AC0410 ANNEX 1: LCAD METHODOLOGY

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1. Baseline farm descriptions

Large dairy farm

Key features:

- 250 ha
- 481 milking cows producing 8626 L milk each
- 131 dairy heifers
- 131 dairy calves
- Annual replacement rate for dairy cows is 30.5%.
- 991 t imported concentrate and hay feed
- 8 weeks outdoor grazing, remaining time indoors
- All excreta generated indoors sent to liquid slurry (tank, with crust is default option)

Total solids and N excretion are calculated from feed input minus retention in Farm Adapt based on IPCC (2006) Tier 2 equations, and feed into housing and storage emissions described below.

Key land management parameters are provided in Table 1.1 based on RB209 recommendations (DEFRA, 2010). Total N application to grass and maize includes all N contained in applied slurries (after storage losses accounted for). Plant available N, volatilisation and leaching losses are calculated using MANNER-NPK, assuming either splash-plate or trailing shoe application (MANNER NPK run with sandy-clay-loam top- and sub- soil, and postcode EX31 – Barnstable, Devon). Slurry is applied to grazing and silage grass in February and September at a rate of 30 m^3/ha, and to maize area in April at a rate of 60 m^3/ha. In addition, for IPCC FCR estimates for forage maize, it was assumed that 5% of peak above ground biomass is incorporated into the soil each year along with below-ground biomass calculated as a proportion of above-ground biomass using ratios given in Table 11.2 of IPCC (2006). FCR N inputs were also calculated for reseeding of grass leys every five years.

Table 1.1. Features of the large dairy baseline farm

Crop	Area	N	P_2O_5	K_2O	Net yield
		kg/ha			t/ha (t DM/ha)
Grazing grass	13	290	20	0	
Silage grass	41.8	340*	80*	250*	40 (10)
Fodder maize	195.2	100*	85*	205*	45 (13.5)
*Fertiliser plus manure available nutrients Net yield after silage loss of 10% in default scenario					

According to the British Survey of Fertiliser Practice for 2010 (DEFRA, 2011), 2.7% of grassland receives lime at 3.4 t/ha, equivalent to approximately 1 t every 10 yrs. This value appears low, and may reflect under-application and lower productivity grasslands. An average lime application rate of 2.5 tonnes every 10 years was assumed for grassland, and 2.5 tonnes every 5 years for maize (as per arable tillage land). For grassland and tillage land, agrochemical application rates were assumed to be 1 and 2 kg ha yr active ingredient, respectively.

Electricity consumption for milking and housing operations of 910 kWh primary energy (350 kWh electricity) per dairy cow per year were taken from the DEFRA project AC0401 report (Warwick HRI, 2007). Diesel consumption is calculated based on field operations in Farm Adapt, and is similar to the 548.7 kWh per milking cow per year specified in Warwick RHI (2007). However, the Warwick report does not contain data for stationary oil use for heating, but assumes this is included in electricity generation. The authors refer to considerably higher (factor 2.5) mobile diesel consumption measured on Irish dairy farms compared with modelled estimates. Heating of water for parlour washing is unlikely to use expensive electricity, so we have assumed that heating oil consumption is equivalent to 50% of electricity kWh (i.e. 175 kWh per milking cow).

In addition, the farmhouse is assumed to use the average heating load of a UK home of 160 kWh/m^{2}yr, and represent twice the average UK home floor area (so totalling 250 m^2), leading to a heating demand of 40,000 kWh per year supplied by an oil boiler (this is the minimum amount of heat displaced in the AD scenarios).

Average dairy farm

Key features:

- 85 ha
- 125 milking cows producing 7124 L milk each
- 36 dairy heifers
- 36 dairy calves
- Annual replacement rate for dairy cows is 26.5%.
- 179 tonnes imported concentrate and hay feed
- 6 months outdoor grazing, 6 months indoors
- All excreta generated indoors sent to liquid slurry

Key land management parameters are provided in Table 1.2 based on RB209 recommendations (DEFRA, 2010). Other management details are as per the large dairy farm, above.

Table 1.2. Features of the average dairy baseline farm

Crop	Area	N	P_2O_5	K_2O	Yield
	ha	kg/ha			t/ha (t DM/ha)
Grazing grass	37	290	20	0	
Silage grass	15.7	340*	80*	250*	40 (10)
Fodder	32.3	100*	85*	205*	45 (13.5)
*Fertiliser plus manure available nutrients.					

Beef and energy farm

Although described alongside other baseline farm descriptions, this farm is a bioenergy scenario farm, based on a scenario outlined by Spackman (2011) where an average sized dairy farm converts to a beef and AD enterprise growing maize and grass to feed an AD unit of approximately 100 kWe capacity. Key features are:

- 85 ha
- 40 beef cattle
- 15,492 kg live weight exported per year
- 28 tonnes imported concentrate and hay feed
- All indoor-excreta sent straight to the AD unit

Key land management parameters are provided in Table 1.3 based on RB209 recommendations (DEFRA, 2010). Other management details are as per the average dairy farm, above.

Table 1.3. Features of the large dairy baseline farm

Crop	Area	N	P_2O_5	K_2O	Yield
	ha	kg/ha			t/ha (t DM/ha)
Grazing grass	0	290*	20	0	
Silage grass	53	340*	80	250	40 (10)
Fodder	32	100*	85	205	45 (13.5)
*Fertiliser plus manure available-N.					

Of the above areas, 45.9 ha of grassland and 20.1 ha of fodder maize are dedicated to AD feedstock production. Depending on user-defined options in the LCAD scenario tool, indirect LUC may be attributed to the area of maize grown for the AD unit (see LUC calculations in the bioenergy feedstock descriptions, below).

Arable farm (mineral fertiliser only)

Both arable baseline arable farms are assumed to be located in E England. For MANNER-NPK model runs, a hypothetical location close to Dereham, Norfolk, was assumed (post code NR20 xxx). The large arable farm covers an area of 400 ha, divided according to Table 1.4. Key land management parameters are summarised in Table 1.4, based on RB209 recommendations (DEFRA, 2010) and average yields (Nix, 2010). Fertiliser-N applications are split accordingly:

- Winter wheat, 40 kg N applied 1st March, 75 kg N applied 15th April and again 15th May (latter application rates increase to 90 kg N for second winter wheat in rotation).
- Spring barley, all fertiliser N applied on 15th April
- Oil seed rape, 50% all fertiliser-N applied in early March, 50% in early April
- For forage maize, all fertiliser-N application on 15th April

Lime application rates of 2.5 tonnes every 5 years (modelled as 500 kg per year across all crops) were assumed, rounded up from UK statistics for lime application in DEFRA (2011) that indicate 10% of tillage land receives lime at an average rate of 4 t/ha every year.

Table 1.4. Land use parameters for the baseline large arable farm

Crop	N	P_2O_5	K_2O	Grain yield	Straw yield	Exported straw yield
	kg/ha			t/ha (t DM/ha)	t/ha (t DM/ha)	t/ha (t DM/ha)
Winter wheat 1	190	60	45	8.75 (7.43)	4.52 (3.62)*	3.03 (2.43)**
Winter wheat 2	220	90	75	7.88 (6.70)	4.34 (3.39)*	2.84 (2.27)**
Spring barley	170	90	65	5.75 (4.90)	3.68 (2.94)	2.46 (1.97)**
Oil seed rape	190	80	70	3.3	NA	NA
*Straw data based on biomass ratios from HGCA (2012) **Assume 67% harvestable straw from WW and SB actually harvested						

An average agrochemical application rate of 2 kg/ha/yr active ingredient was assumed, approximating with Biograce Model assumptions. Seed application rates of 170 kg/ha for winter wheat and spring barley and 5 kg/ha for oil seed rape were taken from Teagasc (2013). Diesel consumption for field operations is calculated in Farm Adapt based on estimated time taken to complete each operation (Nix, 2009) and average hourly fuel consumption data for tractor operations.

For IPCC F_{CR} estimates of N losses, it was assumed that all non-harvested above-ground biomass was incorporated into the soil each year along with below-ground biomass calculated as a proportion of above-ground biomass using ratios in Table 11.2 of IPCC (2006). Above-ground residues (Table 1.5) and harvestable straw (Table 1.4) were taken from Stoddart and Watts (2012). Soil N inputs associated with soil incorporation of biomass N were allocated to the subsequent crop in the rotation.

Table 1.5. Above and below- ground biomass quantities incorporated into the soil following the harvest of each crop in the arable rotation

Crop	AG residues	Incorporated AG residues	Incorporated BG residues
	DM t/ha/yr		
Winter wheat 1	7.14	4.71	3.21
Winter wheat 2	6.44	4.17	2.89
Spring barley	5.53	3.56	2.43
Oil seed rape	6.13	6.13	2.08
Source: Stoddart and Watts (2012) and IPCC (2006).			

Large arable farm + pig slurry

This scenario is identical to the large arable farm scenario above, except that some mineral fertiliser is substituted with pig slurry from a nearby indoor pig farm. It was assumed that 19,934 kg N was imported to the farm in 5098 m^3 of pig slurry, based on N excretion in a typical indoor pig farm of 25,100 kg N (Newell Price et al., 2011). Slurry is transported 5 miles in a tractor tanker and applied to the first winter wheat in the rotation on September 15th at a rate of 22 t/ha and to the spring barley crop on April 15th at a rate of 30 t/ha.

Because pig slurry is often regarded as a waste from intensive pig farms, burdens associated with storage emissions were attributed to the pig farm and not the arable farm using it as a fertiliser. However, in the AP-SF scenario, avoided pig slurry storage emissions are accounted for as an AD credit.

Storage CH_4 emissions are based on IPCC (2006) EFs for liquid slurry/pit storage of fattener/market pig slurry: 6 kg per head (Table 10.14 IPCC 2006). NH_3 emissions are from Misselbrook et al. (2012) for housing and storage assuming N_{ex} 0.51 kg N per 1000 kg animal mass per day (Table 10.19 IPCC 2006), of which 70% in TAN (Webb and Misselbrook, 2004). Slatted floor housing emissions are 29.4% TAN, and tank storage emissions 13% TAN (Misselbrook et al., 2012). Thus, based on N_{ex} in a typical indoor pig farm of 25,100 kg N (Newell Price et al., 2011), counterfactual avoided storage NH_3 emissions are 1958 kg NH_3 per year. Assuming an average pig weight of 50 kg, each pig excretes 9.3 kg N per year so there are 25100/9.3 = 2699 pigs on the farm. Thus, counterfactual storage CH_4 emissions equate to 2699 x 6 = 16,194 kg per year.

After housing losses, 19,934 kg N is exported in slurry to the AD unit. Based on DEFRA (2010) pig slurry TN content (corrected for avoided storage loss) this equates to 5098 tonnes slurry at a TN content of 3.91 kg/tonne (i.e. relatively dilute pig slurry).

For every kg N_{ex} on the pig farm, export to AD immediately after housing avoids 0.078 kg NH_3 and 0.645 kg CH_4 from storage.

2. Upstream and energy-related processes

Ecoinvent v2.2 data were extracted as burdens calculated using the CML LCIA method and for RER system processes excluding infrastructure.

Animal feed production

For LCA data simplicity, concentrate animal feed is assumed to be 100% winter wheat by default, with burden data for processed winter wheat concentrate feed taken from Ecoinvent v2.2 (in reality feed composition will vary but the winter wheat environmental burdens applied may be taken as representative of the range of environmental burdens from different feed types). Where additional feed is imported to the farm in bioenergy scenarios, the LCAD tool user may define SBME or winter wheat as the marginal imported feed type (to reflect the net increase in global concentrate feed demand represented by this management change). SBME replaces WW in the ratio of 0.83 kg/kg on the basis of energy content (13.6 vs 11.3 MJ/kg) (DairyCo, 2013).

The SBME burden of production, processing and transport is calculated using BioGrace activity data (cultivation inputs, processing electricity and natural gas inputs, and transport requirements) for soybeans to produce both SBME and biodiesel (glycerine treated as biodiesel for simplicity). Transport burdens are calculated based on BioGrace transport distances and Ecoinvent v2.2 transport emission factors. Biodiesel produced as a co-product of SBME is assumed to replace diesel, and avoided upstream (and direct GWP) burdens are subtracted from the overall soybean cultivation and processing burdens. This results in the following net burdens for SBME when LUC effects are excluded (**Table 2.1**).

Table 2.1. SBME environmental burdens following a consequential LCA approach that accounts for replaced diesel

Reference flow	kg CO_2e	kg PO_4e	kg SO_2e	MJe	kg Sbe
1 kg SBME	1.45E-01	4.90E-03	2.75E-03	-2.93E+00	-1.41E-03

Although Hortenhuber et al. (2011) attribute LUC to standard SBME using an approach that could be applied to attributional LCA, for consistency with the LCAD tool methodology, no LUC effects are considered if the user selects “Ignore” iLUC. To consider indirect LUC according to LCAD tool user-defined scenarios, winter wheat feed is attributed burdens based on conversion of grassland to arable land within the UK, whilst SBME is attributed additional CO_2e and PO_4 burdens based on land use change from forest to arable in Brazil and grassland to arable in Argentina according to the proportions of feed exported from those countries (FAO Stat, 2013) and assuming that most UK SBME originates from Argentina and Brazil. The fractions calculated to originate from each source country (Table 2.2) correspond closely with data on sources of SBME imported to the EU27 reported in a Netherlands Friends of the Earth (2008) report. The final LUC CO_2e value in Table 2.2 is calculated based on multiplication of cultivation area by LUC factors in PAS 2050 (BSI, 2011).

Table 2.2. SBME feed originating in Brazil or Argentina, and associated iLUC CO_2e burden, expressed per kg additional SBME consumed in the UK

Country	**SBME consumed in UK**	**Mass soy beans required**	**Average yield (Mg ha^{-1} yr^{-1}) FAO**	**Area required**	**Forest to arable CO_2e (kg yr^{-1})**	**Grass to arable CO_2e (kg yr^{-1})**
Brazil	0.605	0.747	3.124	2.4×10^{-4}	8.85	
Argentina	0.395	0.488	2.648	1.8×10^{-4}		0.405
Total						**9.255**

Fertiliser manufacture

For simplicity, fertiliser use in the LCAD tool is assumed to be 100% Ammonium Nitrate. Ammonium nitrate production GHG emissions are taken from Cool farm Tool for GWP and from Ecoinvent for AP, EP and RD (European average 1990s). The latter impacts were not scaled down according to CO_2e reduction because the latter reduction primarily reflects the abatement of N_2O emissions in nitric acid production rather than energy efficiency measures.

P_2O_5 was assumed to be applied as triple superphosphate, and Ecoinvent v2.2 burdens used. K_2O was assumed to be applied in the form of potassium chloride (Ecoinvent v2.2). Agrochemical applications were represented by “unspecified pesticides” in Ecoinvent v2.2, expressed per kg active ingredient applied.

Energy carriers

All energy density data were taken from DEFRA (2012) and BioGrace (2012). Farm-Adapt reports total farm diesel consumption, which was allocated to different grass/crop areas in the LCAD tool in proportion to harvested yield and slurry spreading requirements. For digestate spreading, diesel consumption of 0.5 L/tonne (Dalgaard, 2001) was multiplied by total digestate application for each crop type.

In order to ensure the latest UK specific data were used for energy carriers, CO_2e burdens were taken from DEFRA (2012) for electricity (and also upstream CO_2 burden for diesel), whilst other burdens were taken from Ecoinvent v2.2, scaled down according to reported DEFRA:Ecoinvent CO_2e ratio. According to DEFRA (2012), UK electricity has a lifecycle (Scope 3) CO_2e burden of 0.590 kg per kWh consumed.

For in-field diesel combustion in tractors, NOx emissions were estimated based on EURO III emission standards for $\geq 75 \leq 130$ kW off-road vehicles (new vehicles sold after Jan 2007), equating to 4 g NOx per kWh output (assuming output = 30% diesel input) (Dieselnet, 2013). These emissions are insignificant relative to NH_3. Minor SOx emissions were calculated based on the S content of red diesel, now limited to 10 mg per kg fuel (DfT, 2010).

3. Animal husbandry

Enteric fermentation

Enteric fermentation CH_4 was calculated from equation 10.21 of IPCC (2006), based on feed intake and using a methane conversion factor (Ym) value of 6.5%.

Slurry storage

Slurry storage on dairy farms can be varied in the LCAD tool according to two options: Tank (assumes crust cover); Lagoon. The former represents a typical (default) situation.

Methane emissions are calculated using IPCC (2006) Tier 2 calculations: Eq. 10.23 using volatile solid excretion calculated from Eq. 10.24 in turn based on dry matter intake modelled in Farm Adapt. Methane conversion factors are taken from Table 10.17 of IPCC (2006): 0.11 for storage with crust; 0.68 for lagoon storage.

Housing NH_3 emissions were calculated per livestock unit (LU: 500 kg body mass) per day housed for dairy cows and per calf as per Misselbrook et al. (2012). It was assumed that all indoor-excreted manure on baseline farms is stored as slurry in either a tank with crust or in a lagoon, with the former system being the default. The volume of manure generated and total N excretion (N_{ex}) indoors and outdoors were calculated using an IPCC Tier 2 approach from feed intake and gross energy (GE) requirements in farm-Adapt. Slurry storage EFs of 0.05 and 0.515 total ammonical N (TAN) for tanks (crusted) and lagoons were taken from Misselbrook et al. (2012), assuming 60% of N_{ex} is TAN (Webb and Misselbrook, 2004).

4. Soil emissions

Manure and digestate applications

All direct N_2O emissions are calculated as a proportion of inputs, as per IPCC (2006). However, volatilisation and leaching (and thus indirect N_2O calculations calculated as fractions of NH_3-N and NO_3-N as per IPCC 2006) are based on UK-specific data when the LCAD tool user specifies "MANNER-NPK" in methods section.

MANNER-NPK outputs for various application methods and times are applied to slurry and digestate applications, as previously referred to.

For animal grazing N deposition 6% of TAN was assumed to be volatilised as NH_3 (Misselbrook et al., 2012). A grazing N_{ex} N_2O-N emission factor of 0.02 was applied (IPCC, 2006).

Phosphorus losses were estimated as fixed fractions of P additions to surface soils for grasslands in the west of England (3%) and arable land in the east of England (1%) based on Withers (pers. comm. 2013) and Johnes et al. (1996).

Fertiliser applications

According to Misselbrook et al. (2012): "Ammonium nitrate (and 'other N' category) – a fixed emission factor of 1.8% N applied is now used as there was no consistent evidence of temperature, rainfall, land-use or crop height effects on emission". Thus, a 1.8% N loss factor is applied to all ammonium nitrate N applied.

Fertiliser-N leaching losses are approximated to 10% of all fertiliser-, crop residue- and grazing- N applied across dairy and arable farms (unless IPCC factors selected by LCAD tool users). Indirect N_2O-N emissions are calculated as per IPCC EFs for NH_3-N and NO_3-N (i.e. 0.01 and 0.0075).

Post-application CO_2 emissions from lime are calculated based on IPCC (2006).

Crop residues

For residue-incorporated N, NO_3 leaching was based on the 0.1 factor referred to above.

In addition, depletion in SOC and SON following LUC is accounted for as described in the following section for LUC effects.

5. Bioenergy feedstock production and digestate application

Maize and grass AD feedstocks (dairy and arable)

As per fodder maize and cut-grass management (same management practices and yields assumed), except:

Grass incurs a direct LUC effect on the arable farm that involves biomass and soil C sequestration (negative values = sequestration):

- Biomass C change per ha: [(10.0 t DM x 0.5 t C/t DM) – (13.6 t DM x 0.5 t C/t DM)] / 20 yr = –65 kg C/yr (Eq. 2.15 and 2.16 IPCC, 2006)
- SOC under grassland: SOC_{REF} = 95 t C/ha for cold temperate high activity clay soils (Table 2.3 IPCC, 2006)
- SOC under arable: 95 x 0.69 F_{LU} x 1 F_{MG} x 1 F_I (full tillage, medium input) = 65.55 t C/ha
- IPCC Tier 1 SOC change: (65.55 – 95 t C) / 20 yr = –1.473 t C ha/yr (Eq.2.25 IPCC, 2006)

Grass and maize on the arable farm incur an indirect land use change effect (depending on LCAD tool setting defined by user), equivalent to conversion of grassland to cropland somewhere in the UK, that involves biomass and soil C loss, crop residue N incorporation and soil organic N mineralisation (coupled with SOC mineralisation):

- Biomass C change per ha: [(13.6 t DM x 0.5 t C/t DM) – (10.0 t DM x 0.5 t C/t DM) –] / 20 yr = 65 kg C/yr (Eq. 2.15 and 2.16 IPCC, 2006)
- SOC under grassland: SOC_{REF} = 95 t C/ha for cold temperate high activity clay soils (Table 2.3 IPCC, 2006)
- SOC under arable: 95 x 0.69 F_{LU} x 1 F_{MG} x 1 F_I (full tillage, medium input) = 65.55 t C/ha(
- IPCC Tier 1 SOC change: (95 t C – 95 t C) / 20 yr = 1.473 t C ha/yr (Eq.2.25 IPCC, 2006)
- F_{CRN} = 2400 kg x 0.015 + 10200 kg (Table 6.4 IPCC, 2006) x 0.012 (Table 11.2 IPCC, 2006) = 272 kg N/ha. Over 20 year default transition period = 13.6 kg N/ha/yr
- F_{SOM} = 1.473 x 1/15 x 1000 = 98.2 kg N/ha/yr (Eq. 11.18 IPCC, 2006).

Winter wheat and Oil Seed Rape for biofuels

As per winter wheat (1st crop) and oil seed rape management, except indirect land use change effect (depending on LCAD tool setting defined by user), equivalent to conversion of grassland to cropland somewhere in the UK (calculations as per above see above).

Miscanthus (dairy and arable)

Fertiliser application rates are based on RB209 recommendations. Small crop off-takes of 6 kg N per t DM can be compensated by soil mineralisable N, but an N application rate of 60-80 kg N/ha is recommended from yr 3 onwards.

Harvested crop off-take of P_2O_5 is approximately 1 kg per t DM, with a soil at P index of 1 required. P_2O_5 was assumed to be applied at a replenishment rate of 14 kg/ha from yr 3 onwards.

Harvested crop off-take of K_2O is approximately 8.5 kg K_2O per t DM, variable depending on weather and harvest time. A replenishment application rate of 120 kg/ha/yr was assumed to be applied from year 3 onwards. These values are summarised in Table 5.1.

Table 5.1. Miscanthus nutrient application rates

Nutrient	Max application rate	Average 20-yr application rate
	kg ha^{-1} yr^{-1}	
N	70	63
P_2O_5	14	12.6
K_2O	120	108

Two lime applications of 5 t/ha were assumed over 20 years, averaging 0.5 t/ha/yr as per grass. Crop-residue N incorporation from the previous crop, F_{CRN}, is calculated as per grassland reseeding in the dairy scenario, or the second winter wheat crop in the arable, to reflect preceding grassland or first winter wheat crops, then divided by the 20-year miscanthus crop rotation.

Agrochemical use averages 0.42 kg active ingredient per ha per year (herbicide application pre-planting, first two years, grubbing up) (Styles and Jones, 2007).

Harvesting occurs in late winter/spring with a moisture content below 40% after leaf senescence (DEFRA, 2001). Mowing consumes 8 L ha^{-1}, baling and handling 1.6 L/t (Dalgaard et al., 2001), equating to 58.4 L diesel per ha.

Maintenance operations (fertiliser application) add another 9.5 L diesel consumption per ha per year (Styles and Jones, 2007).

Where grassland is converted to miscanthus, it is assumed that below ground biomass and SOC remain constant, whilst crop residue N incorporation and above-ground biomass C changes are accounted for using IPCC (2006) equations:

- F_{CRN} (kg N) per ha: (2400 x 1 x 0.015 + 10200 x 0.012) / 20 yr = 7.9 kg N/yr (Table 11.2 IPCC 2006)
- AG biomass C change per ha: [(12.8 t DM x 0.5 t C/t DM) – (2.4 t DM x 0.5 t C/t DM)] / 20 yr = +260 kg C/yr

Indirect LUC is ignored where miscanthus replaces grassland, as this is most likely to be rough grassland converted to improved grassland, with possible increases or decreases in soil and biomass C depending on specific management practices.

Where arable land is converted to miscanthus, crop residue N incorporation, above-ground biomass C change, below-ground biomass C change and SOC change and N mineralisation are accounted for using IPCC (2006):

- Biomass C change per ha: [(10 t DM x 0.5 t C/t DM) –(12.8 t DM x 0.5 t C/t DM) – (11.2 t DM x 0.5 t C/ t)] / 20 yr = –350 kg C/yr (Eq. 2.15 and 2.16 IPCC, 2006)
- SOC under Miscanthus: SOC_{REF} = 95 t C/ha for cold temperate high activity clay soils (Table 3.3.3 IPCC, 2006)

- SOC under arable: 95 x 0.69 F_{LU} x 1 F_{MG} x 1 F_I (full tillage, high input) = 65.55 t C/ha
- IPCC Tier 1 SOC change: (95 – 65.55 t C) / 20 yr = –1.473 t C ha/yr (Eq.2.25 IPCC, 2006)

Miscanthus displacement of arable crops incurs an indirect LUC effect (depending on LCAD tool setting defined by user), equivalent to conversion of grassland to cropland somewhere in the UK, that involves biomass and soil C loss, crop residue N incorporation and soil organic N mineralisation (coupled with SOC mineralisation):

- Biomass C change per ha: [(13.6 t DM x 0.5 t C/t DM) – (10.0 t DM x 0.5 t C/t DM)] / 20 yr = 65 kg C/yr (Eq. 2.15 and 2.16 IPCC, 2006)
- F_{CRN} = 2400 kg x 0.015 + 10200 kg (Table 6.4 IPCC, 2006) x 0.012 (Table 11.2 IPCC, 2006) = 272 kg N/ha. Over 20 year default transition period = 13.6 kg N/ha/yr
- F_{SOM} = 1.112 x 1/15 x 1000 = 74 kg N/ha/yr (Eq. 11.18 IPCC, 2006).

N.B: Some scenarios result in a reduction in maize area on the dairy farms owing to changed diet and economic factors as determined by Farm-Adapt optimisation solutions. Where a reduction in maize area occurs, a direct LUC effect involving conversion of cropland to grassland is attributed to bioenergy-induced changes.

AD waste feedstock

There are conflicting data on average food waste composition. The scenario tool used food waste characteristics taken from WRAP (2010), representing extensive sampling specifically of food waste in Wales. It is assumed these characteristics will be representative of the entire UK. An annual average was taken, to even out the significant seasonal variability reflected in the results below. The nutrient concentrations in the table below correspond closely with those reported in Bernstad et al. (2012), when corrected for dry matter content, and are also similar to Rintalla (2011). They differ from values used in MANNER-NPK for P and K.

Table 5.2. Characteristics of food waste in Wales, based on average summer and winter representative samples from across all Welsh local authorities.

	Dry matter	Volatile solids	C	N	P2O5	K2O
	%	kg/tonne (wet)				
Summer	24.2	210.0	115.6	6.9	1.3	3.4
Winter	27.7	257.0	136.6	7.3	1.3	3.3
AVERAGE	**26.0**	**233.0**	**125.9**	**7.1**	**1.3**	**3.3**

Source: Based on data from WRAP (2010).

Digestate application

For the dairy scenarios, Farm Adapt modelling was performed for fixed-output and non-fixed output scenarios. As the results were similar, fixed output was assumed to avoid consequential LCA scenario assumptions.

It is assumed that digestate is separated in all cases. For NMP and modelling simplicity, for the dairy bioenergy scenarios it is assumed that solid fraction contains all P and K, and is spread on maize area, whilst N in the liquid fraction is divided across maize and grass in proportion to N requirements. It is assumed that the liquid fraction has a dry matter content of 2% (MANNER-NPK for digestate liquids). NH_4-N content is based on feedstock characterisation (including Farm Adapt diet-related cattle slurry N content) and AD module outputs. Low NH_4-N concentrations in silage grass and maize digestate concur with results published in AFBI (2012) for silage grass digestate (0.52 kg NH_4-N per tonne out of 4.95 kg total N per tonne).

For arable bioenergy scenarios, the liquid fraction of food waste digestate is applied across the four crops in rotation in proportion to their N requirements whilst the solid fraction applied to crops in proportion to their P_2O_5 requirement. Liquid digestate is applied in September, April and February for WW1, WW2, SB and OSR, respectively.

Total food waste digestation is limited by K_2O excess for the arable farm to 10,000 t/yr in the A-F scenario (to conservatively maintain K_2O surplus below 10 kg/ha/yr).

It was difficult to obtain reliable data on the K_2O content of AD feedstocks, especially silage maize and grass. Values for P_2O_5 and K_2O concentrations in silage grass and maize were calculated from a modelling approach, as equal to soil applications of these nutrients divided by yield. Still, K_2O was the first nutrient to exceed crop requirements with digestate returns from grass, maize and food waste inputs. Although K_2O is not associated with major environmental impacts and is not the focus of nutrient surplus concerns, it was assumed that significant surpluses should be avoided: therefore, the quantities of food waste digested in relevant scenarios was constrained by crop K_2O requirements. Had N requirements been used, considerably greater quantities of food waste could be imported onto on-farm AD units.

6. Bioenergy processing and conversion

AD module

See the description of AD modelling undertaken by the Thünen Institute in Annex 2. In addition, for the heat only SD-S scenario, the electricity demand for operating feeder pumps and mixers was calculated based on a 2.2 kW draw over 33% of the year based on data in RASE (2011) for a similar sized heat only case study. For food waste scenarios, in addition to the 20% parasitc heat demand for digester heating, a further 30% of residual default scenario heat output was assumed to be required for food pasteurisation (based on working group feedback).

For all fuels, lower heating values (net calorific values) were taken from DEFRA (2012) and BioGrace (2012). Specifically for methane, a LHV of 35.9 MJ/m^3 was applied.

Biofuel processing

See the description of biofuel cultivation (for comparison with LCAD tool cultivation data) and processing modelling undertaken by the Thünen Institute in Annex 2.

Miscanthus pellet heating

For every tonne DM, 240 kWh electricity is required for pelleting, and 300 kWh of heating is required for drying (personal communication with UK pellet industry representative). This is on the high side (conservative) side given that miscanthus may not require drying depending on the time of harvest. Miscanthus bales are assumed to be transported 50 km to the pelleting plant, and pellets a further 50 km to end users. Transport emissions were based on >32 t EURO 4 lorry (Ecoinvent v2.2).

1 t DM miscanthus = 18 GJ NCV, so @90% boiler efficiency, 1 kWhth requires 0.222 kg DM miscanthus as harvested. Boiler combustion emissions of NO_x and SO_x were calculated based on thresholds reported by Biomass Energy Centre (2013): 120 mg NOx per MJ and 20 mg SOx per MJ. Note that PM10 and PM2.5 and PAH emissions could be higher from biomass boilers compared with oil and gas boilers, but this effect is not captured by the impact categories used.

7. Counterfactual energy and waste streams

Energy counterfactuals

Replaced electricity = electricity from combined cycle gas turbine power stations operating at 50% conversion efficiency, using Ecoinvent data for gas combustion in power stations. However, the first electricity output from the AD CHP unit replaces imported electricity for milking operations, avoiding grid-average electricity burdens based on Ecoinvent for the UK scale to most recent UK electricity CO_2 emission factor (DEFRA, 2012).

Replaced oil and gas heat from Ecoinvent, differentiated according to smaller <100 kW and larger (>100 kW) boilers. Systems burdens (RER S) were selected to account for upstream fuel supply.

Heating oil = 9.79 kWh/L NCV (DEFRA, 2012). Assume condensing oil boilers 90% efficient so that 1 L = 8.811 kWh useful heat

Natural gas = 9.282 kWh m^{-3} NCV. Assume condensing gas boilers 90% efficient so that 1 m^3 = 8.354 kWh useful heat.

Waste counterfactual scenarios

Two counterfactual waste management options were considered for food waste in the LCA scenario tool: in-vessel composting and landfilling. For composting, environmental burdens were calculated for composting and subsequent land spreading of compost as a soil conditioner based on the following factors:

- Diesel and electricity consumption requirements of 0.84 litres (including spreading) and 40 kWh per tonne wet waste (EC, 2010)
- Methane emissions derived from an MCF of 0.05 for composted animal manure (Table 10.17, IPCC, 2006)
- Ammonia volatilisation from composting operations – 9% of compost N (EC, 2010)
- Ammonia volatilisation following land spreading (MANNER NPK)
- Soil N_2O emissions of 1% of applied N (Tier 1, IPCC, 2006)
- Nitrate leaching based on MANNER-NPK for food/green compost
- Avoided fertiliser manufacture and application emissions based on fertiliser replacement calculated in MANNER-NPK for food/green compost.
- A small SOC credit equivalent to 4% of C in the compost, to reflect this additional source of soil organic matter input (EC, 2010).

For landfilling, methane emissions and electricity generation from captured methane were taken from WRAP (Keith James, pers. comm.), calculated based on IPCC (2006) guidelines using average UK methane capture of 71%, of which 70% is used for electricity generation at 35% generating efficiency. Emissions of NOx and SOx were calculated from fixed ratios to (biogenic) CO_2 emitted from electricity generation provided in EC (2010). Diesel consumption of 1.65 litres per tonne, and electricity consumption of 1% of electricity generated, were taken from EC (2010). Electricity fed into the grid was multiplied by the average UK grid electricity burden as used elsewhere in the LCA tool, and subtracted as a credit that somewhat offset the environmental burden of other landfill processes. Ammonia emissions per tonne of food waste sent to landfill were estimated based on the ratio of ammonia to methane emitted from landfills nationally, as reported in Dragosits and Sutton (2011) and Brown et al. (2012).

It was not possible to find representative data on the net eutrophication burden for landfill. On the one hand, a credit can be calculated according to avoided electricity minus direct NH_3 and NO_x emissions. But on the other hand it is difficult to obtain representative data on the quantity and fate of eutrophying compounds in landfill leachate. Therefore, net EP was set to zero for landfill. The net impact of acidification potential from landfill was estimated to be negligible and set to zero - direct emissions of NH_3, plus NO_x and SO_X from biomethane and diesel combustion are similar to avoided emissions from electricity generated.

Environmental burdens arising from waste collection were not explicitly calculated, as it was assumed these would be similar across the different waste management options employed.

Table 7.1. Net environmental burdens per tonne food waste going to composting and landfill, used to calculate avoided burdens in counterfactual waste management options

	Reference flow	kg CO_2e	kg PO_4e	kg SO_2e	MJe	kg Sbe
Landfill waste	tonne wet waste	517	0.14	0.42	-1563	-0.75
Compost waste	tonne wet waste	170	0.83	1.81	500	0.24

The calculated waste emission factor for composting CO_2e is significantly higher than that specified in the Zero Waste Scotland model (-39 kg CO_2e per tonne: Zero Waste Scotland, 2013). This is in part the result of using MANNER-NPK two-year N availability for compost (c.11%) which may underestimate long-term availability and thus fertiliser replacement.

8. Life cycle impact assessment method

Table 8.1 displays the life cycle inventory characterisation of environmental interventions in the LCA scenario tool, based on CML (2010). LCAD tool data were multiplied by the following factors, and the CML LCIA method was selected in SimaPro to extract relevant burden data (excluding infrastructure) from the Ecoinvent v.2.2 database. .

Table 8.1. Environmental interventions and indicators considered in this study for four impact categories, based on CML (2010)

Impact category	Interventions (characterisation factors for indicator loading; kg per kg intervention)	Indicator
Global warming potential	CO_2 (1); N_2O (298); CH_4 (25)	CO_2e
Eutrophication (RER)	NO_3 (1×10^{-1}); P (3.06); NH_3 (3.5×10^{-1}); NO_x (1.3×10^{-1}); N (4.2×10^{-1})	PO_4e
Acidification (RER)	NH_3 (1.6); NO_x (5×10^{-1}); SO_x (1.2)	SO_2e
Resource depletion (fossil fuels)	Hard coal (27.91); Soft coal (13.96); Natural gas (38.84 per m^3); Crude oil (41.87)	MJe
Resource depletion (elements)	P (5.52×10^{-6})	Sbe

9. Economics

LCAD economics

Farm-Adapt is an established farm economic optimisation tool, and its functionality is described elsewhere. A brief description is provided in the main report. Farm-Adapt was used to calculate farm level net margin changes in AD scenarios based on additional feed imports where relevant, and assuming 100% mineral fertiliser (all slurry exported to AD unit), and no income for feedstock cultivated for the AD unit. To this net margin change, the following income and cost streams were added in the LCAD tool based on AD scenario parameters:

- Fertiliser replacement value of digestate (minus spreading costs)
- Annualised capital investment costs (6% interest rate)
- Annual operating and maintenance costs
- Feedstock and digestate transport costs (for arable scenarios with centralised AD unit, assuming average 5 miles each way)
- Electricity income (avoided imported, export, FITs)
- Heat income (avoided oil heating, RHI)
- Food waste gate fee

The same approach was used for miscanthus and liquid biofuel scenarios. However, rather than calculate transport and processing costs (few reliable commercial data), the net return for the supply chain was calculated as the farm net margin change plus the difference in end-user energy costs, excluding and including subsidies.

Net effects, excluding subsidies, were used to calculate the CO_2 mitigation cost (where life cycle GHG emissions were reduced): i.e. the annual cost of subsidising the overall bioenergy scenario (based on current market structure) so that it breaks even with the baseline farm and energy assumptions was divided by the annual lifecycle GHG mitigation potential of the bioenergy scenario.

This simplification ignores large intermediate economic flows associated with bioenergy transport and processing likely to be associated with various GDP multipliers and that could be regarded as positive returns on bioenergy subsidies at the national level (relative to baseline energy supplies dominated by imported fossil fuels involving few multiplier effects and revenue export to fossil fuel producing countries). Similarly, co-benefits or costs of other environmental burden changes are not considered in the marginal abatement cost. Thus the approach used is a gross simplification but compatible with typical mitigation cost calculations.

AD capital investment and operation and maintenance costs

Dairy AD unit capital investment costs were calculated at a fixed cost of £530 m^{-3} digester capacity (capacities calculated according to feedstock mixes using NNFCC model). Fixed proportions of capital expenditure were allocated to buildings and machinery, with depreciation lifetimes of 20 and 10 years, respectively. Capital investments were converted into annual capital repayments based on loan repayment over building/machinery lifetimes plus accrued interest at a rate of 6%. For the dairy scenarios, NNFCC model costs corresponded closely with guide values provided by Fre-Energy (Fre-Energy, pers. comm. 2013) and with Spack (2011).

Arable AD capital investment costs were underestimated using the “thumb in the air” calculation method of the NNFCC model scaled according to digester capacity. Instead, data from existing or proposed AD plants was used (Future Biogas, pers. comm. 2013; Fre-Energy, pers. comm. 2013).

Operating and maintenance costs were adapted from NNFCC model costs according to the following equation: O&M cost = £4000 (licenses, admin) + £7.99 x m^3 digester capacity (digester maintenance) + £87.58 x kWe CHP capacity (CHP maintenance).

For the heat-only scenario, electricity used for mixing was estimated as a 2.2 kW draw over 33% of the year (RASE, 2011) and costed as an additional O&M cost.

Capital investment and O&M costs are fixed for the various scenarios, and do not vary according to AD design and management scenario settings within the LCAD tool. This reflects the high level of uncertainty associated with these data and a lack of more detailed data for specific components. Instead, the LCAD tool user can apply a scalar function to the default capital costs.

AD income

Electricity export to grid was valued at £0.05 kWh^{-1}. Avoided electricity import (dairy farm scenarios) was valued at £0.15 kWh^{-1}.

In addition, all electricity generated is eligible for FITs at the rates below (Feed in Tariffs Ltd, 2013), plus exemption from the climate change levy worth £0.0047 kWh^{-1} (AEA, 2011).

- ≤250kW: £0.1516/kWh
- >250–500 kWe: £0.1402/kWh
- >500 kWe: £0.0924/kWh

The Renewable Heat Incentive (RHI) currently applies to commercially used renewable heat sourced from a generator < 200 kW_{th} capacity, though the rules are under discussion with a decision on granting a domestic RHI postponed. The LCAD tool has functions for the user to specify whether domestic and larger (> 200 kWth) renewable heat sources are eligible for RHI at the current rate for biogas (£0.073 kWh^{-1}) (Ofgem, 2013). Otherwise, only the animal housing heat used in the LD-S and SD-S is eligible for the RHI incentive in the default situation, based on non-domestic and capacity restrictions.

Avoided heating oil is costed at £0.07/kWh (£0.70/L) including all taxes and delivery (EU Energy Portal, 2013).

The net economic effect of the miscanthus scenarios was calculated as the sum of farm net margin difference plus end-user heating cost difference, both excluding and including subsidies.

Miscanthus

The gross margin for miscanthus cultivation is based on an establishment cost of £1,660 ha^{-1} (annualised assuming repayment over 20 yrs at 6% interest), 2012 farm input prices for fertilisers, diesel and other inputs as described for Farm-Adapt and an income of £60 DM t^{-1} miscanthus at the farm gate (excluding subsidies), resulting in a gross margin of £267 ha^{-1} yr^{-1} at an average yield of 12.6 t DM ha^{-1} yr^{-1}. Including available establishment and maintenance subsidies results in a gross margin of £352 ha^{-1} yr^{-1}. These margins are added to the Farm-Adapt margins calculated for the residual dairy/arable enterprises to generate the net farm margin change in the LD-M, SD-M and A-M scenarios within the LCAD tool.

Capital investment is calculated as a premium per kWhth delivered by msicanthus pellets. Based on Styles and Jones (2007), installation of a small commercial scale miscanthus pellet boiler (100 kW) + pellet storage costs = €30,000, compared with €10,000 for an equivalent sized oil boiler with storage. Difference of €20,000 = £17,000. Amortised at 6% over 20 years, equates to £1,482/yr. Assuming average 50% load factor (438,000 kWh/yr), equates to 0.34 p/kWh “premium” for miscanthus pellet heating.

The miscanthus pellet heating market is not well established, and prices are based on relatively small scale processing. A sale price of £263 per tonne miscanthus pellets (including all taxes and delivery) was taken from Agripellets (2013). This price was converted to a kWhth fuel heating cost and added to the “capital investment premium” for comparison with the cost of heating based on oil including all taxes and charges.

The RHI for biomas boilers < 200 kWth capacity is applied, at the Tier 1 rate of £0.086/kWh for 25% of output and the Tier 2 rate of £0.022/kWh for 75% of output. NB. Tier 1 applies to first 15% rated capacity (RHI co.uk, 2013). If running at an average 60% load factor throughout year (assume represents small commercial premises such as hotel with constant hot water demand and seasonal heating), then 15% capacity = 25% output. Explained at:

The net economic effect of the miscanthus scenarios was calculated as the sum of farm net margin difference plus end-user heating cost difference, both excluding and including subsidies.

Transport biofuels

Data were sought from numerous sources on biofuel processing costs, but were regarded as too commercially sensitive to divulge. Instead, the approach outlined above based on the net difference between fossil- and bio- fuel energy prices was applied.

For the net biofuel cost minus subsidies, wholesale biofuels prices were compared with current (2013) prices for petrol and diesel (crude oil plus margin that includes refining and transport costs) taken from the EU Energy Portal (2013) and converted to GBP at an exchange rate of 0.85 £/€: these were 0.53 and 0.57 £/L for petrol and diesel, respectively. These prices translate into £0.053 and £0.063 per kWh fuel energy content based on BioGrace LHVs.

Wholesale EU price data for bioethanol and biodiesel were taken from a recent report (IISD, 2013), and converted to GBP: £0.536 and £0.765 per L, respectively, equating to £0.091 and 0.083 per kWh biofuel based on BioGrace LHVs.

To calculate the economic returns including subsidies, IISD (2013) data were again used. That report estimated the total subsidy effect for biofuels in the EU to be between €0.48 and €0.54 per litre for bioethanol and between €0.44 and €0.51 per litre for biodiesel, respectively. Mid estimate values translated into subsidies equivalent to £0.073 and £0.044 per kWh bioethanol and biodiesel, respectively, and were added to subsidies revenues in the LCAD tool.

10. Scenario schematics of LCA boundaries

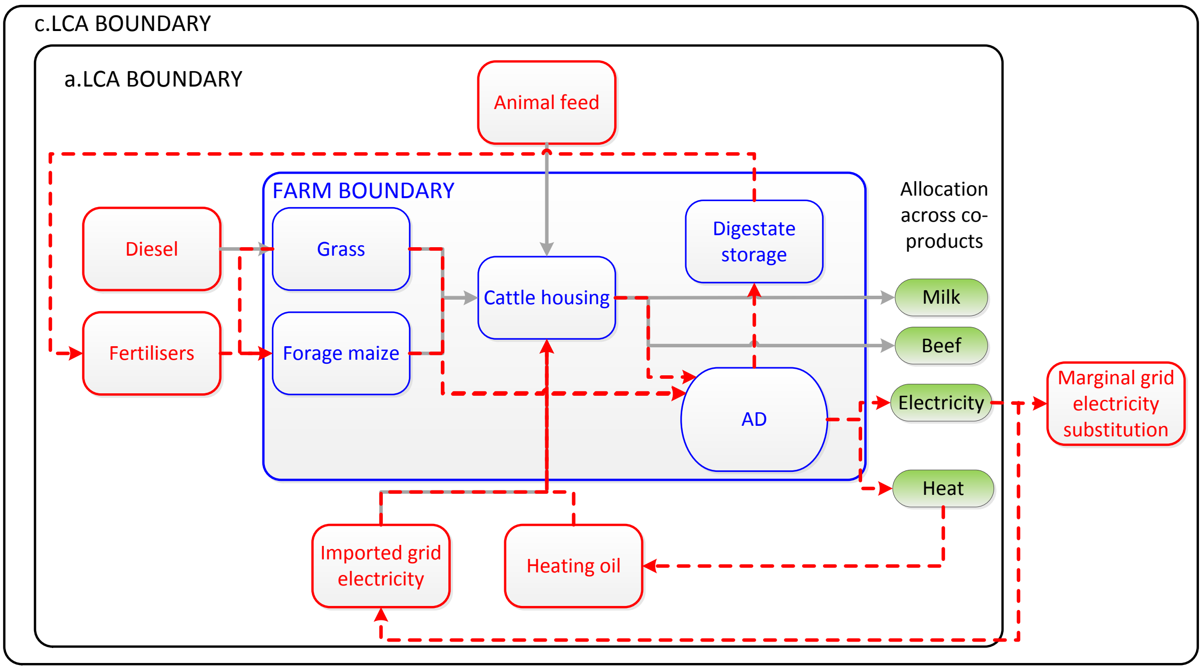

Figure 10.1. Boundaries, flows and processes considered in the LD-S, slurry-only AD scenario

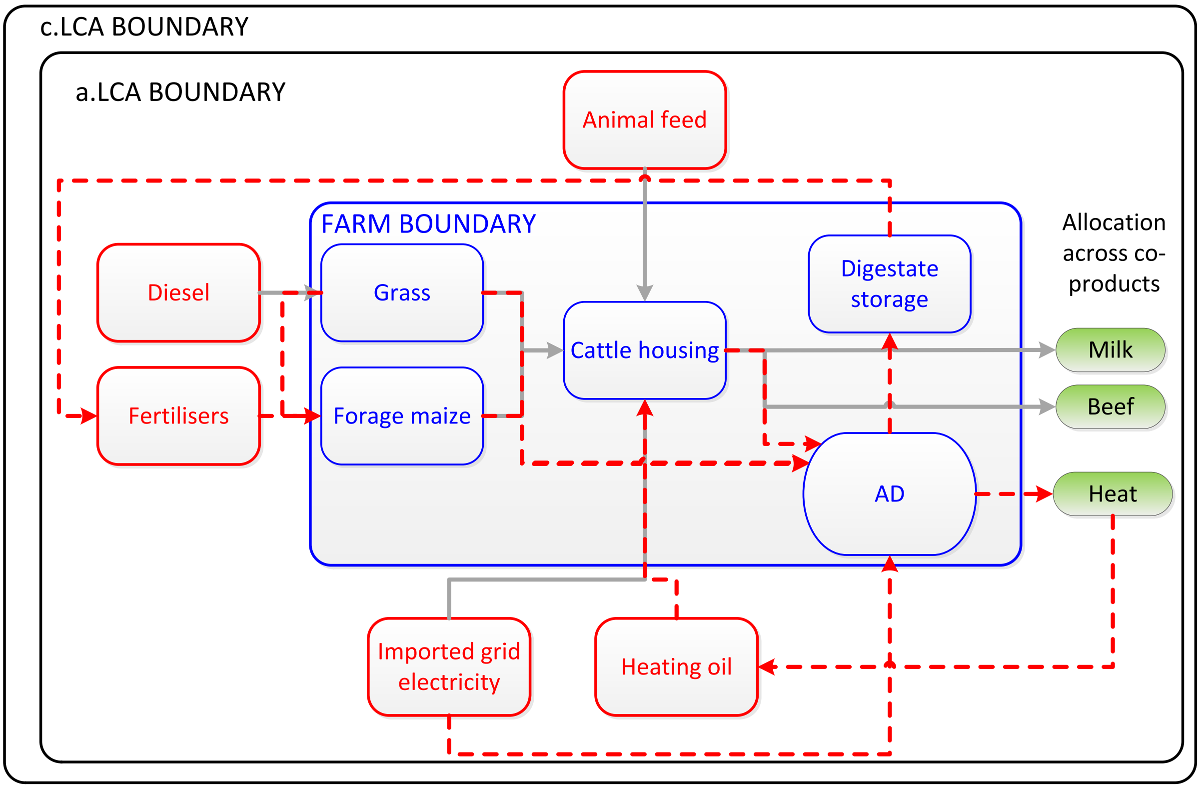

Figure 10.2. Boundaries, flows and processes considered in the MD-S, slurry-only AD scenario

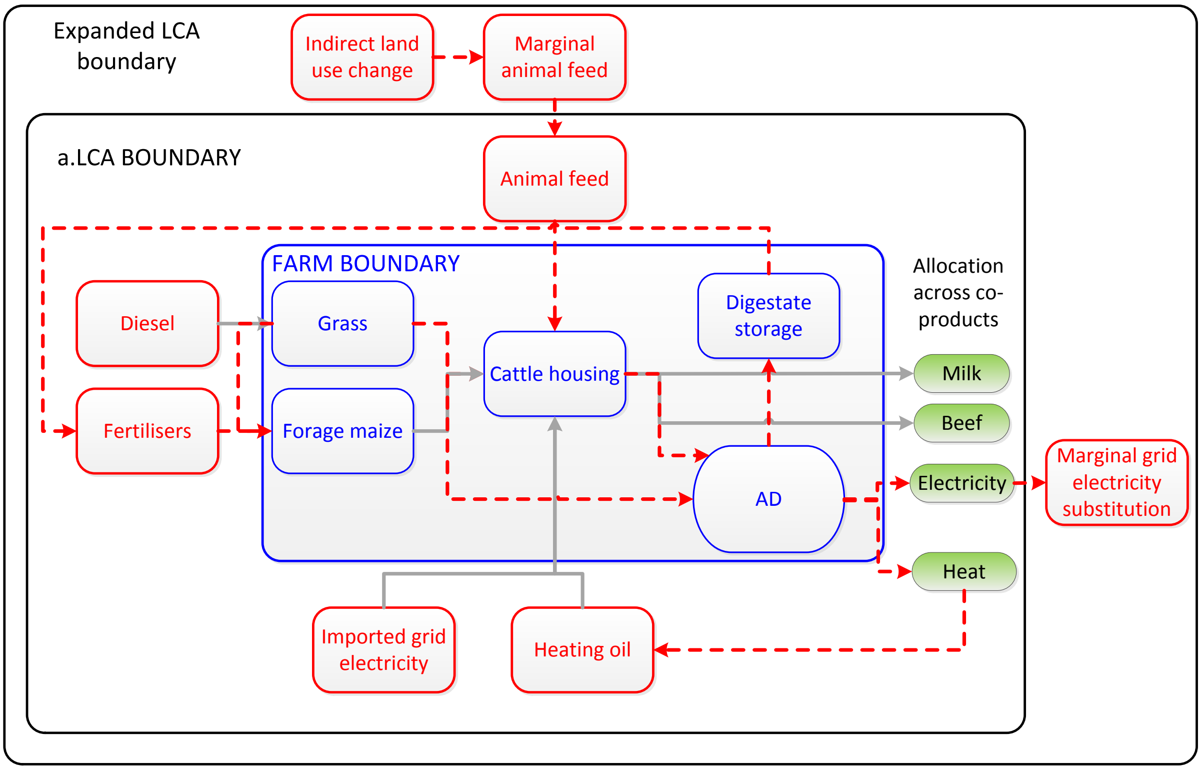

Figure 10.3. Boundaries, flows and processes considered in the LD-SG, slurry and grass AD scenario

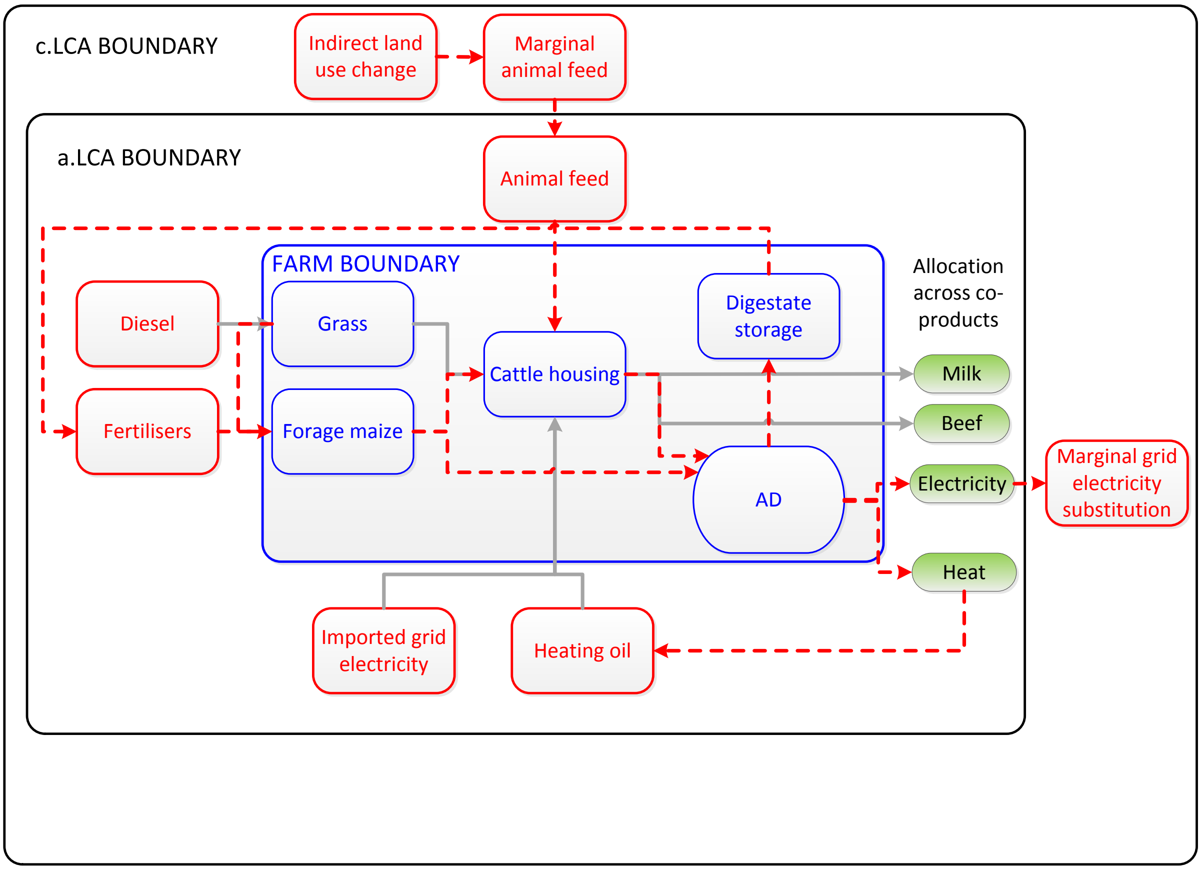

Figure 10.4. Boundaries, flows and processes considered in the LD-SMZ, slurry and maize AD scenario

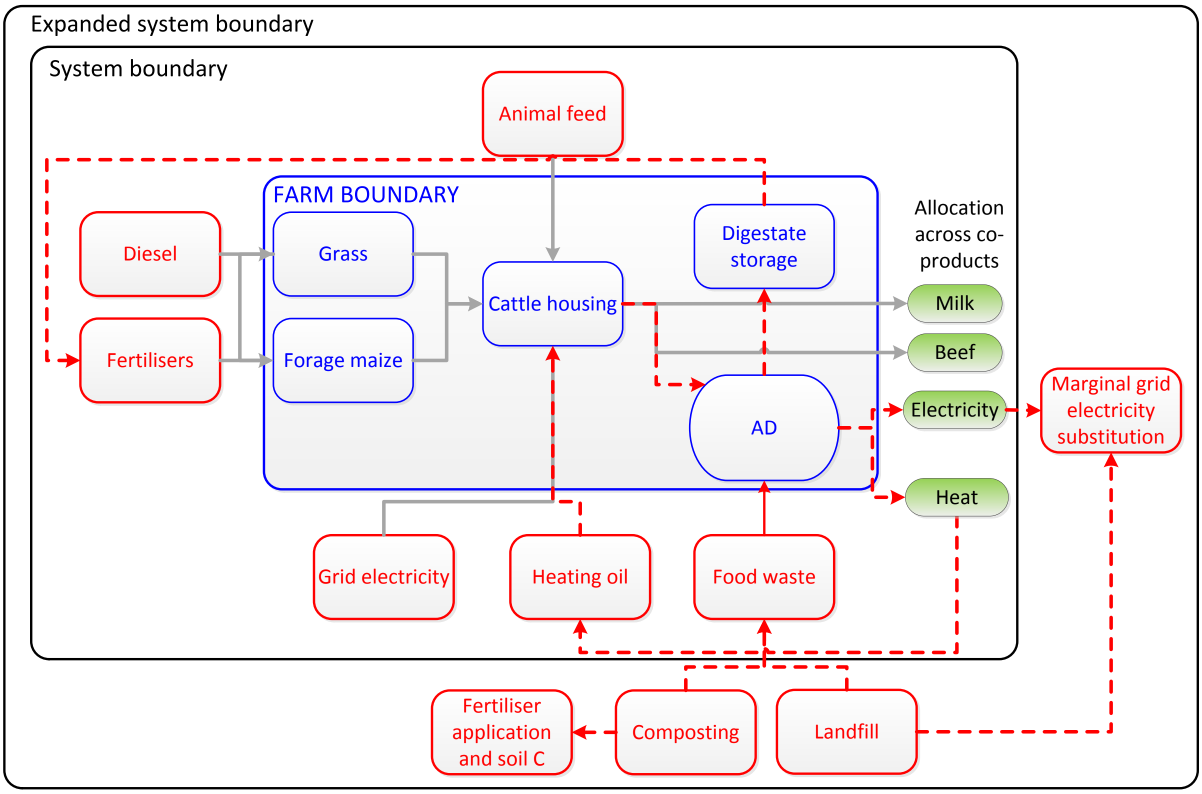

Figure 10.5. Boundaries, flows and processes considered in the LD-SF, slurry and food waste AD scenario

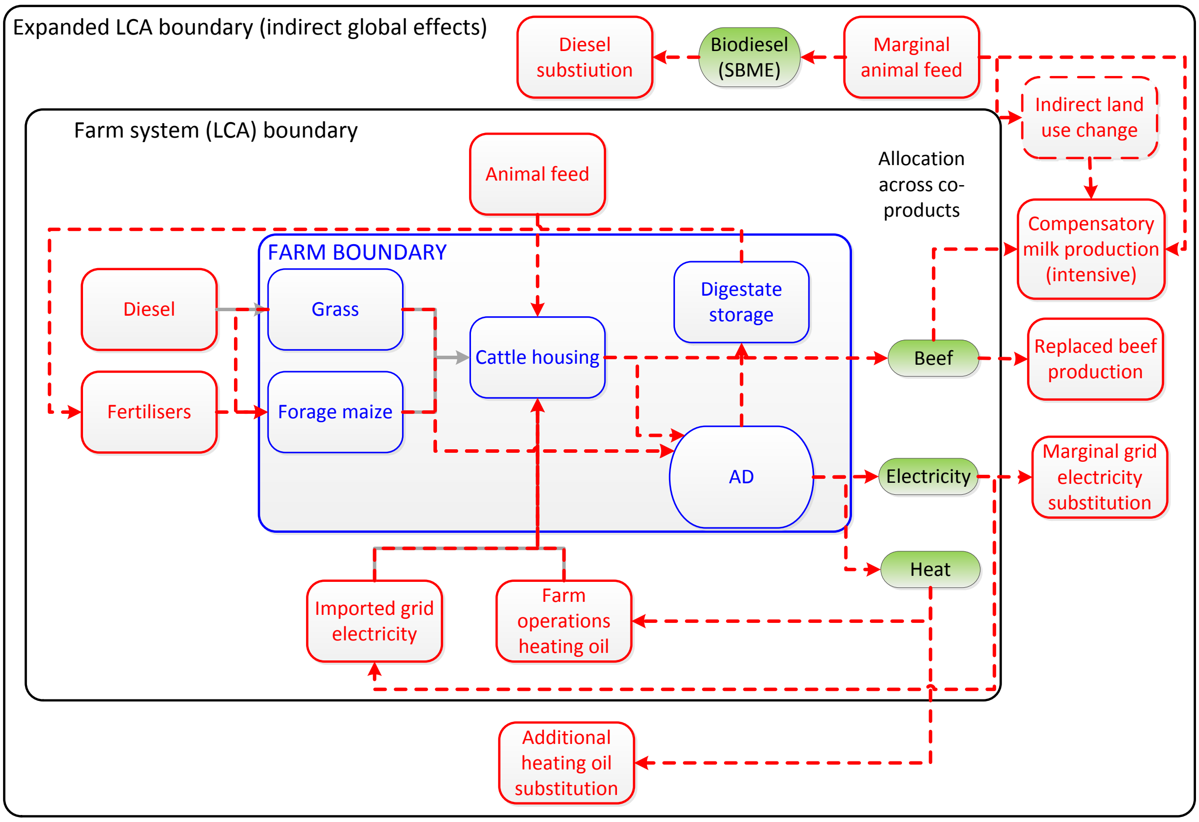

Figure 10.6. Boundaries, flows and processes considered in the BAD-SGMZ, beef plus AD scenario

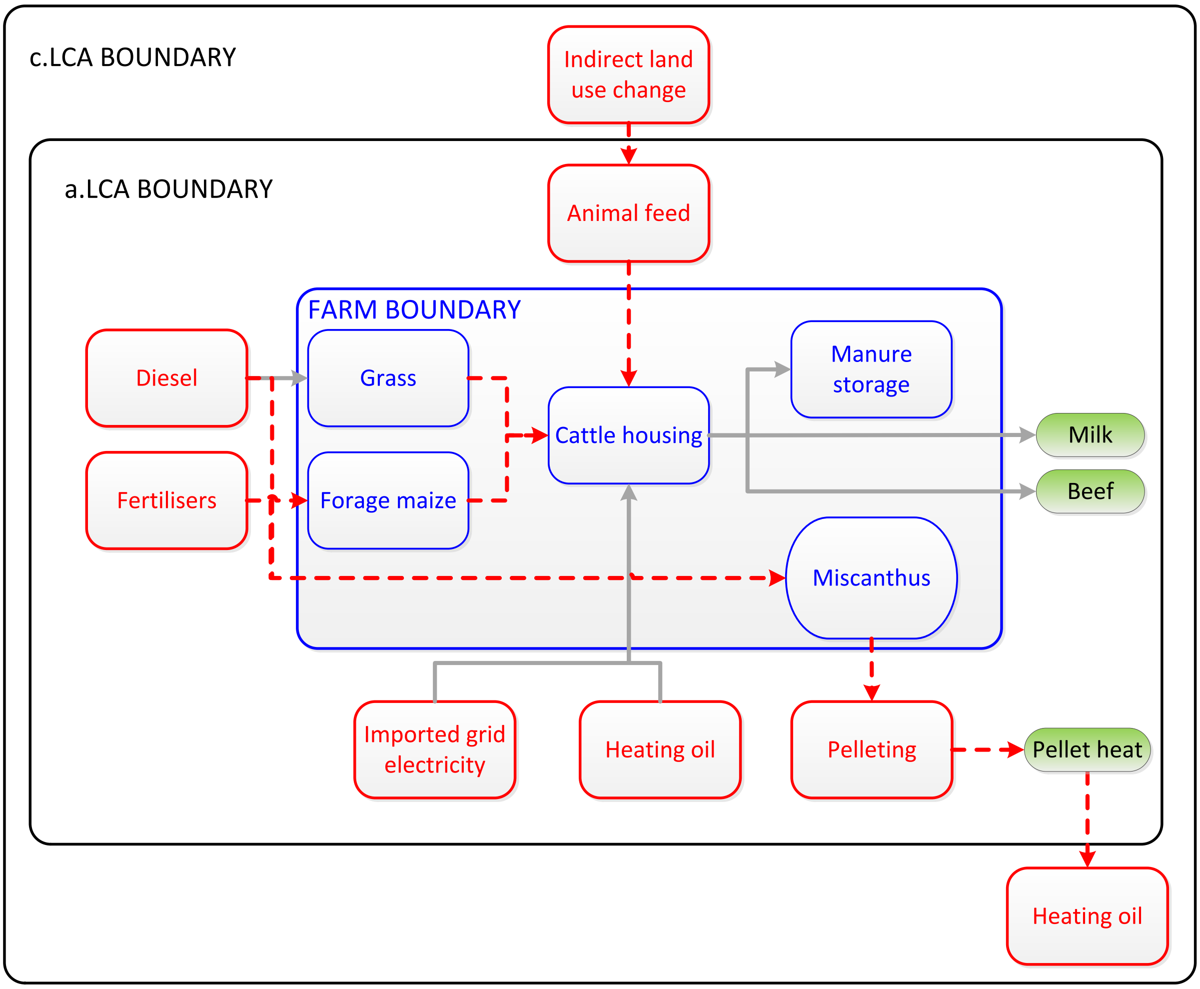

Figure 10.7. Boundaries, flows and processes considered in the LD- and MD-M, miscanthus scenarios

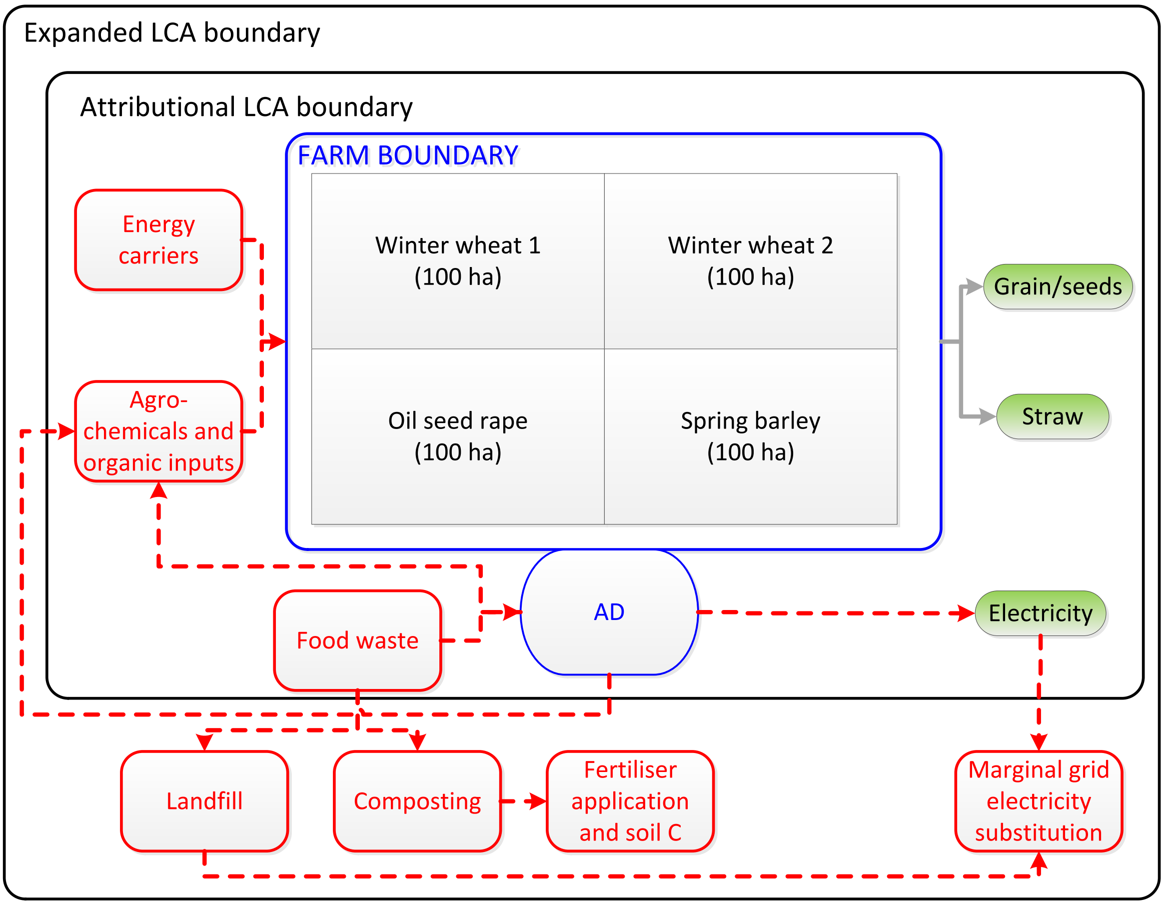

Figure 10.8. Boundaries, flows and processes considered in the A-F, food waste AD scenario

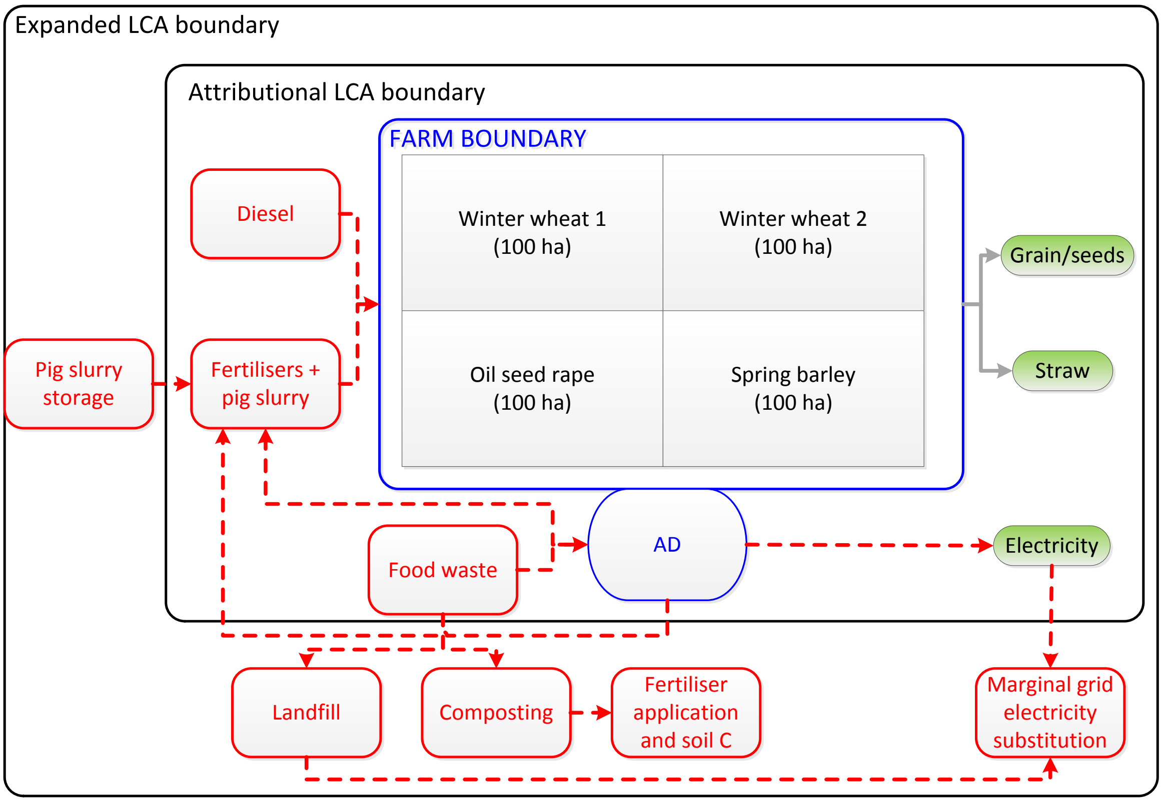

Figure 10.9. Boundaries, flows and processes considered in the AP-SF, pig slurry plus food waste AD scenario

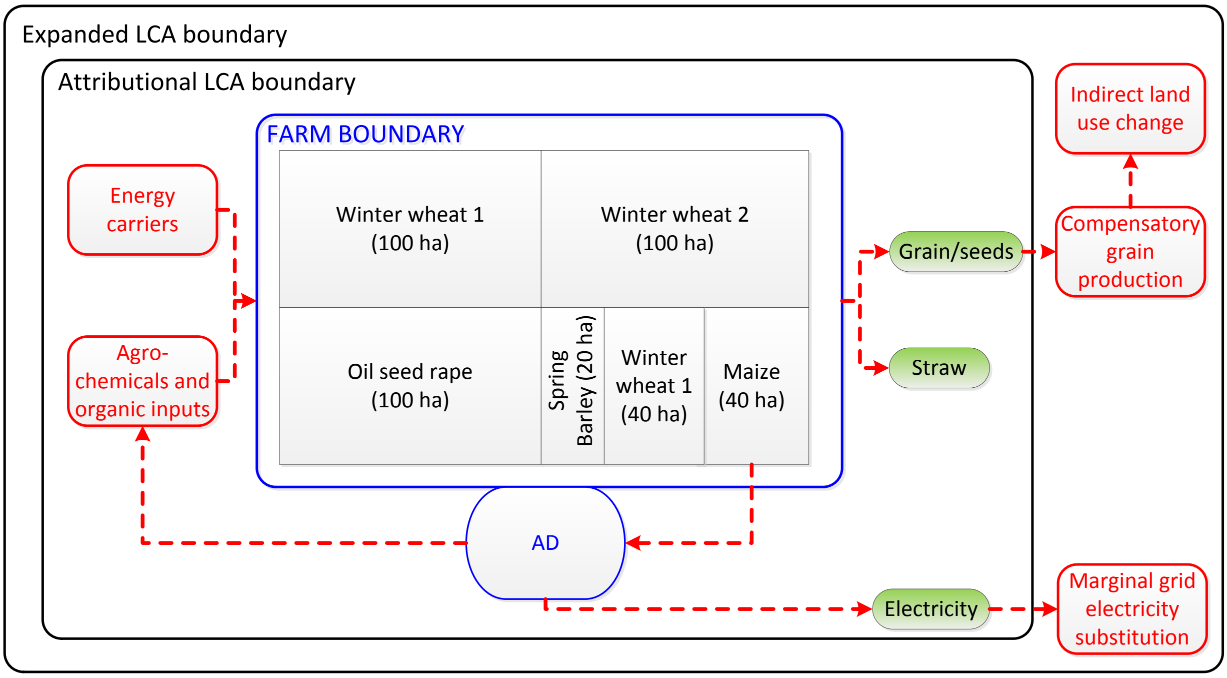

Figure 10.10. Boundaries, flows and processes considered in the A-MZ, maize in rotation AD scenario

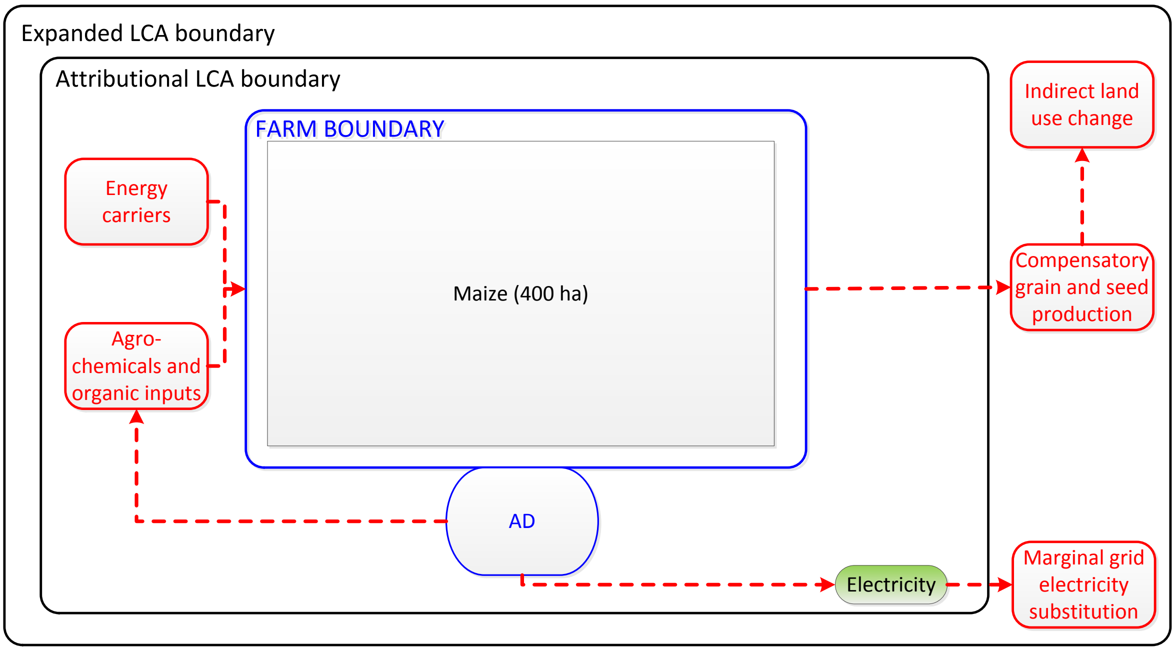

Figure 10.11. Boundaries, flows and processes considered in the A-MZ100, maize monoculture AD scenario

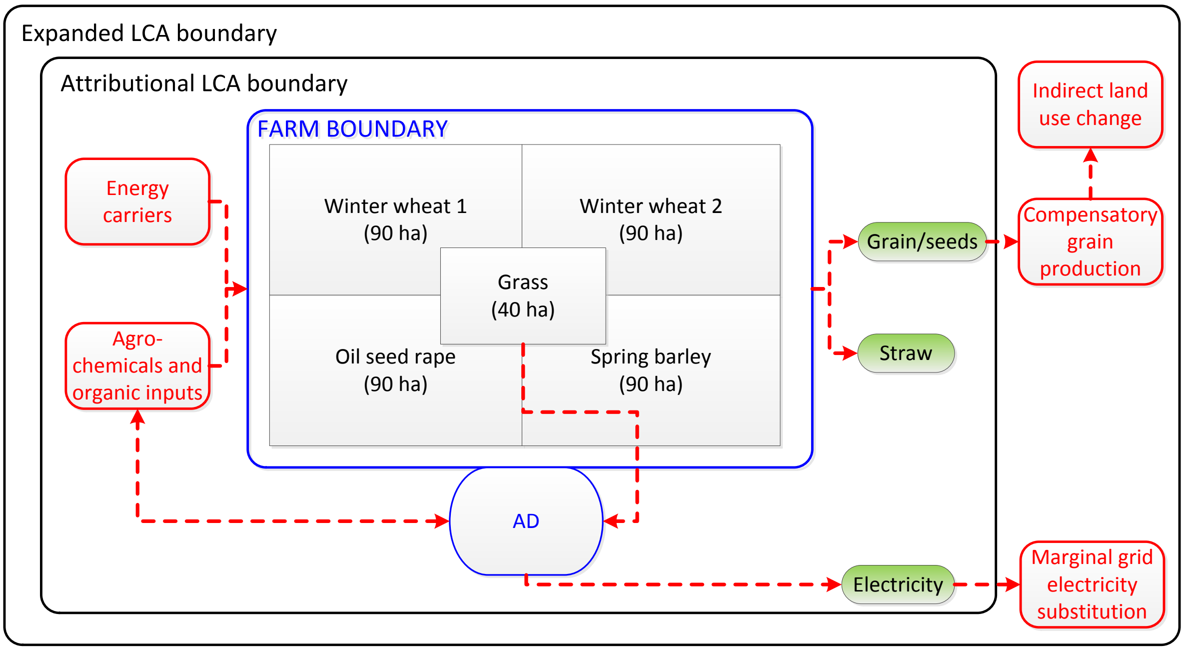

Figure 10.12. Boundaries, flows and processes considered in the A-G, grass AD scenario

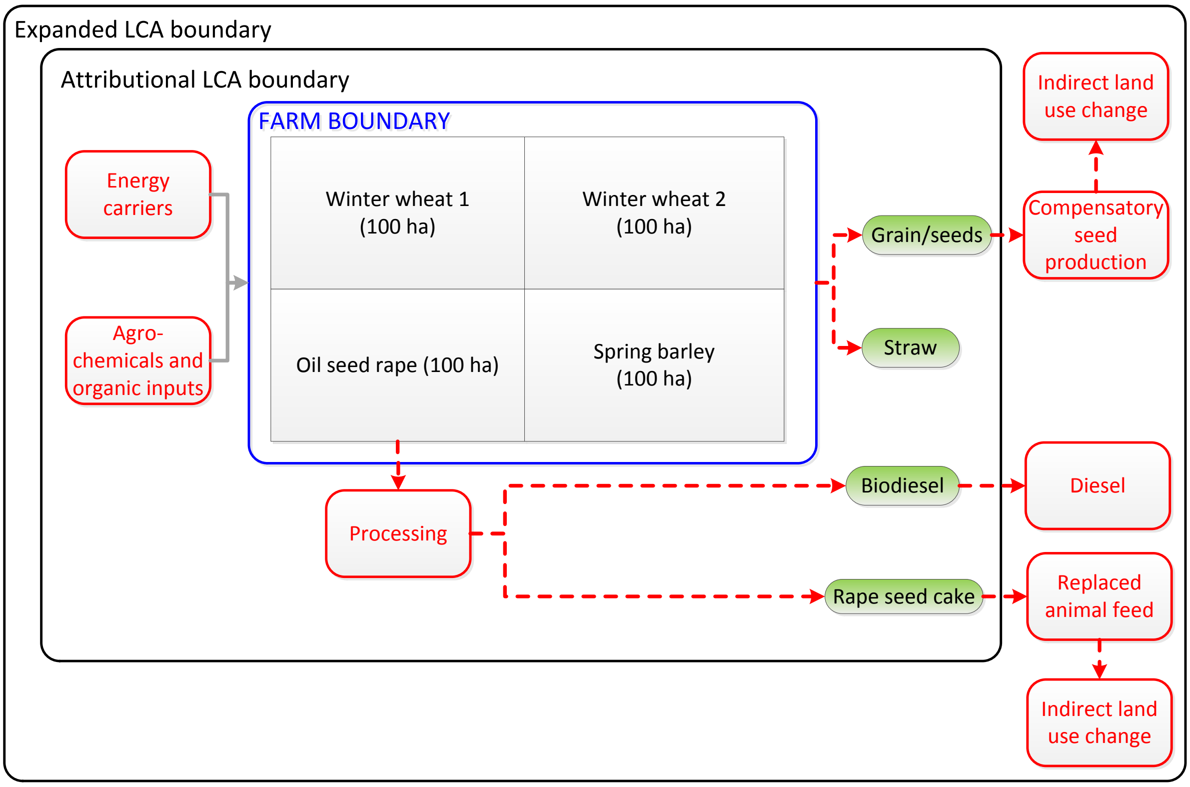

Figure 10.13. Boundaries, flows and processes considered in the A-Bd, oil seed rape for biodiesel scenario

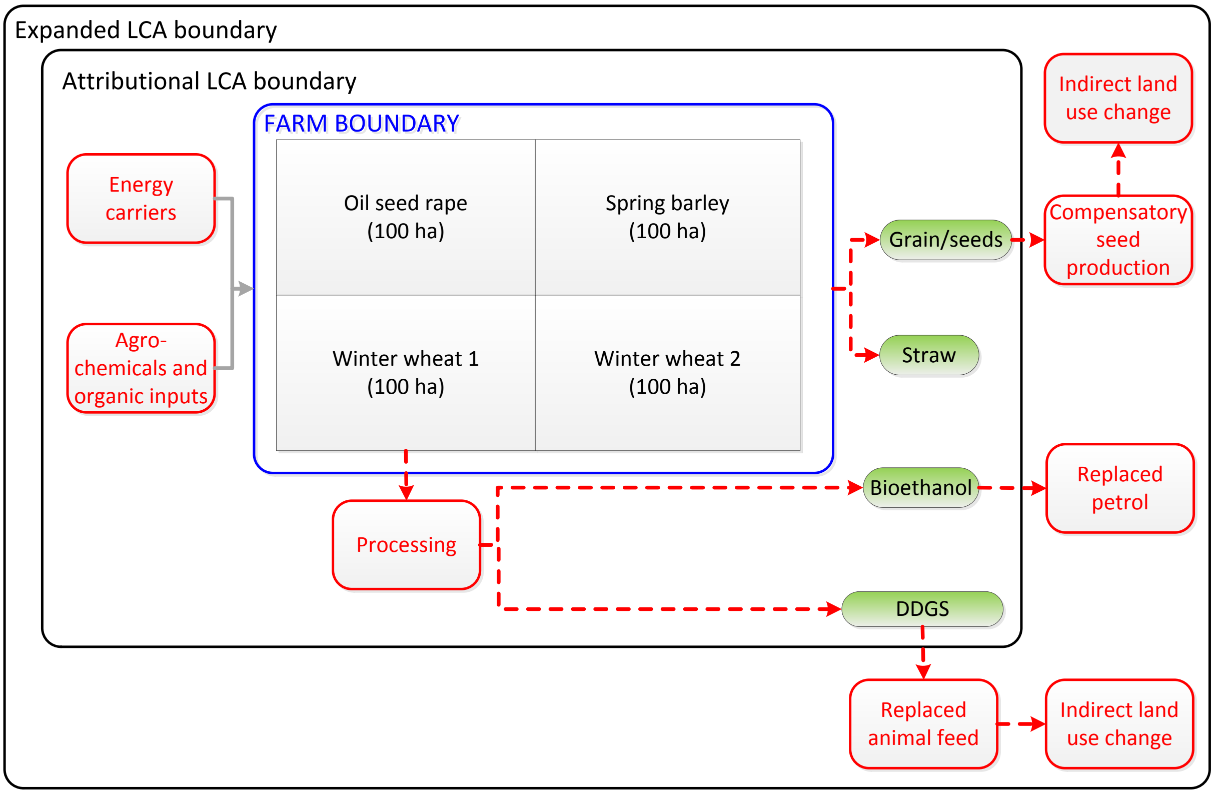

Figure 10.14. Boundaries, flows and processes considered in the A-Et, winter wheat for bioethanol scenario

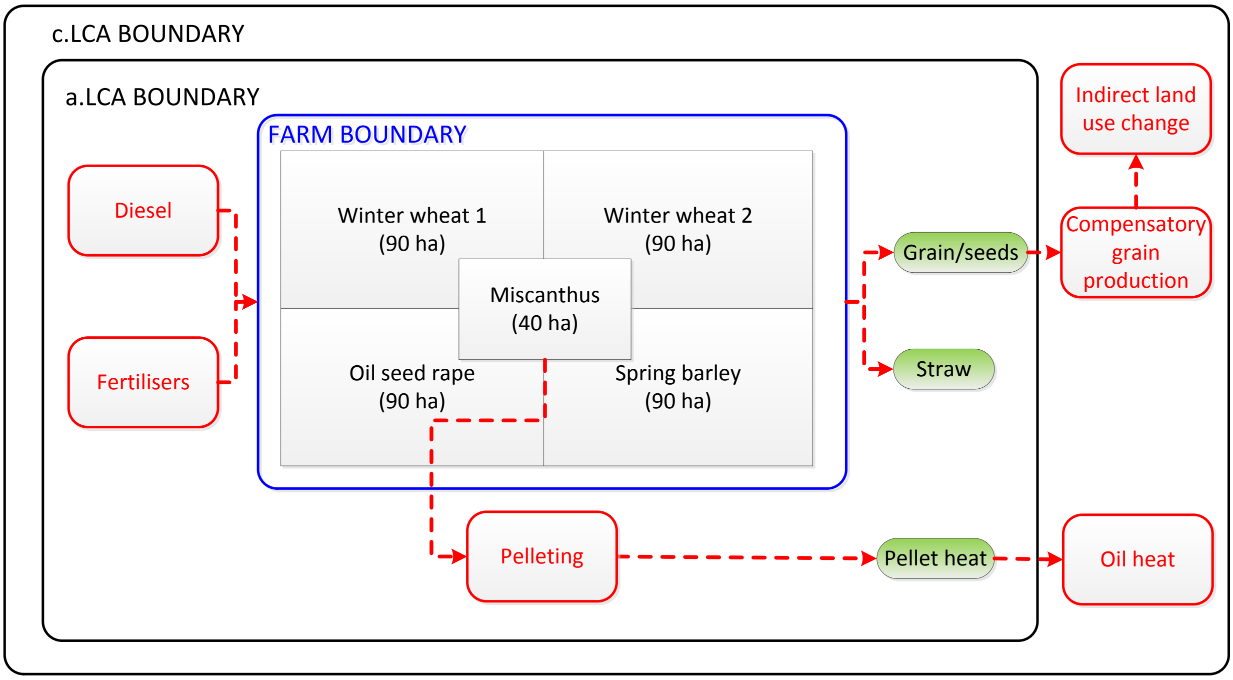

Figure 10.15. Boundaries, flows and processes considered in the A-M, miscanthus for pellet heating scenario

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