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Energy balances for biogas and solid biofuel production from industrial hemp

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ABSTRACT

If energy crops are to replace fossil fuels as source for heat, power or vehicle fuel, their whole production chain must have higher energy output than input. Industrial hemp has high biomass and energy yields. The study evaluated and compared net energy yields (NEY) and energy output-to-input ratios ($R_{O/I}$) for production of heat, power and vehicle fuel from industrial hemp. Four scenarios for hemp biomass were compared; (I) combined heat and power (CHP) from spring-harvested baled hemp, (II) heat from spring-harvested briquetted hemp, and (III) CHP and (IV) vehicle fuel from autumn-harvested chopped and ensiled hemp processed to biogas in an anaerobic digestion process. The results were compared with those of other energy crops. Calculations were based on conditions in the agricultural area along the Swedish west and south coast. There was little difference in total energy input up to storage, but large differences in the individual steps involved. Further processing to final energy product differed greatly. Total energy ratio was best for combustion scenarios (I) and (II) ($R_{O/I}$ of 6.8 and 5.1, respectively). The biogas scenarios (III) and (IV) both had low $R_{O/I}$ (2.7 and 2.6, repectively). They suffer from higher energy inputs and lower conversion efficiencies but give high quality products, i.e. electricity and vehicle fuel. The main competitors for hemp are maize and sugar beets for biogas production and the perennial crops willow, reed canary grass and miscanthus for solid biofuel production. Hemp is an above-average energy crop with a large potential for yield improvements.

1. Introduction

Biomass from agricultural crops has been suggested as an alternative source of energy that has the potential to partly replace fossil fuels for heat, power and vehicle fuel production [1–3]. The replacement of fossil fuels is desirable for the mitigation of CO_2 emissions among other aims. However, for mitigation of CO_2 emissions, replacement of fossil fuels with biofuels based on the energy content is crucial. The fossil fuels used for producing the biofuels must also be accounted for. Recent studies have challenged the ability of biofuels to reduce CO_2 emissions, e.g. ethanol from sugarcane or maize [4] or biodiesel from rapeseed oil [5]. Some biofuels have been reported to increase overall CO_2 emissions, when the complete well-to-wheel production pathway is considered (e.g. [6]). Important parameters influencing the environmental sustainability of biofuels include inflicted land-use change, utilisation of by-products or origin of auxiliary energy [7]. Major concerns relate to the resource efficiency of agricultural biomass production (e.g. [6]).

Energy crops are often compared in terms of resource efficiency, e.g. arable land type, environmental impact, energy and economic efficiency of the gaseous, liquid or solid energy carriers produced [8]. For each well-to-wheel production pathway an energy balance can be calculated that accounts for the energy outputs minus the direct and indirect energy inputs in cultivation, harvest, transport and conversion [9]. Energy balances have been drawn up for most of the first

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generation energy crops, for example maize (e.g. [10]) and wheat (e.g. [11]) for ethanol production and rape seed oil for biodiesel production (e.g. [12]). However, energy balances are lacking for many other crops that are in the stage of commercial introduction as energy crops, e.g. industrial hemp, or for new applications of common crops, e.g. biogas from residual agricultural biomass.

Hemp (*Cannabis sativa* L.) can be used to produce different energy products such as heat (from briquettes or pellets [13,14]), electricity (from baled biomass [15]) or vehicle fuel (e.g. biogas from anaerobic digestion [16]) or ethanol from fermentation [17]). Hemp has potential energy yields that are as high as or higher than those of many other energy crops common in northern Europe, e.g. maize or sugar beet for biogas production and reed canary grass as solid biofuel [18]. As an annual herbaceous crop, hemp fits into existing crop rotations. Hemp requires little pesticide and has been shown to have the potential to decrease pesticide use even for the succeeding crop [19], as it is a very good weed competitor [20]. These characteristics of hemp potentially improve the energy balance, as production of pesticides requires large amounts of energy [21]. Energy conversion of hemp biomass to biogas or ethanol has been shown to have promising energy yields [16,17]. Energy utilisation of hemp biomass processed to solid biofuels in the form of briquettes has been established commercially, and is competitive in a niche market [22].

When comparing energy crops with each other based on their environmental performance (e.g. emissions from production and use of fertiliser, fossil fuel, etc.), it is important to also know the emissions avoided by replacing other sources of energy, i.e. fossil fuels. However, this requires an energy balance, including the energy inputs and outputs of the conversion investigated. Earlier studies regarding the use of hemp for energy purposes have concentrated on calculating the emissions from sole biomass production [23], from electricity production from hemp-derived biogas [24], from hemp diesel production [25] and from hemp pulp production [26]. To our knowledge, no other energy use of hemp biomass (e.g. for biogas, ethanol or solid biofuel production) has been investigated in reference to its energy balance.

The aim of the present study was to evaluate and compare the energy balances of four scenarios for the production of hemp biomass and further fuel processing. These scenarios were: (I) combined heat and power (CHP) from spring-harvested baled hemp, (II) heat from spring-harvested briquetted hemp, and (III) CHP and (IV) vehicle fuel from autumn-harvested chopped and ensiled hemp processed to biogas in an anaerobic digestion process. An additional aim was to compare hemp with other biomass sources used for the final energy products investigated.

2. Methodology

2.1. *Description of base scenarios*

The different utilisation pathways for hemp biomass can be grouped in terms of two different biomass harvest times: Hemp harvested as green plants in autumn if intended for biogas, or as dry plants harvested in spring if intended for solid biofuel production [18]. To compare these pathways, four different energy conversion base scenarios were investigated (Fig. 1).

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 [27]. In CHP production, the combustion heat is used for production of both electricity (power) and heat, e.g. for residential and commercial district heating.

Scenario II describes the production of heat from combustion of spring-harvested, chopped and briquetted hemp. This scenario illustrates the utilisation currently available in parts of Sweden, i.e. combustion in small-scale boilers for heating of private homes [28].

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 [29].

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 other origin than hemp) is increasingly being used in Sweden, Germany and other European countries as vehicle fuel [30].

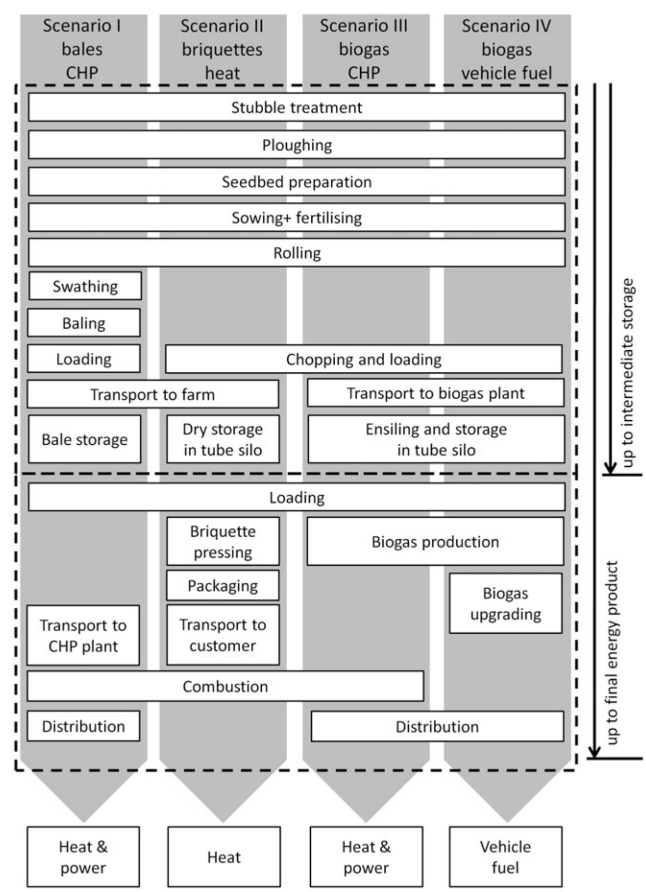

Fig. 1 – Schematic overview of the field and transport operations accounted for in CHP production from baled hemp (scenario I), heat production from briquetted hemp biomass (scenario II), CHP production from hemp-derived biogas (scenario III) and vehicle fuel production from hemp-derived biogas (scenario IV).

2.2. Scenario assumptions

2.2.1. Cultivation area

Hemp biomass was assumed to be produced in the agricultural area called *Götalands södra slättbygder*, *Gss*, extending over the Swedish west and south coast, up to 35 km inland (55°20′-57°06′ N, 12°14′-14°21′ E) [31]. On average, this area produces high yields per hectare of conventional crops. *Gss* comprises approx 330,000 ha arable land [31,32] and is also the area where hemp could be grown with relatively high biomass and energy yields per hectare [18]. A typical short crop rotation in this area is sugar beet followed by spring barley and winter wheat. This rotation was assumed to be extended with one year of hemp cultivation following either sugar beet or winter wheat. It was further assumed that the farm cultivates 150 ha arable land conventionally, with an average field size of 4 ha, reflecting the actual average farming situation in the agricultural area investigated [33].

2.2.2. Soil treatment

Soil treatment was assumed to comprise stubble treatment, ploughing and seedbed preparation. Sowing was assumed to be carried out in combination with fertilisation, with subsequent light soil compaction by a roller. Pesticide treatment was assumed to be unnecessary [19]. These field operations for establishing the hemp crop were identical for all scenarios tested in the present study.

2.2.3. Scenario I

Solid biofuel production in scenarios I and II requires harvest in spring, when moisture content (MC) in the biomass is below a mass fraction of 30% [18], which is required for safe, low-loss storage [34]. In scenario I, hemp was assumed to be cut and laid in swaths, then pressed into large square bales (2.4 m × 1.2 m × 1.3 m). The bales were transported 4 km on average to the farm (see section 2.4). For intermediate storage the bales were wrapped together in a plastic film tube, which is an economic storage option that does not require as much investment as permanent storage buildings. The bales were then transported on demand to a CHP plant, where they were combusted. A CHP plant with an annual production of 780 TJ (el) and 1430 TJ (th) was assumed, which is similar to the dimensions of existing large-scale straw-firing CHP plants, e.g. [27,35]. Baled wheat straw is typically the predominant fuel in such plants and was assumed to account for 95% of the energy produced in the present scenario. The remaining 5% were assumed to be accounted for by baled hemp biomass. The bales were fed into the boiler by means of a conveyor belt. The CHP plant was assumed to be equipped with a flue gas condensing unit for heat recovery [35]. Table 1 lists the major process parameters. The straw/hemp ash mixture was assumed to be transported back to the field and used for fertilising the soil for the next crop at 172 kg ha^{-1}. This dosage was derived from the total amount of ash produced during one year divided by the total annual cultivation area for hemp and straw combined [36]. A standard lime spreader was assumed for spreading of the ash.

2.2.4. Scenario II

For briquette production, hemp is also spring-harvested. Here it was assumed that hemp was chopped (20 mm length) with a maize forage harvester in the field and transported in bulk to the farm, where it was stored dry by compressing it into a silage tube for intermediate storage. Further processing included on-site pressing into briquettes, packaging and transport to local sales places and customers. It was further assumed that 50% of the briquettes were sold as 12 kg bags at petrol stations [40]. Individual transport of the briquettes to

Table 1 – Assumed and calculated process parameters used for modelling the CHP plant.

Parameter		Unit	Assumed value		Source
Nominal effect		MW (el)	35		[35]
		MW (th)	68		[35]
Electric efficiency		%	33		[35]
Thermal efficiency		%	60		[35]
Annual production		TJ	2384		Own calculations
			hemp	straw	
HHV		MJ kg^{-1}	19.1	18.7	[18,37]
Ash content		wt-%	1.8	5.0	[18,37]
Required DM biomass		Mg a^{-1}	6241	121,125	Own calculations
Required cultivation area		ha a^{-1}	1068	34,844	Own calculations
Nutrient removal[a]	N		24	29	
	P	kg ha^{-1}	10	4	Own unpublished results, [38]
	K		7	41	
Electricity production		TJ a^{-1}	787		Own calculations
Heat production		TJ a^{-1}	1431		Own calculations
Indirect energy input		% of produced electricity	4.0		[39]
Ash production		Mg a^{-1}	6165		Own calculations
Nutrient recycling[b]	P	%	38		Own calculations
	K	%	100		Own calculations

a Based on normalised yields for hemp and maize.
b Calculated from the content of P and K in the ash derived from the hemp/cereal straw fuel mix.

the place of combustion was not accounted for, as it was assumed that the bags were picked up 'on route'. The remaining 50% were assumed to be delivered to the place of utilisation in 450 kg bulk bags [40]. The average transportation distance for both bag sizes was calculated (see section 2.4) to be 30 km on average. In both cases, briquettes were assumed to be burned in small-scale domestic boilers (80% thermal efficiency) for heating purposes.

2.2.5. *Scenario III*

For the production of biogas, hemp is harvested in autumn when the biomass DM yield is highest [18]. In this scenario, it was assumed that the crop was harvested by chopping (20 mm length) with a maize forage harvester in the field and transported to the biogas plant, where it was ensiled in a silage tube for intermediate storage. The silage was then fed on demand to the biogas plant. In the biogas reactor the hemp was converted to biogas and a nutrient-rich digestate. The hemp biomass was assumed to be co-digested with maize in a medium-sized biogas plant with an annual production of 90 TJ raw biogas. This capacity corresponds to typical centralised or industrial biogas plants commonly digesting biomass from varying sources [41]. In the present scenario, hemp accounted for 20% of the energy produced, with maize accounting for the remainder. With such a low proportion of hemp, process parameters are likely to resemble those for a process run exclusively on maize. Therefore, this setup was assumed to be realistic for the implementation of a new energy crop as substrate in anaerobic digestion.

The raw biogas was assumed to be combusted in an on-site CHP plant (Fig. 2, top) with total annual production of 30 TJ (el) 40 TJ (th). Table 2 lists the major process parameters used in the present study. Pumping and mixing of the digestion process were assumed to use electricity from the grid, while heating of the biogas plant was assumed to use heat from the CHP process, internally using raw biogas as fuel [48].

The digestate was assumed to be stored at the biogas plant until utilisation as biofertiliser. Fertilisation with digestate was assumed to partly replace mineral fertiliser according to its nutrient content in the production of hemp biomass in the following growing season. Only plant-available ammonium nitrogen (NH_4–N) content in the digestate was assumed to replace mineral nitrogen fertiliser. The amount of NH_4–N in the digestate was calculated from biomass elemental analysis (unpublished results) assuming the degree of mineralisation of the biomass in the digestion process as the production rates of methane and carbon dioxide suggest. A mass fraction of 5% of NH_4–N were assumed lost in the handling and spreading of digestate [49]. Additional organically-bound N was not accounted for. All phosphorus (P) and potassium (K) removed from the fields with the harvested biomass was assumed to be returned through use of the digestate as biofertiliser and to directly replace mineral P and K fertiliser, respectively. Transport of digestate from biogas plant to field was assumed to be achieved by tank truck with no prior dewatering, as transport distances are relatively short [48].

2.2.6. *Scenario IV*

In scenario IV, hemp biomass was assumed to be used and treated as described in scenario III until the production of raw biogas. However, instead of combusting the biogas, it was refined to vehicle fuel (Fig. 2, centre). This upgrading was assumed to be carried out in a subsequent water scrubber unit, which is a common choice of technology in Sweden [45]. The upgrading unit increases the methane content to a volume fraction of 97% in the biogas, which is then pressurised to 20 MPa. The upgrading unit was assumed to have an annual nominal production of 90 TJ of biogas vehicle fuel. The biogas vehicle fuel was assumed to be distributed non-publicly directly at the biogas plant, e.g. for vehicles in public transport.

In contrast to scenario III, heating of the biogas plant was assumed to use heat from a gas boiler, using raw biogas as fuel [48]. Note that scenarios III and IV refer to the same amount of biomass utilised.

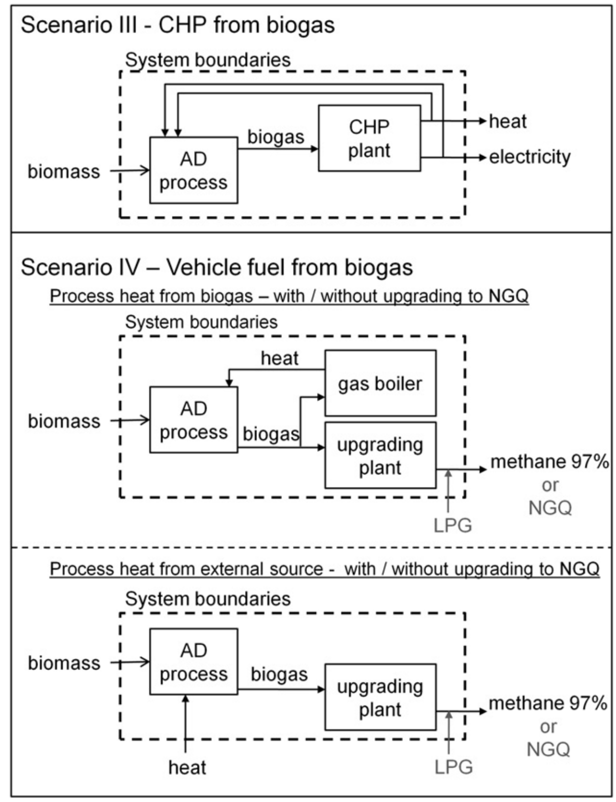

Fig. 2 – Schematic overview of the anaerobic digestion (AD) process and the subsequent utilisation of biogas for base scenario III (top). The centre panel depicts the pathway without (base scenario IV) and with an additional upgrading option from 97% methane content to natural gas quality (NGQ) vehicle fuel (subscenario, grey items). The bottom panel depicts the subscenarios using external heat for the AD process with and without the same upgrading option (grey items).

2.3. *Calculation of energy balances*

For all scenarios, the net energy yield (NEY) was calculated by subtracting the sum of direct and indirect energy inputs ($EI_{dir/ind}$) from the energy output (EO).

Table 2 – Assumed and calculated process parameters used for modelling the anaerobic digestion plant. The tables list the major direct and indirect energy inputs.

Parameter		Unit	Assumed value		References
Digester, size[a]		m^3	2600		Own calculations
Storage tank for digestate, size[b]		m^3	14,500		Own calculations
Feed as VS		$kg\ m^{-3}\ d^{-1}$	3.0		[42]
			hemp	maize	
Required DM biomass		$Mg\ a^{-1}$	2218	6377	Own calculations
Required cultivation area		$ha\ a^{-1}$	215	531	Own calculations
Specific methane yield[c] on VS		$m^3\ kg^{-1}$	0.22	0.32	[16, 24, 43]
Volatile solids content (of DM)		%	93	95	[16, 43]
Nutrient removal[d]	N	$kg\ ha^{-1}$	83	154	Own unpublished
	P	$kg\ ha^{-1}$	35	31	results [18,38],
	K	$kg\ ha^{-1}$	121	216	
Nutrient recycling	N[e]	%	55		Own calculations
	P	%	92		
	K	%	100		
Life time digester and storage		a			[44]
Direct energy input			20		
Heating		$GJ\ ha^{-1}\ a^{-1}$	3.6		[45]
Pumping & mixing		$GJ\ ha^{-1}\ a^{-1}$	0.8		[46]
Indirect energy input[f]					
Anaerobic digester		$GJ\ ha^{-1}\ a^{-1}$	0.49		
Digestate storage		$GJ\ ha^{-1}\ a^{-1}$	0.25		Own calculations
CHP plant (scenario III)		$GJ\ ha^{-1}\ a^{-1}$	0.52		

DM = dry matter; VS = volatile solids.
a Two units of 1300 m^3 each.
b Five units of 2900 m^3 each, dimensioned for the storage capacity for digestate accumulated over 8 months [47].
c Under standard gas conditions of 100 kPa and 273 K.
d Based on a normalised yield for hemp and maize.
e Calculated from 15% losses during digestion and spreading and a share of NH_4–N of 74% according to the degree of mineralisation during the digestion process.
f Indirect energy inputs from transport and assembly of building materials were assumed to be minor and were not accounted for. For simplicity, building materials included only steel, concrete and plastics, assuming a steel digestion reactor and a steel-reinforced concrete tank with plastic gastight roofing for storage of digestate.

$$NEY = EO - \left(\sum(EI_{dir}) + \sum(EI_{dir})\right)$$

The energy output represents the energy derived as electricity, useful heat and vehicle fuel from the conversion processes. 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.

$$R_{O/I} = EO/\left(\sum(EI_{dir}) + \sum(EI_{ind})\right)$$

These calculations were carried out for two different system boundaries: (a) From cultivation until intermediate storage of the hemp biomass (Fig. 1, top) and (b) from cultivation until distribution of the final energy product (Fig. 1, bottom).

The conversion efficiency (η_{conv}) was calculated for each scenario putting the energy output as final energy carrier in relation to the energy content in the harvested biomass:

$$\eta_{conv} = EO/E_{biomass}$$

2.3.1. *Energy input*

Table 3 lists the energy equivalents for production means that were assumed for energy input calculations. Energy input was calculated as the sum of direct and indirect energy inputs [52,62,63]. Direct inputs accounting for fuel consumption from field, transport and storage operations were assumed to be based on the use of fossil diesel, reflecting the current situation. Values for diesel consumption were taken from reference data [64]. 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). Human labour and production and utilisation of non-storage buildings and dismantling/recycling of machinery and building materials were not accounted for, as these were regarded as minor. Solar radiation was not accounted for as it is free.

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 [65]. All fertiliser inputs other than digestate and ash were based on use of mineral fertilisers, according to common practice in conventional agricultural production. The energy contained in machinery was calculated based on the energy used for production of the raw material, the production process and maintenance and spare parts [66]. Machinery for soil treatment and briquette pressing is usually owned by the farmer and was assumed to be so in this study. Machinery capacity data ([64]; hemp harvest: unpublished results) was used to calculate the annual machinery-specific operating hours based on the assumed crop rotation (Table 4). Machinery and equipment for harvest

Table 3 – Primary energy factors and energy equivalents for the production means.

Item	Unit	Energy equivalent		References
		Value used	Literature low - high	
Diesel fuel energy content	MJ L^{-1}	37.4	35.9–38.7	[48,52,53,55,56]
Indirect energy use	MJ MJ^{-1}	0.19[a]	0.10–0.27	[50–52,55,56,58]
Electricity indirect energy use	MJ MJ^{-1}	1.20	1.12–1.92	[39,45,49,54]
Natural gas[b] energy content	MJ m^{-3}	39.6		[45]
Indirect energy use	MJ MJ^{-1}	1.2		[45]
LPG energy content	MJ m^{-3}	93		[61]
Indirect energy use	MJ MJ^{-1}	1.1		[45]
Mineral fertiliser N	MJ kg^{-1}	45.0[c]	37.5–70.0	[11,48,52,56,57,59,60]
P	MJ kg^{-1}	25.0[c]	7.9–39.9	[11,48,52,56,57,59,60]
K	MJ kg^{-1}	5.0[c]	4.8–12.6	[11,48,52,56,57,59,60]
Seeds	MJ kg^{-1}	10.1[d]	2.5–12.2	[55–57,59,60]

a 0.04 MJ MJ^{-1} for lubricants and 0.15 MJ MJ^{-1} for the manufacturing process.
b Natural gas was assumed to be used as external production option of heat for the anaerobic digestion process. Conversion efficiency was assumed to be $\eta = 0.96$ (th) [45]. The indirect energy for the conversion process was assumed insignificant.
c These values reflect the current trend of increasing energy efficiency in nitrogen fertiliser production and increasing energy demand for phosphorus fertiliser production [8].
d Based on the assumption of 7.5 MJ kg^{-1} for the production of the seeds, 0.6 MJ kg^{-1} for coating [60] and 2.0 MJ kg^{-1} for the transport (France-Sweden, 1800 km at 1.1 kJ kg^{-1} km^{-1} [59]).

and transport were assumed to be owned by a contractor, resulting in high numbers of annual machinery operating hours (Table 4).

The indirect energy for the straw-fired CHP plant was accounted for as 4% of the power produced [39]. Indirect energy for the building materials used for the anaerobic digester system was assumed on the basis of a simplified construction including a steel tank digester and steel-reinforced concrete tanks with gastight plastic roofing for storage of the digested residues. Indirect energy for the upgrading plant and for the transport, assembly and dismantling of the biogas plant was assumed to be minor and was not accounted for.

2.3.2. *Hemp biomass yields and energy output*

Assumptions of realistic hemp biomass dry matter (DM) yields, MC and corresponding heating values at harvest dates suitable for biogas and for solid biofuel production have been reported earlier [18] and were used unaltered in this study (Table 5). Harvest time-related biomass energy content was calculated from the biomass DM yields and the corresponding higher heating value (HHV) [18].

Table 5 lists the assumed values of parameters used in calculation of the energy balance. N fertilisation was assumed to follow recommendations for hemp cultivation [14,19]. P and K fertilisation was based on actual nutrient removal rates at the corresponding harvest time as derived from elemental analysis of biomass samples (unpublished results).

In modelling biogas production from hemp, harvest in September–October was assumed to result in a biomass DM yield of 10.2 Mg ha^{-1} [18] and a volatile solids (VS) content of 95% of the DM content [16]. The gross energy output as biogas was then calculated using a specific methane yield of 0.22 m^3 kg^{-1} of VS under standard gas conditions of 273 K and 100 kPa, which was assumed to be a realistic value in commercial production [16,24] (Table 5).

The energy output for the use of hemp biomass as solid biofuel was calculated from the hemp DM yield and the corresponding heating value: 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 lower heating value (LHV) was used. The biomass was assumed to be harvested in spring, corresponding to an MC of 15% and a DM yield of 5.8 Mg ha^{-1} [18]. The low MC is advantageous for combustion, but is also a requirement (MC $\le$ 15%) for briquetting of the biomass [22].

2.4. *Transport distances*

Transport distances of biomass from field to storage and of digestate from biogas plant to field were calculated according to Eq. (1) [69]:

$$d = 2/3 * \tau * r \quad (1)$$

where d (km) is the average transport distance, τ the tortuosity factor and r (km) the radius of the area (for simplicity assumed to be circular with the farm or processing plant in the centre) in which the transport takes place. The tortuosity factor describes the ratio of actual distance travelled to line of sight distance [69]. The parameter τ can range from a regular rectangular road grid ($\tau = 1.27$) to complex or hilly terrain constrained by e.g. lakes and swamps ($\tau = 3.00$) [69]. In this study a median value for τ of 2.14 was assumed.

Transport distances for briquettes to petrol stations and bulk customers were calculated as the radius for coverage of 25% of the study area, using Eq. (1). The coverage area was assumed to provide sufficient customers for the scope of briquette production studied.

2.5. *Distribution of energy products*

The final energy products have to be transported to the final consumers. In the case of heat this is accomplished in a local district heating grid connected to the heat-producing plant. Heat losses were assumed to be 8.2% [70]. Heat from briquette combustion was assumed to occur at the place of heat

Table 4 – Machinery specifications as used in the present study.

Operation	Machine type	Working width (m)	Weight (kg)	Power/power requirement[a] (kW)	Diesel consumption ($L\ ha^{-1}$)	Annual use ($h\ a^{-1}$)	Scenario use[b] ($h\ ha^{-1}$)	Lifetime (a)	Indirect energy[c] (GJ)
Cultivation (all scenarios)									
Stubble treatment	Carrier	3.5	1700	88	8.6	200	0.5	10	67
Ploughing	4 furrow plough	1.4	1280	88	22.9	180	1.8	10	51
Seedbed preparation	Harrow combination	6.0	2500	77	5.7	90	0.4	12	99
Sowing/fertilisation	Seeding combination	3.0	2700	88	9.4	125	1.0	10	98
Rolling	Cambridge roller	6.0	4000	66	3.6	80	0.5	12	158
Spring harvest (as bales), scenario I									
Cutting & swathing	Windrower	4.5	5560	97	10.4	200	1.5	10	240
Baling	Square baler	3.0	9830	112	6.8	225	0.5	10	333
Loading and transport to farm	Wagon train	n.a.	5500	102	3.7	200	0.9	10	197
Storage in plastic wrapping	Bale wrapper	n.a.	4536	14	3.6	250	0.4	10	200
Loading of bales	Tractor with fork	n.a.	7000	100	0.5	850	0.9	12	309
Transport to CHP plant	Truck with trailer	n.a.	15,800	243	20.6	10^{6}[d]	41.0[e]	10	683
Unloading of bales	Tractor with fork	n.a.	7000	100	0.5	850	0.9	12	309
Loading of ash	Front loader	n.a.	13,500	105	0.03	1000	0,01	10	520
Transport of ash	Truck with container	n.a.	17,800	243	0.3	10^{6}[d]	0.5[e]	10	769
Spreading of ash	Tractor with spreader	n.a.	6400	60	0.7	110	0.2	10	278
Spring harvest (as bulk material) (scenario II)									
Cutting and chopping	Forage harvester	4.5	13,240	458	15.2	400	0.5	10	510
Collecting and transport to farm	Forage wagon	n.a.	6500	88	2.5	150	1.1	10	233
Storage	Tractor -driven tube press	n.a.	7000	147	15.9	210	0.2	12	261
Unloading/press feed	Front loader	n.a.	13,500	105	2.5	350	1.1	10	520
Briquette production	Briquette press	n.a.	2800	11	15[f]	1349	36	10	124
Transport to sales place	Truck with trailer	n.a.	15,800	243	5.8	10^{6}[d]	11.5[e]	10	683
Autumn harvest (as bulk material) (scenarios III and IV)									
Cutting and chopping	Forage harvester	4.5	13,240	458	21.1	400	0.7	10	510
Collecting and transport to biogas plant	Truck with dumper trailer	n.a.	15,246	295	29.0	10^{6}[d]	58.1[e]	10	659
Unloading/tube press feed	Front loader	n.a.	13,500	105	4.1	1684	1.1	10	520
Storage	Tractor -driven tube ensiling	n.a.	7000	147	17.7	160	0.6	12	261
Unloading/biogas plant feed	Front loader	n.a.	13,500	105	4.1	1684	1.1	10	520
Transport of digestate to field	Truck with tank trailer	n.a.	12,520	295	15.5	10^{6}[d]	30.9[e]	10	541
Spreading of digestate	Tractor with drag hose trailer	12	4300	200	8.6	358	0.5	10	186
Traction engines (all scenarios)									
For soil treatment operations	Tractor	n.a.	6000	88	n.a.[g]	650	n.a.[h]	12	230
For harvest, transport and storage operations	Tractor	n.a.	9500	200	n.a.[g]	850	n.a.[h]	12	364

n.a. = not applicable.

a Powering soil treatment operations assumed use of a 88 kW tractor. Powering of harvest, transport and storage operations assumed use of a 200 kW tractor.

b For hemp biomass production.

c Total lifetime indirect energy including, material, manufacture and maintenance. Calculated after [66,67] with energy coefficients for steel (17.5 MJ kg^{-1}), cast iron (10.0 MJ kg^{1}) and tyres (85 MJ kg^{-1}). Repair multipliers are taken from [66].

d Unit: km.

e Unit: km ha^{-1}.

f Unit: kWh.

g Included in the respective field operation.

h See respective field operation.

Table 5 – Assumed values for parameters used for calculation of the energy balance of hemp biomass production and utilisation as biogas substrate or solid biofuel, respectively. See section 2.2 for description of scenarios. Roman numerals indicate corresponding scenarios.

Parameter	Unit	Application of biomass as		References
		Solid biofuel	Biogas substrate[a]	
Scenarios		I and II	III and IV	
Cultivation				
N fertilisation[b]	kg ha^{-1}	150	150 (81)	[14, 19]
P fertilisation[c]	kg ha^{-1}	10	35 (32)	Unpublished results
K fertilisation[c]	kg ha^{-1}	8	123 (188)	Unpublished results
Seeds	kg ha^{-1}	20	20	[18]
Biomass				
Harvest period		February to April	September to October	[18]
Harvest losses	%	25	10	[18]
DM yield (after harvest losses)	Mg ha^{-1}	5.8	10.2	[18]
Moisture content	%	15	65	[18]
Specific methane yield[d] on VS	m^3 kg^{-1}	n.a.	0.22	[16,24]
Volatile solids content (of DM)	%	n.a.	93	[16]
HHV[e]	MJ kg^{-1}	19.1	18.4	[18]
LHV[f], dry basis	MJ kg^{-1}	17.4	12.6	[18]
Model				
Average field size	ha	4	4	[68]
Average transport distance				
field → farm storage (bales, bulk)	km	4	n.a.	[64]
farm storage → CHP plant (bales), CHP plant → farm (ash)	km	40 (I)	n.a.	Own calculations, section 2.4
farm storage → petrol station/bulk costumer (briquettes)	km	30 (II)	n.a.	Own calculations, section 2.4
field → biogas plant (bulk), biogas plant → field (digestate)	km	n.a.	15	Own calculations, section 2.4

n.a. = not applicable; DM = dry matter; VS = volatile solids.
a Number in brackets refers to the amount of N, P and K, respectively, derived from the recycling of digestate as biofertiliser. Note that recycling rates for potassium are higher than removal rates by hemp biomass, due to higher potassium removal rates by maize biomass, which accounts for 76% of the recycled digestate. Recycling was only accounted for up to 100% of the removal rates.
b The total nitrogen fertilisation level was assumed to be a fixed amount to ensure crop growth.
c Phosphorus and potassium fertilisation levels adjusted to the amount of nutrient removal.
d Under standard gas conditions of 100 kPa and 273 K.
e HHV = higher heating value.
f LHV = lower heating value.

utilisation, with distribution losses being negligible. Electricity was assumed to be distributed via the electrical grid with losses being 7.6% [70]. Biogas vehicle fuel was assumed to be distributed as 97% methane via a gas filling station directly at the biogas plant, where all biogas vehicle fuel was used for public transportation. As a subscenario to scenario III (section 2.6), biogas was assumed to be further upgraded to natural gas quality (NGQ) and transported to public petrol stations by a natural gas grid. The biogas pipeline to connect the biogas plant to the natural gas grid was assumed to be 25 km long, reflecting the geography of the study area and location of the natural gas grid (not shown).

2.6. *Sensitivity analysis*

A sensitivity analysis was carried out on subscenarios in order to investigate the effect of a number of parameters on the energy input and the NEY of hemp used for energy in all base scenarios.

Diesel consumption for cultivation and transportation, biomass DM yield and transport distances had been identified earlier as sensitive parameters in similar scenarios [71]. Therefore, these parameters were varied in subscenarios to all four base scenarios and their effect on the NEY recorded.

In scenario IV, biogas was assumed to be used to heat the anaerobic digestion process. It may be of economic interest to use all the biogas for upgrading to vehicle fuel, e.g. in order to maximise high value output. Therefore, a subscenario with an alternative external heat source was tested (Fig. 2, centre and bottom). A natural gas boiler ($\eta_{thermal} = 0.96$) was assumed to be used for external heat production [45].

Furthermore, in scenario IV the biogas vehicle fuel, which is similar to compressed natural gas (CNG), was assumed to be distributed at a gas filling station directly at the biogas plant. In a subscenario, the biogas was instead assumed to be distributed to public petrol stations via a natural gas grid (Fig. 2, centre and bottom). In such cases, biogas vehicle fuel is mixed with natural gas, requiring prior adjustment of the Wobbe index of the biogas (97% methane content) to NGQ in north-western Europe. This is usually done by adding liquid petroleum gas (LPG) to 8% content by volume [61]. Note that adjustment of the Wobbe index is only required where the heating value of the natural gas in the grid exceeds the heating value of the injected biomethane, e.g. in Sweden and Denmark [72]. For distribution in the local gas grid, compression of the biogas to only 0.5 MPa is sufficient. However, the biogas has to be compressed to 20 MPa at the gas station for further distribution.

3. Results

3.1. *Energy input in hemp biomass production up to intermediate storage*

The energy input in cultivation, harvest, transport and intermediate storage was found to be 11.7 and 13.0 GJ ha^{-1} for baled and briquetted solid biofuel production from spring-harvested hemp, respectively, and 12.2 GJ ha^{-1} for autumn-harvested, ensiled hemp biomass for biogas production (Fig. 3, top). Although the scenarios showed similar energy inputs, there were large differences in where these inputs were required. Nutrient recycling via digestate (see section 3.4) credited cultivation of autumn-harvested hemp with the use of a reduced amount of mineral fertiliser, resulting in 3.1–3.6 GJ ha^{-1} less energy input than in cultivation of spring-harvested hemp (Fig. 3, top). However, this was counterbalanced by higher requirements for storage and transport in autumn-harvested hemp (Fig. 3, top). Detailed results on direct and indirect energy input in cultivation, transport and intermediate storage are provided in Table 6.

3.2. *Energy balance of hemp biomass up to final energy product*

The four base scenarios differed substantially in their relative amount of energy input in the form of diesel, electricity, fertiliser, machinery and other equipment, production materials and heat requirements (Fig. 3, bottom).

Subsequent 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}) (Fig. 3, bottom). CHP production from biogas was more energy-intense (2.8 GJ ha^{-1}). The most energy-demanding conversion was the production of vehicle fuel (14.1 GJ ha^{-1}), where the upgrading of the biogas to 97% methane content represented 45% of the total energy input. This is reflected in the high amount of electricity required for scrubbing and compression of the biogas (Fig. 3, bottom).

The NEY was highest for CHP production from bales and heat from briquettes (Fig. 4), with high overall conversion efficiencies (86 and 80%, respectively) and high 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. Conversion efficiency was 38% for upgraded biogas (vehicle fuel) and 22% for biogas CHP. Scenarios III and IV had a $R_{O/I} = 2.7$ and 2.6, respectively.

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,

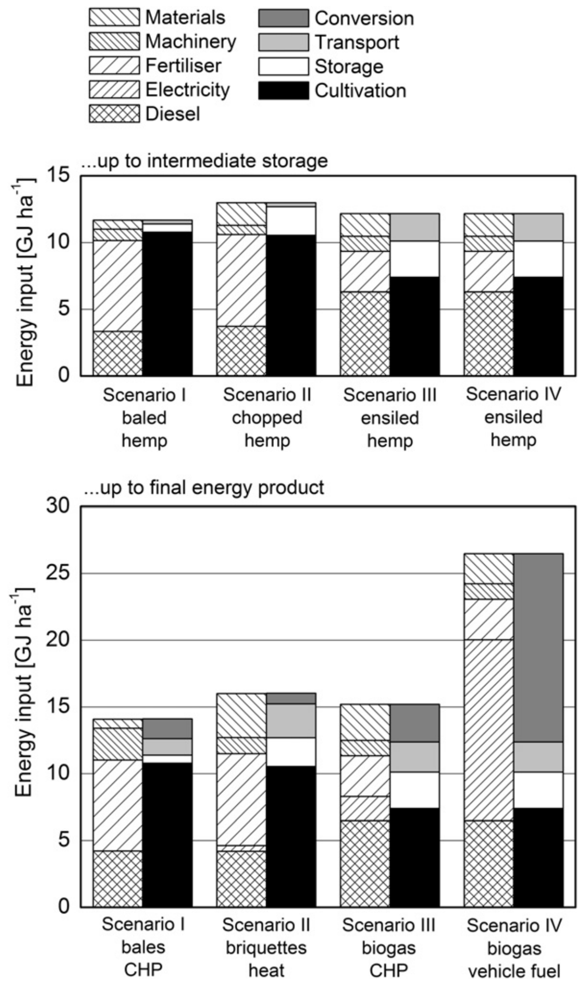

Fig. 3 – Energy inputs according to production means (left part of columns) and process stage (right part of columns) for scenarios I to IV. Energy inputs are given for hemp biomass production up to intermediate storage (top) and up to final energy product (bottom).

respectively (Fig. 5, top). Fig. 5 (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.

Consumption of indirect energy excluding fertiliser-related indirect energy, i.e. energy embodied in machinery and buildings and energy consumed in the production and distribution of the energy carrier used, such as diesel, accounted for 26, 35, 39 and 45% of the total energy input in scenarios I to IV, respectively. Fossil energy sources accounted for 95% of the total energy input for scenarios I to III and 86% for scenario IV.

3.3. *Variations in subscenarios*

Of the parameters tested, a ±30% change in biomass yield had a substantial effect on the absolute value for NEY in GJ ha^{-1}. This effect was largest for scenario III (±43%), followed by scenario IV (±38%) and scenarios I and II (±34 and ±35%, respectively) (Fig. 6). Changes in diesel consumption (±30%)

Table 6 – Direct and indirect energy input of fertilisation, field operations, transport and intermediate storage.

	Energy input – solid biofuel – *scenarios I and II*				Energy input – biogas – *scenarios III and IV*			
	Direct[a]		Indirect	Total	Direct[a]		Indirect	Total
Production means	(kg ha^{-1})		(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(kg ha^{-1})		(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})
Mineral fertiliser N	150		6750	6750	67		3009	3009
P *(scenario I/II)*	9/6		64/104	64/104	3		29	29
K *(scenario I/II)*	7/0		0/30	0/30	0		0	0
Seeds	20		270	270	20		270	270
Field/transport operation	(L ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(L ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})
Stubble treatment	8.6	322	97	419	8.6	322	97	419
Ploughing	22.9	856	278	1134	22.9	856	278	1134
Seedbed preparation	5.7	213	96	309	5.7	213	96	309
Sowing/fertilising combination	9.4	352	177	528	9.4	352	177	528
Ash/digestate spreading incl. transport etc. *(scenario I/II)*	1.0/0	37/0	15/0	52/0	24.0	902	665	1567
Compaction	3.6	135	123	258	3.6	135	123	258
Bale storage line[b]– *(scenario I)*								
Swathing	10.1	377	244	621				
Baling	6.6	247	141	388				
Loading/transport/unloading field-farm	3.5	131	150	281				
Storage in plastic film	3.6	135	471[d]	606				
Bulk storage line[c]–*(scenarios II, left; III and IV, right)*								
Cutting and chopping	15.1	566	168	734	21.0	787	234	1022
Collecting and transport	2.4	90	211	301	28.8	1075	242	1317
Ensiling/storage in tube baler	15.7	588	1564[e]	2152	17.5	654	1636[f]	2290
Total – bale storage line *(scenario I)*	75.0	2803	8875	11,679				
Total – bulk storage line *(scenarios II, left; III and IV, right)*	83.5	3122	9867	12,989	141.5	5295	6856	12,151

a Data on diesel consumption calculated from [64]. Values in L ha^{-1} a^{-1} represent diesel consumption.
b Spring harvest operation: The biomass is cut and swathed using windrower. The biomass is then pressed with a square baler. The bales are loaded onto a trailer using a tractor with a forklift.
c Autumn and spring harvest operation: The biomass is cut and chopped using a conventional forage harvester. The chopped biomass is blown into a tractor–wagon combination.
d Includes 414 MJ ha^{-1} for plastic wrapping for storage.
e Includes 1432 MJ ha^{-1} for plastic tube for storage.
f Includes 1415 MJ ha^{-1} for plastic tube for ensiling/storage.

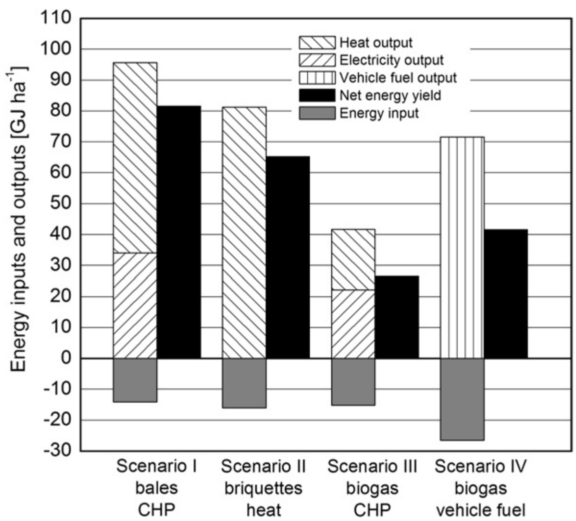

Fig. 4 – Energy output (white), energy inputs (grey) and net energy yields (black) for scenarios I to IV. Output energy shows heat, power and vehicle fuel production from hemp biomass.

and transport distance (−50%; +100%) influenced NEY by less than ±2% for solid biofuel production, by less than ±5% for vehicle fuel production from biogas and by less than ±8% for CHP production from biogas (Fig. 6).

The choice of heat source (internal biogas or external heating) as well as the choice of fuel quality and distribution form (upgrading to NGQ and distribution via natural gas grid) in scenario IV had only a marginal effect on NEY, which varied less by than 3% (Fig. 7).

3.4. *Nutrient recycling*

The large difference in energy input in biomass cultivation between autumn- and spring-harvested hemp is mainly due to replacement of mineral fertiliser by nutrient-rich digestate from the anaerobic digestion of autumn-harvested hemp. Based on the nutrient content of hemp and maize, 55, 92 and 100% of mineral N, P and K, respectively, could be replaced in the cultivation of autumn-harvested hemp (scenarios III and IV). This represents an energy saving of 4.6 GJ ha^{-1}, which corresponds to a reduction of 27% in the energy required for the cultivation and harvest of the biomass. The energy required for transport, storage and spreading of the digestate amounted to 1.6 GJ ha^{-1}.

Utilisation of ash from combustion of hemp (together with straw in scenario I) as a fertiliser had a much more limited impact on the energy balance than digestate. Based on the nutrient content of hemp and straw, 38 and 100% of mineral P and K fertilisers, respectively, could be replaced in the cultivation of spring-harvested hemp. All N is lost in the combustion process. The replacement of mineral fertiliser by utilising the nutrients in the ash corresponded to a saving of 0.07 GJ ha^{-1}. However, the energy required for transport and spreading of the ash amounted to 0.05 GJ ha^{-1}. Fertiliser energy input amounted to approx. 7 GJ ha^{-1} for scenarios I and

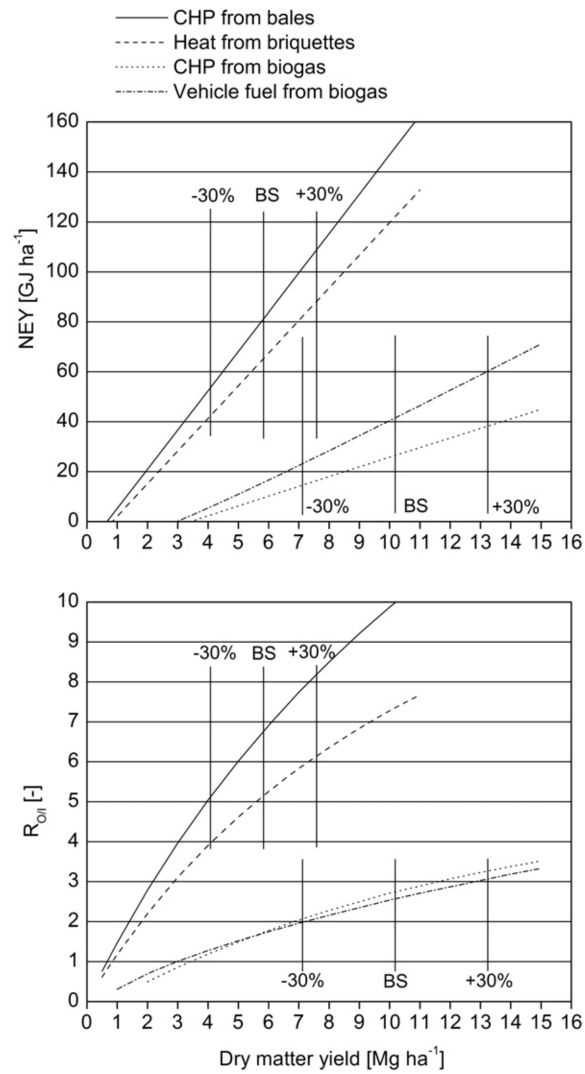

Fig. 5 – Energy output-to-input ratio ($R_{O/I}$) and net energy yield (NEY) as influenced by the biomass DM yield of hemp. Harvest losses of 25% for harvest as solid biofuel and 10% for harvest as biogas substrate [18] were subtracted from the biomass yield.

II and 3 GJ ha^{-1} for scenarios III and IV. This corresponded to 48, 43, 20 and 11% of the total energy input in scenarios I to IV, respectively.

4. Discussion

4.1. *Comparison with other biomass sources*

A comparison of the net energy yield per hectare of hemp with that of other biomass sources based on published data is shown in Fig. 8. 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 and yields 31% above the base scenario (3-year average) for both autumn and spring harvest have been

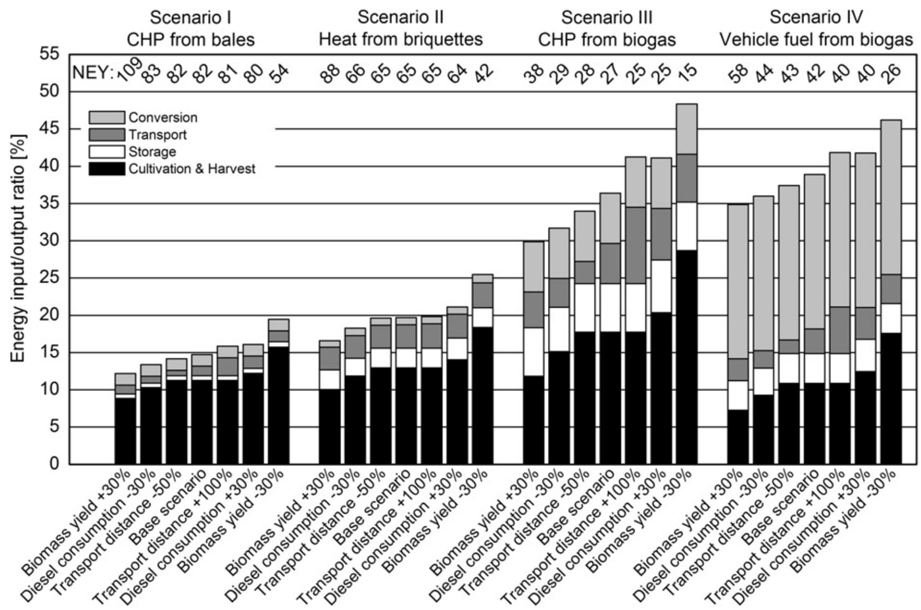

Fig. 6 – Sensitivity analysis for scenarios I to IV. Variation of the energy input/output ratio by changing biomass yield, transportation distance and diesel consumption. NEY = net energy yield, given in GJ ha^{-1}.

reported on good soils [18]. Therefore, in addition to the base scenario, the subscenario with biomass DM yield increased by 30% is shown (Fig. 8).

As harvested biomass in intermediate storage, hemp had similar NEY to other whole-crop silages, e.g. from maize and wheat and similar to sugar beet according to a comparison based on the energy content of the harvested biomass (Fig. 8, top). Sugar beet including tops had 24% higher NEY than hemp in the base scenario and a similar NEY to hemp with hemp biomass DM yields increased by 30%. Furthermore, since sugar beet requires about 70% higher energy input in biomass production, its energy $R_{O/I}$ is about 40% lower than that of hemp in the base scenario [8]. The NEY of ley crops seems

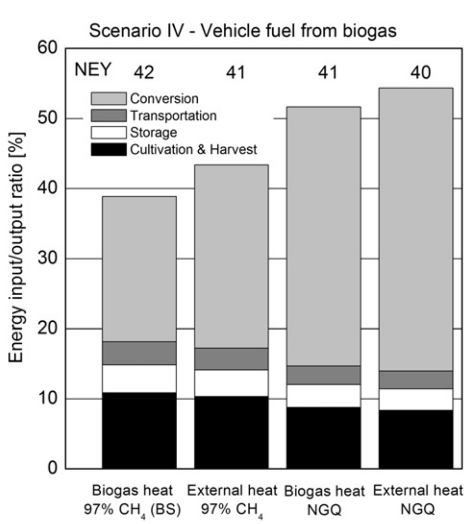

Fig. 7 – Sensitivity analysis for scenario IV. Variation of the energy input/output ratio by changing heat and electricity source and upgrading quality. BS = base scenario. NEY = net energy yield, given in GJ ha^{-1}.

rather low in comparison, but was based on 5-year average yields [8]. These are relatively low compared with those in highly intensive cultivation due to a high proportion of lower-yielding organic cultivation and to partly less intensive cultivation techniques [31].

For solid biofuel production, hemp biomass NEY was substantially lower than that of perennial energy crops such as miscanthus or willow, and even that of whole-crop rye (Fig. 8, top). Hemp has a similar biomass NEY to reed canary grass (Fig. 8, top), which is reflected in similar heat and CHP production of these two crops (Fig. 8, centre). Production of electricity only, i.e. not CHP, from hemp is relatively inefficient with $R_{O/I}$ only 2.6 (Fig. 8, centre). Even if the NEY of willow were recalculated for a comparable electric efficiency [74] and a comparable biomass DM yield (not shown) [75] 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 (Fig. 8, bottom), mostly due to higher specific methane yield [77]. 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 43 and 28% higher NEY, respectively (Fig. 8, 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 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. With a 30% increase in biomass, hemp in

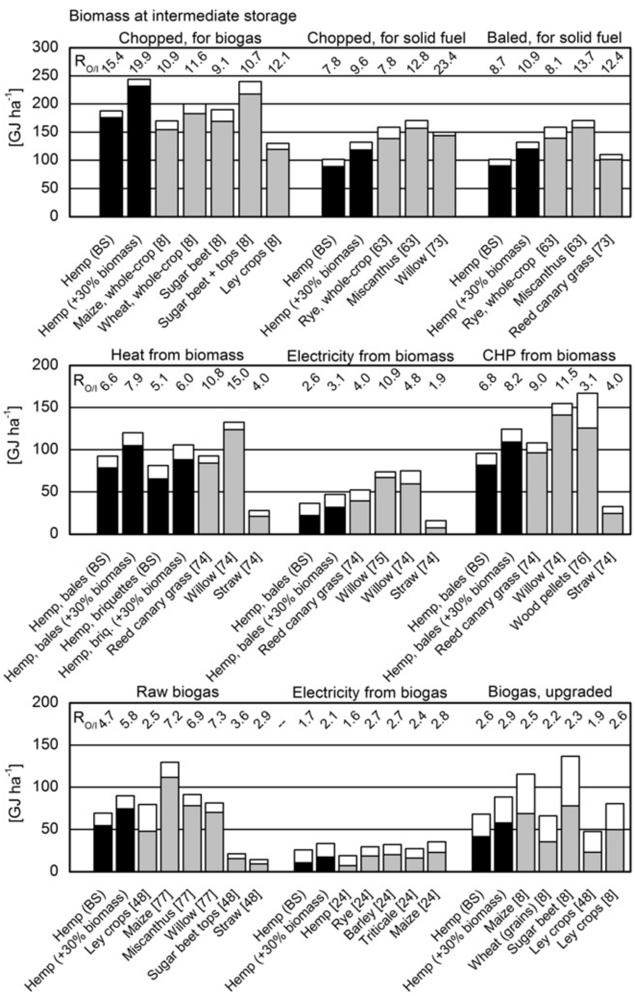

Fig. 8 – Net energy yield for biomass energy content at intermediate storage (top), heat, electricity and CHP from biomass (centre) and raw biogas, electricity from biogas and upgraded biogas (bottom). Black columns denote data for hemp from the present study, both the base scenario (BS) and the subscenario with biomass yields increased by 30%. Grey columns denote individual results from published data [8,24,48,63,73–77]. Numbers in brackets refer to the corresponding reference. 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.

the present study had similar NEY to triticale and 7, 16 and 32% lower NEY than rye, barley and maize, respectively (Fig. 8, bottom). Another study has found a lower NEY for hemp, due to lower energy output [24].

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

Comparison of the data from the present study to that 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, climate and soil conditions) and the conversion efficiency (e.g. due to methane potential, thermal/electrical efficiencies of the technology of choice). For example, it is often unclear whether dry matter yields are based on experimental data or data on 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 investigated scenarios are based.

4.2. *Energy-efficient utilisation of hemp biomass*

Hemp biomass can be utilised in many different ways for energy purposes. However, the four scenarios investigated in the present study exhibited large differences in conversion efficiency, energy output and NEY. When directly comparing the outcome of the scenarios, it should be noted that energy products of different energy quality were compared. Higher quality energy products often require higher energy inputs and have more conversion steps where losses occur, as well as lower conversion efficiencies. For example, biogas vehicle fuel has a high energy density and can be stored with minimal losses. In contrast, heat can be generated with high conversion efficiency, but utilisation is restricted to short-term use in stationary installations (e.g. a district heating grid). However, the direct comparison of energy products derived from the same biomass source can show the best alternative utilisation pathway in a specific situation.

Just as for many other energy crops, utilisation of hemp has not yet been implemented on a large scale. This study shows examples of how relatively small cultivation areas of hemp can be utilised for production of renewable energy products, e.g. briquette production. However, large-scale hemp biomass utilisation can be implemented with the hemp acting as co-substrate for biogas production or co-fired solid biofuel.

The most efficient energy conversion is from hemp biomass to heat and power by combustion, e.g. of bales (scenario I). This is in agreement with a review of findings that puts the highest energy yields at 170–230 GJ ha^{-1} [78]. A 30% increase in the biomass DM yield of hemp would result in hemp being just above the upper limit, i.e. in a very competitive spot, together with most perennial crops.

Since heat has a low energy quality, this option is only viable where heat can be utilised in adequate amounts, e.g. in large-scale biomass CHP plants which are common in Denmark (straw-fired) and Sweden (wood fuel-fired) [27,35,79,80]. The highest energy quality is found in biogas vehicle fuel, which in this study has approx. 30% lower energy output per hectare than CHP from biomass. This option also had the highest energy input of all four scenarios. The option with the lowest conversion efficiency and the lowest energy output and NEY is CHP from biogas. This option only makes sense for wet biomass sources where combustion is not an option, e.g. manure or food wastes, but not for dedicated energy crops such as hemp or maize. Nonetheless, electricity from biogas has become more common in Germany, where feed-in tariffs render this option economically attractive, even though the combustion heat is often only used for electricity production, i.e. the heat energy in the exhaust gases is not used for heating purposes.

Ethanol production from hemp was not investigated in the present study, since this is an option with very high energy inputs [78]. Energy yields from combined ethanol production from hemp and biogas production from the stillage are only marginally higher than that of direct biogas production from the same biomass [81], indicating that an additional conversion process for ethanol production seems to be rather inefficient.

4.3. *Importance of nutrient recycling*

Replacement of mineral fertiliser by digestate corresponded to a saving of 4.4% of the energy content of the biogas produced, including the energy inputs for storage, transport and spreading of the digestate. This confirms earlier findings (2–8%) [48]. Ash recycling resulted in minor replacement of mineral fertiliser. In addition, ash utilisation as a fertiliser required a similar amount of energy, making this option less interesting from an energy balance point of view. However, in light of future phosphorus deposit depletion [82], recycling of ash is an important tool for closing nutrient cycles [83].

It has been shown that less than 100% of recycled nutrients are available to plants directly when spread on the field [78]. The present study did not address this issue, based on the assumption that fractions of nutrients (e.g. of P, K) not available to plants would replenish soil nutrient pools in the long-term. The content of micronutrients and organically-bound macronutrients (N, P, K) was also not accounted for in the present study, but potentially leads to a long-term fertilisation effect. These findings support the concept that nutrient recycling can be important for the overall energy sustainability of biofuels from agricultural energy crops [78].

The present study employed the concept of recycling the same amount of nutrients (minus losses) as were removed with the biomass from the same area of land. This was done irrespective of potential national and regional restrictions as may apply for the utilisation of digestate and ash in agriculture, based on e.g. content of nutrients and heavy metals [84]. Although a detailed discussion of this topic was outside the scope of this paper, its importance for maintaining a healthy basis for agriculture must be recognised.

4.4. *Potential future hemp energy yield improvements*

Use of hemp as an energy crop started only recently with the establishment of new cultivars with low THC content and the corresponding lifting of the ban on hemp cultivation that existed in many European countries until the early 1990s [19]. Therefore, hemp has been developed little as an industrial crop over the past decades [19]. In comparison to well-established (food) crops, hemp has great potential for improvement, e.g. increased biomass yields or conversion efficiencies. Improvements in harvesting technology could reduce harvesting losses, especially in spring harvesting of dry hemp [85].

The low energy conversion efficiency from hemp biomass to biogas may indicate that NEY can be increased by pretreatment of hemp biomass prior to anaerobic digestion, e.g. grinding or steam explosion [81]. Combined steam and enzyme pretreatment of biomass prior to anaerobic digestion could improve the methane potential of hemp by more than 25% [81]. Hydrolysis of maize and rye biomass with subsequent parallel biogas and combustion processes resulted in around 7–13% more energy output, although energy input requirements were 4–5 times higher than when biomass was only digested anaerobically [86]. Energy input for production of hemp biomass for both solid biofuel and biogas purposes is relatively low, situated together with maize at the lower end of the range for annual whole-crop plants [78]. Only perennial energy crops require less average annual energy input over the lifetime of the plantations [78].

4.5. *Environmental impact*

The change in energy source for heating the biogas process in the vehicle fuel option did not have a significant influence on NEY. However, the choice of external heat source may have significant environmental effects. There is probably also a profound economic effect, since heating fuels of lower energy quality (e.g. wood chips, straw or other agricultural residues) could be used for heating the biogas fermenter and about 5% more biogas could be upgraded to vehicle fuel. All scenarios examined here were characterised by high fossil energy input ratios. Fossil diesel accounted for more than 25% of the total energy input in all scenarios. In an environmental analysis, a change of fuel to renewable sources could potentially improve the carbon dioxide balance considerably.

Based on the energy balance for each scenario, the environmental influence of the energy utilisation of hemp can be evaluated, e.g. in a life cycle assessment (LCA). LCAs have been reported for the production of hemp biomass [23], biodiesel [25] and electricity from hemp-derived biogas [24]. However, LCAs for other options such as large-scale combustion for CHP, heat from hemp briquettes or vehicle fuel from hemp-derived biogas are lacking.

4.6. *Competitiveness of hemp*

Hemp can become an interesting crop where other energy crops cannot be cultivated economically (e.g. maize, sugar beet and miscanthus further north in Sweden and other Nordic countries) or where an annual crop is preferred (e.g. to perennial willow, miscanthus or reed canary grass). Due to its advantages in the crop rotation (good weed competition) and marginal pesticide requirements, hemp can also be an interesting crop in organic farming.

Hemp as an energy crop can compete with other energy crops in a number of applications. For solid biofuel production, perennial energy crops, such as willow, miscanthus and reed canary grass, are the main competitors of agricultural origin. Willow and miscanthus have a substantially higher NEY than hemp, but are grown in perennial cultivation systems, binding farmers to the crop over approx. 10–20 years. To achieve a similarly high NEY for hemp, above-average biomass DM yields are required and have been demonstrated on good soils [18].

For biogas production, maize and sugar beet are the main competitors. Maize and sugar beet have often a similar or slightly higher biomass yield than hemp, but a substantially higher methane potential [64,87]. However, energy inputs for utilisation of sugar beet as biogas substrate are high, resulting in similar $R_{O/I}$ to hemp. With increasing latitude of the cultivation site, the growing season becomes shorter and colder, which decreases the DM yield of maize (C_4-plant) faster than that of hemp (C_3-plant) [88]. This is reflected in commercial production in Sweden, where maize and sugar beet are grown up to latitudes of 60° N [1,88]. Hemp can be grown even further north with good biomass yields [89].

5. Conclusions

Hemp has high biomass DM and good net energy yields per hectare. Furthermore, hemp has good energy output-to-input ratios and is therefore an above-average energy crop. The combustion scenarios had the highest net energy yields and energy output-to-input ratios. The biogas scenarios suffer from higher energy inputs and lower conversion efficiencies but give higher quality products, i.e. electricity and vehicle fuel.

Hemp can be the best choice of crop under specific conditions and for certain applications. Advantages over other energy crops are also found outside the energy balance, e.g. low pesticide requirements, good weed competition and in crop rotations (annual cultivation). Future improvements of 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.

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