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Biogas and Ethanol from Wheat Grain or Straw: Is There a Trade-Off between Climate Impact, Avoidance of iLUC and Production Cost?

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Abstract: Current EU policy calls for decreased emissions of greenhouse gases (GHG) by i.e., replacing fossil fuel in the transportation sector with sustainable biofuels. To avoid indirect land use change (iLUC), the EU at the same time strives to limit the use of crops and to increase the use of residues. In this study we compare climate impact and production cost for biogas and ethanol based on wheat grain and straw, respectively, in a Swedish context. The economic competitiveness for ethanol from straw vs. grain is evaluated based on the mandatory emission reduction for fossil vehicle fuels implemented since July 2018 in Sweden. The result of this study clearly shows that biogas and ethanol from straw have the lowest GHG emissions regardless of the calculation method used, although biofuels from grain also fulfill EU GHG reduction criteria even when suggested iLUC factors are included. It was also shown that the cost of producing straw-based biofuels was higher, thus there is a trade-off between climate impact and costs. The GHG reduction mandate adopted in Sweden partly compensates for this, but is not enough to make ethanol from straw competitive from an economic perspective.

Keywords: biofuel; biogas; ethanol; wheat grain; wheat straw; climate impact; iLUC; economy; policy instruments

1. Introduction

According to EU policy, greenhouse gas (GHG) emissions need to be reduced by 40% by 2030 compared to the levels in 1990 [1]. By 2015, the member states had achieved an average emission reduction of 24%. However, emissions from the transportation sector, representing 20% of total GHG emissions, have increased by 16% during the same period [2]. It is thus important to address these emissions if we are to achieve the overall EU GHG emissions target.

The Swedish parliament has approved a new climate policy which includes, among other things, the goal of net zero GHG emissions in Sweden by 2045 [3]. The goal set for emissions from the domestic transport sector (excluding aviation) is a reduction of at least 70% by 2030, compared with 2010. In order to achieve these targets, a combination of several measures such as reducing the need for transportation, improving energy efficiency and electrification, as well as the increased use of biofuels are required [4].

The EU has also set a mandatory target of 10% sustainable biofuels in the transportation sector in each Member State by 2020 [5]. Based on the method of calculation given in the EU renewable energy directive (RED), the average fraction of biofuels used in 2015 was 6.7% [6]. Sweden has the highest proportion of renewable transportation fuels in the EU (24%). However, more than 90% of the biofuel consumed in Sweden is imported [7]. With an increasing demand for biofuels in other countries, it seems unlikely that Sweden would be able to continue to import the increasing amount needed in the future. Thus, an increase in the consumption of biofuels calls for a considerably higher level of domestic production than today.

Current EU policy requires that the production of biofuels be sustainable, which means, for example, that GHG emissions arising from the production of biofuels in new plants must not exceed 40% of the emissions from fossil vehicle fuels or 33.5 g CO_2eq MJ^{-1}. In recent amendments, EU policy also focusses on reducing the use of crops as feedstock for biofuel production, and increasing the use of residues. Member States are only allowed to use 7% biofuels from crops to meet the mandatory target of 10% sustainable biofuels mentioned above. One reason for this is the concern that changes in land use might cause additional GHG emissions [8].

Changes in land use are often divided into direct land use change (dLUC) and indirect land use change (iLUC). The former term is used when land is converted from one state to another to grow biofuel crops (e.g., clearing forest to grow wheat for making ethanol). The latter describes the changes in land use that take place, for example, as a consequence of a bioenergy project, but which is not geographically connected to it. The reasoning behind this is theoretical; if biofuel crops are cultivated on existing agricultural land this might displace other crop production, causing a change in land use elsewhere. The effects of iLUC are closely associated with the demand and supply of agricultural commodities, and the change in market behaviour that can be triggered by biofuel projects [9].

Due to the much debated issue of land use, the EU has amended the RED, adding so called iLUC factors, to impose a GHG emission penalty on the use of certain feedstocks, such as cereals and other starch-rich crops, sugar and oil crops, for biofuel production. The iLUC factor for ethanol produced from cereals is 12 g CO_2eq MJ^{-1} biofuel. However, the quantification of these iLUC factors has been criticized, as the economic equilibrium models used are complex optimization models based on the assumption of perfect markets involving numerous assumptions. Also, the results from different studies vary considerably [9]. According to Popp et al., it is also common that the positive impact of co-products that can be used as feed is underestimated [10]. Several alternatives to these economic models have been developed, often based on a causal descriptive or normative approach. These approaches tend to be simpler than economic models, and require less data, however, they are less detailed and therefore have higher uncertainties [11]. An overview of the causal descriptive models used to estimate iLUC can be found in Ahlgren et al. [12].

Straw is an agricultural residue, not a food crop, so the above arguments do not apply. However, the iLUC concept is closely associated with demand and supply of agricultural products. If straw has a current use, e.g., as bedding material, it could be replaced by other products e.g., sawdust, triggering market ripple effects, which could lead to additional GHG emissions. Using straw that would otherwise be left on the field to decay, and that is not required for soil organic carbon maintenance, will have no iLUC effect [13,14]. However, if straw is utilized in the future for biofuel production, a market demand will develop. There may also be a demand for straw as feedstock for the production of chemicals, bio-plastics, textiles, pharmaceuticals, etc. The question is, for how long time straw can be considered to be "iLUC-free". In this study, we have assumed that straw has no iLUC effect, mainly due to the lack of methods of quantifying these effects.

Since one of the main objectives with biofuels is a reduction in overall GHG emissions, it is important to include direct as well as indirect effects in any analysis. Even if some feedstocks are considered "iLUC-free", biofuels from these feedstocks do not necessarily have the lowest GHG emissions if direct and indirect effects are included.

Since the implementation of biofuels also calls for appropriate policy instruments, a detailed understanding of the various contributions to the cost of biofuel production is necessary. For example, Sweden is implementing a new policy instrument for low-blend renewable vehicle fuels by which suppliers of fossil vehicle fuels are obliged to cut GHG emissions by a certain percentage each year by blending in biofuels. For petrol, the reference value has been set to 93.3 g CO_2eq MJ^{-1}, and the required emission reduction in 2020 will be 4.2%. Since the GHG mandate is defined in terms of an emissions reduction and not the volume of biofuel, this policy instrument favours biofuels with low emissions. If the supplier does not meet this obligation, the penalty will be up to €0.8 kg^{-1} CO_2-eq. [15].

In this study, the GHG emissions and production costs of four different biofuel production systems were analysed. The main kinds of domestic biofuel production in Sweden today are biogas based on waste and residues and ethanol based on cereal grain. Bearing in mind current EU restrictions on the production of biofuels from crops, and that Swedish regulation favours biofuels with low GHG emissions, we compared the use of wheat straw to the use of wheat grain as feedstock for ethanol and biogas production in a Swedish context. The purpose is to identify drawbacks and benefits if residues are prioritized over energy crops for the production of biofuels. To exemplify how reduced GHG emissions could be given an economic value, the results are also applied in the context of the Swedish GHG reduction mandate. Thus, the cost for the mandatory emission reduction is calculated using ethanol from grain versus straw applying the production cost and GHG emissions calculated in this study.

2. Materials and Methods

The study was based on a range of *method applications* and data inventories, which are summarized here, and further described in the following sections or in the appendices:

- Inventory and analysis of statistics and data for biomass quantification and the identification of relevant regions and regional differences.
- Inventory and analysis of georeferenced data on soil properties for subsequent simulation of the effects of straw removal on soil organic carbon (SOC) content.
- Assessment of material and product flows in biofuel production using published data on the use of wheat straw and grain for ethanol and biogas production.
- Assessment of GHG emissions according to the ISO (International Organization for standardization) standard for life cycle assessment and by applying the methodology defined in the EU RED.
- Assessment of feedstock production costs using a stepwise calculation method considering field operations, transport and storage.
- Assessment of biogas and ethanol production cost using investment analysis based on the annuity method.

2.1. Feedstock Production and Transport

Sweden is a long, narrow country, extending over 15 degrees of latitude, which means that conditions for the production of cereals and the collection of straw will vary considerably. From an agricultural perspective, Sweden is divided into eight different production regions. In this study we have assessed the four most productive regions (PR1–PR4), each of which is characterised by similar soil type, topography and climate (see Figure 1 and Table 1). Together these four regions represent 58% of the arable land in Sweden and 96% of the Swedish winter wheat cultivation area [16]. The winter wheat grain yields used in this study were calculated as 5-year averages based on official statistical sources in the form of standard biomass yields, and varied from 4.6 to 6.6 t dry matter (DM)/ha in the four regions studied (Table 1). For comparison, the average yield of common wheat in 2011–2015 in the EU was 5.0 t DM/ha [17].

Winter wheat straw yields were calculated based on the amount of harvested grain using regional straw/kernel ratios [18]. The amount of straw recovered was assumed to be the total amount of straw minus an unrecoverable stubble of 20 cm. The impact of straw removal on the SOC content was simulated for each of the four production regions based on data on current mean average SOC content, the bulk density of soil and its clay content, and the minimum and maximum SOC content in the production region (see Appendix C). The introductory carbon balance model (ICBM) was used to simulate the amount of SOC lost due to mineralization. The model was calibrated for each production region against data from long-term field experiments. Data on annual yields and SOC content were available for two different crop rotations with 13–16 different fertilization regimes for each field experiment. These data were used to calculate the amounts of residue left on the field. The ICB model was calibrated by adjusting the reaction coefficient for the outflow from the old carbon pool in order to maximize the coefficient of determination of the model predicting the change in SOC content.

The resulting first-year outflow of carbon from the old carbon pool was compared to the amount of carbon added to the old carbon pool from both wheat crop residues left in the field and carbon added as digestate. Wheat crop residues included straw, stubble and root biomass. The fraction of carbon added to the soil expected to enter the old carbon pool was calculated from the amount of carbon added and the humification coefficient (h = 0.15 for straw and stubble; 0.35 for root biomass; 0.27 for digestate) [19]. This is a simplification, since h is the fraction of the annual outflow from the young carbon pool that enters the old carbon pool, resulting in indicative values of stabilized carbon. Also, applying h = 0.15 for calculating the potential negative SOC impacts of straw removal should be seen as a worst case scenario, since straw humification has been suggested to have substantially lower coefficients in more recent studies ($h = 0.002 - 0.028$ for the PRs studied) [20]. The SOC balance was then calculated by adding the amount of carbon added to the old carbon pool minus the amount of annually mineralized carbon.

Of the total harvestable amount of straw (taking into account weather conditions preventing harvest), three categories were defined that could be used for biofuel production:

- Straw fraction 1, corresponding to the amount of SOC mineralised.
- Straw fraction 2, currently removed and used for other purposes [21].
- Straw fraction 3, available for bioenergy production without having any impact on SOC and without competing with any other uses.

Straw fractions 1, 2 and 3 combined can be regarded as the "technical potential", and straw fraction 3 as the ecologically or market "restricted potential". The proportions of each fraction in the different regions vary, depending on local conditions and current use of straw, see Figure 2. In this study, the production cost and GHG emissions were calculated for ethanol and biogas produced from wheat grain and two different amounts of straw removed: (1) The restricted potential including only straw from fraction 3, and (2) the technical potential including straw from fractions 1–3, where straw removal will compete with current use and have a negative impact on SOC content.

The distance over which the feedstock would have to be transported was calculated for each region and biofuel production system, assuming removal of these different fractions of straw. Background data and further assumptions regarding the assessed production system are given in Appendix A.

Table 1. Total area, fraction of arable land and standard yields for winter wheat (2012–2016) in the assessed production regions [14–18].

Production Region	Total Land Area	Arable Land	Fraction of Total Arable Land Sweden	Average Grain Yield	Average Area under Winter Wheat Production
	(ha)	(%)	(%)	(kg DM ha^{-1})	(ha)
PR1—Gothenland southern plainsslättbygder	552,021	48.5	10.2	6573	93,293
PR2—Gothenland central plains	967,796	30.1	11.1	5468	33,293
PR3—Gothenland northern plains	1,203,550	32.5	14.9	5273	99,177
PR4—Svealands plains	2,963,151	19.5	22.1	4631	90,017

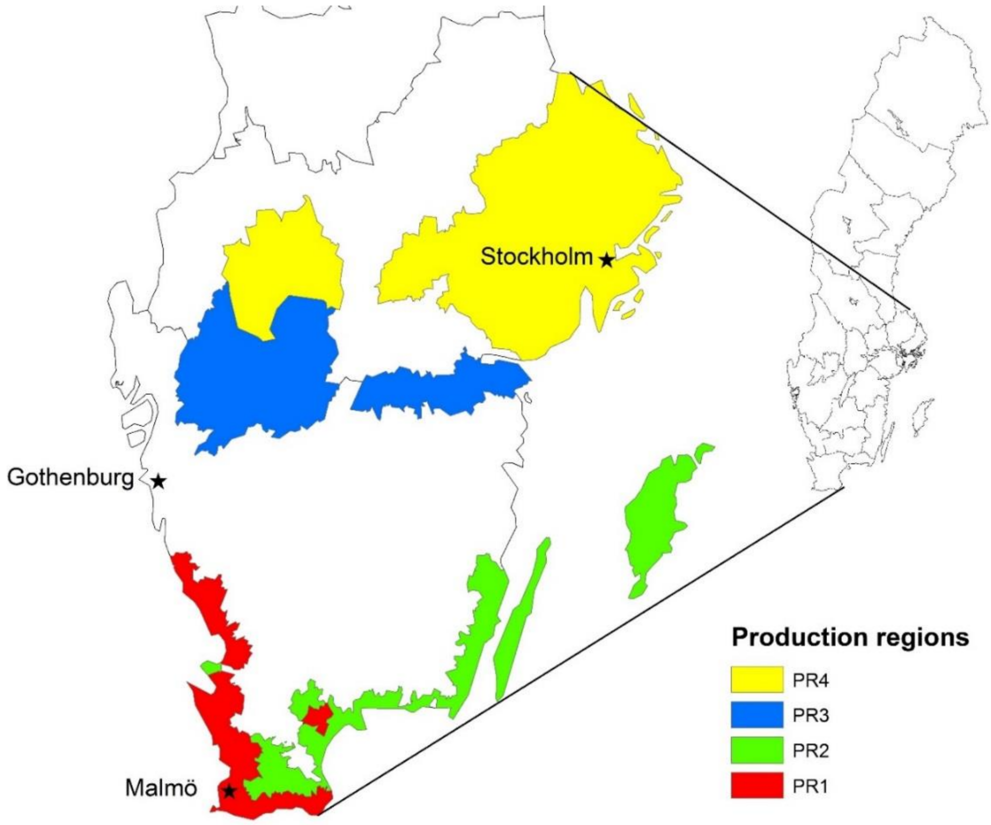

Figure 1. Map showing the four most productive agricultural regions in Sweden.

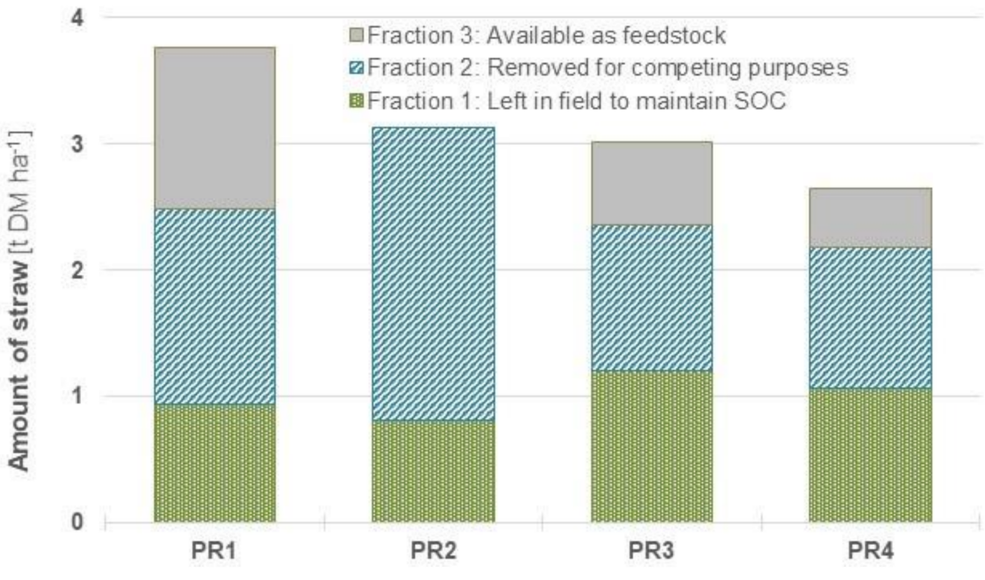

Figure 2. Distribution of straw fractions in the assessment of the different production regions (PR1–PR4).

2.2. Ethanol and Biogas Production and Distribution

Although most of the biofuel used in Sweden is currently imported, there is some domestic commercial-scale production of both ethanol (from grain) and biogas (mainly waste-based) for biofuel applications. Techno-economic data for all production systems were collected from recent studies in which the production of ethanol and biogas from grain or straw had been modelled under Swedish conditions. The scale of production, overall system design and handling of co-products, etc., were chosen so as to be representative of current practice in Sweden.

2.2.1. Ethanol

There is currently one major ethanol production plant in Sweden, with an annual production of approximately 4.9 PJ based on wheat (80%) and barley (20%) grain. Here and in the following sections, energy content is expressed as lower heating value (LHV) for all products. In the present study, mass flow, energy balances and investment costs were based on a model plant producing 4.2 PJ ethanol from 440,000 t DM of grain. In addition to ethanol, it was assumed that the plant also produced distiller's dried grain with solubles (DDGS), which is dried to 88% DM and used as animal feed [22]. To maximise the biofuel production it is also possible to use the DDGS as feedstock for biogas production. Due to economic reasons this is, however, not practised in Sweden today and therefore not included in this paper.

In the production of ethanol from straw, the location of the plant—so as to ensure a sufficient regional supply of feedstock—has been identified as an important factor for economic feasibility [23]. Production based on an annual straw supply of 120,000 to 200,000 t DM has been considered necessary to give economies of scale in previous Swedish studies [23–26]. In the present study, calculations are based on an annual straw supply of 200,000 t DM and process performance was optimized by applying high-DM fermentation and organic acid pre-treatment [26].

Most of the DM in cereal grain is starch (based on hexose sugars), while the proportion of hexoses in straw is only about 1/3 of the DM. For straw, ethanol production from hexoses alone has thus been shown to be insufficient to provide economic profitability [26]. Suggested alternatives are the integration of pentose-based fermentation, or the production of biogas in combination with use of the lignin for pellet or combined heat and power production [23,26]. Upgrading of the biogas to vehicle fuel quality has also been shown to have good potential to improve profitability [26]. The solid residue, which is rich in lignin, could also be interesting for further thermochemical conversion. In this study, calculations are based on the fermentation of hexose sugars to ethanol, pellet production from the lignin-rich solid residue after enzymatic hydrolysis, and anaerobic microbial production of methane from the pentose-containing liquid residue after pre-treatment together with the stillage.

The energy required for the distribution of ethanol to filling stations was calculated assuming the use of trucks with a filling capacity of 35 t and an average fuel consumption of 5 kWh per km including empty return transport [27]. The transportation distance was set to 30 km. It was assumed that the biogas was injected into a low-pressure gas grid and distributed to filling stations connected to the grid, which was the case for 40% of the upgraded biogas produced in Sweden in 2016 [28].

Feedstock demand, product yields, additives and energy demand for grain- and straw-based ethanol production are summarized in Table 2. In the case of straw, external energy was required for upgrading of the biogas produced.

Table 2. Material and energy flows in the production of ethanol from wheat grain and straw.

Material and Energy Flows	Grain	Straw	Reference
Feedstock demand (t DM/y)	440,000	200,000	[24,25]
Energy input—process (MWh/t DM)			
Natural gas [a]	1.05		[24]
Wood chips		0.11 [b]	[27]
Electricity		0.04 [c]	[27]
Energy input—distribution (MWh/t DM)			
Diesel (truck transport)	0.004	0.002	Present work
Electricity (filling station)		0.006	[27]

Table 2. *Cont.*

Material and Energy Flows	Grain	Straw	Reference
Additives/Chemicals (kg/t DM)			
Acetic acid		1.1	[25]
Ammonia (25%)		40	[25]
Antifoam		0.4	[25]
Enzyme, 1 g	1.1		
Enzyme, 2 g		5.6	[25]
H_2SO_4	7.3		[24]
$MgCl_2/MgSO_4$		0.1	[25]
Molasses		26	[25]
NaOH	7.3		[24]
$(NH_4)2HPO_4$		1.1	[25]
NH_4OH	7.3		[24]
Phosphoric acid		3.5	[25]
Yeast	0.002		[24]
Water	2200	55,900	[26]
Main product (MWh/t DM)			
Ethanol	2.67	1.1	
Methane		0.8	[24,25]
Co-products (MWh/t DM)			
Electricity, incl. internal use	0.25	0.09	[24,25]
Electricity, net output	0.18	0.05	[24,25]
Lignin pellets (at product humidity) [d]		1.2	[24,25]
DDGS (at product humidity) [e]	1.55		[24]

[a] Used for economic calculations and to calculate GHG emissions in the sensitivity analysis. In the bases case, GHG emissions are calculated based on the use of 1.12 MWh/t DM of wood chips (assuming 85% efficiency instead of 90% for natural gas). [b] Upgrading of biogas. [c] Upgrading and compression of biogas. [d] Corresponds to 206 kg DM/t DM straw. [e] Correspond to 345 kg DM/t DM grain.

2.2.2. Biogas

There are currently 62 plants in Sweden producing biogas of vehicle fuel quality [28]. In 2016, the feedstock at these biogas plants was mainly sewage sludge, manure and various kinds of municipal and industrial organic waste [29]. Although most biogas plants use a mixture of feedstock, the data used in this study are based on a previously published study in which model calculations were applied to plants using grain or straw only [27].

In addition to biogas, the process generates a liquid digestate that contains all the components of the additives and feedstock not converted into biogas (mainly CH_4 and CO_2). In Sweden, 96% of the digestate produced at large-scale co-digestion plants is utilized as biofertilizer on farmland [28]. It is also possible to pelletize the digestate and used it as fertilizer or fuel [29]. This practise is, however, uncommon in Sweden and is therefore not evaluated in this study. When analysing GHG emissions and production cost, we assumed that the biofertilizer would replace conventional mineral fertilizers, taking into account the additional cost and emissions associated with storing and field application compared to mineral fertilizers. The calculated nutrient and carbon contents in digestate are presented in Table 3.

Table 3. Material and energy flows in the production of biogas from wheat grain and straw [27].

Material and Energy Flows	Grain	Straw
Feedstock demand (t DM/y)	13,100	21,500
Energy input—process (MWh/t DM)		
Wood chips	0.48	0.29
Electricity	0.21	0.26

Table 3. *Cont.*

Material and Energy Flows	Grain	Straw
Energy input—distribution (MWh/t DM)		
Electricity (filling station)	0.03	0.03
Additives/Chemicals (kg/t DM)		
$FeSO_4$	0.03	
N		8.69
P		0.25
Trace elements	0.12	0.07
Process water	3200	4200
Main product		
Methane (LHV) (MWh/t DM)	3.5	2.1
Co-products		
Biofertilizer (kg/t DM)	145	479
whereof		
NH_4-N	14	8.3
P	5.2	0.6
K	5.5	10
C	108	247

In order for biogas to be utilized as a vehicle fuel, CO_2 and various contaminants must be removed by upgrading [30]. The production capacity at existing upgrading plants in Sweden in 2015 varied from 20 to 3450 m^3/h, with an average of 600 m^3/h [31]. However, from an economic point of view, there is a clear efficiency of scale favouring larger installations. Upgrading technologies also differ regarding their energy and water demand, as well as methane emissions and methane concentration in the upgraded gas [27]. The optimal solution at specific sites is thus determined by local conditions. The feedstock demand, and energy input for biogas systems with a production of 1000 m^3/h were calculated based on previous findings and are given in Table 3. As for combined ethanol/biogas production, it was assumed that the biogas was injected into a low-pressure gas grid.

2.3. Economic Assessment

The economic assessment included the production and transport of domestic feedstock to the biofuel production plant, the production and distribution of ethanol and biogas, as well as the production and economic value of co-products such as DDGS, digestate and lignin pellets.

The cost of feedstock production and storage was calculated based on current agricultural practices in Sweden, including, for example, fertilization recommendations. The biofuel production and distribution costs are based mainly on the findings of recent techno-economic studies on biofuel production in Sweden, together with some updated market prices, for example, for process energy. The cost of transportation of feedstock and digestate in biogas production is based on the calculated transportation distance, assumptions on average vehicle speed, and the time required for loading and unloading, as well as hourly rates for different forms of transport carriage. For all economic data, a currency exchange rate of €1 = SEK9.0 was assumed. Further details on the assumptions and background data are given Appendices A and B.

2.3.1. Capital Cost

The capital cost was calculated based on a weighted average cost of capital (WACC) and depreciation time. The WACC was set to reflect the cost to the producer of acquiring the capital, the expected revenue from alternative investments, and the perceived risk associated with the investment. The depreciation time was set to reflect the anticipated technical life time of the investment, but could also be chosen to reflect the perceived risk, such that high-risk projects are assigned a short depreciation time. Following the assumptions made for ethanol production by Joelsson et al. [22,26]

the weighted average cost of capital was set to 11% and the depreciation time was set to 20 years for all investments. In the sensitivity analysis, the WACC was set to 6% and the depreciation time to 15 years, based on the assumptions made in recent calculations of biogas production cost in Sweden [27].

2.3.2. Current Market Price for Vehicle Fuels in Sweden

To evaluate the feasibility of each biofuel system, the calculated production cost was compared with market prices (autumn 2017) for fossil vehicle fuels in Sweden, as presented in Table 4.

Table 4. Market price (2017) of diesel, petrol and compressed natural gas (CNG) excl. VAT (€/GJ) [32–34].

Market Price	Diesel	Petrol	CNG
Fuel price	17.4	17.4	25.5
Energy and CO_2 tax	14.3	21.4	6.8
Total price	31.7	38.8	32.3

2.4. Greenhouse Gas Emissions

GHG emissions were calculated as global warming potential (GWP) in a 100-year perspective using the EU RED calculation method. The results are expressed per MJ fuel produced, and compared with current GHG reduction criteria and GHG emissions due to iLUC effects [5,8]. The system boundaries were chosen to include the production of raw material up to the point of delivery of biofuel to consumer, and emissions from production were allocated to multiple products based on energy content (LHV at product moisture content). Biofuel feedstocks classified as by-products from other production were set to have zero emission until the point of collection.

In addition, a life cycle assessment was performed based on the approach outlined in the ISO standard [35]. The functional unit was 1 MJ (LHV) of biofuel at the filling station, and the system boundaries were the same as in the EU RED calculations. The main difference of relevance to the present study is that in the ISO method a systems expansion is recommended in the case of multiple products. This includes the assessment of what the co-products are likely to replace, and the resulting benefits in terms of GHG reduction. In addition, the zero-emission approach for by-products applied in the EU RED was replaced by a calculation of the impact of removing the straw from the field. Emphasis was placed on the effects on SOC content, since this is an aspect often discussed in relation to the removal of crop residues. To allow comparison between the results, no other aspects were changed, thus GWP characterization factors and emissions based on typical average emissions were maintained in both assessments. The assumptions and data are summarized in Appendix C.

2.5. Sensitivity Analysis

The uncertainty in the data chosen for material flows, yields and emissions was evaluated from different perspectives depending on the feedstock and process. In addition, the sensitivity of the end result to aspects that can be regulated through policies on EU level, such as the choice of emission factors for electricity, was evaluated for all production systems. The data used in the base case and evaluated alternative values are summarized in Table 5. Assumptions, calculations and references are presented in Appendix B (costs) and Appendix C (GWP).

Winter wheat cultivation in four Swedish production regions was evaluated to demonstrate the impact of varying cultivation conditions and transport distances on both production cost and GWP. Other cultivation-related effects evaluated from a GWP perspective were the emissions associated with mineral nitrogen fertilizer production, and the impact of replacing diesel (with a low blend of biodiesel) with biodiesel. Both indoor and outdoor straw storage were evaluated in the cost calculations.

The production of ethanol from grain is a well-established commercial process, and data on yields, both for ethanol and DDGS, and inputs in the process are considered reliable. In the present study, the source of process energy was evaluated, since the typical Swedish conditions assumed in the base case might not be typical in other countries. The type of protein animal feed replaced by DDGS, and the impact of the market value were also evaluated.

When considering straw for ethanol production, the uncertainty in the experimental co-product yield of biogas was taken into consideration by using a low yield in the base case. The impact of a higher yield was also evaluated, which leads to additional processing emissions, and the net impact on GWP and costs is reported in the results. Other aspects evaluated were the enzyme dosage and the GHG emissions resulting from enzyme manufacturing.

Biogas production, upgrading and gas grid injection for vehicle fuel applications are well-established full-scale processes, and the inputs and emissions are considered reliable. However, the yield used here was based on a theoretical calculation and both higher and lower yields were evaluated.

Table 5. Values evaluated in the base case (bold) and alternative values (Further information on the selected emission values and references can be found in Appendixs B and C).

Input—Production	Units	Value	Description
Energy supply—electricity	g CO_2eq MJ^{-1}	**34.9** 124 13.1	**Nordic mix** EU28 mix Swedish mix
Energy supply—heat	g CO_2eq MJ^{-1}	**4.0** 77	**Wood chips** EU mix natural gas
Fuel for crop production and transport	g CO_2eq MJ^{-1}	**80.4** 23.2	**Diesel with low-blend biodiesel** Biodiesel
Mineral N manufacture	kg CO_2eq kg N^{-1}	**4.45** 7.8	**Average use Sweden** Western European average
Enzyme dose	g enzyme (100 g cellulose)$^{-1}$	**1.7** 6.0 6.8	**Used in techno-economic study** Max. trial dose recommended Next-generation enzymes
Enzyme manufacture emissions	kg CO_2eq $kg_{enzyme}{}^{-1}$	**5.5** 8.0 0.9	 Next-generation enzymes
Methane yield—straw	m^3 (t DM)$^{-1}$	**224** 202 247	
Straw storage cost	€ (t DM)$^{-1}$	**0.02** 0	**Indoor** Outdoor
Capital cost **- Depreciation** - Depreciation **- WACC** - WACC	 years % 	 **20** 15 **11** 6	
Investment subsidy	%	**0** 30	
Co-products			
DDGS—sales price	€ (t DM)$^{-1}$	**0.24** 0.34 0.14	
Methane yield (straw ethanol process)	MJ (t DM_{straw})$^{-1}$	**2900** 6666	**Experimentally derived** Theoretically calculated

In this study, the investment cost is reflected in the cost of capital, including the depreciation time and the WACC. For ethanol from grain and biogas upgrading and distribution, the investments assumed are considered reliable even if the actual cost is time- and site-dependent. For ethanol from straw, the assumptions are probably more uncertain. In the sensitivity analysis, this was evaluated by changing the depreciation time and the WACC, while keeping the investment cost constant. Finally, the impact of an investment subsidy was also evaluated.

3. Results and Discussion

GHG emissions and production costs were calculated for ethanol and biogas from both wheat grain and wheat straw. The purpose was not only to present updated and comparable values for these biofuel production systems, but also to identify drawbacks and benefits if residues are prioritized over energy crops for the production of biofuels. Based on our base case assumptions, Figures 3 and 4 show production cost and GHG emissions, calculated according to the EU RED and the ISO methodology, for the production of ethanol and biogas from grain and straw originating from PR1. For straw, the results given here include the removal of fraction 3 only (see Section 2.1). To exemplify how reduced GHG emissions could be given an economic value, the results are also applied in the context of the Swedish GHG reduction mandate.

3.1. Production Cost

The production cost for biofuels is calculated to €324–€334/GJ depending on feedstock and fuel, see Figures 3 and 4.

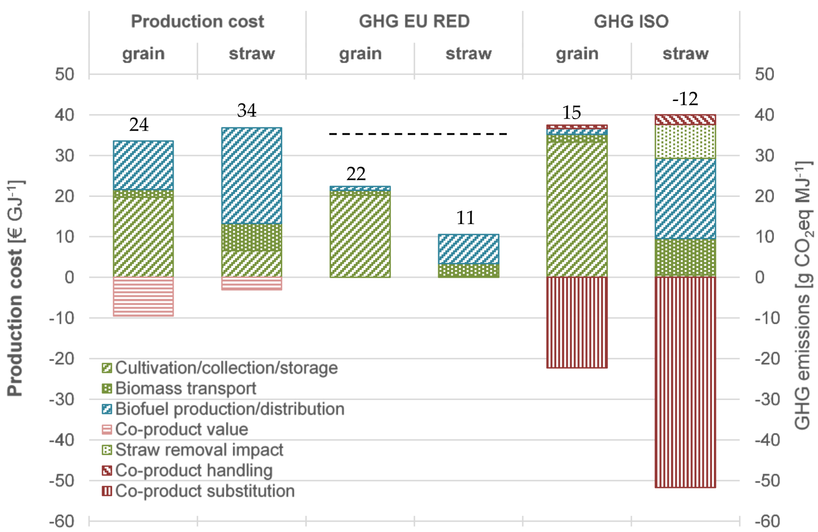

Figure 3. Production cost and emissions for ethanol produced in PR1 calculated according to the methods in the EU RED and the ISO standard. The dotted line indicates maximum GHG emissions for new installations according to the EU RED. Numbers above the columns indicate net value.

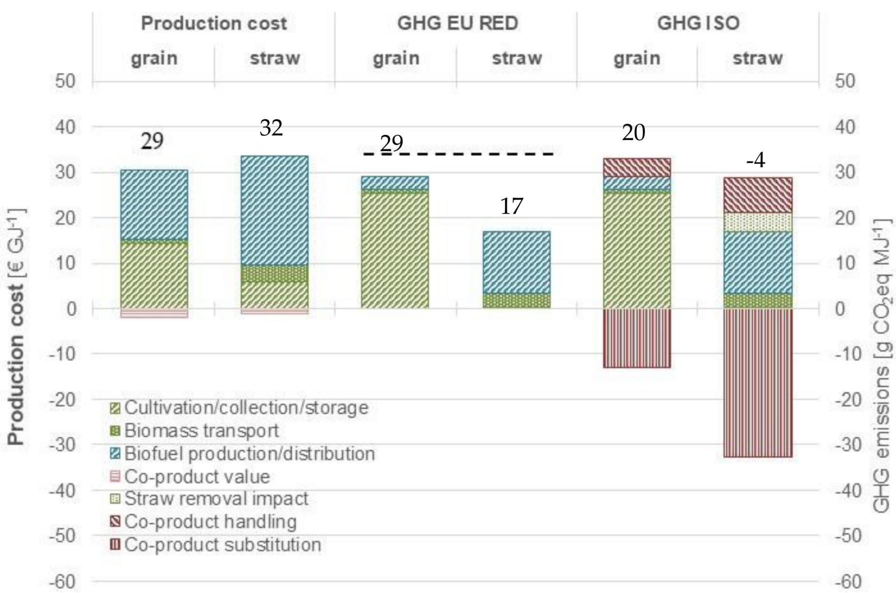

Figure 4. Production cost and emissions for biogas produced in PR1 calculated according to the methods in the EU RED and the ISO standard. The dotted line indicates maximum GHG emissions for new installations according to the EU RED. Numbers above the columns indicate net value.

The cost is higher when using straw as feedstock than when using grain. However, the production cost for biofuels based on straw is still lower than the market price of petrol (€39/GJ,) and comparable to the prices of diesel and CNG (€32/GJ) including taxes. It is notable that the cost of grain has a substantial impact on the overall biofuel production cost, while the costs for the collection and storage of straw are not so important and that straw is a cheaper feedstock, even when the transportation cost is included.

The overall production cost is also affected by the economic value of the co-products. This is especially the case when producing ethanol from grain, where the value of the DDGS corresponds to approximately 50% of the biomass cost. Thus, the feasibility of such biofuel production is highly dependent on the market price not only of wheat and biofuel, but also feed such as soybean. It should be noted that the price of straw is not directly affected by the market prices of agricultural commodities. However, the amount of available straw is indirectly affected by the wheat and livestock market, which influence the total amount available and alternative uses of straw.

3.2. Greenhouse Gas Emissions

For the production of biofuels from grain, GHG emissions are dominated by biomass production as such. If straw is used, emissions from biomass transport, as well as the biofuel production process, increase, although the total emission is still lower compared to biofuels from grain. The current requirement for biofuels to be considered sustainable in the EU is a 60% reduction of GHG emissions compared to fossil fuels [8]. Both grain- and straw-based biofuels fulfil this requirement, but the reduction is greater for straw-based ethanol and biogas, with savings of 89 and 82%, respectively. In addition, ethanol production from grain has been assigned an iLUC-based GHG emission factor, which is set to 12 g CO_2eq MJ^{-1} [8]. When this is included, the GHG reduction for grain-based ethanol will decrease to 63%, approaching the limit of what is currently considered sustainable from a GWP perspective.

However, it should be noted that combining GHG emission calculations based on the EU RED methodology with GHG emissions calculated based on an iLUC effect actually constitutes a methodological error. The EU RED is an attributional GHG accounting system for existing specific production chains, while the iLUC is based on economic equilibrium models that estimate the large-scale patterns in global land-use change as an effect of implementing a biofuel policy. Since iLUC factors are implemented in EU biofuel policies, it is however a useful exercise to determine how biofuel producers could be affected.

If GHG emissions are calculated according to the ISO methodology, the net emissions will be lower for all biofuel systems (see Figures 3 and 4). This is mainly due to the emission savings when co-products are included, instead of applying energy-value-based allocation, as in the EU RED. This confirms the climatic advantages of straw-based biofuels, which have the lowest net emissions, irrespective of the method applied.

3.3. Impact of Regional Differences and Ratio of Straw Removal

Results in Figures 3 and 4 were shown for PR1, the region with the most favourable conditions, and with a degree of straw removal that does not affect current utilization or the SOC content. The impact on production costs and emissions of locating a biofuel production plant in regions with lower share of arable land and lower cereal yields (Table 1, PR2–4) was evaluated, together with a higher rate of straw removal (fractions 1–3, see Figure 2).

If a biofuel production plant is located in such a region, the feedstock cost will increase, see Figure 5. When using grain, the overall production cost increases by about 20% for ethanol and 10% for biogas when comparing PR4 with PR1. The majority of the cost increase, 80–90% for ethanol and 90–100% for biogas production, is due to increased crop cultivation cost at lower yields. For straw, the cost increase is solely due to the longer transport distances. The larger ethanol production plant is thus influenced more, with a cost increase of more than 20% in PR4 compared to PR1 when only the currently unutilized straw is used (fraction 3), and 10% when all straw is removed (fractions 1–3).

Using straw for ethanol production in PR4 is also the only production system where the biofuel production cost is higher than the market price of petrol (€39/GJ). For biogas production, the impact of changing PR and collecting a higher share of straw is low due to the smaller amounts needed at each plant. If all the straw were to be collected (fractions 1–3), the production cost would be lower than current market prices of petrol in all the production regions investigated.

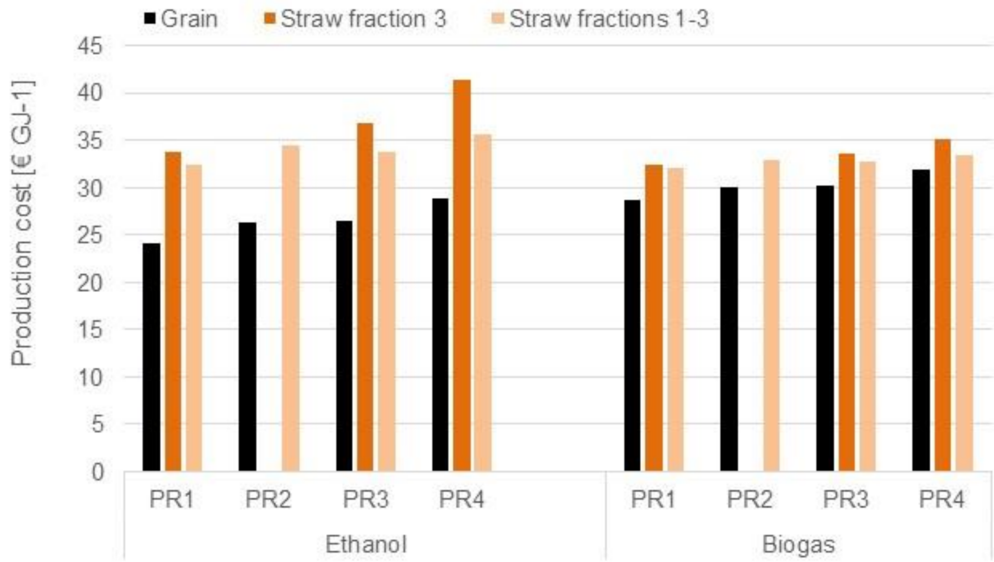

Figure 5. Cost impact of regional differences and ratio of straw removal. PR2 has no available straw in fraction 3.

The same comparison was made for impact on GHG emissions (see Figure 6). Regardless of PR and method of calculation, GHG emissions were lower for biofuels produced from straw than from grain. All systems also exhibited a GHG saving larger than 60%. If an impact of iLUC for grain based ethanol was included, as given in the iLUC directive (12 g CO_2eq MJ^{-1}), a 60% saving in GHG emissions would not be obtained in PR4. For the EU RED calculations, the GHG emissions followed the same pattern as the costs, where lower yields gave the main impact for grain based fuels, and longer transport distances increased the emissions for straw-based fuels.

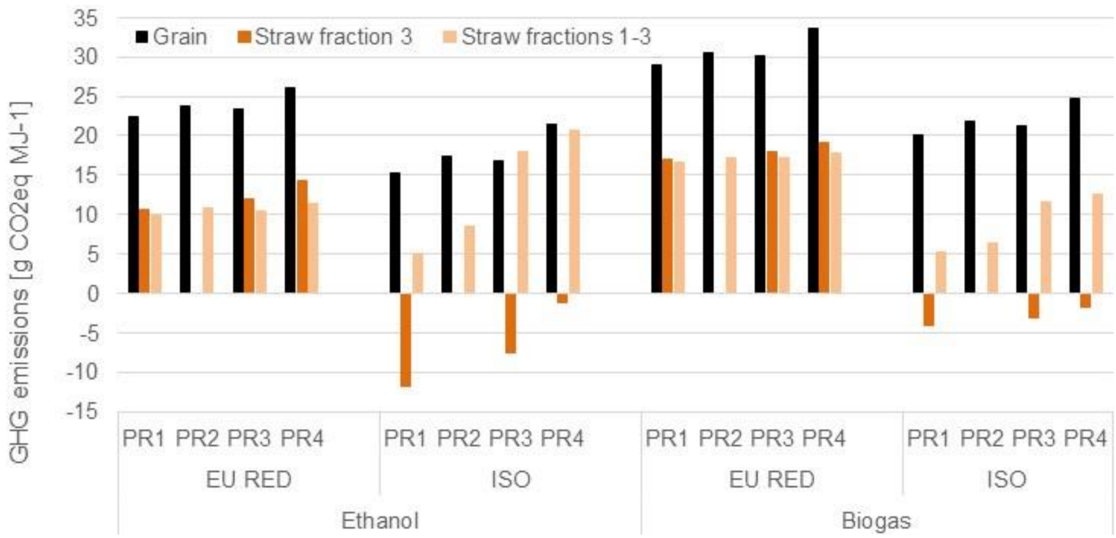

Figure 6. GHG emission impact of regional differences and ratio of straw removal. The outcome using two calculation methods (EU RED and ISO) is compared. PR2 has no available straw in fraction 3.

The ISO calculations showed a more complex picture. As shown in more detail for PR1 in Figures 3 and 4, the different methods applied for handling co-products gave less GHG emissions for grain and straw fraction 3 in all PR. In addition, the ISO calculations included the potential negative impact on SOC when all straw was collected (fractions 1–3). This SOC impact was the main reason to the higher emissions when comparing the use of straw fractions 1–3 to removal of only straw fraction 3, the benefit of the shorter transport distance only having a minor impact. This illustrates how relevant emissions or avoided emission can be missed when the method is as simplified as in the EU RED.

3.4. Sensitivity Analysis

The aspects evaluated in the sensitivity analysis are shown in Figure 7 (production cost) and Figure 8 (GHG emissions according to the EU RED methodology).

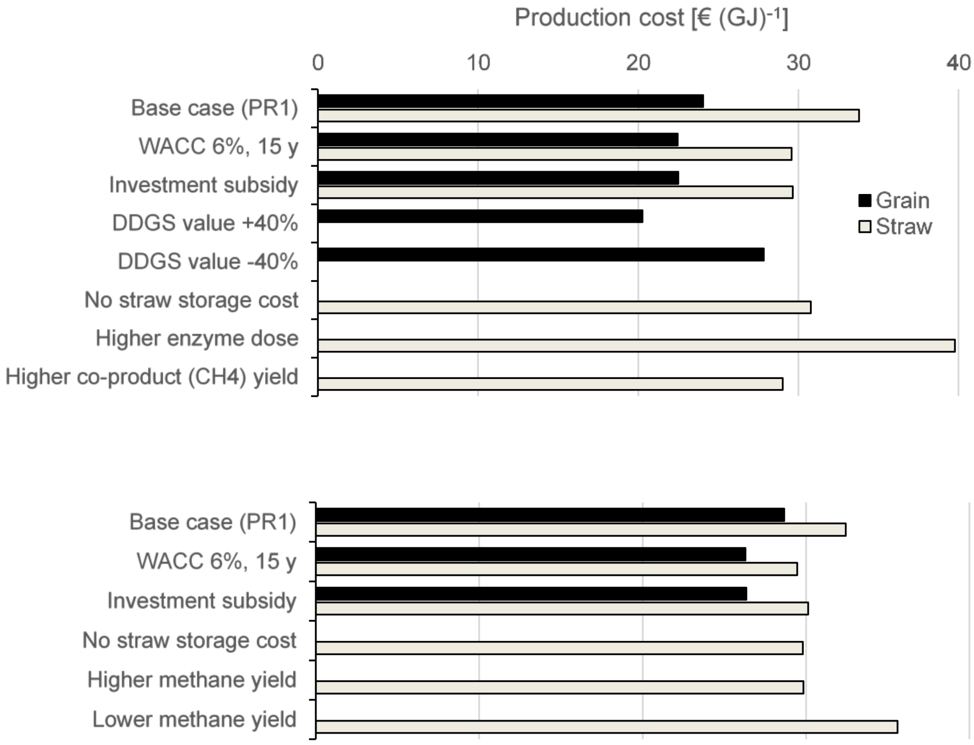

Figure 7. Results of the sensitivity analysis on the production costs for various ethanol (**above**) and biogas (**below**) production systems.

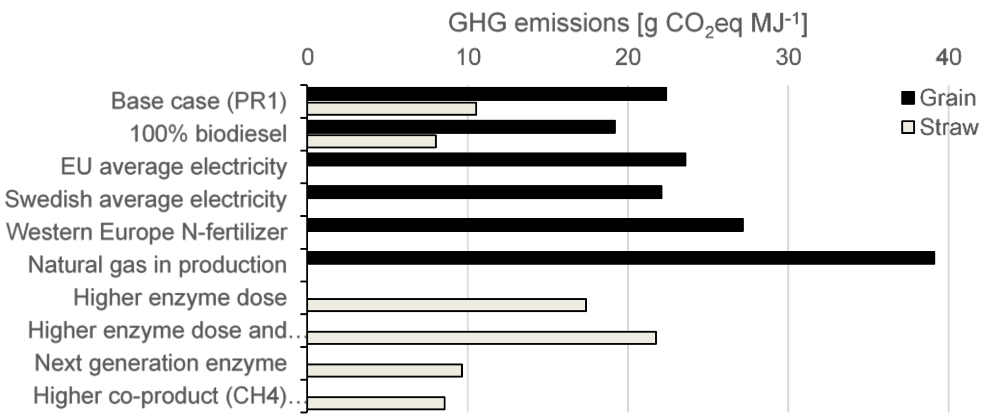

Figure 8. *Cont.*

Figure 8. Results of the sensitivity analysis on GWP for various ethanol (**above**) and biogas (**below**) production systems.

As mentioned above, the calculated production cost is lower than the current market price of petrol in all biofuel production systems analysed. The production cost of biofuels from grain is dominated by the cost of the grain. Reducing the interest or the depreciation time, or implementing an investment subsidy would thus have a minor impact on the overall production cost. Although the economic value of the DDGS has a high impact on the ethanol production cost, grain-based ethanol still has the lowest cost even if the market price of DDGS is reduced with 40%.

When straw is used for biofuel production, reducing the capital cost has a greater impact. An investment subsidy of 30%, for example, would lead to a production cost for both biogas and ethanol that is lower than the current market price of all fossil vehicle fuels in Sweden. Finding a cheaper storage solution for straw will also have a positive effect although not dramatic. The ethanol production cost is reduced with approximately 10% if the straw storage cost is set to zero. Finally, it is clear that parameters such as methane yield and enzyme dosage have at least as high an impact as changing the capital cost or the storage cost. Thus, it is crucial to gain a better understanding of these parameters in a full-scale process. However, the production cost only exceeds the current market price of petrol in the case with the highest enzyme dose.

Regarding GHG emissions, the only single factor among those evaluated that increases emissions above the 60% reduction limit is the use of a fossil energy supply, natural gas, in grain-based ethanol production. The emissions for EU average electricity and the typical emission for Western European nitrogen fertilizer also give notable increases in total emissions. Thus, an energy supply based on a high share of renewables and low-emission nitrogen fertilizer production are, not unexpected, aspects that are relevant to low-emission biofuel production. If all diesel used for agricultural operations and transport is replaced with biodiesel (here 50% FAME and 50% HVO, see Appendix C), this would also give a significant reduction of GHG emissions. For straw-based biofuels, methane yield, enzyme dose and GHG emissions from enzyme production have impact on overall emissions. However, the parameters evaluated here do not risk the possibility of achieving a GHG saving of 60% or higher.

3.5. Ethanol from Grain vs. Straw with a GHG Reduction Mandate

As presented in the introduction, Sweden has implemented a system with a GHG reduction mandate for low-blend of biofuels in petrol and diesel. With this system, the amount of biofuel required depend on its GHG reduction. A biofuel with low emissions will thus have a higher value than a biofuel with higher emissions. The calculated consumer price for petrol, including the mandatory low-blend of ethanol in 2020 (4.2%) is presented in Figure 9. The amount of ethanol required is based on the GHG emission calculated according to the EU RED and the cost is based on the result presented in Figure 3. Even with the advantage given by the reduction mandate system, ethanol from straw is still the more expensive option. However, the overall cost of the fuel blend will only increase by approximately 1% if the fuel supplier chooses ethanol made from straw instead of grain. As can be seen in Figure 9, using ethanol produced from straw is also cheaper than paying the penalty for not fulfilling the reduction mandate.

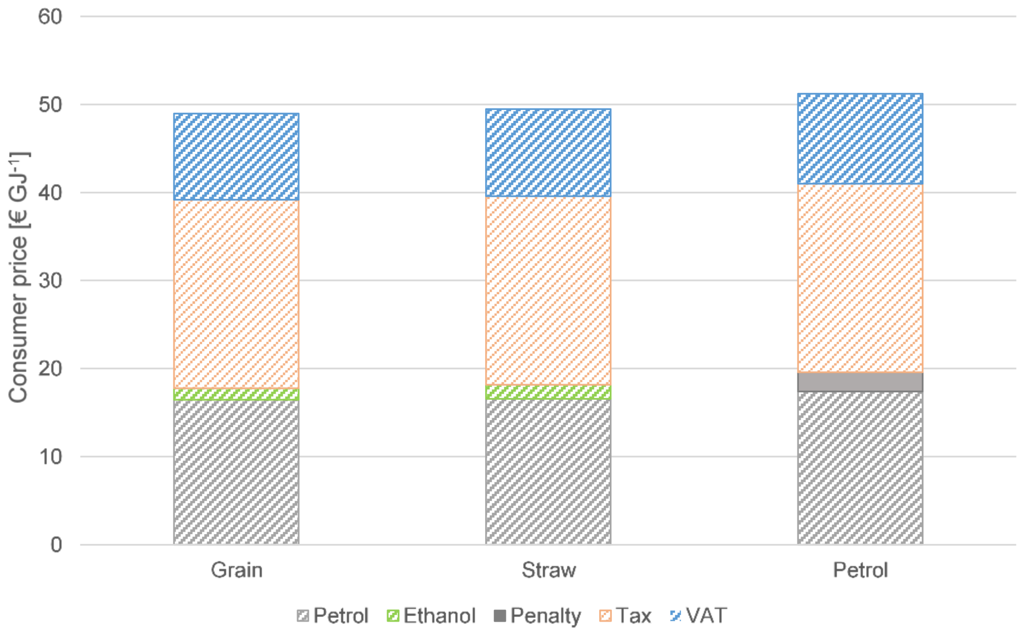

Figure 9. Consumer price for petrol including low-blend of ethanol from grain or straw based on the Swedish low blend reduction mandate for 2020.

4. Conclusions

Wheat grain and straw are two examples of agricultural feedstocks that could be used to produce biofuels such as biogas and ethanol. The results of this study clearly shows that straw-based production gives biofuels with lower GHG emissions, regardless of the calculation method applied. From an economic perspective, the production cost for biofuels from both grain and straw are lower or similar to the market price of fossil fuels. The production of biofuels from grain is far less costly, despite the fact that the cost of the feedstock is higher than that of straw. Thus, there is a trade-off between cost and climate impact in these studied comparisons of biofuels from the grain and the straw from wheat.

In this study, climate impact has been calculated according to the method given in the EU RED, which is applied in the currently implemented European biofuel policies, as well as according to the ISO standard for LCA. Biofuels from straw were found to have the lowest climate impact regardless of calculation method. The method in the EU RED is, however, simplified and does not include the whole biofuel production system. Thus, there is a risk that relevant emissions or avoided emission is excluded and that implemented policy instruments does not favour the biofuels with the lowest GHG emissions. To avoid this, the method applied in the EU RED should be modified so that co-products and changes in SOC is fully included for all biofuels and feedstock.

In a Swedish context, the production of biogas and ethanol from both grain and straw fulfils current demands on GHG emission reductions in the EU RED. In fact, the production of biofuels from grain could still meet the reduction requirements even including the iLUC-factors suggested in the amended EU RED. This would, however, demand a production system characterized by a high share of renewable energy carriers (both in transport and production), and the use of mineral fertilizers produced with low GHG emissions.

The reduction mandate recently adopted in Sweden is used as an example of policy implications of the observed trade-off between climate impact and cost. Such a system increases the competitiveness of ethanol from straw over grain, but does not compensate completely for the higher production cost. Fuel suppliers are thus likely to use as much biofuels from crops as is permitted by current policy instruments. However, producing ethanol from straw instead of grain would have only a minor impact on the fuel price to the consumer. Thus, if there is a shortage of ethanol from grain, or policy instruments limit the use of this feedstock, producing ethanol from straw is a highly viable option.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Feedstock Production, Transport and Storage

All relevant field operations (stubble treatment, ploughing, harrowing, sowing, etc.) were included in the production of wheat grain and straw. Field operations were modelled for grain and straw production in each production region, in order to calculate the energy inputs, such as the consumption of diesel, electricity and heat, and other inputs, such as fertilizer, seed and pesticides. Production means such as machinery, buildings and infrastructure were included in the economic evaluation, but were not included in the environmental assessment.

Appendix A.1. Cultivation Input

A seeding rate of 180 kg/ha was assumed for winter wheat production [36]. It was assumed that harvested grain was stored in conventional cereal silos. The energy required for grain storage was calculated assuming an input in the storage facility of 7 MJ/m^3/y and a grain density of 770 kg/m^3. Pesticide and limestone inputs during cultivation were calculated based on recommendations for southern Sweden [36]: 3.0 kg of active ingredient (196–288 MJ/kg active ingredient [37]), and 200 kg liming agent (0.03 MJ/kg [38]) added as 800 kg/ha every fourth year.

The amounts of plant nutrients applied for winter wheat cultivation in the different production regions (PR) were calculated based on recommendations by the Swedish Board of Agriculture for nitrogen [39] and typical biomass nutrient contents of phosphorus and potassium [40] (Table A1). Recommendations for nitrogen application for winter wheat grown for feed purposes were translated into a basic and a yield-corresponding amount using simple linear regression. It was assumed that only mineral fertilizer was used. It was also assumed that the plant nutrients removed with the straw would be replaced in the form of mineral fertilizer. Typical straw nutrient contents were used to calculate these amounts [27] (Table A2).

Table A1. Parameters used for the calculation of plant nutrients required for winter wheat fertilization.

Production Region	Base Amount	Biomass Nutrient Content		
	N [a]	N [a]	P [b]	K [b]
	[kg ha^{-1}]	[% of DM]	[% of DM]	[% of DM]
PR1–3	30	1.81	0.36	0.50
PR4	40	1.88	0.36	0.50

[a] Calculated from recommendations in [39]. [b] Calculated from [38] assuming a moisture content of 14%.

Table A2. Nutrient content of winter wheat straw [27] used to calculate plant nutrients removed.

Production Region	Biomass Nutrient Content		
	N	P	K
	[% of DM]	[% of DM]	[% of DM]
PR1–4	0.57	0.03	1.06

Appendix A.2. Energy Inputs

Suitable machinery was selected for each field operation, and the corresponding diesel consumption was calculated from typical specific diesel consumption data, field capacity and annual use [41]. Specific energy inputs are given in Table A3. A further 4% was added to the calculated diesel consumption to account for oil lubrication, and assigned the same emissions as the diesel. Before storage, it was assumed that the grain was dried to a moisture content of 14%. It was also assumed that the straw was stored indoors at the production plant.

Table A3. Specific energy inputs of selected production means required for the cultivation and harvesting of wheat grain and straw.

Material	Units	Energy Input	Reference
Diesel	[MJ/L]	38.9	-
Electricity	[MJ/kWh]	3.6	-
Fertilizer N	[MJ/kg]	48.0	[42]
Fertilizer P	[MJ/kg]	18.7	[42]
Fertilizer K	[MJ/kg]	5.8	[42]
Machinery	[MJ/t]	33.8–44.2	[43]

Regarding transport of wheat grain and straw, it was assumed that the wheat grain was transported to the biofuel production plant by tractor and field trailer for distances less than 12 km. For greater distances, reloading to, and transport by, truck was assumed. It was further assumed that wheat straw was baled and transported to the biofuel production plant by truck-mounted self-loading trailers. The average transport distance for grain and straw was calculated based on the feedstock demand of the biofuel production facility and the corresponding crop intensity in each production region using the equation presented by Overend [44]. A circular area with the facility at the centre, and a tortuosity factor of 1.3 [45] were assumed. Calculated transportation distances are given in Table A4.

Table A4. Average transport distance [km] for feedstock transportation in the various production regions (PR).

Production Region	Grain		Straw			
			Technical Potential		Sustainable Potential	
	Biogas	Ethanol	Biogas	Ethanol	Biogas	Ethanol
PR1	6.1	35.6	13.5	41.3	17.8	54.4
PR2	11.2	64.9	38.7	118.0	n/a	n/a
PR3	8.6	50.2	18.6	56.8	31.2	95.4
PR4	13.5	78.2	30.0	91.5	54.3	165.7

Total energy input (diesel, heat electricity) for grain and straw production in each PR, for both biogas and ethanol production are given in Tables A5–A7. For straw, data are presented for fraction 3 and fractions 1–3 (as described in Section 2.1). It was assumed that fractions 1–3 was recovered even when calculating the energy input (and costs) of sustainable straw removal, to simulate common practice, i.e., the harvest of full technical potential, but not every year. The effects of reducing the amount of sustainable straw removal were instead simulated by increasing the transport distance.

Table A5. Primary energy input in winter wheat grain production in the different production regions (PR) for the production of biogas and ethanol.

Parameter	Primary Energy Input (Biogas Production) [MJ ha^{-1}]				Primary Energy Input (Ethanol Production) [MJ ha^{-1}]			
	PR1	**PR2**	**PR3**	**PR4**	**PR1**	**PR2**	**PR3**	**PR4**
Material								
Fertilizer N	7140	6181	6012	6072	7140	6181	6012	6072
Fertilizer P	444	369	356	313	444	369	356	313
Fertilizer K	192	160	154	135	192	160	154	135
Seed	1620	1620	1620	1620	1620	1620	1620	1620
Pesticides	518	518	518	518	518	518	518	518
Liming	9	9	9	9	9	9	9	9
Operation								
Stubble treatment	231	231	231	231	231	231	231	231
Ploughing	1060	1060	1060	1060	1060	1060	1060	1060
Harrowing	528	528	528	528	528	528	528	528
Sowing	425	425	425	425	425	425	425	425
Rolling	240	240	240	240	240	240	240	240
Fertilizer application	166	166	166	166	166	166	166	166
Spraying	241	241	241	241	241	241	241	241
Combine harvesting	1730	1434	1371	1202	1730	1434	1371	1202
Transp. field–facility	874	417	667	241	50	12	20	7
Transp. field–farm	0	410	35	489	1099	950	897	800
Transp. farm–facility	0	44	4	98	474	670	510	663
Drying (electricity)	1398	1163	1122	985	1398	1163	1122	985
Drying (heat)	3227	2684	2588	2273	3227	2684	2588	2273
Total	**20,116**	**17,962**	**17,406**	**16,898**	**20,865**	**18,723**	**18,127**	**17,542**

Table A6. Primary energy input in winter wheat straw production in the different production regions (PR) for the production of biogas and ethanol, when removing amounts of straw according to the technical/restricted straw potential.

Parameter	Primary Energy Input (Biogas Production) [MJ ha^{-1}]				Primary Energy Input (Ethanol Production) [MJ ha^{-1}]			
	PR1	**PR2**	**PR3**	**PR4**	**PR1**	**PR2**	**PR3**	**PR4**
Fertilizer								
N	1029	856	825	725	1029	856	825	725
P	17	21	18	17	21	18	17	15
K	233	194	187	164	233	194	187	164
Operations								
Baling	157	130	126	111	157	130	126	111
Collection [1]	493	438	431	400	493	438	431	400
Transport [2]	555/672	639/-	577/787	646/995	890/1246	1145/-	957/1597	1166/2232
Total	**2488/2604**	**2274/-**	**2163/2373**	**2060/2409**	**2823/3179**	**2780/-**	**2543/3183**	**2580/3647**

[1] Including transport to farm. [2] Transport from farm to biofuel production plant.

Appendix A.3. Feedstock Production Costs

Feedstock production costs were assessed using a stepwise calculation method considering field, transport and storage operations. Machine-hours were calculated for each operation assuming typical machinery suitable for the task, and using data on machinery capacity, wheat grain and straw yields, and transport distances. Data on machinery costs were taken from advisor recommendations [46].

Storage costs were not included in the feedstock production costs, but were instead included in the processing stage at the biofuel plant. Specific costs of electricity and fertilizers are given in Table A7. The total feedstock production cost for grain and straw are given in Tables A8–A11.

Table A7. Specific costs of selected production means required for feedstock production.

Material	Units	Cost	Reference
Electricity	[€-ct./kWh]	5.72	[47]
Fertilizer N	[€/kg]	1.11	[48]
Fertilizer P	[€/kg]	2.44	[48]
Fertilizer K	[€/kg]	0.78	[48]

Table A8. Feedstock production costs for winter wheat straw in the different production regions (PR) for the production of biogas and ethanol, when removing amounts of straw according to fraction 3 and fractions 1–3.

Parameter	**Feedstock Production Cost (Biogas Production) [€ ha^{-1}]**				**Feedstock Production Cost (Ethanol Production) [€ ha^{-1}]**			
	PR1	**PR2**	**PR3**	**PR4**	**PR1**	**PR2**	**PR3**	**PR4**
Fertilizer								
N	24	20	19	17	24	20	19	17
P	3	2	2	2	3	2	2	2
K	31	26	25	22	31	26	25	22
Operations								
Baling	37	31	30	26	37	31	30	26
Collection [1]	50	44	43	40	50	44	43	40
Transport [2]	56/68	64/-	58/79	65/100	90/125	115/-	96/161	117/225
Cultivation	58	48	46	41	58	48	46	41
Harvest	37	31	30	26	37	31	30	26
Storage	0	0	0	0	0	0	0	0
Transport	105/117	108/-	101/122	105/140	139/175	159/-	140/204	157/265
Total	**200/212**	**187/-**	**177/199**	**172/207**	**234/270**	**238/-**	**216/280**	**224/332**

[1] Including transport to farm. [2] Transport to biofuel plant.

Table A9. Feedstock production costs for winter wheat straw in the different production regions (PR) for the production of biogas and ethanol, when removing amounts of straw according to fraction 3 and fractions 1–3.

Parameter	**Feedstock Production Cost (Biogas Production) [€ t DM^{-1}]**				**Feedstock Production Cost (Ethanol Production) [€ t DM^{-1}]**			
	PR1	**PR2**	**PR3**	**PR4**	**PR1**	**PR2**	**PR3**	**PR4**
Material								
Fertilizer N	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Fertilizer P	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Fertilizer K	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2
Operations								
Baling	9.9	9.8	9.9	9.9	9.9	9.8	9.9	9.9
Collection [1]	13.2	14.1	14.4	15.2	13.2	14.1	14.4	15.2
Transport [2]	14.9/18	20.5/-	19.3/26.2	24.5/37.8	23.8/33.3	36.8/-	31.9/53.3	44.3/84.8
Cultivation	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
Harvest	9.9	9.8	9.9	9.9	9.9	9.8	9.9	9.9
Storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transport	28/31.1	34.6/-	33.6/40.6	39.7/53	37/46.5	50.9/-	46.3/67.6	59.4/99.9
Total	**53.2/56.3**	**59.8/-**	**58.8/65.8**	**64.9/78.2**	**62.2/71.7**	**76.1/-**	**71.5/92.8**	**84.7/125.2**

[1] Including transport to farm. [2] Transport to biofuel plant.

Table A10. Feedstock production costs [€ ha^{-1}] for winter wheat grains in the different production regions (PR) for the production of biogas and ethanol.

Parameter	Production Costs (Biogas Production) [€ ha^{-1}]				Production Costs (Ethanol Production) [€ ha^{-1}]			
	PR1	**PR2**	**PR3**	**PR4**	**PR1**	**PR2**	**PR3**	**PR4**
Material								
Fertilizer N	111	165	143	139	165	143	139	141
Fertilizer P	36	58	48	46	58	48	46	41
Fertilizer K	16	26	21	21	26	21	21	18
Seeds	56	84	84	84	84	84	84	84
Pesticides	49	98	98	98	98	98	98	98
Liming	17	17	17	17	17	17	17	17
Operations								
Stubble treatment (cultivator)	27	27	27	27	27	27	27	27
Ploughing	113	113	113	113	113	113	113	113
Harrowing	56	56	56	56	56	56	56	56
Sowing	58	58	58	58	58	58	58	58
Rolling	25	25	25	25	25	25	25	25
Fertilizer spreading	18	18	18	18	18	18	18	18
Spraying	34	34	34	34	34	34	34	34
Combine harvest	196	162	155	136	196	162	155	136
Transp. field-facility	54	26	41	15	3	1	1	0
Transp. field-farm	0	25	2	30	68	59	56	50
Transp. farm-facility	0	4	0	10	48	67	51	67
Drying (ventilator electricity only)	120	100	96	84	120	100	96	84
Drying (heat production)	118	98	94	83	118	98	94	83
Total	**1305**	**1190**	**1157**	**1115**	**1369**	**1261**	**1221**	**1177**

Table A11. Feedstock production costs [€ t DM^{-1}] for winter wheat grains in the different production regions (PR) for the production of biogas and ethanol.

Parameter	Production Costs (Biogas Production) [€ t DM^{-1}]				Production Costs (Ethanol Production) [€ t DM^{-1}]			
	PR1	**PR2**	**PR3**	**PR4**	**PR1**	**PR2**	**PR3**	**PR4**
Material								
Fertilizer N	17	30	27	30	25	26	26	30
Fertilizer P	5	11	9	10	9	9	9	9
Fertilizer K	2	5	4	4	4	4	4	4
Seeds	9	15	16	18	13	15	16	18
Pesticides	8	18	19	21	15	18	19	21
Liming	3	3	3	4	3	3	3	4
Operations								
Stubble treatment (cultivator)	4	5	5	6	4	5	5	6
Ploughing	17	21	21	24	17	21	21	24
Harrowing	9	10	11	12	9	10	11	12
Sowing	9	11	11	13	9	11	11	13
Rolling	4	5	5	5	4	5	5	5
Fertilizer spreading	3	3	3	4	3	3	3	4
Spraying	5	6	7	7	5	6	7	7
Combine harvest	30	30	29	29	30	30	29	29
Transp. field-facility	8	5	8	3	0	0	0	0
Transp. field-farm	0	5	0	7	10	11	11	11
Transp. farm-facility	0	1	0	2	7	12	10	14
Drying (ventilator electricity only)	18	18	18	18	18	18	18	18
Drying (heat production)	18	18	18	18	18	18	18	18
Total	**198**	**218**	**219**	**241**	**208**	**231**	**232**	**254**

Appendix B. Biofuel Production Cost

The biofuel production cost consists for example of the costs of capital, feedstock, process energy, additives, operation and maintenance. Furthermore, each biofuel production system analysed generates different co-products, which provide additional income, reducing the biofuel production cost. The investment cost applied, summarized in Table A12, is based on recent techno-economic studies of biofuel production under Swedish conditions. Table A13 gives the cost of process energy, additives and chemicals, together with costs of maintenance and various services. In addition, the production of ethanol from grain and straw also include a fixed cost of approximately €4.4 and €3.0 million to account for insurance and labour, etc. [22,26]. Finally, the economic value of the co-products is presented in Table A14. Base case cost calculations for the storage of straw are based on indoor storage [48] when the straw is to be incinerated. It is also possible to store straw outside which could be a more cost-efficient option. However, no studies could be found on the impact of outdoor storage on the feedstock quality. To give an indication of the possible reduction in production cost resulting from cheaper storage, the straw storage cost was set to zero in the sensitivity analysis.

Table A12. Investment costs (million €) for biogas and ethanol production plants using wheat grain and straw, respectively [22,26,27].

System Components	Biogas		Ethanol	
	Grain	Straw	Grain	Straw [1]
Biogas plant	3	4		
Ethanol plant			174	131
Upgrading of biogas	2	2		7
Compression and distribution of biogas	0.1	0.1		2
Digestate storage	1	3		
Filling stations	4	4		14
Total investment cost	**10**	**13**	**174**	**154**

[1] The investment cost of the ethanol plant includes biogas production and digestate handling. Investments for upgrading and distribution of vehicle gas are adapted from values given in the literature [27].

Table A13. Various operational costs associated with the production of biogas and ethanol from wheat grain and straw.

Operational Cots	Cost	Reference
Process energy		
Electricity from the grid for biofuel production [1]	€57/MWh	[47]
Natural gas [2]	€37/MWh	[47]
Heat from external supplier	€26/GJ	[27]
Additives and chemicals		
Acetic acid	€0.2/kg[3]	
Enzymes (ethanol from grain)	€3.3/kg enzyme solution	[22]
Enzymes (ethanol from straw)	€3.0/FPU	[26]
N	€1.1/kg	[48]
P	€2.4/kg	[48]
$FeSO_4$	€4.1/kg	[27]
Trace elements for biogas production	€21,600	[27]
Ammonia (25%)	€0.2/kg	[3]
Phosphoric acid (50%)	€0.6/kg	[3]
Antifoam	€2.2/kg	[3]
$(NH_4)\ 2HPO_4$	€0.7/kg	[3]
$MgCl_2/MgSO_4$	€0.2/kg	[3]
Molasses	€0.1/kg	[3]
Cooling water	€0.02/m^3	[49]
Processing water	€0.2/m^3	[49]
Maintenance		
Biogas plant	5% of investment	[27]
Digestate storage	0.5% of investment	[27]
Upgrading plant	3% of investment	[27]
Vehicle gas filling stations	3% of investment	[27]

Table A13. *Cont.*

Operational Cots	Cost	Reference
Services		
Digestate transport		
- Fixed cost	€0.95/t	[50]
- Transport cost	€0.04/t	[50]
Digestate application	€2/t	[27]
Distribution of biogas	€8.9/MWh	[51]
Distribution of ethanol	€0.01/dm^3	[52]
Storage of grain [3]	€0.01/kg	[53]
Storage of straw	€0.02/kg	[48]

[1] Average electricity price in 2016 for industries using 2–20 GWh annually. Includes energy price, electricity certificate, grid and electricity tax for industries. [2] Average price in 2016, including energy and gas grid, for industries using 30–300 GWh/y. [3] O. Wallberg, personal communication.

Table A14. Economic value of co-products the production of biogas and ethanol from wheat grain and straw respectively.

Co-Product	Unit	Reference
Macro-nutrients in digestate		
N	€1.1/kg	[48]
P	€2.4/kg	[48]
K	€0.8/kg	[48]
DDGS [1]	€0.24/kg DM	[54]
Electricity [2]	€27/MWh	[55]
Electricity certificates [3]	€15/MWh	[56]
Lignin pellets [4]	€0.09/kg DM	[26,57]
Carbon dioxide	€0.003/kg	[26]

[1] Distillers dried grains with solubles, average market price 2010–2016 for DDGS as protein feed. [2] Average Nordpool spot price in 2016. [3] Average market price in 2016. [4] Assuming 50% of the average market price for wood pellets used by large consumers in 2016.

Appendix C. Greenhouse Gas Emissions

The impact on climate is expressed as global warming potential (GWP) in carbon dioxide equivalents (CO_2eq) and includes emissions of CO_2 from fossil origin, methane (CH_4) and nitrous oxide (N_2O). Characterization factors on a 100-year perspective were used according to IPCC [58]. In addition, changes in contribution to soil organic carbon (SOC) content were expressed as a CO_2 emission or uptake, as appropriate.

Tables A15–A17 summarize the emission data used in the study, together with references and explanations. In cases where alternative emission data have been evaluated, both the data used in the base case and the alternative data are given (entries in italics).

Table A15. Emissions resulting from energy input. Values in italics are alternative values used in sensitivity analysis. All other values were those used in the base case (values refer to the lower heating values for fuels).

Energy Source	Emission [g CO_2eq MJ^{-1}]	Ref.	Comment
Fossil fuel reference	83.8	[8]	Comparator when calculating the GHG emission saving according to the EU RED
Diesel	80.4	[59]	Average Swedish fossil diesel blend in 2016, containing 21% (vol.) biodiesel
HVO	*14.0*	*[59]*	*Swedish biodiesel consisting of hydrogenated vegetable oil (HVO), average emission in 2016*
FAME	*32.3*	*[59]*	*Swedish biodiesel consisting of fatty acid methyl ester (FAME), average emission in 2016*

Table A15. *Cont.*

Energy Source	Emission [g CO_2eq MJ^{-1}]	Ref.	Comment
100% biodiesel	*23.2*		*The alternative value for 100% biodiesel, calculated assuming a 50/50 blend of HVO and FAME*
Electricity, Nordic mix	34.9	[60]	Currently used in Swedish reporting of GHG emissions for biofuels according to the EU RED
Electricity, Swedish mix	*13.1*	*[61]*	*Suggested future emission in Swedish reporting of GHG emissions for biofuels according to the EU RED*
Electricity, EU28 mix	*124.2*	*[61]*	*Alternative value for evaluating the impact of EU average electricity in calculations of GHG emissions for biofuels according to the EU RED*
Wood chips	3.4	[62]	Used together with a heat conversion efficiency of 85%
Natural gas	*69*	*[63]*	*Used together with a heat conversion efficiency of 90%*

Table A16. Emissions from inputs in grain and straw cultivation. Values in italics are alternative values used in the sensitivity analysis. All other values were used in the base case.

Cultivation Input	Emission [kg CO_2eq kg^{-1}]	Ref.	Comment
Mineral fertilizer N	4.5		Swedish average mineral N utilization 2016 [1]
Mineral fertilizer N	*7.8*	*[64]*	*Western European production*
Mineral fertilizer P	2.3	[65]	
Mineral fertilizer K	0.7	[65]	
Seeding material	0.3	[65]	
Lime	0.1	[66]	
Pesticides	11	[65]	Per kg active substance

[1] Emissions during the production of mineral N calculated based on the method of Ahlgren et al. [67], using the region of origin of import to Sweden in 2016: 72% Nordic, 12% Russian and 16% Western European [68]. Regional production emissions were 3.1 kg CO_2eq (kg N)$^{-1}$ for Nordic production and 8.1 for Russian production [64].

Table A17. Emissions from biofuel production: additives and methane losses in biofuel production. Values in italics are alternative values used in sensitivity analysis. All other values were used in the base case.

Process Additive	Emission [kg CO_2eq kg^{-1}]	Ref.	Comment
Acetic acid	0.6	[69]	
Ammonia	3.2	[65]	Per kg N
Phosphoric acid	3.0	[65]	
Antifoam	1.3	[70]	
(NH_4) $2HPO_4$	3.3	[65]	
$MgSO_4$	0.1	[69]	
Molasses	0.1	[24]	
Enzymes	5.5	[70]	Revised based on reduced fossil energy input in the production of Cellic CTec3 (Novozymes)
Enzymes	*8.0*	*[24,70]*	*2014 emission data for Cellic Ctec3*
Trace minerals	0.4	[69]	Yeast extract [1]
CH_4 from biogas production	0.5 [2]	[27]	
CH_4 from biogas upgrading	0.2 [2]	[27]	Includes emission from flare [3]

[1] In the technical background data used [27], a trace mineral solution of unknown content is added. The emission value used is that for yeast extract. [2] Percentage of the produced CH_4. [3] The loss of CH_4 during upgrading is 0.1%. In addition, 4% of the gas is assumed to be flared (during process failure, maintenance, etc.), 2% of which passes the flair unburnt and is emitted to the atmosphere.

In addition to GHG emissions during enzyme manufacture, the effects of varying the enzyme dose were evaluated. The dose used in the techno-economical evaluation is that used for straw-based ethanol production: 1.7 g (100 g cellulose)$^{-1}$ (Novozymes enzyme solution Cellic Cetc3 for lignocellulosic ethanol production) [26]. The maximum dose recommended by Novozymes, of 6 g (100 g cellulose)$^{-1}$ [71], was used as an alternative value in both GWP and cost calculations. Recent studies on new types/combinations of lignocellulosic enzymes (Cellic 1.0, Novozymes) indicate that further decreases in emission will be possible per gram enzyme solution, but a higher dose will be required [72], still leading to a slightly lower GWP. The combined impact of dose and emissions during the manufacture of next-generation enzymes on GWP was also evaluated.

In the study of combined ethanol and biogas production from straw, two biogas yields were given, an experimental yield and a theoretically calculated yield. The lower experimental value was used in the base case for the GWP calculations, while the higher theoretical yield was used as an alternative value in the sensitivity analysis.

For biogas from straw, the biogas yield is based on a theoretical calculation, previously presented in Lantz et al. [27] which to the best of our knowledge, has not been verified on a large scale, since straw would likely be used as a co-substrate together with other feedstocks. This uncertainty is reflected by evaluating the impact on cost and GWP of 10% higher and lower methane yields from straw.

Appendix C.1. Co-Product Substitution

In the ISO methodology, the greenhouse gas emissions from the use of the co-products is based on estimates concerning the products they will replace. In the present study, co-product substitution is based on assumptions regarding the products that will be replaced under typical Swedish conditions. However, this substitution will also cause emissions in some cases.

In the production of grain-based ethanol, the co-product is DDGS, which is assumed to replace currently dominating animal protein feed products in Sweden. The two dominating types of animal protein feed in Sweden in 2010 were soybean meal and rape meal (from the press cake after rape seed oil production), representing more than 90% of the total consumption [73]. The effects of substitution are calculated based on protein; the contents in DDGS, rape meal and soybean meal being 34%, 34% and 45%, respectively [54]. The ratio between soybean meal and rape meal, on a protein basis, in current animal feed is 52/48. The GHG emissions from the transportation and processing of these protein feeds at the largest animal feed production site in Sweden (Lidköping) have been calculated and found to be 849 and 461 g CO_2eq (kg DM)$^{-1}$ for soybean and rape meal, respectively [74]. The transport of DDGS from the biofuel production plant to the animal feed production plant is assumed to take place at a load of 32.4 t DM per truck, over a transport distance of 250 km [74], with the same fuel consumption as for biofertilizer transport (see below). The resulting emissions and avoided emissions of this substitution are summarized in Table A18. It is interesting to note that, based on Swedish protein feed consumption data from 2010 [74], four ethanol production plants of the size assumed here (440,000 t DM cereal grain per year) would cover the whole Swedish protein feed demand, and exploiting other markets or other applications of the DDGS as a co-product would change the climate benefits.

In the production of straw-based ethanol, the co-products are biogas and fibre pellets. It is assumed that the biogas is upgraded and distributed via the natural gas grid (as in the biogas-only cases) and replaces natural gas. The assumed energy use and emissions for upgrading and distribution are the same as for the biogas-only cases, and the emissions and avoided emissions of this substitution are also summarized in Table A18. The fibre pellets are assumed to replace wood chips.

The co-product from biogas production using both feedstocks is biofertilizer. The composition of the biofertilizer leaving the biofuel production plant is presented in the main paper (Table 3). Nitrogen losses will occur during storage and field application, reducing the amount of nutrients available, and generating GHG emissions, Table A19. Methane losses during biofertilizer storage were taken from Lantz et al. [27], where they were calculated using emission factors from liquid manure storage and the residual methane potential in the biofertilizer, which gives a methane loss during storage corresponding to 0.5% of the collected biogas for production from straw, and 0.1% for production from grain [27]. The amounts given in Table A18 are after losses during storage and application.

The carbon content in the biofertilizer is calculated based on the assumption of an original carbon content of 47% of DM in the feedstocks, and with losses during processing based on biogas yields [75]. The contents of the remaining nutrients originate from the original feedstock, where organically bound N is partly mineralized to NH_4^+, or is added during processing [27].

The SOC impact of the application of biofertilizer was not modelled in detail since this requires assumptions on where and when the biofertilizer is applied. Instead, data were taken from a previous study concerning the effect of adding biofertilizer from crop digestion on SOC [75]. In that study, the biofertilizer contribution to SOC was modelled for PR1, where 43% of the biofertilizer was used to fertilize winter wheat, and 57% for grass ley, and for PR2, where the corresponding applications to winter wheat and grass ley were 58% and 42%, respectively. The proportion of added carbon integrated into long-term stable SOC was found to be 23% of the amount added, and the annual amount of stable SOC was calculated as an average over 40 years [75]. This value was used to estimate the contribution of biofertilizer to long term stable SOC in all the PRs studied in the current study.

The demand for biofertilizer is assumed to be high, but its distribution may be limited by crop rotations, weather conditions, etc. We therefore assumed that it would be possible to use the biofertilizer on 30% of the arable land in the production regions, which is reflected by a higher transport demand. The average proportion of arable land in the four PRs and the same equation as that for biomass transport were used for the calculation (see Appendix A). The biofertilizer load per vehicle was assumed to be 35 t, and the fuel consumption for loading, unloading and field application were taken from Lantz et al. [27].

Table A18. Emissions and benefits (avoided emissions) associated with co-products at substitution per tonne DM of the original feedstock (straw or grain) added to the main process in PR1. (Negative values indicate avoided emissions.).

	Co-Product Amounts (Underlined) and Emissions	
Grain-based ethanol		
DDGS	0.34	[t DM (t DM)$^{-1}$]
Transport to feed production plant	7.7	[kg CO_2eq (t DM)$^{-1}$]
Substitution of soybean meal & rape meal	−192	[kg CO_2eq (t DM)$^{-1}$]
Straw-based ethanol		
Upgraded methane	2780 [1]	[MJ (t DM)$^{-1}$]
Input upgrading/distribution electricity	5.6	[kg CO_2eq (t DM)$^{-1}$]
Input upgrading/distribution heat	1.3	[kg CO_2eq (t DM)$^{-1}$]
Methane losses	2.6	[kg CO_2eq (t DM)$^{-1}$]
Substitution of natural gas	−193	[kg CO_2eq (t DM)$^{-1}$]
Fibre pellets	4320	[MJ (t DM)$^{-1}$]
Substitution of wood pellets	−14.8	[kg CO_2eq (t DM)$^{-1}$]
Grain-based biogas		
Biofertilizer containing:		
NH_4-N	12.4 [2]	[kg (t DM)$^{-1}$]
P	5.2	[kg (t DM)$^{-1}$]
K	5.5	[kg (t DM)$^{-1}$]
C	108	[kg (t DM)$^{-1}$]
Transport and field application	5.8 [5]	[kg CO_2eq (t DM)$^{-1}$]
Biofertilizer storage [3]	6.8	[kg CO_2eq (t DM)$^{-1}$]
N_2O emission at application [4]	39	[kg CO_2eq (t DM)$^{-1}$]
NPK substitution	−71	[kg CO_2eq (t DM)$^{-1}$]
SOC benefit	−92	[kg CO_2eq (t DM)$^{-1}$]
Straw-based biogas		

Table A18. *Cont.*

	Co-Product Amounts (Underlined) and Emissions	
Biofertilizer containing:		
NH_4-N	7.5 [2]	[kg (t DM)$^{-1}$]
P	0.6	[kg (t DM)$^{-1}$]
K	10	[kg (t DM)$^{-1}$]
C	247	[kg (t DM)$^{-1}$]
Transport and field application	6.9 [6]	[kg CO_2eq (t DM)$^{-1}$]
Biofertilizer storage [3]	20	[kg CO_2eq (t DM)$^{-1}$]
N_2O emission at application [4]	30	[kg CO_2eq (t DM)$^{-1}$]
NPK substitution	−42	[kg CO_2eq (t DM)$^{-1}$]
SOC benefit	−210	[kg CO_2eq (t DM)$^{-1}$]

[1] After losses during upgrading. [2] The amount of NH_4-N replacing mineral N, where losses during storage (see Table A19), and emissions at application have been subtracted. [3] Both CH_4 and NH_3 are lost during storage (see Table A19). [4] The increase in N_2O emission compared to mineral N fertilization. The emission is higher as it is calculated based on the total N content in the biofertilizer, where NH_4-N is 66% of the total N for grain-based biogas, and 60% for straw-based biogas. The amount of NH4-N added is also higher than the required mineral N due to the higher loss of NH_3 at application (see Table A19). [5] The corresponding emissions for PR2, PR3 and PR4 are 9.0, 8.7 and 11.2 kg CO_2eq (t DM)$^{-1}$, respectively. [6] The corresponding emissions for PR2, PR3 and PR4 are 4.4, 5.6 and 7.0 kg CO_2eq (t DM)$^{-1}$, respectively.

Table A19. Emissions resulting from field application of mineral fertilizer and biofertilizer.

	Emission		Reference
Nitrogen loss			
Ammonia losses			
Biofertilizer storage	1	[%] (NH_3-N of N-tot)	[75]
Mineral fertilizer field application	0.91	[%] NH_3-N of N-tot?)	[76]
Biofertilizer field application	10	[%] (NH_3-N of NH_4-N)	[77]
N_2O emissions at field application			
All N in field (mineral N, biofertilizer N, N in crop residues)	1	[%] (N_2O-N of N-tot)	[58]
Indirect N_2O emission			
Leakage to water [1]	0.75	[%] (N_2O-N of NO_3-N)	[58]
Emission to air	1	[%] (N_2O-N of NH_3-N)	[58]

[1] The leakage to water is different in the different PRs. The values used for nitrate run-off were: 32.9, 27.5, 11.9 and 9.7 kg NO_3-N ha^{-1} for PR1, PR2, PR3 and PR4, respectively [78].

Appendix C.2. SOC Simulation

The data used to parameterize the ICB model for the simulation of SOC mineralization are summarized in Table A20.

Table A20. Data for the parameterization and long-term field experiments used for calibration of the ICB model [79] for SOC simulations used in the SOC balance estimations [80,81].

PR	SOC Content (%)	Mean Bulk Density (t/m^3)	Mean Clay Density (%)	Field Experiment	Reaction Coefficient
1	1.77 (1.25–2.98)	1.38	13.8	Ekebo	0.0089
2	1.97 (1.25–2.95)	1.16	12.9	Orupsgården	0.0081
3	2.06 (1.45–2.99)	1.22	19.9	Högaså	0.0102
4	2.08 (1.48–5.55)	1.06	18.7	Kungsängen	0.0070

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