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Environmental sustainability analysis of UK whole wheat bioethanol and CHP systems

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Abstract

The UK whole-wheat bioethanol and straw and DDGS based combined heat and power (CHP) generation systems were assessed for environmental sustainability using a range of impact categories or characterisations (IC): cumulative primary fossil energy (CPE), land use, life cycle global warming potential over 100 years (GWP_{100}), acidification potential (AP), eutrophication potential (EP) and abiotic resources use (ARU). The European Union (EU) Renewable Energy Directive's target of greenhouse gas (GHG) emission saving of 60% in comparison to an equivalent fossil based system by 2020 seems to be very challenging for stand-alone wheat bioethanol system. However, the whole-wheat integrated system, wherein the CHP from the excess straw grown in the same season and from the same land is utilised in the wheat bioethanol plant, can be demonstrated for potential sustainability improvement, achieving 85% emission reduction and 97% CPE saving compared to reference fossil systems. The net bioenergy from this system and from 172370 ha of grade 3 land is 12.1 PJ y^{-1} providing land to energy yield of 70 GJ ha^{-1} y^{-1}. The use of DDGS as an animal feed replacing soy meal incurs environmental emission credit, whilst its use in heat or CHP generation saves CPE. The hot spots in whole-system identified under each impact category are as follows: bioethanol plant and wheat cultivation for CPE (50% and 48%), as well as for

ARU (46% and 52%). EP and GWP_{100} are distributed among wheat cultivation (49% and 37%), CHP plant (26% and 30%) and bioethanol plant (25%, and 33%), respectively.

Keywords: bioethanol, biorefinery, polygeneration, CHP, sustainability, LCA

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1. Introduction

In 2008/9, UK surplus wheat (dry basis) was around 3900000 Mg available for the production of bioethanol [1]. Alongside, 3500 kg ha^{-1} of accompanying wheat straws (dry basis) were produced, 60% of which, after incorporating the rest into the soil for retaining the soil nutrients, could have been made available for the generation of combined heat and power (CHP) [2]. In the UK, there is around 5000000 Mg y^{-1} of straw available for bioenergy purposes, 54% coming from wheat, after accounting for its other current uses [3]. Transport is the main energy consuming sector in the UK, accounting for a quarter of the UK domestic energy use and GHG emissions. 93% of those emissions come from road vehicles [4]. In order to reduce emissions and energy imports, the target is to introduce 5.26% of renewable fuels into the transport fuel by 2013/14 [5]. To meet this bioethanol demand, a production capacity of 1 billion L will be required in the UK by the year indicated. The amount of excess wheat available in the UK could provide 1.62 billion L y^{-1} of bioethanol (according to bioethanol process studies in [6]). The target fraction for electricity from renewable resources is set at 10% by 2010 and 30% by 2020 (2% from small-scale generation) [7]. This implies that 48.2 PJ y^{-1} of electricity is required from biomass by 2010 [8]. The excess straw available in the UK (at 14.6 MJ kg^{-1}) can supply 29.2 PJ y^{-1} of electricity.

The EU Renewable Energy Directive has imposed a constraint on biofuel systems that only those saving 60% GHG emissions in comparison to the fuel they replace will be eligible for consideration for the 2020 target of 10% renewable energy in transport [9]. Whilst achieving this target from the bioethanol production alone can be an important consideration, integrated energy systems have greater potential in improving overall sustainability. The utilisation of rape seed to produce a range of products, biodiesel from the oil, heat from straw, heat and gas from glycerol and rape cake as animal feed has been investigated to achieve 60% emission reduction target [10]. Their studies have demonstrated the sustainability of indigenous biofuels in Ireland in comparison to equivalent biofuel imports from other resources [10–12]. A comprehensive comparison amongst various potential renewable energy systems in the UK has been shown by a streamlined LCA approach [13]. An excellent overview of environmental impact analysis of the large scale deployment of dedicated bioenergy crops (e.g. short rotation coppice (SRC) willow and poplar, miscanthus) and biomass for biofuels (e.g. wheat, sugar beet, oilseed rape) in the UK has also been reported [14]. A range of GWP_{100} (as CO_2-eq) values between 41 g MJ^{-1} and 80 g MJ^{-1} from bioethanol plants using different feedstock (sugar cane, sugar beet, wheat, corn), with corresponding potential GHG reductions in a range of 10% – 53% was shown [15]. With a similar approach, the life cycle assessment (LCA) of bioethanol and CHP production systems from wheat straw, considering additional aspects like crop residue removal and decrease in grain yields has also been presented [16]. The calculations showed that the use of crop residues in a biorefinery reduced GHG emissions by about 50% and fossil energy demand by more than 80%. The effect of the processing scale and different allocation methods (economic, physical and by system expansion) have been analysed within the Sweden context [17]. The results showed that the differences between various scales are small and suggested system expansion as an appropriate allocation method. A GWP_{100} (as CO_2-eq) of 43.5 g MJ^{-1} from a wheat-based large scale bioethanol facility based on economic allocation was presented.

The above studies mainly focus on the analysis of key contributing factors in LCA of bioenergy systems from different feedstock [10–18]. However, the trend is to make comparisons among them but give less attention to the improvement of environmental performance on a specific system from their current status as in the case of bioethanol plants. Additionally, the LCA of integrated energy systems in the UK is under-explored. It is also imperative to undertake such studies in the appropriate context and present the assumptions, results and validations in the most transparent and coherent way.

The current work explores, through the life cycle methodologies, the improvement in environmental sustainability from wheat bioethanol to the whole wheat bioethanol plants, in which the DDGS and the wheat straws are also used to generate CHP, thereby enhancing the renewable energy mix into the system. Building upon bioenergy system overviews presented in literature [10–29], a detailed evaluation of the UK wheat bioethanol and lignocellulosic CHP plants was performed in the context of environmental sustainability. The life cycle impact (LCI) methods were used with impact factors from individual substances extracted from various sources [19–29], amongst which the more relevant ones are presented in **Table 1.** For various energy carriers, e.g. natural gas, electricity, diesel, etc., the factors from [19] were used.

Table 1 Common substances and characterisation factors for impact categories used in this study (per kg).

SUBSTANCE	GWP_{100} (CO_2-eq) kg [20]	AP (SO_2-eq) kg [21]	EP (PO_4^{3-}eq) kg [21]
CO_2	1		
CH_4	25		
N_2O	298		
CO	1.9		
NO_x (not N_2O)		0.7	0.13
SO_x		1	
H_2SO_4		0.65	
NH_3		1.88	0.33
NO_3^-			0.42
PO_4^{3-}			1

The specific objectives of this study include:

1) Assess the environmental impact of the UK wheat bioethanol plant [6] as a stand-alone system as well as a whole wheat system integrated with wheat straw CHP plant [30] using cumulative primary (fossil) energy (CPE), land use, global warming potential in a horizon of 100 years (GWP_{100}), acidification potential (AP), eutrophication potential (EP) and abiotic resources use (ARU) as IC.
2) Establish the marginal benefits in terms of GWP_{100} and primary energy savings, compared to the fossil resources to be replaced, e.g. natural gas for heat and electricity and gasoline for bioethanol.
3) Study the relative LCI of DDGS as a commodity to the production of heat and CHP, compared to its usage as animal feed.

2. System definition

Fig. 1 depicts the following alternatives evaluated through life cycle methodologies:

1) Stand-alone bioethanol plant; wheat bioethanol and straw CHP to grid system.
2) DDGS as a source of heat for wheat bioethanol plant.
3) DDGS as a source of CHP for wheat bioethanol plant.
4) Straw based CHP plant supplying energy to bioethanol plant and DDGS as an animal feed.

Additionally, alternative 5) is a combination of the cases in 2 and 4, wherein selling of DDGS is also considered.

The basis of the conversion plants is 12000000 Mg y^{-1} of wheat grain and the corresponding amount of excess straw available, 360000 Mg y^{-1} (after assuming retention of the straws cultivated in the soil of 40% to maintain the soil's nutritional value). The yields and energy contents of products are reported in **Table 2**.

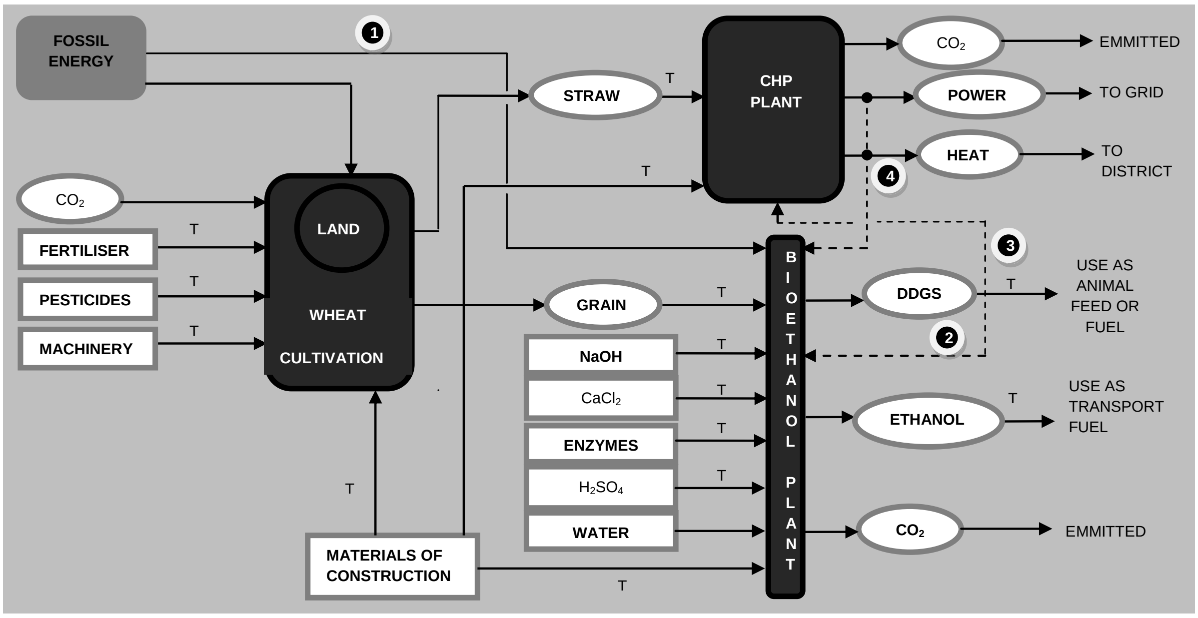


Fig. 1 The system evaluated. T: indicates transportation of materials. Dashed lines indicate the integration alternatives explored.

The boundaries of each subsystem include the farm and the plant gates for LCA. The allocation between the grain and the straw is by their economic values. For the conversion subsystems, three activities were separately evaluated and combined: LCI of materials of construction, plant operation, and transportation. The spreadsheet-based wheat bioethanol process model developed for technical analysis and economic feasibility [6] has been adopted. The results of simulation of biomass integrated gasification combined cycle (IGCC) plant for CHP generation in Aspen Plus were extracted for LCA [30]. The end use of ethanol is combustion as transportation fuel and of DDGS is in animal food processing in the base case, or as fuel for energy production in other cases. The electricity and heat generated from either the straw or from the DDGS were used within the bioethanol plant and added to adjacent grid connection and district heating system. Complementary energy such as electricity and natural gas is taken from the grid where necessary.

The LCI of individual co-production was allocated based on associated activities and operations. For shared facilities, this allocation was done by economic values. Different common functional units (unit mass of dry matter (DM) of product, unit energy, year and in the case of wheat cultivation, ha) were used for comparisons.

Table 2 Summary of yields (in dry matter basis) of wheat cultivation and bioethanol and CHP generation plants.

Subsystem	Product	Yield	Unit	LHV [a] MJ kg^{-1}
Wheat cultivation [19]	Wheat	6960	kg ha^{-1}	18.6
	Straw	3490	kg ha^{-1}	14.6
Bioethanol plant [6]	Ethanol	0.34	kg kg^{-1} (wheat basis)	26.7 [13]
	DDGS	0.25	kg kg^{-1} (wheat basis)	18.2
Straw CHP plant [30]	Electricity	1.06	kWh kg^{-1} (straw basis)	
	Heat	0.567	kWh kg^{-1} (straw basis)	
	Efficiency	40	%	

a. LHV: lower heating value.

3. Life cycle assessment

3.1 Wheat cultivation

The LCI data of wheat cultivation in the UK (**Fig. 2**) were extracted from [19]. Various applications of nitrogen fertiliser are generally made followed by sprayings of pesticides (2 doses assumed). The grain (with moisture content of 15% – 18%) once harvested is dried to avoid deterioration during storage and then is transported to the grain store. A mass fraction of the straws of about 40% are chopped and ploughed back to the soil to retain and improve the nutrient balance, soil fertility and organic carbon content. The rest is baled and used within the farm or is sold for other purposes [2]. The wheat yield of 6960 kg ha^{-1} and the corresponding straw yield of 3500 kg ha^{-1} were determined (in dry basis) using 200 kg ha^{-1} of nitrogen fertiliser. Urea mass fraction of 20% and the rest ammonium nitrate were assumed as fertilisers [19]. A total CO_2 binding of 10.5 Mg ha^{-1} by photosynthesis by the wheat plant was used [24].

The GHG emissions during the field operations are primarily from the usage of energy and fertilisers. N_2O emissions from the nitrogen fertiliser and organic matter decomposition in soil produce impacts [15]. Direct field emissions from nitrogen fertiliser and organic matter decomposition in soil and indirect field emissions from nitrogen volatilisation, and deposition of nitrogen volatilised as $NH_3 + NO_x$, were determined based on the estimated factors by IPCC, Tier 1 [22].

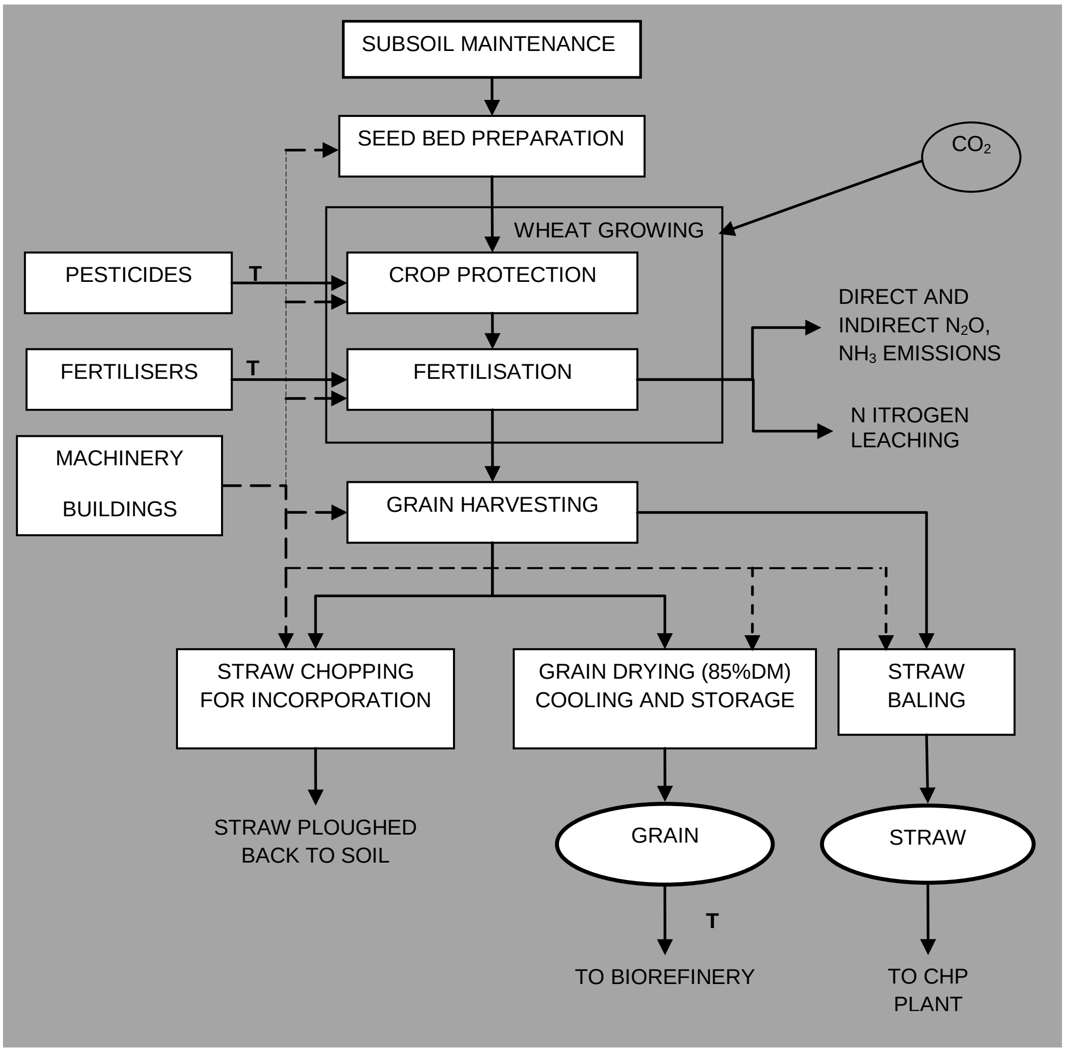


Fig. 2 The main activities in the UK cultivation system. Every activity implies machinery operations with its inherent energy use and environmental impact for manufacturing, housing and transportation. Transportation is denoted by T. DM: dry matter.

The total CPE and allocation of impacts to grain and straw were predicted following the default relative economic value factor of straw to grain of 0.05 [19] and depending on 40% of straws incorporated in the soil in this study. The activities up to grain harvesting were common since the straw production (baling) occurs only after grain harvesting (**Fig. 2**). The resulting allocation values in different functional units are given in **Table 3**.

Table 3 Allocation of CPE and environmental impacts from wheat cultivation.

Product	**Functional unit**	**CPE MJ**	**GWP$_{100}$ (CO_2-eq) kg**	**EP (PO_4^{3-}-eq) kg**	**AP (SO_2-eq) kg**	**ARU (Sb-eq) kg**
Grain	ha	18335	3426	16.1	15.8	10.8
Straw	ha	632	77	0.2	0.2	0.30
Total	**ha**	**18967**	**3503**	**16.3**	**16.0**	**11.1**
Grain	Mg	2634	492	2.3	2.3	1.5
Straw	Mg	181	22	0.1	0.1	0.1
Grain	y	3.16 PJ	591000 Mg	2770 Mg	2720 Mg	1850 Mg
Straw	y	0.109 PJ	13300 Mg	41.7 Mg	42.5 Mg	52.6 Mg
Total	**y**	**3.27 PJ**	**604000 Mg**	**2810 Mg**	**2760 Mg**	**1910 Mg**
Land use		**Grade 2 Ha**	**Grade 3a ha**	**Grade 3b ha**	**Grade 4 ha**	
Total	y	151685	172370	186159	193054	
Grain	Mg	0.13	0.14	0.16	0.16	

The results are assimilated for a range of activities, Fertilisers and Pesticides (F&P), Field Operations (FO), Grain Conditioning (GC), and Direct and Indirect Field Emissions (FE) in **Fig. 3**. The CPE and GWP$_{100}$ impacts from various wheat production activities are compiled in **Table 3**. The output raw energy available in the form of grain and straw (calculated from LHV in **Table 2**) gives a land productivity of 129.5 GJ ha^{-1} from an input CPE of 18.967 GJ ha^{-1} (**Table 3**). This leads to an energy ratio, E_{ratio} = output LHV / input CPE, of 6.82 from the wheat cultivation system.

The GWP$_{100}$ impact from the field is essentially due to N_2O releases. The field emissions are also the most important factor to eutrophication potential (99.9%, not shown in **Fig. 3**) due to NO_3^- leaching and NH_3 emissions. Regarding acidification potential, it is dominated by NH_3 emissions.

As illustrated, FE and fertiliser production are the hot spots in the LCA of wheat production. Both are related to the nutrient balance in the soil which is still an issue to address in agricultural systems. Decreases in the application of nitrogen fertilisers can improve the overall environmental performance of wheat production and subsequent processing.

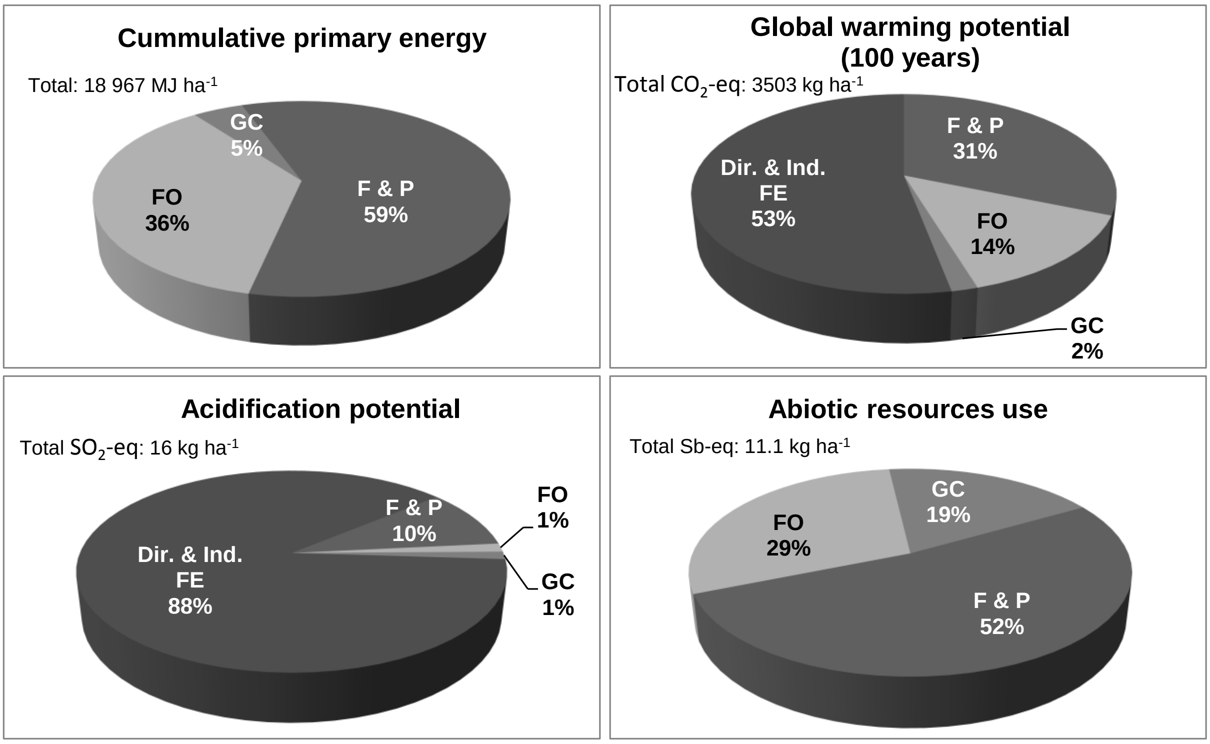


Fig. 3 Distribution of CPE and main environmental impact categories from wheat cultivation. FO: Field Operations, F&P: Fetilisers and Pesticides, Dir. & Ind. FE: Direct and Indirect Field Emissions, GC: Grain Conditioning.

3.2. Wheat bioethanol system

The wheat to bioethanol process model comprising hammer milling, liquefaction, saccharification, fermentation, centrifugation, ethanol recovery and drying as the main units [6] was used for the generation of mass and energy balance presented in **Fig. 4**. The simulation is based on the processing of the total wheat grain produced from cultivation into 404000 Mg y^{-1} of ethanol, 361000 Mg y^{-1} of CO_2 (emitted to atmosphere), and 295000 Mg y^{-1} of DDGS. The plant operates for 330 days a year and the plant life was assumed to be 10 years. Water recovered from the distillation columns is recycled into the process. For the base case, natural gas is used to supply the heat required by the fermentation, distillation and drying.

The various substances consumed, α-amylase, $CaCl_2$ (liquefaction), glucoamylase, H_2SO_4 conc. (saccharification) and yeast (fermentation) in the bioethanol production are presented in **Table 4**. NaOH is also required; a detailed inventory of its production was included [27]. Yeast was assumed to have equivalent LCI as glucoamylase. Additional emissions were accounted for the transportation of the substances from their production gate to the bioethanol plant assuming a distance of 120 km. Wheat is assumed to be transported from the farm gate to the bioethanol plant located within a radius of 25 km estimated from the total land use (grade 3a in **Table 3**). A mass fraction of 30% of all materials transported by lorry and the rest by rail [19] was assumed to determine the energy requirements and environmental impact from transportation.

Table 4 Substances and environmental impacts data (per kg).

Substance	CPE MJ	GWP_{100} (CO_2-eq) kg	EP (PO_4^{3-}-eq) kg	AP (SO_2-eq) kg	Ref.
α – amylase	15	1	0.0015	0.005	[28]
Glucoamylase	90	7.7	0.0215	0.023	[28]
$CaCl_2$	8.40				[29]
H_2SO_4 Conc.	–3	0.004		0.005	[29]

The main materials of plant construction considered were steel and concrete assuming mass fractions of 70% and 30%, respectively. The steel requirement was determined from the preliminary sizing of the key equipment made up of tanks and columns, and other vessels according to [31 –33]. Residence time used in the calculations and amounts of steel are presented in **Table 5**. A detailed inventory for stainless steel grade 316 [25] was used to determine the environmental impact from the amounts in **Table 5**. At the end of the life of the plant the steel can be recycled, thus considered a credit within the inventory. The emissions from concrete production were estimated from that of cement [26]. The LCI was increased by 20% and 10% for buildings and general structural elements in the facility and for the decommissioning of the plant at the end of life, respectively. A distance of 120 km was assumed for the transportation of materials of construction, as before.

Table 5 Main equipment and amount of steel required assuming cylindrical shapes.

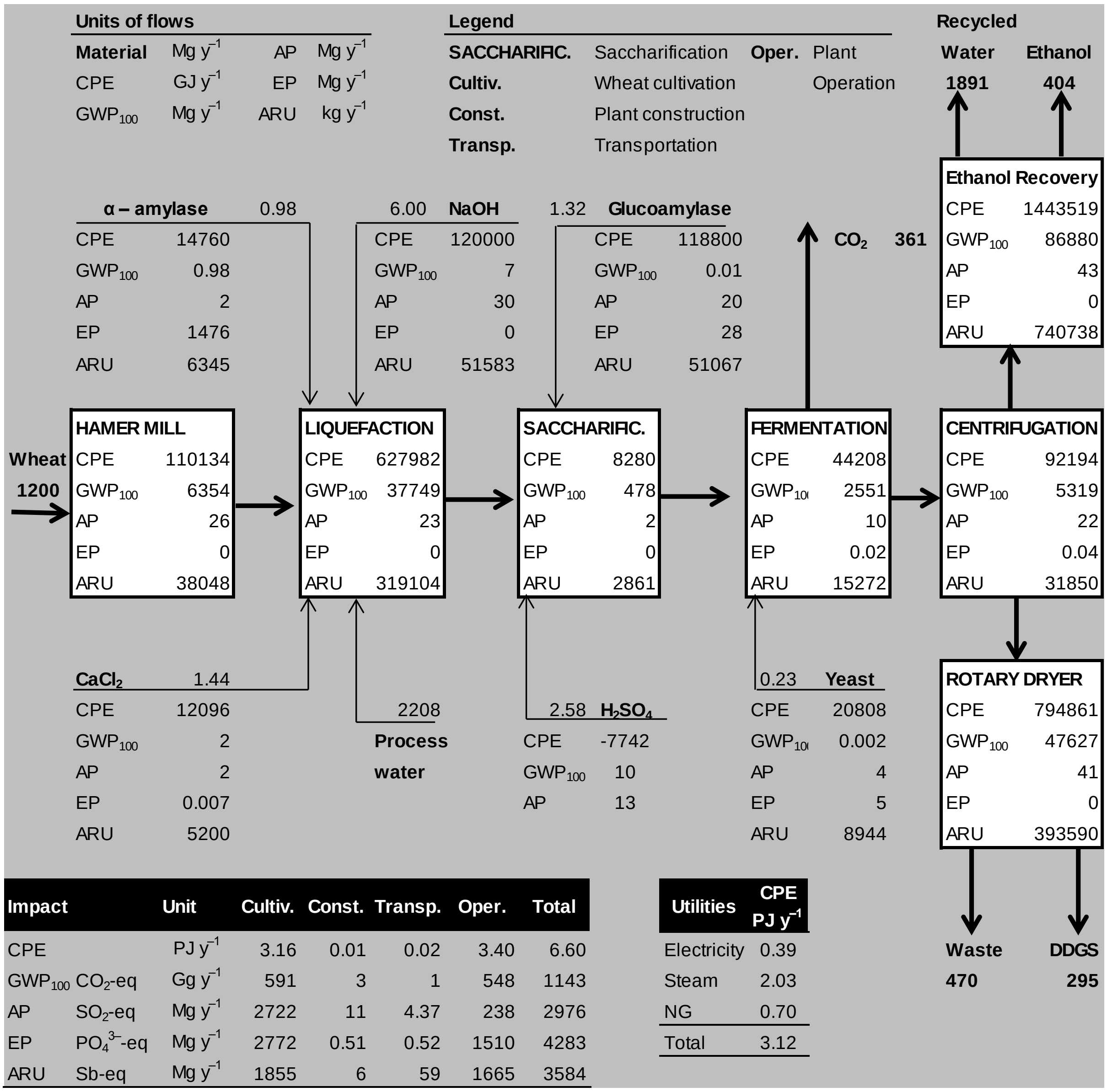
Unit	RT [a] [31] h	Capacity m^3	Steel [b] kg
Liquefaction	1	364	10779 (1%)
Saccharification	5	2020	33810 (4%)
Fermentation (10 tanks)	68	27475	420294 (52%)
Centrifugation	1	1083	22312 (3%)
Ethanol recovery	3 columns	5188	123154 (15%)
Rotary dryer	1	1083	22312 (3%)
Condensate tank	6	14100	123479 (15%)
Ethanol tank	24	4369	56541 (7%)
TOTAL			**812682**

a. RT: Residence time.
b. Numbers in brackets are mass fractions of the total amount.

Fig. 4 depicts the environmental impact and CPE flows for the cradle to the bioethanol plant gate subsystem including wheat cultivation, transportation and plant operation and construction. The construction stage represents only a small fraction (1% or less) of the total environmental impact of the plant.

The impact from wheat grain production is the maximum, followed by bioethanol process operation, transportation and materials of construction in all the IC. The GHG emission from the process is caused from the use of energy and fermentation. The GWP_{100} (as CO_2-eq) from cradle to the bioethanol plant gate represented a value of 0.95 kg kg^{-1} for the UK wheat grain processed, or 6.78 Mg ha^{-1} (based on grade 3a in **Table 3**).

Based on the LHV and yields of ethanol and wheat in **Table 2**, an annual energy production (*E*) of 10.8 PJ y^{-1} through ethanol is obtained from 22.3 PJ y^{-1} of cumulative primary energy. In terms of the land use, the energy conversion from wheat to bioethanol translates to a land productivity of 62.7 GJ ha^{-1} y^{-1} (based on land grade 3a in **Table 3**). The ethanol distillation columns and rotary dryer are the most energy consuming processes within the bioethanol plant, indicating points for potential improvement. Replacing natural gas-based energy and electricity from the grid with renewable CHP using integrated systems can further enhance the environmental sustainability of bioethanol production and usage, discussed later.



Impact		Unit	Cultiv.	Const.	Transp.	Oper.	Total
CPE		PJ y^{-1}	3.16	0.01	0.02	3.40	6.60
GWP_{100}	CO_2-eq	Gg y^{-1}	591	3	1	548	1143
AP	SO_2-eq	Mg y^{-1}	2722	11	4.37	238	2976
EP	PO_4^{3-}-eq	Mg y^{-1}	2772	0.51	0.52	1510	4283
ARU	Sb-eq	Mg y^{-1}	1855	6	59	1665	3584

Utilities	CPE PJ y^{-1}
Electricity	0.39
Steam	2.03
NG	0.70
Total	3.12

Fig. 4 Material and energy balances and environmental impacts associated with every stream and unit operation in the wheat bioethanol plant.

The economic values assigned in the study [6] have been taken as a basis for the allocation of LCI to ethanol and DDGS. The total environmental impact under each category for each product was determined by the allocation factor of the product (*AF*) multiplied by the total environmental impact from common unit operations (*CEI*), plus the environmental impact from the unit operations used in the final recovery of that particular product (*REI*); i.e.: $AF \times CEI + REI$. The allocation factor was calculated from the ratio of the value flow of the product (mass flow multiplied by economic value) divided by the sum of value flow of all products. This results in the factors of 0.962 and 0.038 for ethanol and DDGS, respectively. The LCI allocation to bioethanol and DDGS by economic values is presented in **Table 6**.

Table 6 LCI allocation to ethanol and DDGS by economic value (from cradle to the plant gate).

Product	Functional unit	CPE	GWP_{100} (CO_2-eq)	AP (SO_2-eq)	EP (PO_4^{3-}-eq)	ARU (Sb-eq)
		PJ	Mg	Mg	Mg	Mg
Ethanol	y	5.64	1057711	2826	4122	3098
DDGS	y	0.96	85598	150	161	486
Total	**y**	**6.60**	**1143309**	**2976**	**4283**	**3584**
Ethanol	Mg	0.00001394	2.62	0.01	0.01	0.0077
DDGS	Mg	0.00000325	0.29	0.001	0.001	0.0016

Table 7 presents cradle-to-grave GWP_{100} of wheat bioethanol production, including combustion, CO_2 binding and product transportation. By considering the impact allocation to ethanol and DDGS by their economic values, the reduction in GWP_{100} impact of 39% is obtained in comparison to gasoline system. From the corresponding CPE (13.94 GJ Mg^{-1}) and the energy produced from ethanol (**Table 2**), the energy ratio for bioethanol production is $E_{ratio} = 1.92$. This ratio reported for the production of gasoline is 0.84 [14]. Thus, energy saving of 56% can be estimated. On the other hand, considering that 1 kg of DDGS can

replace 0.8 kg of soy meal for animal feed [34] and the corresponding GWP_{100} of 0.726 kg kg^{-1} soy meal [35], 72% of GHG emissions can be avoided by the replacement of soy meal in animal feed. A potential energy saving of 21% was estimated from the use of DDGS as animal feed.

The GWP_{100} (as CO_2-eq) from the production of bioethanol from the UK wheat determined (51.6 g MJ^{-1}) fits within the range of (40.8 – 79.6) g MJ^{-1} given in [15] with potential GWP_{100} reduction by 10% – 53%. The resulting value is also comparable with 43.5 g MJ^{-1} from bioethanol production in [17] and 44 g MJ^{-1} reported in [14], based on similar system definition and economic allocation.

Table 7 Results of GWP_{100} (CO_2-eq) and corresponding savings from the use of bioethanol as transport fuel and DDGS as animal feed, respectively.

	Unit	Ethanol	DDGS
Allocation from production	kg kg^{-1}	2.62	0.29
Ethanol combustion		1.91	–
Transportation		0.01	0.001
Total GWP_{100}		**4.5**	**0.29**
CO_2 binding by wheat		–3.16	–0.12
Net GWP_{100}		**1.38**	**0.17**
	g MJ^{-1}	**51.6**	–
Energy produced	MJ kg^{-1}	26.72	–
Total CPE		13.94	3.25
E_{ratio}	–	**1.92**	–
Reference values	–	gasoline	soy meal
GWP_{100}	g MJ^{-1}	84.6 [14]	–
	kg kg^{-1}	–	0.726 [35]
E_{ratio}	MJ MJ^{-1}	0.84 [14]	–
CPE	MJ kg^{-1}	–	4.13 [34]
GWP_{100} reduction	**%**	**39**	**72**
CPE savings	**%**	**56**	**21**

3.2.1 Sensitivity analysis

Sensitivity analysis was carried out by variation of the percentage of renewable electricity in the electricity mix, percentage of renewable fuel in transportation fuels and nitrogen fertilisation rates. The impact sources affected by these parameters are: transportation, field operation and drying. The biogenic carbon capture is not affected by these parameters and therefore CO_2 binding and carbon emissions from end use of products are not changed. The initial UK electricity mix is 43.3% from natural gas, 32.9% from coal, 2.6% from fuel oil, 18.2% from nuclear energy and 3% from renewable energy [19]. It was assumed that the biofuels replace an equivalent amount of fossil fuels and that the use of biofuel results in at least 50% reduction in CPE and GWP_{100} with respect to fossil fuels. The results of sensitivity analysis are shown as follows.

- 10% increase in renewable electricity in the electricity mix increases CPE by 0.02 PJ y^{-1} and reduces GWP_{100} by 1144 Mg y^{-1}, EP by 0.005 Mg y^{-1}, AP by 2.07 Mg y^{-1} and ARU by 17.7 Mg y^{-1}.

- 10% biofuel in transportation fuels increases CPE by 0.07 PJ y^{-1} and reduces GWP_{100} by 3382 Mg y^{-1}, EP by 0.10 Mg y^{-1}, AP by 11.2 Mg y^{-1} and ARU by 5.86 Mg y^{-1}.

- 10% reduction in nitrogen fertilisation rates increases CPE by 0.14 PJ y^{-1} and reduces GWP_{100} by 33351 Mg y^{-1}, EP by 142 Mg y^{-1}, AP by 346 Mg y^{-1} and ARU by 0.08 Mg y^{-1}.

Major changes came from the variation in nitrogen fertilisation rates. The estimated field emissions using IPCC guidelines are another source of uncertainty.

3.3. Wheat bioethanol and straw CHP to grid system

The biomass IGCC-based CHP system has been techno-economically proven to be competitive and environmentally superior to equivalent fossil-based (e.g. natural gas-based) CHP systems [30] and their implementation seems to be a reality [36]. The LCA of a process simulated in Aspen Plus by Sadhukhan et al. for the processing of 5.44 Mg d^{-1} straw (with moisture and ash mass fractions of 8.5% and 8.61%, respectively, and LHV of 14.6 MJ kg^{-1})

into the production of 241 kW of electricity and 129 kW of waste heat, was undertaken [30]. The scaled up LCA results in terms of CPE and GWP_{100} corresponding to 361000 Mg y^{-1} of straw processing into 1.38 PJ y^{-1} of electricity and 0.737 PJ y^{-1} of heat generation, and thereby whole system LCI results under all five IC are presented for the base case (alternative 1 in **Fig. 1**).

The GWP_{100} from the straw-based CHP plant is mainly from the operation (98%) and the rest from the straw production and transportation and the plant construction. This impact mainly results from the emissions of the exhaust gas from the combustion of the syngas from straw gasification, made up of CO_2 (molar fraction of 25%), nitrogen (molar fraction of 62%) and steam (molar fraction of 13%) in the cases under consideration. However, by considering CO_2 fixation by straw (Carbon mass content of 36.6%) there is a credit of 1.34 Mg Mg^{-1}. Then, the net GWP_{100} (as CO_2-eq) is reduced to 18 g kWh^{-1}. Thus, around 94% reduction in GHG emissions can be achieved by the CHP generation from wheat straw with respect to equivalent production of CHP from natural gas [19]. Alternative to gasification is the combustion of straw to produce heat and/or electricity. The electricity-only system has been analysed with the plant gate as system boundary and taking into account the CO_2 balance between that released by the processing and combustion and that fixed by the wheat plant [13]. Another conversion alternative is the wheat straw-based bioethanol and acetic acid system with lignin supplying CHP. However, wheat straw can be interchangeably used between CHP and bioethanol production, without any difference in environmental impacts.

Unlike the bioethanol plant, the construction stage in wheat straw CHP system becomes important in the case of CPE (28%) and AP (25%), respectively. Transportation also has impact towards ARU (35%). For the other IC, the wheat straw cultivation incurs the maximum impacts, contributing by 66% to CPE, 68% to AP and 65% to ARU, respectively. Plant operation contributes the most to EP (98%).

Table 8 compiles the results of bioenergy production from the base case system (alternative 1), wheat bioethanol and DDGS as animal feed; and straw-based CHP to grid. The following analysis is done for the system as a whole without any allocation of impacts. The net bioenergy produced is 12.9 PJ y^{-1}, 84% of which in the form of ethanol and the rest in the form of CHP. Therefore, the bioenergy harvested from the land cultivated after conversion is 74.9 GJ ha^{-1} y^{-1}. The E_{ratio} obtained is 1.91. The CPE requirements by the whole wheat cultivation, bioethanol plant operation and transportation and construction of the wheat bioethanol and CHP system are 3.27 PJ y^{-1} (**Table 3**), 3.40 PJ y^{-1} (**Fig. 4**), 0.067 PJ y^{-1} and 0.041 PJ y^{-1}, respectively. The CPE to produce the equivalent amount of energy and soy meal corresponds to 12.9 PJ y^{-1} from gasoline (E_{ratio} 0.84 [14].), 1.1 PJ y^{-1} from heat generation from natural gas boiler (E_{ratio} = 0.7, assumed), 4.4 PJ y^{-1} from electricity mix (3% of renewable mix in the current UK context), and 0.97 PJ y^{-1} from soy meal production (**Table 7** and **Table 8**). This gives a total CPE of 19.37 PJ y^{-1} with an overall E_{ratio} = 0.66. Therefore, about 65% energy savings can be achieved from the whole bioenergy system.

Table 8 Annual products and bioenergy generated from the overall system (alternative 1).

Subsystem	Feedstock/ Product	Flow rate Gg	Bioenergy PJ	Soy meal equivalent Gg
Cultivation	Wheat grain	1200	22.3	–
Bioethanol Plant	Ethanol	404	10.8	–
	DDGS	295	–	236
Cultivation	Wheat straw	361	5.27	–
Straw CHP Plant	Electricity	–	1.38	–
	Heat	–	0.737	–
Total bioenergy equivalent to gasoline and fossil CHP Systems			12.9	–

In the cradle to product utilisation (ethanol combustion) analysis of the whole base case (wheat bioethanol and straw CHP to grid) system, the total GWP_{100} (as CO_2-eq) is calculated as the sum of that from the whole wheat cultivation (**Table 3**), wheat bioethanol plant operation (**Fig. 4**), straw CHP plant operation, total transportation (4110 Mg y^{-1}), plant construction (4910 Mg y^{-1}) and ethanol combustion (at 1.9 Mg Mg^{-1}). To get the combined net GWP_{100}, the total CO_2 binding by the whole wheat plant is credited (1810000 Mg y^{-1}). **Fig. 5** shows a systems diagram that represents the GWP_{100} flows from the different sources throughout the system life cycle per unit of total bioenergy produced (**Table 8**). This results in 57% reduction in GWP_{100} from stand-alone wheat bioethanol and straw CHP systems compared to gasoline production and combustion system [14], natural gas based heat generation system at 70% thermal efficiency [19] and soy meal production system [35] together.

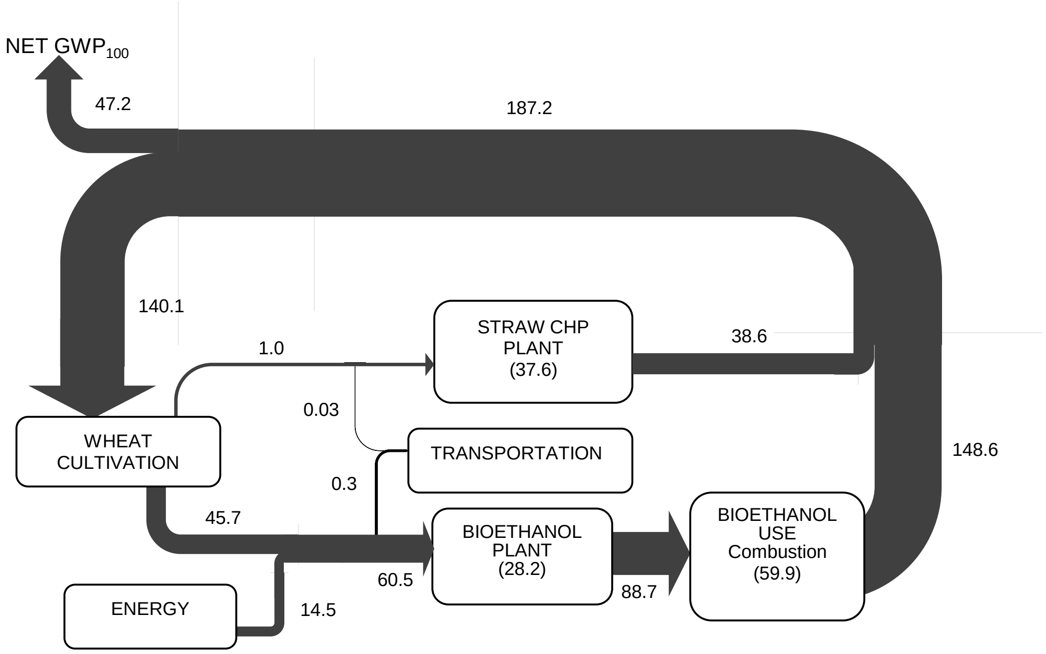


Fig. 5 Life cycle GWP_{100} (CO_2-eq), in g MJ^{-1}, of the production of bioenergy (as ethanol, heat and electricity) and DDGS in a whole wheat-based system. Values for CHP and bioethanol plant include GWP_{100} from other raw materials, process emissions and construction.

Fig. 6 shows the percentage distribution of CPE, EP, AP and ARU for various subsystems included in the wheat bioethanol and straw CHP to grid system: whole wheat cultivation, wheat bioethanol plant operation, straw CHP plant operation, transportation and construction. The hot spots in the system are wheat cultivation and bioethanol plant for CPE (48% and 50% respectively), as well as for ARU (52% and 46% respectively). EP and GWP_{100} are distributed among the three subsystems: wheat cultivation (47% and 37% respectively), plant (27% and 30% respectively) and bioethanol plant (26%, and 33% respectively). Wheat cultivation (91%) and bioethanol plant (8%) dominate the contribution to AP.

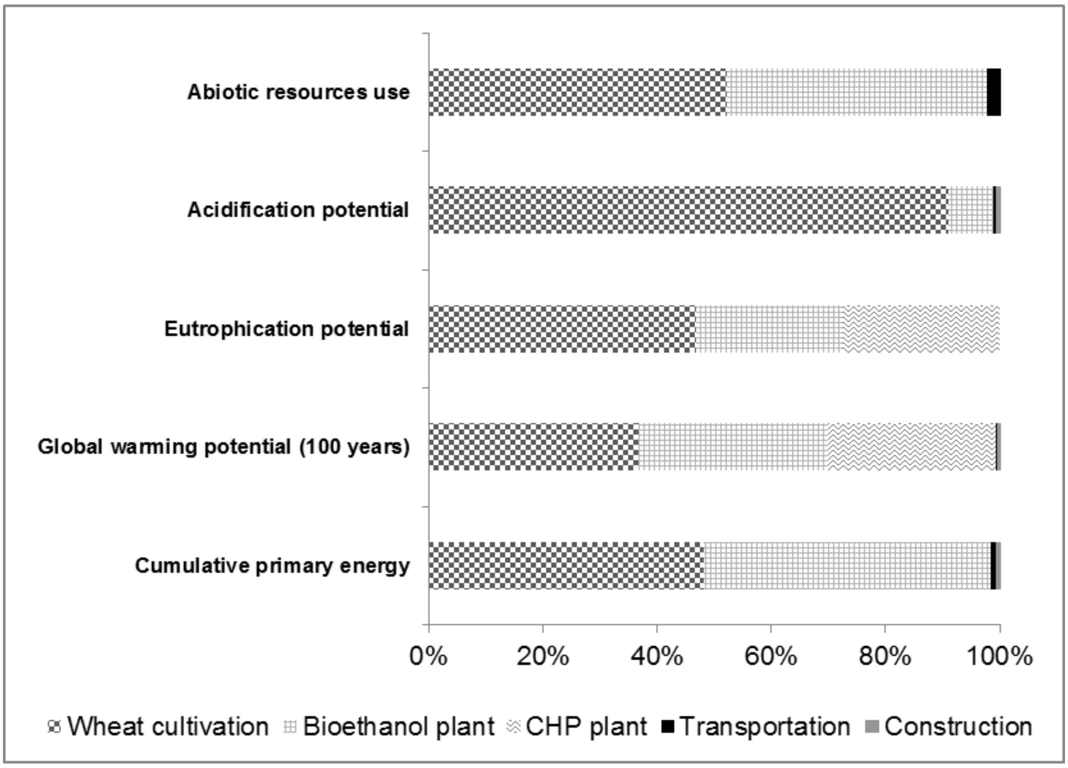


Fig. 6 Environmental impact of wheat bioethanol and straw CHP to grid system.

Results presented here are comparable with those reported in literature for similar systems. The GWP_{100} (as CO_2-eq) value allocated to electricity (0.541 kg kWh^{-1}, without CO_2 balance consideration) from the CHP plant are comparable to those obtained from electricity generation from gasification of short rotation coppice willow chips of 0.482 kg kWh^{-1} for GWP_{100} with energy ratio of 19.3 [18]. The results of LCA of bioethanol and CHP production systems from wheat straw showed that the use of crop residues in a biorefinery reduces the GHG emissions by about 50% and fossil energy demand by more than 80% [16].

4. Integrated system GWP_{100} and CPE saving analyses

The effect of the integration of the various bioenergy systems (straw- or DDGS-based CHP plant, heat production from DDGS and bioethanol plant) on the GWP_{100} reduction and CPE saving from the production and usage of bioethanol in reference to gasoline was analysed. The calculation of the combined net GWP_{100} and CPE was carried out following the substitution method taking the credits from the equivalent fossil-based energy and soy meal replacement by DDGS. The comparative reference systems for heat and electricity from straw are natural gas boiler for the generation of heat and grid electricity (UK electricity mix), respectively. **Table 9** summarises the results of GWP_{100}, CPE, bioenergy production and the corresponding savings for each case. Additionally, an integrated system (5) wherein a part of DDGS-based heat and straw-based CHP are used in the wheat bioethanol plant is considered.

Analysing the wheat grain production and bioethanol plant operation using the heat from the natural gas boiler and electricity from grid (1), the resulting GWP_{100} comes from the cultivation of grain (economic allocation, **Table 3)**, bioethanol plant operation and construction, raw materials transportation (**Fig. 4**), bioethanol transportation calculated assuming distribution within a radius of 120 km, ethanol combustion, and the corresponding

CO_2 binding to wheat grain (**Table 7**). The credit from replacing 236000 Mg y^{-1} of soy meal equivalent is –171000 Mg y^{-1}. The net GWP_{100} of 422000 Mg y^{-1} corresponds to 39.0 g MJ^{-1} (**Table 9**), thus achieving a reduction by 54%. This GWP_{100} from overall wheat bioethanol and DDGS system is less than the impact allocated to cradle to bioethanol product utilisation route by economic values in **Table 7**, due to the account of credit from the replacement of soy meal by DDGS.

Nevertheless, both approaches (39% based on bioethanol allocation and 54% based on bioethanol and DDGS co-production and utilisation, respectively) demonstrate that a stand-alone UK wheat bioethanol subsystem may not meet the EU Renewable Energy Directive constraint on GHG emission reduction by > 60% by 2020. Therefore, other alternatives to improve environmental performance of the bioethanol production need to be studied. In case of CPE, the saving is 56% with respect to the production of gasoline. The following cases make reference to the values from the wheat bioethanol plant as in base case (1).

For alternative number (2), the production of 2.95 PJ y^{-1} of heat from burning all the DDGS (LHV of 18.2 MJ kg^{-1}, carbon mass content of 45%) [37] is utilised within the bioethanol plant. The bioethanol plant heat requirement (as steam) from natural gas is completely replaced by the heat from DDGS and 0.95 PJ y^{-1} of excess heat is produced for the grid. Therefore, the CPE of 2.03 PJ y^{-1} and 1.36 PJ y^{-1}, respectively, are subtracted from the base case and the net CPE of the system is reduced to 3.20 PJ y^{-1}. The net bioenergy produced is now of 11.8 PJ y^{-1} and the overall effect is an increase in the energy ratio to 3.67. This gives savings of 77% in fossil CPE from the production of bioethanol with respect to the production of gasoline. However, the net GWP_{100} (as CO_2-eq) is increased to 874000 Mg y^{-1} due to the addition of 487000 Mg y^{-1} from DDGS combustion, even after the credits from the replacement of 122000 Mg y^{-1} and excess heat of 83300 Mg y^{-1} (**Table 9**). No additional CO_2 binding is credited since DDGS comes from the processing of wheat grain (and the corresponding credit was already accounted in the base case (1)). Also, the electricity is supplied from the grid. As a result, the balance over case (2) indicates higher GWP_{100} impact of 80.9 g MJ^{-1} bioethanol produced yielding a marginal saving by 4%.

An alternative 3, where the DDGS (moisture and ash mass contents of 8% and 3.9% respectively) is used as a raw material for the CHP plant and the energy generated is delivered to the bioethanol plant and the excess electricity is exported to grid, is considered. The DDGS conversion process provides 0.78 PJ y^{-1} of heat and 1.47 PJ y^{-1} of electricity (**Fig. 7**). All the electricity requirements (0.12 PJ y^{-1}) by the bioethanol plant are thus completely replaced by the renewable electricity. 39% of the heat required by the bioethanol plant is also replaced. Thus, the corresponding credits can be subtracted from the impacts of the base case as before. Thus, after using the heat and required electricity within the bioethanol plant, the net bioenergy produced by the bioethanol (10.8 PJ y^{-1}) and DDGS CHP (1.4 PJ y^{-1}) system is 12.2 PJ y^{-1}. As in case (2), the net GWP_{100} is increased from that of the base case due to the fact that CO_2 emissions are added to the system from the DDGS CHP plant and there is no credit for DDGS replacing soy meal. This system benefits from the production of renewable electricity and can achieve GWP_{100} savings by 17% after credits. 93% of the CPE is replaced by an equivalent amount of bioenergy (bioethanol-DDGS based CHP).

In alternative (4), the straw-based CHP is integrated with the bioethanol plant. The allocated GWP_{100} to straw from the wheat cultivation system must be included into the base case GWP_{100}. Additionally, the CPE and the GWP_{100} from the straw-based CHP plant operation and construction and straw transportation should be added. However, the integration of straw-based CHP with bioethanol plant can take advantage of additional CO_2 binding by the straw. Besides, DDGS is sold for animal feed, replacing soy meal and gaining the corresponding credits as in the base case (1). Similarly to case (3), the straw based CHP plant replaces a part of the heat required by the bioethanol plant (37%) and there is excess electricity exported to grid. The resulting net GWP_{100} reduction is 85%, fulfilling the EU Directive 60% emission reduction target. By taking all the credits, the CPE requirement by the system reduces by 97%. The net bioenergy is 12.1 PJ y^{-1} (**Table 9**) from 172370 ha of grade 3 land use (**Table 3**) providing land energy yield of 70 GJ ha^{-1} y^{-1}.

Case 5 was explored by integrating the bioethanol plant with the straw-based CHP plant and DDGS combustion to supply the balance of heat (steam) required by the bioethanol plant. This case is a combination between cases 2 and 4. The integration is about supplying the entire heat requirement of 2.0 PJ y^{-1} from the straw CHP plant (0.74 PJ y^{-1}) and from the DDGS heat (1.26 PJ y^{-1}) that completely replace the fossil-based heat (steam). The electricity requirement and the excess electricity generation are similar as in case 4. 126000 Mg y^{-1} of DDGS are required (assuming energy content as in case 2) to supply the balance of heat. Therefore, the system can still gain credits from 168000 Mg y^{-1} of DDGS replacing 135000 Mg y^{-1} soy meal, thus resulting in GWP_{100} and CPE savings. The overall GHG emission reduction is 63% with respect to the use of gasoline. The CPE for the base case (1) is not only replaced by the production of bioenergy, but additionally energy in the form of excess electricity and bioethanol is saved. This system thus also achieves the EU Directive’s 60% GHG emission reduction target.

In summary, the integration of wheat straw CHP and bioethanol plant proved to be an effective way to achieve the EU Directive GWP_{100} reduction target, while saving fossil CPE. The complete replacement of heat (steam) and electricity by straw CHP and DDGS in alternative 5 is another option in which GWP_{100} is lower but more fossil CPE can be saved. The incentives for the reduction of GWP_{100} beyond the target and the capital costs involved in the two integrated systems would finally determine the selection of one of these alternatives. The LCA approach presented took detailed account of CO_2 binding by wheat plant and the emissions from fermentation and combustion (ethanol, DDGS and/or straw). The saving results found for alternatives 4 and 5 are similar to those reported in [16].

Table 9 Summary of overall results on GWP_{100} (CO_2-eq) in Mg y^{-1}, CPE in PJ y^{-1} and corresponding savings.

Alternative	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
GWP_{100} from different subsystems and combustion					
Cultivation	591000	591000	591000	604000	604000
Bioethanol plant	555000	555000	555000	555000	555000
CO_2 binding	–1330000	–1330000	–1330000	–1810000	–1810000
Ethanol combustión	774000	774000	774000	774000	774000
DDGS combustión	–	487000	–	–	208000
CHP plant	–	–	488000	487000	487000
Subtotal GWP_{100}	**590000**	**1080000**	**1080000**	**610000**	**818000**
CPE and GWP_{100} credits					
From DDGS replacing soy meal					
GWP_{100} credit	171000	0	0	171000	98000
CPE credit	0.98	0	0	0.98	0.56
From fossil based energy replaced					
Heat		2.95	0.78	0.74	2
GWP_{100} credit		206000	48100	45100	122000
CPE credit		3.39	0.79	0.75	2.03
Electricity		0	1.47	1.38	1.38
GWP_{100}		0	273000	256000	256000
CPE		0	4.73	4.44	4.44
Net GWP_{100} after credits	422000	874000	760000	137000	341000
Net CPE after credits	5.62	3.20	1.09	0.47	–0.43
Values from reference fuel (gasoline)					
GWP_{100}	914000				
CPE	12.9				
Final results					
Net bioenergy	10.8	11.8	12.2	12.1	12.1
GWP_{100} (g MJ^{-1})	**39.02**	**80.91**	**70.37**	**12.63**	**31.55**
GWP_{100} reduction	**54%**	**4%**	**17%**	**85%**	**63%**
E_{ratio}	**1.92**	**3.67**	**11.10**	**27.62**	**–**
CPE saving	**56%**	**77%**	**92%**	**97%**	**103%**

5. Conclusions

A cradle to grave LCA of the UK whole wheat-based bioethanol and straw-based CHP system has been performed considering the various IC including GWP_{100} and CPE. It is demonstrated that the wheat cultivation, wheat bioethanol plant and straw CHP plant, if deployed in an integrated manner, can be more environmentally sustainable than the reference fossil-based system.

A transparent and comprehensive approach that included LCA of the UK whole-wheat cultivation, transportation and construction and operation of plants and utilisation of end products has been demonstrated. The analysis showed that the state-of-the-art bioethanol systems may not achieve the EU Directives' minimum GHG emission reduction target of 60%. Therefore, five integrated systems, wherein bioethanol energy requirements were met by lignocellulosic energy, were proposed. Cases 2 and 3, with DDGS used as a source of heat and CHP, respectively, improve the energy use of the system thereby saving CPE, but incur no emission reduction. The other two integration alternatives with bioethanol energy requirements met by straw CHP (alternative 4) and straw CHP and DDGS heat (alternative 5) respectively, achieve the EU Directive's target GHG reductions. The system in alternative 4 offers GWP_{100} reduction by 85% and CPE savings by 97%, whilst the system in alternative 5 achieves the EU Directive's target GWP_{100} reduction (63%) and CPE saving of more than 100%. The system assessed has also the advantage that no land use change is involved and impact on water is also negligible. A high yield of total bioenergy per ha must be attained implying an efficient use of land, a factor that is important considering that the land is a limiting resource. Concluding from various integration synergies within bioenergy systems and integrated energy system alternatives this study clearly demonstrates an urgent need for greater exploitation of lignocellulosic energy systems into biorefineries.

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