While significant differences in biomass dry matter yield of hemp were found between years for the specific harvesting periods relevant for biogas or solid biofuel, no significant differences were observed between different N fertilisation levels within each trial year (*Figure 17*; **Paper I**).

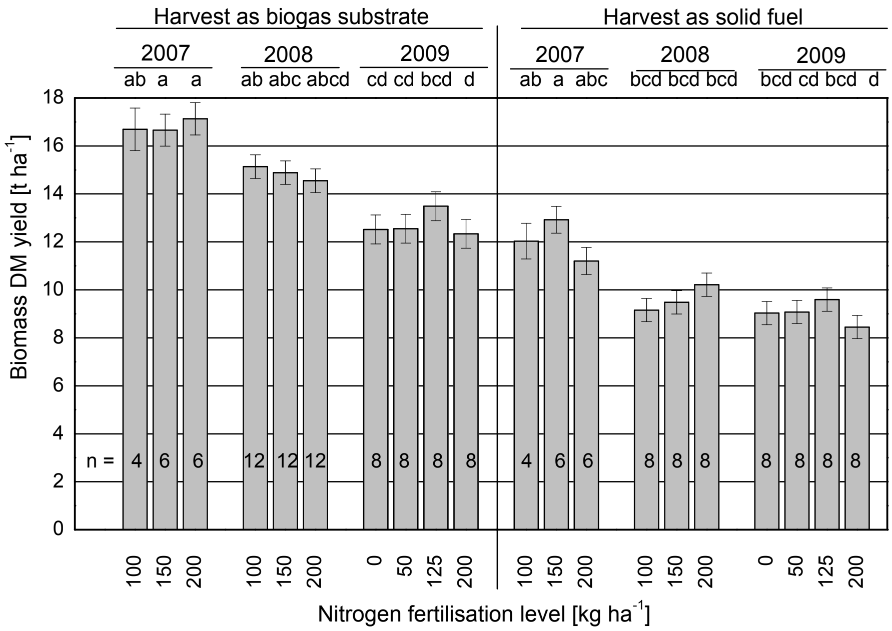

Figure 17. Average dry matter (DM) yield of industrial hemp at harvesting dates relevant for use as biogas substrate (highest DM yield) or solid biofuel (lowest MC content). Different letters indicate significant differences in DM yield for different years and N fertilisation level, separately for biogas and solid biofuel application. Numbers on bars (n) indicate number of samples. Error bars indicate standard error.

35. The term 'spring' represents different months in each year (i.e. March-April 2008 February-March 2009 and March-April 2010).

3.5 Energy balance

3.5.1 Energy input

The four base scenarios differed substantially in their relative amount of energy input (*Figure 18*). The energy input in cultivation was found to be 10.8 and 10.4 GJ ha^{-1} for baled and briquetted solid biofuel production from spring-harvested hemp, respectively, and 7.4 GJ ha^{-1} for autumn-harvested, ensiled hemp biomass for biogas production (*Figure 18*; **Paper IV**).

After intermediate storage, processing of the stored biomass requires energy inputs for conversion and additional transport. Conversion energy requirements differed substantially between the scenarios: inputs were low for solid biofuel combustion in the form of briquetted biomass (0.8 GJ ha^{-1}) and for CHP production from bales (1.5 GJ ha^{-1}) (*Figure 18*). CHP production from biogas was more energy-intensive (2.8 GJ ha^{-1}). The most energy-demanding conversion was the production of vehicle fuel (14.1 GJ ha^{-1}), where upgrading of the biogas to 97% methane content represented 45% of the total energy input. This reflects in the high amount of electricity required for scrubbing and compression of the biogas (*Figure 18*).

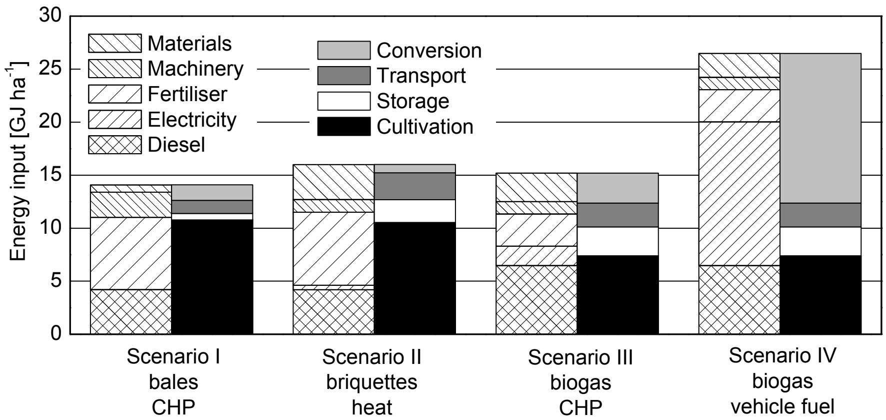

Figure 18. Energy inputs according to production means (left part of columns) and process stage (right part of columns) for scenarios I to IV.

3.5.2 Energy output

For CHP production from solid biofuel, approx. 23 and 41% of the energy contained in the biomass in the field was made available as useful power and heat, respectively (Scenario I, *Figure 19*). Heat production from hemp briquettes resulted in approx. 55% of the energy being made available as useful heat (Scenario II, *Figure 19*).

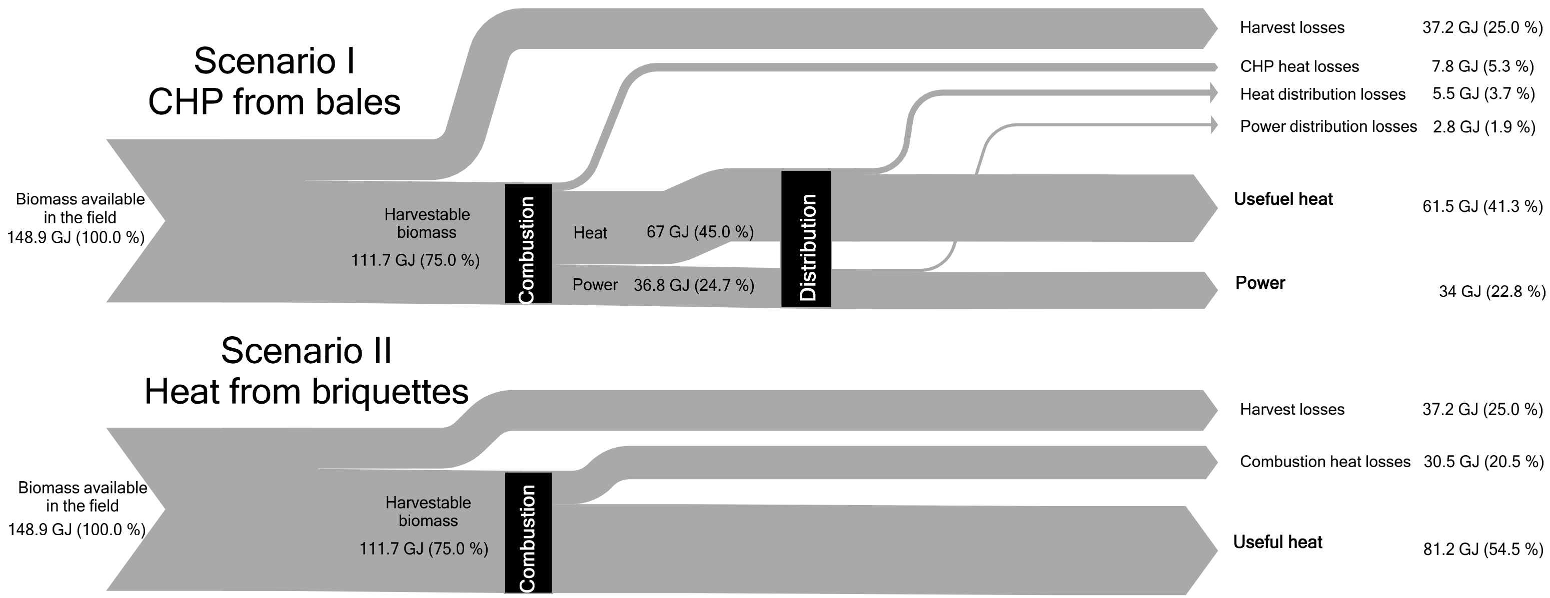

Figure 19. Energy flow diagram accounting for losses and process inefficiencies in the production of CHP from hemp bales (Scenario I, top) and heat from briquettes (Scenario II, bottom).

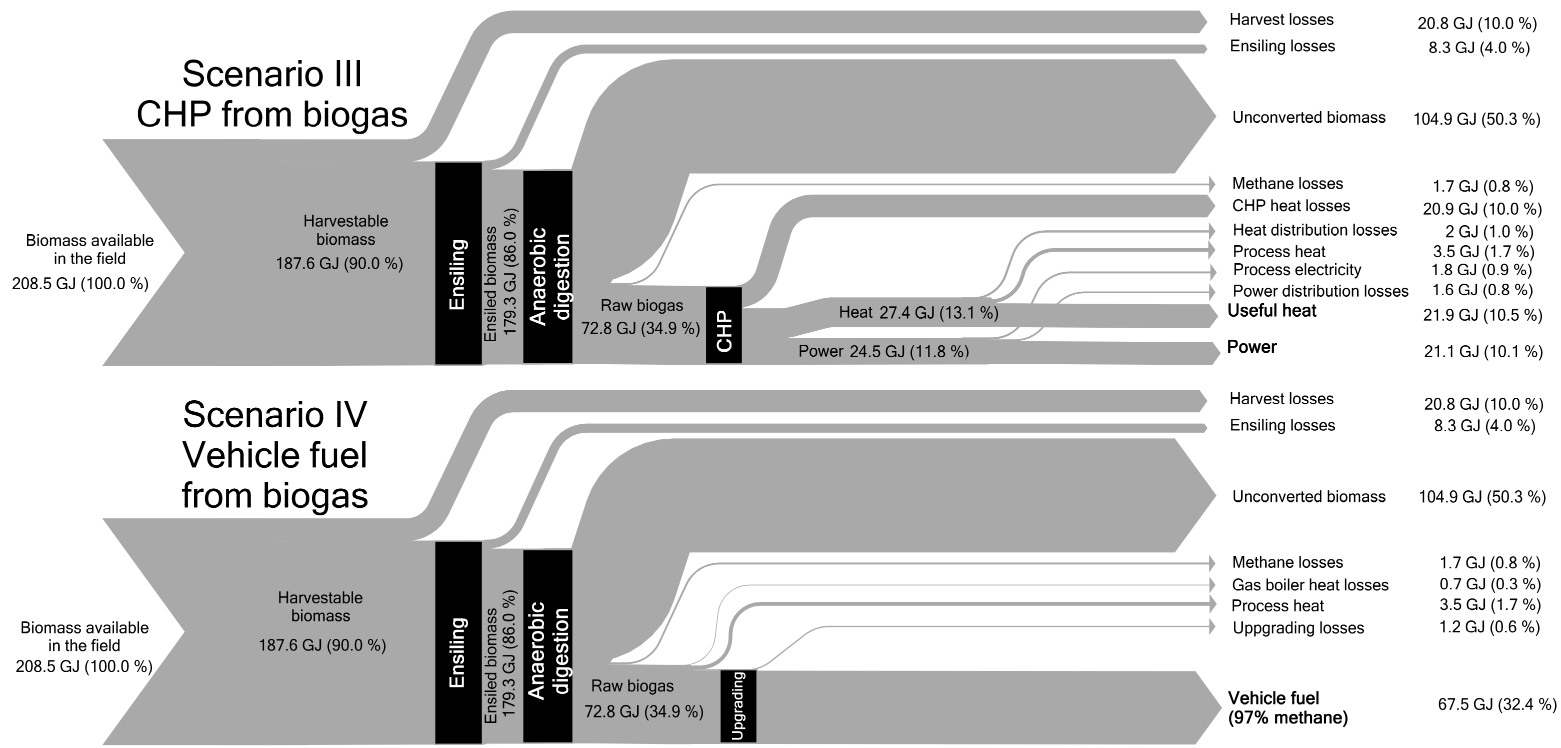

Figure 20. Energy flow diagram accounting for losses and process inefficiencies in the production of CHP (top) and vehicle fuel (bottom) from hemp-derived biogas.

For CHP production from biogas, only 10 and 11% of the biomass energy originally available in the field was made available as useful power and heat, respectively (Scenario III; *Figure 20*). Production of vehicle fuel (97% methane) from biogas resulted in approx. 68% of the energy being conserved in the energy carrier (Scenario IV, *Figure 20*)

3.5.3 Net energy yield

The net energy yield (NEY) per hectare was highest for CHP production from bales and heat from briquettes with 81 and 65 GJ ha^{-1}, respectively (*Figure 21*; **Paper IV**). Overall, conversion efficiencies for these pathways were high (86 and 80%, respectively) as were the output-to-input ratios ($R_{O/I}$ of 6.8 and 5.1, respectively). The NEY of biogas CHP and vehicle fuel production was substantially lower, 24 and 42 GJ ha^{-1}, respectively. Conversion efficiency was 38% for upgraded biogas (vehicle fuel) and 21% for biogas CHP. Both scenarios had $R_{O/I}$ = 2.6.

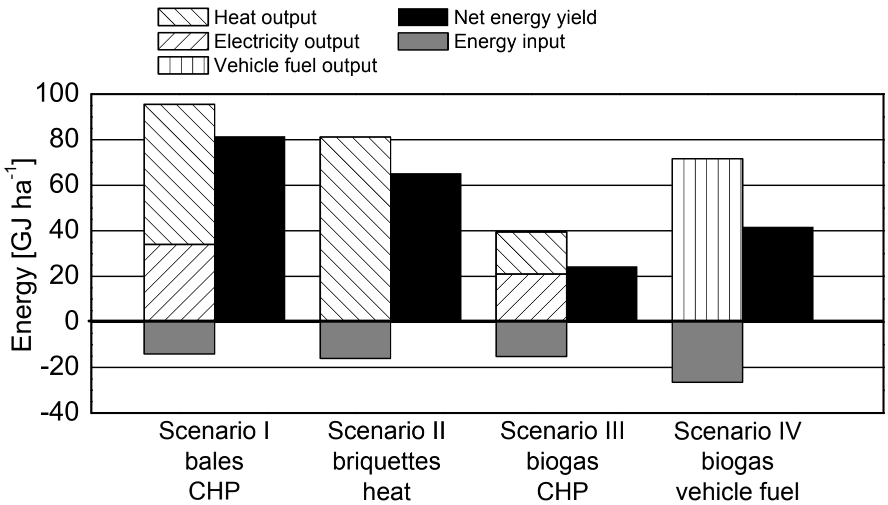

Figure 21. Energy output (white), energy inputs (grey) and resulting net energy yields (black) for scenarios I to IV. Output energy shows heat, power and vehicle fuel production from hemp biomass.

For each tonne DM increase in biomass yield, NEY increased by 15.7, 13.1, 3.9 and 5.8 GJ ha^{-1} for scenarios I to IV, respectively (*Figure 22*, top). *Figure 22*, bottom, shows the influence of hemp biomass DM yield on $R_{O/I}$ for each scenario. The two solid biofuel scenarios were strongly yield-dependent, while the two biogas scenarios were far less sensitive to changes in biomass DM yield.

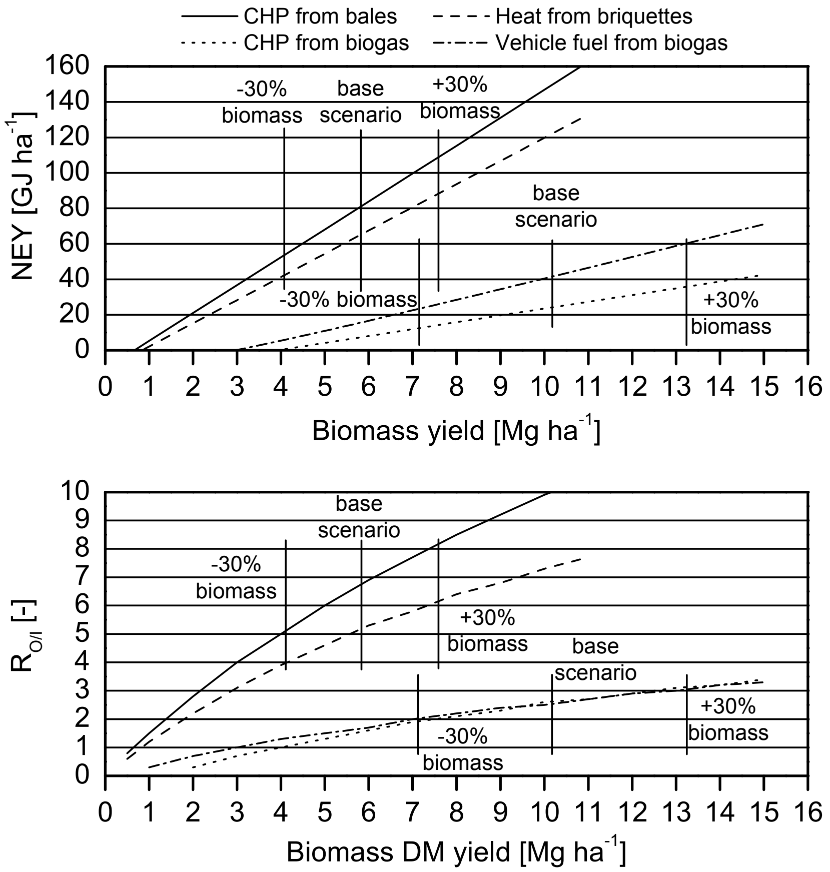

Figure 22. Net energy yield (NEY; top) and energy output-to-input ratio ($R_{O/I}$; bottom) as influenced by the adjusted biomass DM yield of hemp.

4 General discussion

4.1 Hemp cultivation

4.1.1 Influence of high latitudes on hemp biomass yield

Hemp may be a suitable energy crop at high latitudes in general. The hemp cultivar Futura 75 used in the studies of this thesis is medium to late-maturing[36], a trait believed to lengthen the growing period and therefore to increase the biomass yield, since little biomass increase can be expected after flowering (van der Werf *et al.*, 1996; van der Werf *et al.*, 1995). Flowering of hemp is reported to require roughly a maximum day length of 14 hours (Lisson *et al.*, 2000; Borthwick & Scully, 1954). This limit is reached at the southern study site in the beginning of September (Giesen, 2010), which coincides with the maximum biomass DM yields in all three years (**Paper I**). At even higher latitudes (e.g. >60°N) the limit is reached two to three weeks later, prolonging the growing period. However, the growing season for hemp at such latitudes is often 1-2 months shorter in comparison with southern Sweden. Nonetheless, earlier studies have shown that hemp can also give a relatively high biomass yield at latitudes >60°N, e.g. in northern Sweden (Finell *et al.*, 2006; Sundberg & Westlin, 2005) and in Finland (Pahkala *et al.*, 2008), that are only approx. 10-35% lower than those in southern Sweden.

4.1.2 Influence of nitrogen fertilisation on hemp biomass yield

Field trials in southern Sweden from this study indicate that there is scope to reduce N fertiliser levels while maintaining high DM yields. Similar findings

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36. Maturation represents preparations of the plants for reproduction, i.e. flowering and subsequent seed production.

of high hemp biomass yields on low fertilised plots were reported earlier (Scholz *et al.*, 2001).

Nitrogen fertilisation is applied in crop cultivation in order to increase yields of biomass or protein compounds. Despite large intervals for nitrogen applications, no significant increase in DM yield due to N fertilisation was found for harvesting dates relevant for biogas or solid biofuel production from hemp (**Paper I**). This indicates that nitrogen was not the growth-limiting factor in this study. Similarly, a previous study found no DM yield differences between plots fertilised with N at 80, 160 and 240 kg ha^{-1}, whereas unfertilised plots had a significantly lower DM yield (Iványi & Izsáki, 2007).

4.1.3 Annual variation of the hemp biomass yield

Although significant, the differences in DM yields for hemp between years found in the field trials of this thesis were within the normal variation range for crops (Porter & Semenov, 2005).

Biomass yields often vary with the weather conditions during cultivation. Major parameters influencing biomass yield are accumulated temperature and precipitation, which are dependent on e.g. geographic location and sowing date. Differences in sowing date in the field trials led to differences in accumulated temperature and precipitation. These parameters can partly explain the yield differences found, which is confirmed by findings from earlier studies, where later sowing dates resulted in lower DM yields in the magnitude of 3-4 Mg ha^{-1} for one month of delay (Rice, 2008; Crowley, 2001; van der Werf *et al.*, 1996; van der Werf, 1994).

4.2 Hemp energy yields

4.2.1 Biomass energy yield

Autumn-harvested hemp has a biomass energy yield (BEY) similar to that of other high-yielding biogas crops, including maize and sugar beets (*Figure 23a*; **Paper I**). For biogas production, a combination of high BEY per hectare and high specific methane yield is crucial for the competitiveness of an energy crop. Maize being a high-yielding competitor is the main substrate for biogas production in Germany. Sugar beets are currently discussed as biogas substrate, e.g. in Germany, but so far only used to a limited extent. Furthermore, sugar beet tops are usually not recovered, although interesting as a biogas substrate.

Spring-harvested hemp has a BEY approx. twice that of wheat straw and similar to that of spring-harvested reed canary grass (*Figure 23b*). Cereal straw is a by-product from food and feed production and competes with hemp as solid biofuel despite its low yield per hectare. Using cereal grains as solid biofuel is ethically disputed and therefore usually limited to batches unfit for food and feed production. Similar to hemp, reed canary grass is a relatively new energy crop in northern Europe, used for solid biofuel production only to a limited extent. Willow grown in a short-rotation coppice (SRC) exceeds the energy potential of hemp by approx. 50% (*Figure 23b*). Regarding biomass energy yield per hectare, hemp is therefore competitive to most common and new energy crops in northern Europe.

The BEY represents the potential energy yield from biomass. As a second step, evaluation of the potential yield of useful energy from biomass conversion is needed.

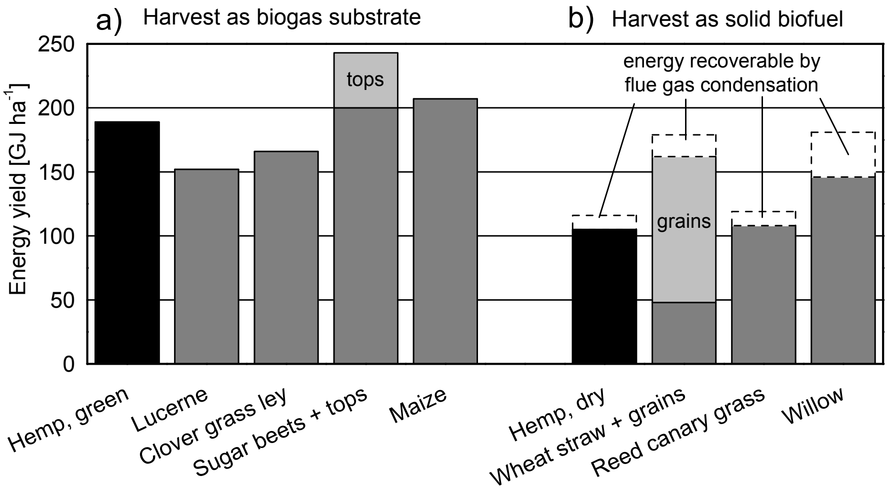

Figure 23. Comparison of annual biomass energy yields for hemp and other agricultural biomass feedstock used as (a) biogas substrate or (b) solid biofuel, respectively. The black bars show data from the present study for hemp, based on DM yields adjusted for average soils in the studied region in southern Sweden. Other data were calculated from standard biomass DM yields for the study area (SCB, 2009) and the corresponding HHV (Amon *et al.*, 2004; Börjesson, 1996) or LHV (Börjesson, 1996; Helsel & Wedin, 1983) for use as biogas substrate and solid biofuel, respectively. The light grey bars show additional biomass energy yield of sugar beet tops and wheat grains. Dashed white bars show maximum additional energy as calculated from the DM yield and the corresponding HHV, which is available if biomass is dried or if flue gas energy can be utilised.

4.2.2 Energy yields for hemp as a biogas substrate

Autumn-harvested hemp can be converted to biogas with high energy yields per hectare, resulting in production of methane, a high-quality vehicle fuel. The methane energy yield (MEY) per hectare of hemp exceeded that of DME from willow, ethanol from wheat grain and biodiesel from rapeseed considerably

(*Figure 24*; **Paper II)**. In first generation biofuels for transportation, only the energy-rich plant parts are used for biofuel production, e.g. wheat grains for ethanol and rapeseed for FAME production. In contrast, biogas production from lignocellulosic crops such as hemp and maize uses the whole crop, which explains the relatively high fuel energy yields per hectare of these alternatives.

Hemp had a methane energy yield slightly less than that of maize and sugar beet (*Figure 24*; **Paper II)**. Although yielding less methane energy, the relatively new energy crop hemp has a potential that is used only to a limited extent. This reflects in a low energy conversion efficiency for hemp of only 47%, while that of maize and sugar beet is around 70% (*Figure 24*).

The conversion degree is proportional to the specific methane yield, which is high for the main carbohydrates (cellulose and hemicellulose) and low for lignin. The high carbohydrate content and relatively low lignin content of hemp biomass were unaffected by the growth stage (i.e. the corresponding harvest date) of hemp. This indicates promising potential for increasing the MEY, independent of harvest date, by improving digestibility of hemp, e.g. by pretreatment of the biomass (Sun & Cheng, 2002; **Paper III**). Promising results have been demonstrated for steam explosion of hemp (Kreuger *et al.*, 2011b) and other lignocellulosic feedstock such as wheat and oat straw for bioethanol production (Dererie *et al.*, 2011; Erdei *et al.*, 2010).

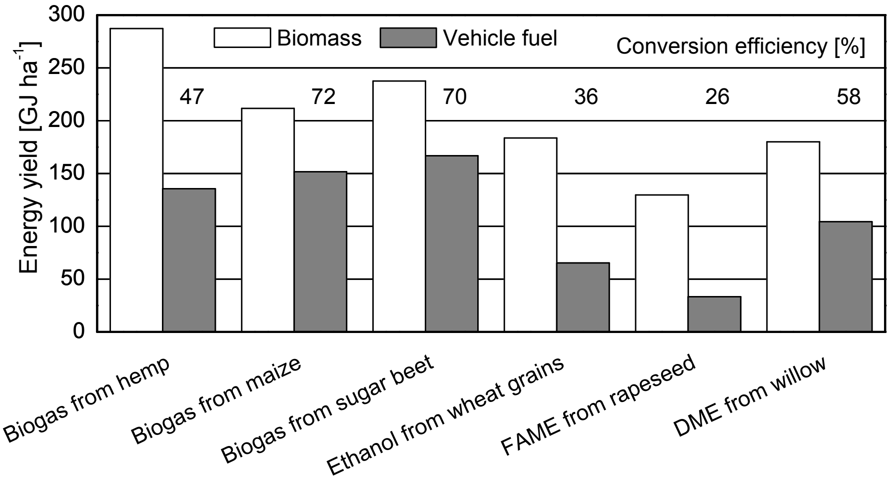

Figure 24. Comparison of the annual energy yields for biogas from hemp (this study) with reference values for other renewable transportation fuels from crops cultivated in southern Sweden (Agriwise, 2009; Schittenhelm, 2008; Börjesson, 2007). White columns depict the energy content of the biomass produced, calculated from the whole-crop DM yield and the corresponding HHV. Grey columns depict the energy yield of the transportation fuel produced, calculated from the DM yield of the plant part used (e.g. grains, seeds) and the corresponding HHV. Numbers above columns represent conversion efficiency in percent. FAME = fatty acid methyl ester for use as biodiesel. DME = dimethyl ether.

4.2.3 Energy yields for hemp as a solid biofuel

The combustion energy yield (CEY) for autumn-harvested hemp was previously reported to be between 135 and 170 GJ ha^{-1} (Scholz *et al.*, 2001), which was confirmed in the present study. The average CEY of 201 GJ ha^{-1} in 2007 in the present study was exceptionally high due to higher DM yields than in 2008 and 2009, indicating the potential to increase average energy yields by further cultivation improvements.

If latent heat from water vaporisation in combustion is not utilised, approx. 8-12% less energy[37] can be yielded from hemp. Therefore, a low MC is favourable for this application, as the MC influences the energy yield as expressed by the LHV of the material. For hemp, the MC decreases with later harvesting date, increasing the energy yield. In parallel, biomass is lost, e.g. by leaf senescence, decreasing the energy yield. The two factors counterbalance each other, leading to the unchanged energy yield per hectare between September and April. This finding needs to be confirmed for other locations and years. However, the general trends in MC and DM yield during the study period indicate a degree of independence of the CEY from the harvesting date. This leaves space for optimising the harvesting date according to other parameters, e.g. storage[38] of the biomass, machinery availability and the chemical combustion properties.

As a third step, evaluation of the realistic yield of useful energy from biomass conversion is needed.

4.2.4 Net energy yield

Hemp has high net energy yields (NEY) similar or higher than that of most other high-yielding energy crops common in northern Europe (*Figure 25*; **Paper IV**). The biomass DM yield per hectare of hemp in the base scenario is rather conservative. Furthermore, hemp is a relatively new energy crop with great potential for yield improvements, e.g. on good soils. Yields approx. 30% above the base scenario (3-year average) for both autumn and spring harvest have been reported on good soils in this study (**Paper I**). Therefore, in addition to the base scenario, an alternative scenario with a 30% higher biomass DM yield for hemp is shown (*Figure 25*).

37. Corresponding to moisture contents (MC) between 10-30%.

38. For storage, MC<30% is desirable to avoid losses due to microbial degradation (Festenstein *et al.*, 1965).

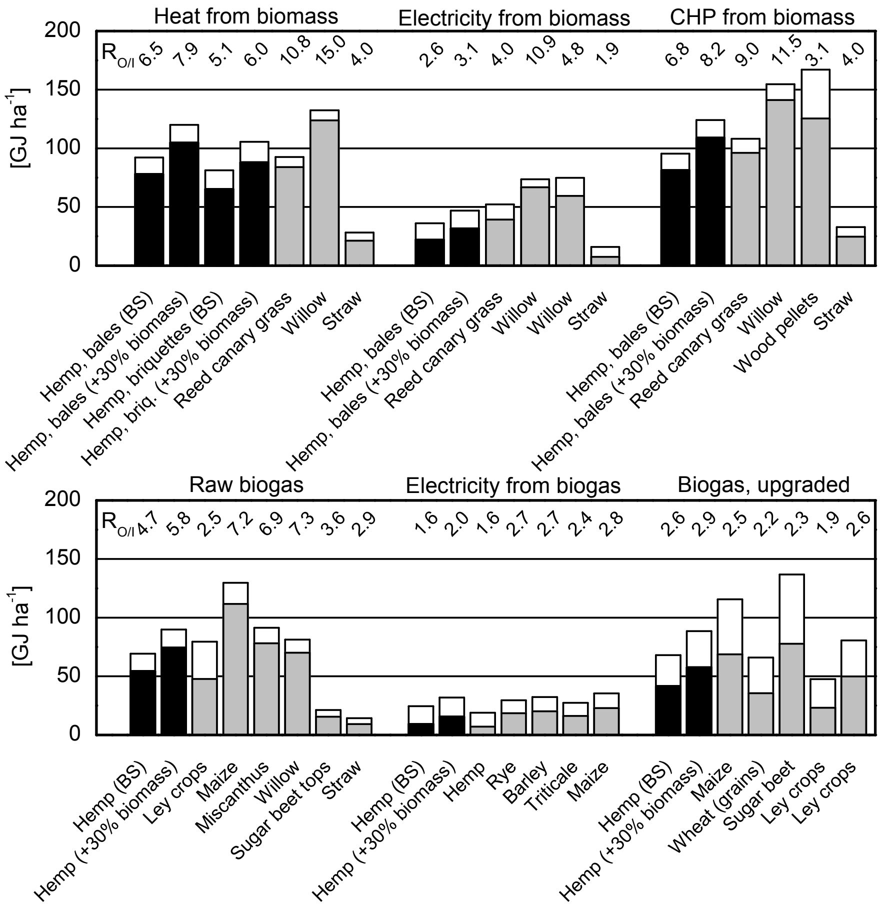

Figure 25. Net energy yield for heat, electricity and CHP from biomass (top) and raw biogas, electricity from biogas and upgraded biogas (bottom). Black columns denote data for hemp from the present study, both the base scenario (BS) and the alternative scenario with +30% biomass. Grey columns denote individual results from published data. The white part of the columns indicates the corresponding energy input. The corresponding output-to-input ratio ($R_{O/I}$) is shown above each column. References: (Börjesson *et al.*, 2010; Caserini *et al.*, 2010; Plöchl *et al.*, 2009; Uellendahl *et al.*, 2008; Berglund & Börjesson, 2006; Hagström, 2006; Heller *et al.*, 2003).

Hemp has similar heat and CHP production to reed canary grass (*Figure 25*, top). Production of electricity only, i.e. not CHP, from hemp is relatively inefficient with $R_{O/I}$ only 2.6 (*Figure 25*, top). Willow exceeds heat and CHP production of hemp significantly. Even if the NEY of willow were recalculated for a comparable electric efficiency (Hagström, 2006) and a comparable biomass DM yield (Heller *et al.*, 2003) as in the present study, it would still be about twice that of hemp (not shown).

Production of raw biogas from hemp has similar NEY to that of ley crops, while maize has about twice the NEY of hemp (*Figure 25*, bottom), mostly due to higher specific methane yield (Uellendahl *et al.*, 2008). These results are reflected again in electricity and vehicle fuel production from biogas (upgraded) for these crops. Miscanthus and willow grown in Denmark and southern Sweden have a higher biomass yield, while their methane potential is similar to that of hemp (not shown), resulting in considerably higher NEY (*Figure 25*, bottom). With a 30% increase in biomass yield, hemp has a similar NEY to miscanthus and willow, while maize still has 50% higher NEY.

Generally for all biomass sources, electricity production from biogas has a relatively low NEY due to the double conversion of biomass to biogas and biogas to electricity. The NEY could be improved if the heat from power generation were used for heating purposes, i.e. in residential or commercial heating by employing combined heat and power (CHP) production. Hemp in the present study had similar NEY to triticale and considerably lower NEY than rye, barley and maize (*Figure 25*, bottom). However, a lower NEY due to lower energy output was reported earlier for hemp (Plöchl *et al.*, 2009).

For the production of upgraded biogas, sugar beet has a substantially higher NEY than hemp, mainly due to much higher methane potential. However, since the energy inputs for utilisation of sugar beet are substantially higher than for hemp, the $R_{O/I}$ is similar to that of hemp.

Comparison of the data from the present study with data from other studies also shows that the production and conversion models employed for calculating the energy balance can differ substantially, the two most variable parameters being the biomass DM yield (e.g. due to fertilisation, weather and soil conditions) and the conversion efficiency (e.g. due to methane potential, thermal/electrical efficiency of the technology of choice). For example, in the literature it is often unclear whether dry matter yields are based on experimental data or data from commercial production, i.e. accounting for field and harvest losses. A comparison of this kind therefore needs to bear in mind the variability of assumptions upon which the scenarios investigated are based.

4.3 Suitability of hemp as biogas substrate

4.3.1 Harvest period

The results indicate that the optimal harvesting period is several weeks long, which may be of practical importance when the availability of harvesting machinery is limited. The specific methane yield was not found to be significantly different between the different harvest dates studied (**Paper II)**. The highest methane energy yield per unit area can therefore be expected when

DM yield is highest, i.e. from September to October (**Paper I**). This harvest period coincides with the period in which the highest DM yields were reported for hemp used for fibre production (Mediavilla *et al.*, 2001). The significant decrease in DM yield from September to October in one year of the study showed that potential extension of this harvesting period is likely to be dependent on the prevailing growing and weather conditions. Earlier harvesting is likely to result in decreased DM yield due to interruption of growth, while later harvesting is likely to result in biomass loss due to senescence.

4.3.2 Substrate handling

Hemp biomass can be ensiled for medium to long-term storage, as is required when a biogas plant is to be supplied with substrate outside the harvesting period. Hemp biomass MC of approx. 60-75% at harvesting is favourable for biogas production. Furthermore, with a MC within this range, the least DM losses are to be expected during ensiling (McDonald *et al.*, 1991). Still, these losses can be significant (Heiermann *et al.*, 2009). Although ensiling is likely to lead to losses of biogas potential, the digestibility and therefore methane content in the biogas have been found to increase in ensiled hemp biomass (Heiermann *et al.*, 2009). However, these findings of increased methane potential in ensiled biomass are not undisputed. Only recently it was reported that many studies reporting methane potentials for ensiled biomass used methods for determining the moisture content of the biomass samples that underestimated the dry matter content of the samples investigated (Kreuger *et al.*, 2011a). This led on to an overestimation of the methane potential and for a number of substrates no significant difference in methane potential was found between fresh and ensiled biomass.

4.4 Suitability of hemp as solid biofuel

4.4.1 Ash properties

Ash properties in spring-harvested hemp are substantially better than in autumn-harvested hemp. Delaying harvest of hemp until spring decreased chlorine levels in the biomass to a level which indicates that the risk for chlorine-aided alkali-fouling is low (Baxter *et al.*, 1998). The S/Cl ratio was above 2 for spring-harvested hemp, indicating a low risk of corrosion during combustion of hemp biomass (van Loo & Koppejan, 2008). This is different from other straw fuels and agricultural biomass residues, which usually have S/Cl ratios below 2 (*Figure 26*; **Paper III**) (Miltner *et al.*, 2006). However, boilers can be designed for fuels known to have high alkaline and chlorine contents, e.g. cereal straw fuels (Miltner *et al.*, 2006).

Hemp ash properties are superior to those of other straw fuels. Spring-harvested hemp had a Miles index below 0.34 kg/GJ, indicating a low risk of slagging and fouling (Miles *et al.*, 1995). The Miles index and the S/Cl ratio of hemp are similar to those of woody materials and dissimilar to those of straw-like biomass sources such as whole-crop cereals, miscanthus and reed canary grass (*Figure 26*). Straw can potentially have a Miles index below 0.34 kg/GJ and an S/Cl ratio above 2, but the literature also reports ranges for these two indices that indicate a high risk of corrosion during combustion (*Figure 26*). The IDT of hemp is similar to that of wood bark and reed canary grass and higher than that of willow, cereal straw, cereals and miscanthus (*Figure 26*), indicating a low risk for slagging and fouling.

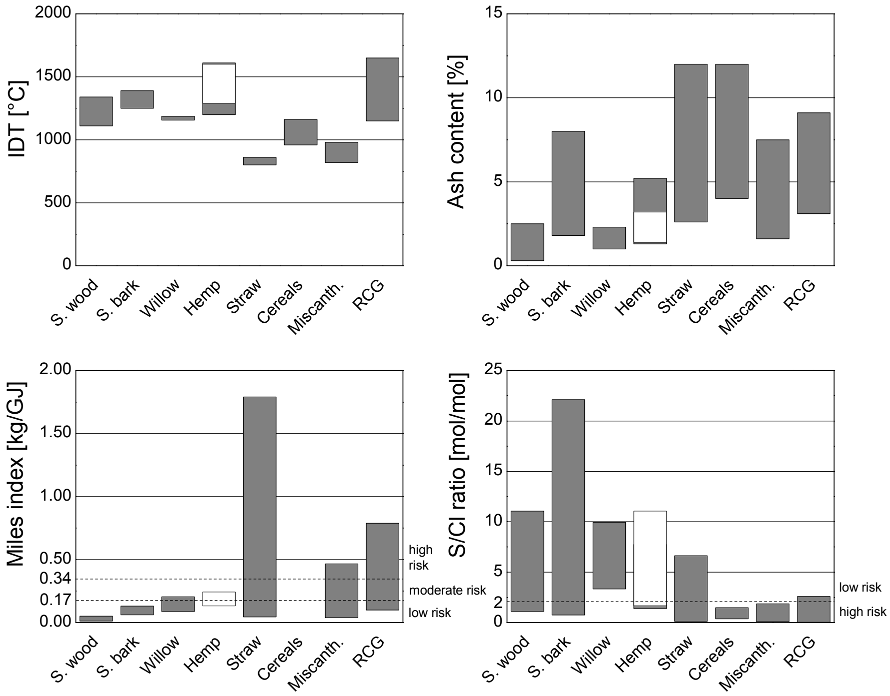

Figure 26. Comparison of initial deformation temperature (IDT), ash content, Miles index and S/Cl ratio for hemp in the present study (white columns) with literature data for selected biomass sources (grey columns), representing solid biofuels from both forestry and agricultural origin. S. = spruce. Cereals = whole-crop cereals. RCG = reed canary grass. Columns denote minimum to maximum values. Bark is mostly combusted in the pulp and paper producing industry and is not likely to be available to biomass boilers combusting energy crops, but given here for reference. References: (BIOS Bioenergiesysteme, 2011; ECN, 2009; Dahl & Brøchner Andersen, 2008; Gilbe et al., 2008; van Loo & Koppejan, 2008; Finell et al., 2006; Forsberg et al., 2006; Norberg, 2006; Obernberger et al., 2006; Kaltschmitt et al., 2000; Wilén et al., 1996; Miles et al., 1995).

Hemp as a solid biofuel has ash characteristics of wood fuels. This is clearly shown in the ternary $CaO-SiO_2-K_2O$ diagram (*Figure 16*; **Paper III**), where spring-harvested hemp samples clustered together with wood fuels such as willow, coniferous wood and wood residues (branches, tops, bark and sawdust). The location of this cluster in the diagram indicates a low risk of significant sintering problems and a high IDT (*Figure 16*) (Fernandez Llorente & Carrasco García, 2005). In contrast, miscanthus, reed canary grass and cereal straw samples clustered together in an area characterised by low IDT and a high risk for significant sintering problems. The boundaries marking the risk zone for sintering were derived from analysis of a selected number of solid biofuels (Fernandez Llorente & Carrasco García, 2005) and therefore act only as an indication of the fuel quality of hemp.

A major competitor to hemp, cereal straw often causes problems with corrosion and sintering (Marmolin *et al.*, 2008; Miles *et al.*, 1995), although these effects can be decreased by washing the straw (Nikolaisen *et al.*, 1998). This procedure requires energy equivalent to about 10% of the energy content of the straw (Nikolaisen *et al.*, 1998). Instead, weathering of cereal straw in the field might be a more practical solution. However, no difference in operating costs was observed in a boiler between use of yellow and grey (weathered) straw (Hinge, 2009). Straw is the more cost-efficient solid biofuel, but due to low DM yield per hectare, availability might be limited within a given transport distance to the CHP plant. In contrast, hemp has approximately twice as high DM yield per hectare (**Paper I**).

Hemp is also dissimilar to miscanthus and reed canary grass, which are more associated with cereal straw as regards the major elements responsible for slagging, fouling and corrosion (**Paper III**). Biomass of miscanthus and reed canary grass is characterised by a much higher ash content and often lower IDT (*Figure 26*) and potentially much greater nutrient removal rates (compare section 4.5.1). However, miscanthus has been shown in this study to have energy yields substantially higher than hemp, while reed canary grass has about the same energy yield per hectare (**Paper IV**). Miscanthus, reed canary grass and willow are cultivated as perennial crops, binding farmers to a specific crop for 10-20 years. This might prove unattractive to farmers, limiting the availability of these crops to a CHP plant.

The high IDT of hemp found in this study indicates that hemp combusted at the normal furnace temperatures of biomass boilers (800-900°C; Baxter *et al.*, 1998) is not likely to cause slagging and fouling. Earlier studies reported that determination of the IDT of fuel samples by observation showed differences between wood and agricultural residues, but did not clearly identify fuel problems (Miles *et al.*, 1995). Furthermore, it has to be noted that the importance of these ash melting properties strongly depends on the type of combustion unit and heat exchanger used (Paulrud, 2004). Most deposits occur during post-combustion and therefore cannot be predicted solely by analysis of the fuel composition (Miles *et al.*, 1995).

Even if the ash fusion test used in the present study (ANSI, 1968) showed high IDT for hemp ash, actual ash melting might start at lower temperatures in combustion tests, e.g. in a production-scale boiler (Paulrud & Nilsson, 2001). For example, IDT values determined by the bed agglomeration test are reported to be 150-200°C and 600°C lower than those by the ash fusion test for reed canary grass with low and high ash content, respectively (Paulrud, 2004). If results are transferable, the bed agglomeration test would probably still give a high IDT for spring-harvested hemp. In addition, the composition of ash produced under laboratory conditions does not always resemble that of ash produced in boiler combustion (Paulrud, 2004).

In order to check the technical suitability of hemp as a solid biofuel, detailed combustion tests with boilers suitable for combustion of straw and wood fuels, respectively, are necessary. Only a few small-scale combustion tests of hemp biomass have been documented (Söderström & Sjölander, 2011; Gilbe *et al.*, 2008; Tung *et al.*, 2008; Sundberg & Westlin, 2005; Jensen & Nikolaisen, 2001; Kaufmann, 1997). Technical problems in handling the fuel or limited fuel availability have resulted in limited data on the combustion quality in some of these combustion tests (Söderström & Sjölander, 2011; Sundberg & Westlin, 2005). Combustion tests are necessary to reveal if actual slagging, fouling and corrosion occurs with hemp as a solid biofuel.

4.4.2 Handling and combustion technology

Hemp as a solid biofuel has a number of viable handling and combustion technology options. Herbaceous fuels, such as straw, miscanthus, reed canary grass and industrial hemp, which are chopped to particulate fuels, have particle shapes and sizes which give them poor bulk handling characteristics, i.e. a low bulk density, poor flow properties and a high tendency to bridge over openings (Mattsson, 1997). Instead of such fuels being handled in bulk, they are often aggregated to bales or compacted to briquettes or pellets before further handling, transport and combustion.

Fuel processing of hemp is likely to require baling of the biomass, since this is a proven, cost-effective system and because the bales function as plugs in the burner openings in some of the newer boilers built for operation on solely straw-like fuels (Hinge, 2009; Sander & Skøtt, 2007). However, to some extent, biomass fuels (e.g. straw, wood) are processed into pellets to facilitate transport (Sander & Skøtt, 2007) and to make them available for boilers with pellet handling systems. Production of hemp bales (Svensson *et al.*, 2010; **Paper IV**), pellets (Nilsson *et al.*, 2011b) and briquettes (Alaru *et al.*, 2011; El Saeidy, 2004) is possible, but may require MC between 10% and 20% (O'Dogherty & Wheeler, 1984).

Use of hemp as a solid biofuel is feasible in several boiler systems. Firstly, hemp can be combusted in boilers built for woody biomass. These boilers are often based on fluidised bed technology, which is normally not suitable for straw due to the low IDT of straw (Hinge, 2009). Although suitable, hemp will probably not be combusted as sole fuel in such boilers, since these are often designed for a MC higher than that of spring-harvested hemp (Sundberg & Westlin, 2005). However, blends of hemp biomass with e.g. fresh wood chips have been successfully combusted in a wood chip boiler (Söderström & Sjölander, 2011). Secondly, hemp can be combusted in boilers built for firing of straw-like solid biofuels, e.g. boilers with moving or vibrating grates (Hinge, 2009). The high flexibility of hemp applications as a solid biofuel may be attractive to both farmers and potential fuel customers.

4.4.3 Variations in hemp fuel properties

Spring harvested hemp has above-average fuel properties that are – in major aspects – independent of location and cultivar. Major fuel properties of hemp were not significantly influenced by different hemp cultivars, trial locations and trial years. The content of the major ash-forming elements, HHV, IDT, S/Cl ratio, Miles index and total ash content of hemp biomass did not vary, although southern and northern field trials were 900 km apart. This indicates that the major fuel properties are stable across a wide range of cultivation parameters and for a number of different cultivars.

Since the soil type can influence content and composition of ash in crops, e.g. reed canary grass (Burvall, 1997), these results have to be confirmed for other soil types and locations.

4.5 Sustainability of hemp biomass production

4.5.1 Nutrient removal and recycling

Plant nutrients in crop cultivation are often supplied in the form of mineral fertiliser. The most important plant nutrients are nitrogen (N), phosphorus (P) and potassium (K). While production of N requires large amounts of energy, P resources are globally limited[39]. To avoid or postpone future depletion and in order to decrease fertiliser-related energy costs, plant nutrients removed from the field by harvest and removal of biomass can partly be recycled in the form of e.g. undegraded biomass (e.g. in digestate) or ash (e.g. from combustion of biomass). The amount of nutrients removed per hectare and the fate of the removed nutrients depends on the application of the biomass.

The digestate can be used as biofertiliser in food, feed and energy crop cultivation. This nutrient recycling via digestate results in approx. 30% less energy input in cultivation of autumn-harvested hemp compared with spring-harvested (**Paper IV**). Amounts of nutrients removed from the field are high for biomass used for biogas production (*Figure 27*). In the anaerobic digestion process, biomass is partly degraded and mineralised. When the digestate containing undigested biomass is spread on fields for use as biofertiliser, mineralised nitrogen is available to plants. However, during storage and spreading mineralised nitrogen may be partly lost to the atmosphere. P and K can be assumed to be returned to the field almost entirely in the digestate. Even if not all nutrients are mineralised (plant-available), continuing mineralisation of the undigested biomass will replenish soil nutrient stocks for P and K. Similarly, biomass-bound nitrogen is released and plant-available at a later time. Digestate can therefore be considered to be both directly fertilising (similarly to mineral fertiliser) and a long-term biofertiliser. This can be of advantage if plants fertilised with digestate can take up the nitrogen later in the growing season when it is mineralised. This is best ensured by plants such as sugar beet, maize or hemp that are harvested late in the autumn. If nitrogen is not taken up and bound organically at the time of mineralisation, further amounts of nitrogen may be lost to the atmosphere or – worse - to water bodies causing eutrophication.

The amounts of nutrients removed from the field are low for hemp solid biofuel production (*Figure 27*). The decreases in the content of the nutrients is probably related to both nutrient losses from the plants (e.g. senescing leaves) and wash-out effects by precipitation (Nikolaisen *et al.*, 1998; Landström *et al.*, 1996). Ash from large-scale combustion of the biomass can potentially be used as a fertiliser. However, combustion may also concentrate undesirable elements (e.g. heavy metals) in the ash. Nutrient recycling in the form of ash to agricultural fields is normally only practised if the ash is from a defined source,

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39. Besides being limited, P-rich ores often also contain amounts of heavy metals, e.g. cadmium (Cd). Purification of P from ores with relatively high Cd content is significantly more costly than that of Cd-poor ores.

e.g. cereal straw (Ottosson *et al.*, 2009) and energy crops, but usually not from combustion of other materials.

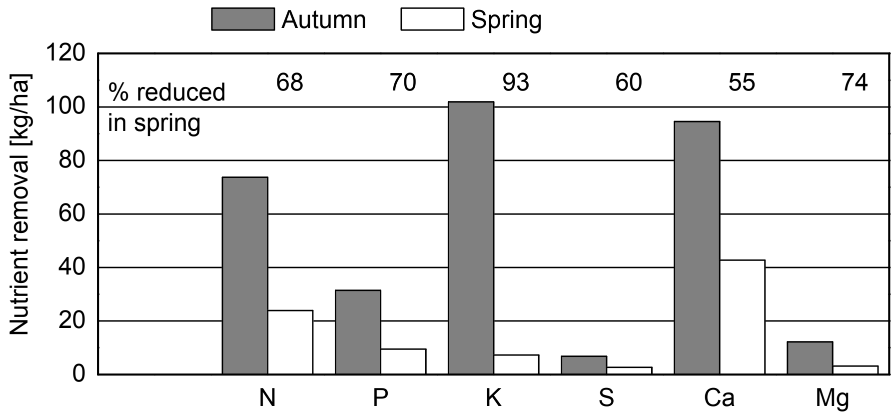

Figure 27. Average removal of selected macro-nutrients at harvest in autumn (grey columns) and in spring (white columns) corresponding to the amount of biomass harvested per hectare.

Plant nutrients in other sources, e.g. waste water, can be utilised by fertilising crops (Li *et al.*, 2009). Since these waste streams often contain undetermined amounts of organic substance that are potentially harmful to humans and animals (Palmquist & Hanæus, 2005), fertilisation of crops for feed and food production is not appropriate. Fertilisation of energy crops with these urban nutrients is advantageous in several ways. Firstly, energy for production of the mineral fertilisers replaced by urban nutrients is saved. Secondly, waste water treatment costs are reduced significantly (Rosenqvist & Ness, 2004). Thirdly, renewable energy can be produced from the energy crops. Trials with willow acting as vegetation filter for waste water have been successful (Hasselgren, 1999; Perttu, 1999). However, issues concerning risks of accumulation of heavy metals and recalcitrant organic constituents in the cultivated soil and potential leaching of plant nutrients are not yet sufficiently investigated (Perttu, 1999).

Hemp biomass had a low content of cadmium in this study (**Paper III**), but on contaminated soils, hemp is able to extract heavy metals from the soil in amounts higher than many other agricultural crops (Angelova *et al.*, 2004). Thus heavy metals could be concentrated in the plant biomass. During combustion in large-scale combustion plants, ash fractions with high heavy metal content could be removed from the recycling scheme for plant nutrients (Ottosson *et al.*, 2009; Obernberger *et al.*, 1997). Thereby, the amount of heavy metals in the cycle would not increase, but rather decrease, while the major fraction of plant nutrients, except nitrogen[40], could be recycled e.g. to agriculture.

4.5.2 Pesticide use

Hemp cultivation requires very limited amounts of pesticide (see section 1.6.3). Few insect pests are known to exist in hemp crops and fungal diseases are rare (McPartland & Hillig, 2006; Ranalli, 1999). Since hemp plants shade the ground quickly after sowing and thereby outgrow weeds, herbicides are not required (van der Werf *et al.*, 1995; Lotz *et al.*, 1991). However, a weed free seedbed is required. This can be achieved for example by preparing a stale seedbed in combination with a harrowing step prior or in combination with drilling (Melander *et al.*, 2005).

Pesticide requirements have a potentially strong influence on the energy input in cultivation, since energy requirements for pesticide production are high (Kaltschmitt & Reinhardt, 1997; Pimentel, 1980). Many other annual energy crops in large-scale cultivation require relatively large amounts of pesticides, e.g. maize and sugar beet cultivated for biogas production (Meissle *et al.*, 2010; Märländer *et al.*, 2003). However, in large monocultures of hemp, pests (e.g. the hemp flea) could potentially become an issue as well (Bocsa & Karus, 1998). In well-designed crop rotations, a low pesticide use in hemp cultivation can be expected even for large-scale cultivation.

4.5.3 Crop rotation effects

Hemp is a strong weed suppressor, resulting in low herbicide requirements for hemp cultivation. Furthermore, in a crop rotation this weed suppression effect can even improve the weed situation for the following crop (van der Werf *et al.*, 1995).

Similarly, hemp suppresses soil pathogens and soil health might therefore be improved with introduction of hemp into a given crop rotation. (Kok *et al.*, 1994). Hemp has been reported to be an excellent preceding crop for cultivation of cereals crops (Deeley, 2002), resulting in yield increases of 10-20% in cereals (Bocsa & Karus, 1998). For winter cereals this is only possible if hemp is harvested in autumn, e.g. as biogas substrate or for fibre production. For spring-harvested hemp used as solid biofuel, practically any spring-sown crop can be used in succession.

Hemp, being an annual crop, is relatively easy to insert into an existing crop rotation. There it may function as a break crop[41], e.g. in cereal cultivation.

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40. Nitrogen is lost to the atmosphere during combustion.

Farmers interested in cultivating energy crops are often hesitant about tying fields into the production of one crop, e.g. willow and miscanthus, over the economic lifespan of the plantation, i.e. 10-20 years (Deeley, 2002).

Cultivation of hemp over two to three years in the same field does not lead to significant biomass yield losses, due to a high self-tolerance of hemp (Bocsa & Karus, 1998). Therefore, hemp functions very well as a crop in crop rotations.

4.5.4 Economics

Hemp biomass production for energy purposes is economically feasible even for small-scale cultivation areas. However, non-energy applications may require cultivation on a much larger scale. For example, there is interest in using hemp for production of fibre boards. However, implementing hemp as a raw material source for this purpose in just one production line would require a volume of biomass corresponding to cultivation on approx. 1.000 hectares (Svennerstedt *et al.*, 2011). Today, implementation of such a large-scale cultivation of hemp from one year to another would be difficult, since practical experience is lacking among farmers and advisors. In contrast, options for using hemp biomass for energy purposes, e.g. briquette production from small-scale hemp cultivation (10-20 ha), can already be commercially viable (Jonsson, 2011; Forsberg *et al.*, 2006). Based on such small-scale start-ups, experience and knowledge can be built to implement use of industrial hemp on a larger scale for both energy and non-energy purposes. Therefore, use of hemp for energy purposes might prove to be a stepping stone in building industry structures that can use hemp for non-energy purposes.

In a biorefinery, combination of several production pathways, e.g. for both energy and non-energy products, may improve energy efficiency and overall economics. This concept integrates production of a selection of high-value products (e.g. building block chemicals, fibres) and subsequent use of low-value bulk residues, e.g. for production of renewable energy carriers. Industrial hemp, with its high biomass yield (**Paper I**), high fibre content (van der Werf, 1994), oil-rich seeds with an interesting profile of polyunsaturated fatty acids (Vogl *et al.*, 2004; Grigoriev, 2002) and antioxidants (Blade *et al.*, 2006) and promising fermentation conversion efficiency (**Paper II**), is an interesting biomass source in this respect.

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41. The break crop 'breaks' the series of crops belonging to the same botanical family in order to deprive soil-borne crop pathogens of their host and thereby decreasing the magnitude of infection for the subsequent crop (Kirkegaard *et al.*, 1997).

4.5.5 Environmental impact of hemp cultivation

Hemp biomass cultivation and use has a relatively low overall environmental impact. The environmental impact of a crop cultivated for energy use can be measured, e.g. as the sum of all emissions caused during the cultivation, harvest, transport and storage. Similarly to the methodology applied for compilation of an energy balance, major field operations and production means can be labelled with corresponding emissions. Besides emissions of greenhouse gases, other impact categories[42] need to be accounted for.

Hemp has been reported to have high biodiversity friendliness when grown as a fibre and food crop (Montford & Small, 1999). Furthermore, hemp has been characterised as a low-input and low-impact crop[43] relative to food crops, e.g. sugar beet and potato (van der Werf, 2004). For biogas-based electricity production, hemp had a disadvantageous greenhouse gas balance due to an unfavourable energy balance (Plöchl *et al.*, 2009). In principle, **Paper IV** has confirmed the unfavourable energy balance for all energy crops used for electricity production from biogas, especially if heat from power generation is not utilised. Biodiesel production from hemp seed oil has been reported to have a much lower overall environmental impact than fossil diesel, even in case where the stalks and leaves were not used for energy purposes (Casas & Rieradevall i Pons, 2005). However, no studies to date have investigated the more energy-efficient production pathways of biogas for vehicles and CHP from hemp for their environmental impact.

Evaluation of the environmental impact of hemp cultivation lay outside the scope of this thesis. However, an analysis of hemp crop cultivation of the type included in a life cycle assessment (LCA) is required for further evaluations of hemp as an energy crop, e.g. against sustainability criteria for biofuels (EC, 2009). Furthermore, an LCA study of the different energy and non-energy application pathways of hemp is required as a basis for comparison of different energy carriers and non-energy products of hemp.

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42. Impact categories include global warming, stratospheric ozone depletion, acidification, eutrophication, photochemical smog, terrestrial toxicity, human health, resource depletion, land and water use (NRML, 2006).

43. All inputs in crop cultivation and biomass use result in emissions that can cause an environmental impact, e.g. carbon dioxide emissions causing global warming.

5 General conclusions

Industrial hemp has a high energy yield per hectare for both solid biofuel and biogas production that is similar or superior to that of most energy crops common in northern Europe (**Papers I** and **IV**).

The high energy yield of biogas from industrial hemp is based on a high biomass yield per hectare and a good specific methane yield with large potential for increases by pretreatment of the biomass. Harvest date in autumn has no significant impact on the specific methane yield and therefore the methane energy yield per hectare is highest in autumn when the hemp biomass yield is highest. Hemp as a biogas substrate surpasses crops used for first generation biofuel production (e.g. wheat, rapeseed) and with pretreatment might even compete with maize and sugar beet for biogas production. Industrial hemp is a high-yielding crop for biofuel production based on lignocellulosic crops (**Papers II** and **IV**)

The energy yield per hectare of industrial hemp for use as a solid biofuel is highest in autumn when the biomass yield is highest. However, important combustion-related fuel properties, such as content of alkali metals and chlorine, ash melting temperature and ash content, are significantly improved when industrial hemp is harvested in spring instead of in autumn. The major fuel properties of hemp are not influenced by choice of cultivar and large differences in latitude between cultivation sites. Fuel properties of hemp are similar to those of wood and willow and superior to those of straw, miscanthus and reed canary grass. Despite lower energy yield per hectare when spring-harvested, hemp competes well with that of products from forestry (e.g. wood chips) and agriculture e.g. straw, miscanthus, reed canary grass, willow) for heat, power and combined heat and power (CHP) production (**Papers I** and **IV**).

Industrial hemp has a good net energy yield per hectare in most applications, except electricity production from biogas. This option shows unfavourable net energy yields for any energy crop, especially if the heat from power generation is not utilised. Furthermore, hemp has good energy output-to-input ratios and is therefore an above-average energy crop. Use of hemp as solid biofuel has the highest net energy yield per hectare and energy output-to-input ratio. Use of hemp as a biogas substrate suffers from higher energy inputs and lower conversion efficiencies, but produces a high quality vehicle fuel (**Paper IV**).

Advantages over other energy crops are also found outside the energy balance, e.g. low pesticide requirements, good weed competition and suitability for crop rotations. Future improvements in hemp biomass and energy yields may strengthen its competitive position against maize and sugar beet for biogas production and against perennial energy crops for solid biofuel production.

6 Areas of future research

In order to implement hemp as an energy crop in large-scale bioenergy carrier production, further analyses of its sustainability are required. Environmental, economical and social impacts have to be studied further in order to create a sound knowledge basis for comparisons with competing energy crops and other biomass types.

The energy balances complied in this thesis can be used to apply environmental, economic and social costs and benefits to the different applications of industrial hemp biomass. Specifically, greenhouse gas emissions and biomass production costs of hemp as biogas substrate and solid biofuel are of major interest.

Biomass yield may be increased by a detailed nutrient balance for industrial hemp accounting for plant and soil nutrient contents, as well as corresponding water requirements.

The good combustion properties of spring-harvested hemp biomass as indicated by the fuel property analyses in this study need to be confirmed in large-scale combustion tests. Furthermore, more field trials, both in other locations and on other soil types, are needed to confirm the independence of the above-average fuel properties of spring-harvested hemp from choice of cultivar, location and soil type.

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Svensk sammanfattning

Industrihampa (*Cannabis sativa* L.) – en högavkastande energigröda

Bioenergi är för närvarande den snabbast växande källan för förnybar energi. Strängare hållbarhetskriterier för produktion av fordonsbränslen och ett ökat intresse för kraftvärmeproduktion baserad på biomassa har skapat efterfrågan på högavkastande energigrödor med god omvandlingseffektivitet.

Denna avhandling presenterar studier av industrihampa som energigröda för produktion av biogas och fastbränsle. I fältförsök har utvecklingen av biomassa- och energiavkastning, specifikt metanutbyte och biomassans bränsleegenskaper undersökts under tillväxten och den efterföljande vissningsfasens förlopp, dvs. från höst till följande vår.

Hampans energiavkastning för både biogas- och fastbränsleproduktion är lika hög som eller överlägsen de flesta andra vanliga energigrödor i Nordeuropa. Den höga energiavkastningen för hampa i form av biogas beror på en kombination av hög biomassaavkastning och högt specifikt metanutbyte. Det finns dessutom en stor potential att höja det specifika metanutbytet med hjälp av olika förbehandlingsmetoder, t.ex. ångexplosion. Energiavkastningen per hektar i form av metan är högst om hampan skördas under hösten, dvs. när biomassaavkastningen är högst.

Energiavkastningen för hampa som fastbränsle är också högst under hösten. Denna skördetidpunkt är dock ogynnsam för viktiga bränsleegenskaper, t ex halt av alkalimetaller, klor och aska samt asksmälttemperatur. Om hampan får stå kvar på fältet över vintern och skördas först under våren, så förbättras dessa bränsleegenskaper betydligt. De viktigaste bränsleegenskaper påverkas däremot inte av årsmån, stora skillnader i latitud eller val av hampasort.

Nettoenergiavkastningen per hektar för hampa är bra för användning som biogassubstrat eller fastbränsle. Dessutom har hampa relativ hög energikvot mellan utbyte och insats (output/input-förhållande). Hampa kan därför anses vara en energigröda som är bättre än genomsnittet.

En jämförelse av olika energisystem baserade på hampa visade att användning av hampa som fastbränsle gav högst nettoenergiavkastning och energikvot (output/input). System baserade på hampa för produktion av biogas krävde högre energiinsatser och gav lägre omvandlingseffektivitet, men gav å andra sidan fordonsbränsle, dvs. en energibärare av högre kvalitet.

Utöver gynnsam energibalans har hampa andra fördelar, t.ex. lågt pesticidbehov bl.a. genom en mycket god förmåga att konkurrera med ogräs. Hampa är en lämplig avbrottsgröda i spannmålsintensiva växtföljder. Den stora potentialen att öka hampans biomassa- och energiavkastning kan i framtiden stärka dess konkurrenskraft mot majs och sockerbetor för biogasproduktion och mot perenna grödor för produktion av fastbränsle.

Deutsche Zusammenfassung

Industriehanf (*Cannabis sativa* L.) – eine ertragreiche Energiepflanze

Bioenergie ist die zurzeit am schnellsten wachsende Quelle, die zur Produktion erneuerbarer Energien beiträgt. Strengere Nachhaltigkeitskriterien für die Produktion von Treibstoffen und ein wachsendes Interesse an Kraftwärme-kopplung (KWK) aus Biomasse haben zu einer erhöhten Nachfrage an ertragreichen und effizient zu Energieträgern umwandelbaren Energiepflanzen geführt.

In der vorliegenden Studie wurde die Eignung von Industriehanf als Energiepflanze zur Produktion von Biogas bzw. Festbrennstoff untersucht. In Feldversuchen wurden Biomasse- und Energieerträge über den Zeitraum von Wachstum und den nachfolgenden Verwelkungsprozess (d.h. vom Herbst bis zum folgenden Frühjahr) untersucht und in Zusammenhang mit dem spezifischen Methanertrag bzw. der Zusammensetzung der Biomasse gestellt.

Die Energieerträge von Hanf zur Verwendung als Biogassubstrat bzw. als Festbrennstoff erwiesen sich als ähnlich hoch oder höher im Vergleich zu den Erträgen der meisten in Nordeuropa üblichen Energiepflanzen. Der hohe Biogas-energieertrag von Hanf beruht auf der sehr hohen Biomasseproduktion per Hektar und einem guten spezifischen Methanertrag. Es besteht außerdem ein großes Potenzial zur Steigerung des Methanertrages mit Hilfe geeigneter Vorbehandlungsmethoden. Soll Hanf als Biogassubstrat verwendet werden, ist Ernte im Herbst zum Zeitpunkt der höchsten Biomasseerträge vorteilhaft.

Der höchste Energieertrag von Hanf als Festbrennstoff wird ebenfalls im Herbst erreicht. Zu diesem Zeitpunkt sind jedoch wichtige verbrennungs-relevante Stoffeigenschaften wie zum Beispiel der Gehalt an Alkalimetallen, Chlor und Asche als auch die Ascheschmelztemperatur unvorteilhaft. Wird der Hanf über den Winter im Feld belassen und erst im Frühjahr geerntet, verbessern sich diese Brennstoffeigenschaften deutlich. Die wichtigsten

Brennstoffeigenschaften von Hanf sind unabhängig von Variationen der Wachstumsbedingungen, Breitengrad und Cultivar.

Hanf erzielt gute Nettoenergieerträge per Hektar in den meisten Anwendungen. Weiterhin ist das Verhältnis von erzielter zu eingesetzter Energiemenge (Output/Input-Verhältnis) vergleichsweise hoch in den meisten untersuchten Anwendungen. Hanf ist daher eine überdurchschnittliche Energiepflanze. Als Festbrennstoff hat Hanf die höchsten Nettoenergieerträge und Output/Input-Verhältnisse. Als Biogassubstrat leidet Hanf unter höheren Energieeinsätzen und niedrigerer Umwandlungseffizienz, liefert jedoch Fahrzeugtreibstoff, einen sehr hochwertigen Energieträger.

Über eine günstige Energiebilanz hinaus hat Hanf andere Vorteile, zum Beispiel einen niedrigen Pestizidbedarf, gute Unkrautbekämpfungseigenschaften und gute Vorfruchtseigenschaften (als *break crop*) in Getreide-intensiven Fruchtwechseln. Das große Potenzial für zukünftige Steigerungen der Biomasse- und Energieerträge von Hanf kann dessen Konkurrenzfähigkeit gegenüber Mais und Zuckerrüben zur Produktion von Biogas und gegenüber mehrjährigen Pflanzen zur Produktion von Festbrennstoff weiter verstärken.

Appendix

Table A1. *Hemp varieties, their utilisation, relevant plant parameters and data on approval within the EU and Canada.*

Cultivar	Utilisation	Sex	Bred in	Maturity group	Year of breeding	EU 2009	EU 2010	EU 2011	Canada 2011
52092		dioecious	Turkey						
52137		dioecious	Turkey						
Alp King	fibre	dioecious	Switzerland	medium					
Alyssa[a]	seed/fibre		Canada		2004				x
Anka	seed	monoecious	Canada		1999				x
Armanca			Romania					x	
Asso	fibre	dioecious	Italy		2004	x	x	x	
Beniko	fibre	monoecious	Poland	early	1985	x	x	x	
Bialobrzeskie	fibre	monoecious	Poland	medium early	1968	x	x	x	
Canda			Canada						x
Cannakomp			Hungary		2003	x	x	x	
CanMa			Canada						x
Carma	fibre	monoecious	Italy			x	x	x	
Carmagnola	fibre	dioecious	Italy	late	landrace	x	x	x	x
CS[b]	fibre		Italy		1960s	x	x	x	
Carmen	seed/fibre		Canada						x
Carmono	fibre	monoecious	Italy		1990s				
CFX-1			Canada						x
CFX-2			Canada						x
Chamaeleon	fibre	dioecious	Netherlands		2002	x	x	x	
Codimoni[c]	fibre	monoecious	Italy		2004	x	x	x	
Crag	fibre		Canada						x
CRS-1			Canada						x
Delores	seed		Canada		2007				x
Delta Llosa	fibre		Spain			x	x	x	
Delta 405	fibre		Spain			x	x	x	
Denise	fibre, seed	monoecious	Romania			x	x	x	
Deni[d]			Canada						x
Diana	fibre, seed	monoecious	Romania				x	x	
Dioica 88	fibre	dioecious	France	very late	1998	x	x	x	
Dneprovskaya Odnodomnaya		monoecious	Ukraine		1980				
Dolnoslaskie			Poland						

Cultivar	Utilisation	Sex	Bred in	Maturity group	Year of breeding	EU 2009	EU 2010	EU 2011	Canada 2011
Eletta Campana	fibre	dioecious	Italy		1960s				
Epsilon 68	fibre	monoecious	France	late	1996	x	x	x	
Ermes	fibre	monoecious	Italy		1990s				
Ermakovskaya Mestnaya			Russia		landrace				
ESTA-1	seed		Canada						x
Fasamo	fibre	monoecious	Germany	very early	1998		x	x	x
Fédora 17	fibre	monoecious	France	medium	1998	x	x	x	
Fédora 19	fibre	hybrid population	France	early					
Fédrina 74	fibre	hybrid population	France	medium-late			x	x	x
Félina 32	fibre	monoecious	France	early	1998	x	x	x	
Félina 34	fibre	hybrid population	France	medium-early	1974	x	x		x
Férimon 12	fibre	monoecious	France	early	1981	x	x	x	x
Ferrara		dioecious	Italy		landrace				
Fibramulta 151	seed, fibre	dioecious	Romania	medium	1965				
Fibranova	fibre	dioecious	Italy	late	1950s	x	x	x	x
Fibriko			Hungary		1989				x
Fibriko TC			Hungary		2007				
Fibrimon	fibre	monoecious	Germany		1950s				
Fibrimon 21	fibre	monoecious	France		1950s				
Fibrimon 24	fibre	monoecious	France		1972	x			x
Fibrimon 56	fibre	monoecious	France	medium	1972				x
Fibrimor	fibre	dioecious	Italy		2003	x	x	x	
Fibrol			Hungary			x	x	x	
Finola	seed	dioecious	Finland	early	2003				x
Flajsmanova			former Yugoslavia						
Futura 75	fibre	monoecious	France	medium-late	1998	x	x	x	
Futura 77	fibre	monoecious	France	medium-late			x	x	
FxT	fibre, seed	monoecious	Hungary	medium-early					
Glera		monoecious	Ukraine						
Gluchivski-33		monoecious	Ukraine						
Gluchivski-46		monoecious	Ukraine						
Glukhov 33			Ukraine						
Grace			UK		2004				
Hei Bei	fibre								
Helvetica 01		dioecious	Switzerland	medium-early					
Helvetica 02		dioecious	Switzerland	medium-early					
Helvetica 03		dioecious	Switzerland	medium					
Helvetica Tell		dioecious	Switzerland	medium-early					
Ida			Canada						
Irene	fibre, seed	monoecious	Romania	medium-early	1995				
Joey			Canada						x
Jutta			Canada						x
K (Chinese) x V (wild)	fibre		Hungary						
KC Dóra			Hungary		2009		x	x	
Kenevir	fibre	dioecious	Turkey						
Kinai Egylaki		monoecious	China						

Cultivar	Utilisation	Sex	Bred in	Maturity group	Year of breeding	EU 2009	EU 2010	EU 2011	Canada 2011
Kinai Kétlaki	fibre	dioecious	China						
Kinai unisexualis	fibre	dioecious, but only females	Hungary						
Kompolti	fibre	dioecious	Hungary	late	1954	x	x	x	x
Kompolti Hybrid TC	fibre, seed	dioecious	Hungary	late	1983	x	x	x	
Kompolti Hyper Elite			Hungary						
Kompolti Sargaszaru			Hungary		1974				x
Kozuhara zairai	fibre	landrace	Japan						
Krasnodarskaya	fibre		Former USSR						
Kuban		dioecious	Ukraine		1984				
Lipko		hybrid population	Hungary		2003	x	x	x	
Livoniae	seed	dioecious	Latvia	medium					
Lovrin 110	fibre, seed	dioecious	Romania	medium-late	1981	x	x	x	x
Mechaja copt			Bulgaria						
Medisins					1998				
Moldovan	seed, (fibre)	dioecious	Romania	medium					
Mona			Sweden						
Moniseed			Hungary		2004	x		x	
Monoica			Hungary			x	x	x	
Multiseed			Hungary		2004	x		x	
Novosadska[e]	fibre	dioecious	former Yugoslavia	late					
Novosadska konplja			former Yugoslavia		1950s				
Novosadska plus		dioecious	former Yugoslavia	late					
Odnodomnaja Bernburga	fibre		former USSR						
Pesnica			Slovenia		landrace				
Petera	fibre		Canada		2007				x
Rano		dioecious	Germany						
Rastslaviska	fibre		Czech Republic						
Red petiole	fibre	dioecious	Italy		2002	x	x	x	
Rudnik			Slovenia						
S-204	fibre	monoecious	France						
S-206	fibre	monoecious	France						
Santhica 23	fibre	monoecious	France	medium	1996	x	x	x	
Santhica 27	fibre	monoecious	France	medium	2003	x	x	x	
Santhica 70	fibre	monoecious	France	late	2007	x	x	x	
Schurig			Germany						
Secuieni 1	fibre, seed	monoecious	Romania	medium-early	1984				
Silesia	fibre	monoecious	Poland?			x	x	x	
Silistrensi			Bulgaria						
Silvana			Romania			x	x	x	
Solotonosker 11[f]		monoecious	Ukraine	medium-early					x
Solotonosker 15[f]			Ukraine	medium-early					x
Suprafibra	fibre		Italy		1960s				
Swissmix		dioecious	Switzerland	early					
Szarvasi			Hungary			x	x	x	
Szegedi 9	fibre		Hungary						
Tibolaj	fibre								
Tiborszallasi	fibre	dioecious	Hungary	medium-	2003				

Cultivar	Utilisation	Sex	Bred in	Maturity group	Year of breeding	EU 2009	EU 2010	EU 2011	Canada 2011
				late					
Tisza			Hungary					x	
Tygra	fibre	monoecious	Poland			x	x	x	
UC-RGM			Canada						x
Uniko B	fibre	dioecious	Hungary	medium	1969	x	x	x	x
Uniko-B (F1)	fibre	unisexual	Hungary	medium					
USO 1[f]	fibre		Former USSR						
USO 11[f,g]	fibre	monoecious	Ukraine	medium-early	1984				x
USO 13[f]		monoecious	Ukraine		1986				
USO 14[f]	fibre, seed	monoecious	Ukraine	very early-early	1999				x
USO 15[f,g]		monoecious	Ukraine		1995				x
USO 16[f]	fibre		Ukraine		1980				
USO 31[f]	fibre, seed	monoecious	Ukraine	very early-early	1997	x	x	x	x
V (wild) x Kompolti	fibre		Hungary						
Waliser Queen		dioecious	Switzerland	very early					
Wielkopolskie			Poland				x	x	
X59			Canada						x
Yvonne			Canada						x
Zenica		dioecious	Ukraine		1990				
Zenit	seed, fibre	monoecious	Romania				x	x	

[a] also known as *Alisa*
[b] also known as *Carmagnola Selezionata*
[c] also knwon as *Codimono*
[d] also known as *Denny*
[e] also known as *Novosadski*
[f] also known as *Juznaja Odnovremenno Sozrevajuscaja* or *JSO* or *Juso* or *Yuso*
[g] also known as *Zolotonosha* or *Solotonosker* or *Zolotosskaja*