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Can farmers mitigate environmental impacts through combined production of food, fuel and feed? a consequential life cycle assessment of integrated mixed crop-livestock system with a green biorefinery

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Abstract:

This study evaluates environmental impacts of an integrated mixed crop-livestock system with a green biorefinery (GBR). System integration included production of feed crops and green biomasses (Sys-I) to meet the demand of a livestock system (Sys-III) and to process green biomasses in a GBR system (Sys-II). Processing of grass-clover to produce feed protein was considered in Sys-II, particularly to substitute the imported soybean meal. Waste generated from the livestock and GBR systems were considered for the conversion to biomethane (Sys-IV). Digestate produced therefrom was assumed to be recirculated back to the farmers' field (Sys-I). A consequential approach of Life Cycle Assessment (LCA) method was used to evaluate the environmental impacts of a combined production of suckler cow calves (SCC) and Pigs, calculated in terms of their live weight (LW). The functional unit (FU) was a basket of two products "1 kg_{LW}-SCC + 1 kg_{LW}-Pigs", produced at the farm gate. Results obtained per FU were: 19.6 kg CO_2 eq for carbon footprint; 0.11 kg PO_4 eq for eutrophication potential, - 129 MJ eq for non-renewable energy use and – 3.9 comparative toxicity units (CTU_e) for potential freshwater ecotoxicity. Environmental impact, e.g. greenhouse gas (GHG) emission was primarily due to (i) N_2O emission and diesel consumption within Sys-I, (ii) energy input to Sys-II, III and IV, and (iii) methane emission from Sys-III and Sys-IV. Specifically, integrating GBR with the mixed crop-livestock system contributed 4% of the GHG emissions, whilst its products credited 7% of the total impact. Synergies among the different sub-systems showed positive environmental gains for the selected main products. The main effects of the system integration were in the reductions of GHG emissions, fossil fuel consumption, eutrophication potential and freshwater ecotoxicity, compared to a conventional mixed crop-livestock system, without the biogas conversion facility and the GBR.

Keywords: livestock, green biorefinery, biomethane, beef, pig, environmental sustainability.

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1. Background

Fossil fuel is still one of the principal input to the modern agricultural system and one of the largest commodities produced and consumed (Gielen *et al.*, 2016). Major environmental challenges that human are facing are primarily due to climate change and predicted shortage of fossil fuels. Both fossil fuel shortage and greenhouse gas (GHG) emissions, however can be mitigated through the production of biofuels (FAO, 2012). Moreover, the increasing demand of agricultural biomasses to produce both fuel and non-fuel products is said to exacerbate the issues related to agricultural sustainability (Lin et al., 2006). The 'persistent critique' on the competitive use of biomass for fuel and food is also on the escalation of global food prices (Flammini, 2008). In addition, effects of indirect land use change (iLUC, as claimed for inducing GHG emissions, e.g. due to biofuels production is widely debated (Khanna et al., 2011). Moreover, there are also many critical urgings on iLUC issues, which stressed on the need to delineate a more scientifically robust and consistent method for assessing the impact, if it should be included in the carbon footprint assessments (Finkbeiner, 2013; Langeveld *et al.*, 2014).

The global agenda of sustainable development has also urged to investigate on the options to meet the demand of food, feed and chemicals to the growing population (IEA, 2011). Identified new value chains in the biomass conversion pathways has unavoidably demanded to optimize agricultural productivity and the biomass conversion systems (Kremen *et al.*, 2012). The increasing demand of agricultural biomasses in multifold sectors is also said to put additional pressure on livestock sector (Thornton, 2010). Livestock sector is one of the world's largest consumers of natural resources (Steinfeld *et al.*, 2006). The European Union (EU) livestock sector is the largest producer of the world's meat, milk and eggs. It contributed around 40% of the EU's agricultural production values (Eurostat, 2012). It has also supported to the rural development and to a better functioning of agro-ecosystem (Lutzeyer, 2014). On the other hand, in EU countries, such as France, Germany, the UK and Denmark the cattle population is decreasing (European Commission, 2012). Likewise, Danish Ecological Council (2008) reported that the pig production in Denmark is high, but for a more sustainable agriculture scenario, it stressed on the need to reduce 30% of annual pigs production by 2020. Agronomic-consequences resulting due to the changes in the population density of livestock production, e.g. cattle, are on the management of grassland, which has importance for nature conservation and biodiversity (Isselstein *et al.*, 2005). Systemic synergies between the crop and livestock systems that can provide solutions to increased demand of agricultural commodities without compromising the productivity and with minimum environmental damages is thus relevant.

Most of the impacts on livestock production are expected to be indirect, due to variations in feed availability, indicating on the need of holistic sustainability assessments of a mixed crop-livestock system, i.e. involving both crop and livestock activities (Thornton *et al.*, 2009). In general, farmers pursuing a mixed crop-livestock system are producing about half of the world's food (Herrero *et al.*, 2010). Hence, integrating decentralized technologies to a conventional livestock system not only can add new value chains to the sector, but is also important at mitigating the prevailing environmental problems of the sector. This has been realized also in the form producing cascades of biobased products through biorefinery so that multiple demands of agricultural and other commodities can be met (Parajuli *et al.*, 2015b). Nonetheless, it is imperative to identify whether an agricultural sector can be a principal driver for sustainable supply of green energy and other products demanded in different production sectors. Combination of different biomass conversion technologies in the form of an integrated biorefinery has great potential for a combined production of fuels, chemicals, materials and power (Fatih Demirbas, 2009). Furthermore, green biorefinery (GBR) technology is considered as one of the noble solutions for the optimal utilization of the grassland biomass and to produce alternative biobased products (Kamm *et al.*, 2009). In a GBR technology, green biomass is separated into a fiber-rich press cake and a nutrient-rich press juice. The bulk chemical content contained in the press cake (e.g. cellulose, starch, and dyes) and green juice (e.g. proteins, free amino acids, organic acids, enzymes, and minerals) are argued for having good economic values, as they can be used as raw materials to produce high-quality fodder and cosmetic proteins, human nutrition, chemicals (e.g. lactic acid and lysine). The technology also facilitates the conversion of the co-produced substrates to biogas (Kamm and Kamm, 2004). Production of green protein from a GBR is important, particularly in a situation, where the livestock sector is highly reliant on imported protein sources (such as soybean and soymeal), e.g. in European countries (FAOSTAT, 2013). Likewise, management of biodegradable waste generated from GBR can be a sustainable option to maximize the resource use efficiency, e.g. in the form of producing biogas and its upgrading.

A Life cycle assessment (LCA) method is widely used as a tool to assess environmental performance of different products and services (European Commission, 2015; ISO, 2006). In LCA studies, whenever, a product system yields multiple products, choices on the approach to handle the co-products are unavoidably connected (Thomassen et al., 2008). Generally, such issue is handled either by: sub-dividing the multi-functional processes, system expansion and allocation (European Commission, 2010; ISO, 2006). Attributional and consequential approaches of LCA method were evolved along with the methodological debates over the allocation problems and carrying over the arguments for the choice of data (Thomassen et al., 2008). Within attributional approach, allocation can be avoided by using system expansion, but the products' allocation method is widely used (Thomassen et al., 2008). Assessments relying on attributional LCA approach are most often seeking to quantify the environmental impact potentials associated with a given product or service. Typically, attributional assessments rely on allocation for cutting of data demanding background systems to simplify the modelling and assessment. When applying the consequential approach assessors are generally seeking to identify and quantify the changes within a product system caused by provision of a given product or service under various circumstances. As is obvious, the two approaches are intended for providing answers to quite different questions. Nevertheless, the two approaches are mixed, by e.g. avoiding all or selected allocations in attributional assessments by inclusion of background systems to account for such issues as avoided impacts (Curran, 2015). In a consequential approach, the co-products are substituted with the related alternative products, preferably the marginal products (Schmidt, 2008).

The current study aims at evaluating environmental performance of an ideal mixed crop-livestock system, within which, a green biorefinery technology is also integrated. The system was designed in such a way to bring together, the farmers pursuing two different livestock farms- cattle and pig, e.g. in a form of "farmers-cooperative", so that the local resources can be optimally utilized and shared. The special focus of the study is to answer (i) whether an integration of a livestock farm with an industrial processing of biomass to produce both food and non-food products can reduce environmental burdens of livestock products, and (ii) where do most of the environmental burdens would accrue within the assumed system. The system integrations were in the form of utilizing agricultural land (Sys-I) producing crops: to meet the demand of green biomass in a green biorefinery (GBR) technology (Sys-II) and to supply the produced feed crops to a livestock system (Sys-III). Two livestock production units "suckler beef" (SCC) and "Pigs" were considered within a livestock production system (Sys-III). It was argued that a decline in a dairy based beef production is expected due to reduced number of dairy cows, and for potentially leading to an expansion of beef production based on suckler herds (Nguyen *et al.*, 2010a). This makes relevant to consider the SCC system to investigate for their better environmental footprints. The SCC system is classified as semi-extensive, where a combination of outdoor grazing in summer and indoor feeding with grass silage and concentrates in winter are considered for feeding the cattle. It is regarded as a complex system where beef produced originates from the suckler cow and its offspring – either bull calves or heifer calves for meat and for the replacement (Nguyen et al., 2010a).

2. Materials and methods

2.1 Description of the overall system

The schematic diagram covering the loop of material flows within the considered integrated system is shown in Fig.1. The integrated system hereafter is referred as the 'main integrated system', i.e. S_1-GBR. Agriculture system (Sys-I) is the mainstay for producing different crops (cereals and grasses) required to the livestock system (Sys-III). In Sys-II, green biomass (grass-clover) is processed for producing green protein (here after, referred as feed protein), and the fibre products (here after referred as fodder silage) (see section 2.7). The green protein and the fibre products (press cake) are suitable as feed to animals (Hermansen et al., 2017; Kamm et al., 2009). The fodder silage is generally considered as energy-feed to livestock, e.g., spring barley and maize. Sugar fractions in the press cake (approximately 33%) of the total fibre fractions (on DM basis) can further utilize to convert into high value chemicals, as was modelled in Parajuli *et al.* (2017a), but in the current study further conversion of the biomass were not considered. The rest of the fibre particle contained in the press cake is widely considered being suitable as livestock feed (Kamm et al. 2009). Hence, the products delivered from Sys-II were assumed to be consumed in Sys-III. The benefits of such are thus covered in terms of displacing the equivalent amount of the alternative products, as are supplied conventionally (see section 2.3). The products delivered from the livestock system (Sys-III) are the live weight (LW) of pigs and SCC, assumed to be produced by a proposed "consortium of the farmers". Livestock manure produced from Sys-III and the decanted press juice (i.e. residues) produced from Sys-II were considered as substrates for the biogas conversion process in Sys-IV. In Sys-IV, biogas was further assumed to be upgraded to biomethane.

Biomethane can be treated as an alternative to pipeline fuel or transportation fuel (Fatih Demirbas, 2009). Likewise, digestate was considered as an alternative to the synthetic fertilizer, and was assumed to be recirculated back to the same farm. Synergies established through the systems integration were aimed at utilizing most of the available resources generated within the farm for a combined production of food, feed, fuel and the crop nutrients. Detailed assumptions on handling of the products are described in section 2.3.

Fig. 1. Overall assessment framework considered for accounting the resource use in the integrated system (S_1-GBR).

2.2 Functional unit, system boundary and the environmental impact categories

Within the cattle farm, SCC was considered for the assessment, as approximately 70% of the number of the cows in the EU-27 is represented by "suckler beef" (Nguyen et al., 2010a; Weidema *et al.*, 2008). The assumed integrated farm system has multiple final products, such as LW of SCC and Pig, feed protein, fodder silage, biomethane and the recovered digestate (Fig. 2), recirculated and brought in the market, as explained in section 2.1. Considering the multiple co-products delivered from the integrated system, the functional unit (FU) was decided as a 'basket of products' constituting "1 kg_{LW}-SCC + 1 kg_{LW}-Pigs", as a source of food products, and was evaluated at the farm gate. A "product-basket" approach was also considered in different studies, e.g. related to: the food consumption in Europe (Notarnicola *et al.*, 2017), integrated biorefinery (Parajuli et al., 2017a) and in the evaluation of different farming systems (Marton *et al.*, 2016). The LW of livestock products (i.e. 1000 $kg_{LW,}$ each) in terms of their equivalent weight at slaughter was reported to be approximately 750 kg and 547 kg (slaughter weight) for pigs and SCC meat respectively (Nguyen et al., 2010a; Nguyen *et al.*, 2010b). A typical feature of the cattle rearing system is described in section 2.6.

Fig. 2. System boundary considered for S_1-GBR**.** Values not shown for the materials are described in the respective sections. *Feed protein is assumed to be supplied to the livestock system (Sys-III) thereby substitutes the marginal protein supply. Utilization of fodder silage and recovered digestate also substitute the corresponding marginal products

The selected environmental impact categories with their units are: (i) Global Warming Potential-100 years (GWP_{100}), or carbon footprint (kg CO_2 eq), (ii) Eutrophication Potential (EP) (kg PO_4 eq), (iii) Non-Renewable Energy (NRE) use (MJ eq) and (iv) Potential Freshwater Ecotoxicity (PFWTox), expressed as 'comparative eco-toxic units' (CTUe). The first three impact categories were assessed using the "EPD" method (Environdec, 2008), while PFWTOx was calculated using the ILCD method. The current study considered the inclusion of potential soil carbon sequestration in the overall carbon footprint assessment, particularly related to the feed production system. Potential risks of pesticides and nitrate leaching to the aquatic ecosystem are also included, which are of wider interests to asses to outline regional/local policies for reducing the eutrophication , e.g. in aquatic ecosystem (European Commission, 2010). Furthermore, generally in most of the LCA studies, impacts of pesticides are often calculated without considering the emission distributions of the active ingredients (a.is) to air and freshwater (Birkved and Hauschild, 2006), and/or those if however included, the effects of the local climatic parameters on the emission distributions were not considered. This study has considered the emission distribution of pesticides to freshwater and air in a specific agro-climatic conditions and related pesticides application practices, the results of which were adapted from the studies reported by Parajuli *et al.* (2016) and Parajuli *et al.* (2017b). The selected environmental impact categories are among the ISO preliminary list (ISO, 2006), and are relevant whenever a production system or processes are to be evaluated for identifying potential measures for accounting and minimizing agro-ecological problems (European Commission, 2010). It also intended to consider both local and global environmental effects (van der Werf and Petit, 2002), which are induced during the material processing and consumption. The modelling for impact assessment was facilitated by the use of the LCA software 'SimaPRO 8.0.4' (PRé Consultants, 2015).

2.3 Life Cycle Assessment approach

A consequential approach of LCA (Ekvall and Weidema, 2004) was used to evaluate the environmental impacts of producing the main products. In the current study, after deciding the FU, the co-products were assumed to substitute the alternate products (Fig. 2, Table-1). Feed protein (from Sys-II) was assumed to substitute the marginal source of livestock feed, i.e. soybean meal (Dalgaard *et al.*, 2007b). For this, the substitution factor was proportionately calculated considering the ratio of the equivalent amount of crude protein (CP) available from the feed protein to the CP available from soybean meal (Table 1). Import of soybean meal was assumed to be from Brazil (Parajuli *et al.*, 2015a). Fodder-silage produced from the same system was assumed to substitute the market available marginal energy-feed, i.e. Ukrainian Barley (Muñoz *et al.*, 2014). These co-products would thus reduce the import dependency of the related feeds, and provide environmental credits to the assessed products, wherever applicable. Likewise, biomethane produced from Sys-IV was considered as an alternate to liquefied natural gas (LNG). The requirements for compressed natural gas vehicle fuel, e.g. "as defined by the Swedish standard SS 155438 requiring the methane content of the fuel gas to be 97 ± 2%, can be fulfilled by biomethane" (Bauer *et al.*, 2013). Recoverable crop nutrients from the digestate (produced from Sys-IV) was considered recirculating back to the farmers' field. Recovered nutrients (in the form of N, P, K) was assumed to substitute the marginal fertilizers (Table 1). The equivalent fertilizer efficiency assumed in the case of applying the digestate is discussed in section 2.5. A sensitivity analysis was also performed after considering the different utilization pathways of manure and biogas end uses , with respect to the corresponding alternative products (section 2.10.2).

Table 1. Basic assumptions considered for the substitutions of the alternative products.

2.4 Life cycle inventory and data sources

The Life Cycle Inventory (LCI) covered the background and the foreground processes related to the designed farm system. The background processes covered the undesired emissions, resulting due to the production and supply of materials entering to the foreground system (Fig. 2). Related emissions at background level were based on 'consequential unit process library' and were adapted from Ecoinvent v3 (Weidema *et al.*, 2013). At the foreground level, LCI of each production systems (Figs. 1-2), as considered in S_1-GBR were evaluated. The geographical boundary was considered a Denmark. The evaluation of the foreground processes is detailed in the following sections. They are presented in terms of producing each, 1000 kg_{LW} of SCC and pigs, along with the co-products (Fig. 2).

2.5 Feed production system

The total land use estimated for producing 1000 kg_{LW} of pigs and SCC each were found to be 0.55 ha and 3.26 ha respectively (Table 2). Land use assumed for growing the selected feed crops (Sys-I) represented the Danish arable land with sandy soil (NaturErhvervstyrelsen, 2015). Yields of maize and grass-clover were averaged from the Danish farm yield (2007-2011) (Kristensen, 2015; Statistics Denmark, 2013). Yields for winter wheat grain and spring barley grain were based on Statistics Denmark (2013) and Oksen (2012). Straw represents 55% of the net cereal yield (Taghizadeh-Toosi *et al.*, 2014). Types of pesticides and the mass of active ingredients (a.is.) assumed to be applied to Sys-I were based on Ørum and Samsøe-Petersen (2014). With regard to the emissions related to the pesticides, the first step adopted was to calculate the emission distribution fractions of a.is., to air and freshwater, particularly during the farm application process (Birkved and Hauschild, 2006). The second step was to calculate the freshwater ecotoxicity jointly considering the emission distribution fractions and the comparative toxicity units (CTUe) of each a.is (Fantke *et al.*, 2015). Emission distribution fractions of the considered a.is for the selected crops were adapted from Parajuli et al. (2016) and Parajuli et al. (2017b). Finally, total PFWTox was calculated considering both farm based emissions (foreground level) and emissions of chemicals due to the production of assumed materials (background level). With regard to the direct primary energy input to Sys-I, it was calculated considering the frequency of farm operations (e.g. ploughing, irrigation, harvesting) (Jørgensen *et al.*, 2011) and their related specific fuel consumptions. The specific fuel consumption for different farm operations were considered as according to the Danish practices (Dalgaard *et al.*, 2001).

GHG emissions due to soil organic carbon (SOC) change was calculated in a 100-years perspective, and the emission reduction potential was assumed to be 9.7% of the added net carbon (C) to soil (Petersen *et al.*, 2013). The net C was calculated as: C-input from the reference crop's residues minus C-input from the main crops' residues minus C-available from the digestate applied to the field. C-input from the crop residues was based on the harvest index and C from root and exudates (Taghizadeh-Toosi et al., 2014). Spring barley (with 100% straw incorporated to soil) was assumed as the reference crop, as the crop can be regarded with lowest gross margin (Weidema, 2003). In the case of winter wheat, the demanded straw in Sys-III (Table 2) was removed from the field, whilst straw from spring barley was incorporated back to soil (detailed in SI-1, Table S1.1). With regard to the case of removing straw, its consequences (Petersen and Knudsen, 2010) was calculated in terms of: (i) loss of soil C and (ii) the compensation of nutrients (N,P,K), equivalent to the amount that would be available from straw, if it was instead ploughed back to the field. The effect of removing straw, including the diesel consumption for baling the removed straw was thus 149 kg CO_2 eq per t DM straw, as calculated after Parajuli *et al.* (2014).

Input of synthetic fertilizers (N=Nitrogen, P= Phosphorus, K= Potassium) followed the Danish regulation (NaturErhvervstyrelsen, 2015) (see SI 1, Tables S1.2.a-1.2.b). The maximum limit on the use of livestock manure was set to 170 kg N/ha, considering the "Nitrates Directive's limit" in Danish farm (EPA., 2012). For this, digestate produced after the biogas conversion (Tables 3-4) was assumed to be recirculated to Sys-I. N-available from the digestate for the plant uptake (N-efficiency) was estimated compared to synthetic fertilizer (N-syn), and was assumed to be 75% and 70%, respectively for cattle and pig slurry (Wesnæs *et al.*, 2009). In the case of P and K, it was assumed to substitute the same nutrient elements of the synthetic fertilizers (Sommer et al., 2008). Mass and N-balance induced due to the application of available digestate are shown in Table 3. Mass of digestate to be required for each livestock unit was calculated after considering the N-digestate demand (Table 3), as required for producing the respective feed crops (Table 2). The deficit mass of digestate was 32 ton, which was assumed to be transported from other livestock farms, at 10 km distance. The contribution to SOC change due to the application of digestate was assumed leading to an accumulation of soil N, which causes a lower risk for leaching, and it was credited to the agricultural system (Sys-I). It can be due to change in the Soil Organic Carbon (SOC) stock, assuming C/N =10 in total soil-N. SOC stock change was modelled with the use of the C-tool (Petersen et al., 2013; Taghizadeh-Toosi et al., 2014). SON was calculated after 20 years growth with the assumed crops' yield and the corresponding SOC change (SI-1, Table S1.2.a). A N-budgeting method (Brentrup *et al.*, 2000) was used to calculate the N-leaching, after accounting the net N-input, related N-emissions and SON change. Both direct and in-direct N_2O-N emissions were calculated (IPCC, 2006). N-emissions from manure handling processes, particularly for ex-animal to ex-housing were also considered. Emission factors related to manure handling processes are tabulated in SI-1, Table S1.3. Assumptions on the manure flow characteristics are detailed in SI-1, Table S1.4. N_2O-N emissions, particularly during the digestate-application was assumed to be 64% and 60% lower compared to the direct application of cattle and pig manure respectively (Sommer and Birkmose, 2007) (see SI-1, Table S1.2.a). The calculated N and P emissions, also covering the entire fluxes as described above are shown in Table 2. The calculated emissions were found within the range reported mainly for conventional practices of raising livestock (see section 3.5).

Table 2. Materials inputs and outputs related to feed production system (Sys-I); all data are per 1000 kg_{LW}-Pigs and Suckler Cow Calves (SCC) respectively.

2.6 Livestock production system

In a typical Danish pig production system, feed consumption per 1000 kg_{LW}-Pigs was reported as approximately: 430 kg for the sow, 380 kg for the weaner and 1830 kg for the finisher (Dalgaard *et al.*, 2007a). In general, the feed conversion ratio was found to be 2.6, however it ranged from 2.6 -3.3 kg feed to 1 kg weight gain (Dalgaard et al., 2007a; Nguyen et al., 2010b). The distribution of the selected feed crops (Table 2) followed the "feed-nutrients standards", as suggested for the pig production system (Kjeldsen, 2016; Tybirk, 2016) (see SI-2, Table 2.2). In the current study, the standard was mainly considered to distribute the total amount of cereals (grains), as reported in Nguyen et al. (2010b) to barley and winter wheat grain; and also for the demanded protein feed to be covered by the both rapeseed cake and soybean meal (Table 2). Cereal crops demanded in the pig production unit were assumed to be covered from the pig farm (Table 2). Soybean meal was assumed to be produced and imported from Brazil (FAOSTAT, 2013). The demand of rapeseed cake was also fulfilled by supplying it from the available local market. Additional feedstuff comprised of fish meal and a small amount of minerals (Table 2). Energy input (Table 4) to the pig housing was based on Dalgaard et al. (2007a).

With regard to SCC production, typical life cycle of rearing the cattle constitutes as: replacement rate per cow is 20% (i.e. 0.2 cows slaughter per year), 0.45 bull calves are weaned per cow (slaughtered at the age of 16 months), 0.45 heifer calves are weaned per cow (of which 0.2 are used for replacement at the age of 24 months and 0.25 slaughtered at 16 months age) (Nguyen et al., 2010a). With regard to the total feedstuffs (Table 2), it was partly based on Nguyen et al. (2010a). The total feed quantity was distributed as per the different types of feed crops (Table 2), considering the dietary characteristics and the feed distribution pattern, as reported in Kristensen *et al.* (2015) (see SI-2, Tables 2.2-2.3). Generally, the SCC system relies on a combination of low productive permanent pasture and highly productive (highly fertilized) grassland (Nguyen et al., 2010a). Such combination was also followed at the time of deciding the feed crops, as assumed to be grown in Sys-I (Table 2). Table 4 presents primary energy input to the cattle housing and the outputs from the livestock husbandry (e.g. LW of SCC, manure and the undesired emissions).

Table 3. Digestate available as the source of crop nutrients, all values are per 1000 kg_{LW}-Pigs and SCC respectively.

Table 4. Materials input and outputs of the livestock system (Sys-III), all data are per 1000 kg_{LW}-Pigs and SCC respectively.

2.7 Green biorefinery system

The primary assumptions on the mass and energy flows to a GBR technology (Sys-II) were partly based on the studies reported by O'Keeffe *et al.* (2011), Kamm et al. (2009) and Parajuli et al. (2017a). The detail description on the mass flow characteristics during the conversion of 5.2 t DM of grass-clover (Table 5) to feed protein and other constituents is illustrated in SI-3, Fig S3.1. The equivalent demand of feed protein was proportionately calculated from the CP content in the produced feed protein cake (O'Keeffe et al., 2011) and the CP of soybean meal (NorFor, 2017), primarily considering the demand of protein in Sys-III (Tables 1 and 5). The additional green biomass, as required to cover the demand of protein (Table 5), resulted to occupy additional 0.67 ha of an arable land (Table 2). With regard to the conversion process, it was assumed that the process is initiated with mechanical processing (i.e. chopping) of the biomass (O'Keeffe et al., 2011) with 20% DM at harvest (Møller *et al.*, 2005). The process was then followed by the extraction of press-juice (DM 5 %) and press-cake from a mechanical screw-press. The fractions of press juice and the press cake were set to 70% and 30% respectively of the fresh matter (O'Keeffe et al., 2011). The CP content was assumed to be 23% of the juice dry matter (including the press juice available from the washing of press cake), which led to produce 0.47 t DM CP from 2.05 t DM of press juice (see SI, Fig S3.1, Block 6). After the dehydration and drying process, the produced feed protein was 0.24 t DM (65% of the total CP product, on a DM basis), assuming the extraction efficiency of 51% of the CP content in the total press juice (or, 5% per t DM green biomass) (see block 6 in Fig S3.1). Likewise, the conversion factor for the fibre product (i.e. fodder silage) was assumed to be 60% per t DM-fibre fraction contained in the green biomass (or, 33% per t DM of the supplied green biomass) (O'Keeffe et al., 2011). Other materials contained in the reference flow of the biomass within Sys-II were considered to be recovered in the 'waste streams'. The waste stream was considered as substrates for the biogas conversion. Total primary energy input calculated for extracting feed protein and other products from Sys-II is shown in Table 5.

Table 5. Material flows considered for the production of feed protein and fodder silage in the GBR system (Sys-II), all data are per 1000 kg_{LW}-Pigs and SCC respectively.

2.8 Biogas conversion and upgrading

Management of residues included both decanted juice produced from Sys-II and manure from Sys-III (see Fig. 1) to be utilized for the biogas conversion process. The decanted juice was assumed to be 6% of the dry matter fraction of the juice (see SI 3, Fig. S3.1), which was close to the amount reported in Kamm et al. (2009). The total mass of fermentable substrate for the production of biogas from the decanted juice was based on the volatile substance (VS, 82 % of the decanted juice) (O'Keeffe et al., 2011) (see Table 5). The conversion of manure to biogas followed the manure flow characteristics (Table 3 and SI-1, Table S1.4). Assumptions on the losses occurring during the storage and at housing are shown in Table 4. Electricity for pumping and stirring manure-slurry (in-house to storage) was based on Wesnæs et al. (2009) (Table 6). Total energy consumption during the conversion of biogas was for handling: the total manure (ex-housing) (Sys-III, shown in Table 4) plus mass of the decanted juice generated from Sys-II (Table 5). The methane yield due to the conversion of the available substrates are shown in Table 6. The methane content in the biogas was assumed at 0.65 m^3 CH_4/m^3 biogas (Table 6). The produced biogas was then assumed to be upgraded to biomethane (methane concentration shown in Table 6). Amine scrubber technology was assumed for biogas upgrading, as methane loss was reported higher for other technologies (Bailón and Hinge, 2012). Other most widely used technologies are water scrubbing and pressure swing adsorption (PSA) (Bauer et al., 2013). Biomethane recovery was assumed to be 99% (Table 6) (Bailón and Hinge, 2012). The study has also made evaluations on the alternative conversion pathways of biogas, and are discussed in the sensitivity analysis (section 2.10).

Table 6. Conversion of the residues to biogas and upgrading to biomethane, all data are per 1000 kg_{LW}-Pigs and SCC respectively.

2.9 Accounting impacts due to indirect land use change

Indirect land use change (iLUC) was considered in terms of induced GHG emissions: (i) due to the utilization of a productive land for producing the selected feed crops and (ii) due to avoided impacts, as the co-products were assumed to displace the corresponding agricultural commodities. For the first part, iLUC factor was assumed to be 1.73 t CO_2 eq $ha^{-1}y^{-1}$ (Schmidt and Muños, 2014). The total land use considered for calculating the iLUC impact is shown in Table 2. For the second part, avoided iLUC was considered (Fig. 2), if whenever the co-products are displacing the alternative agricultural products. It was assumed that during the substitutions of agricultural commodities, it would also avoid the iLUC effects associated with them (Schmidt and Brandao, 2013; Tonini *et al.*, 2016b). In the case of straw, iLUC was excluded (Schmidt and Brandao, 2013), as it considered a different reference situation (see section 2.5), and assumed no displacements of agricultural commodities for the considered quantity of straw. Avoided impacts due to iLUC were calculated for the substitutions of soymeal and Ukrainian barley, which were assumed to be displaced by feed protein and fodder silage respectively (see section 2.3). It was calculated by considering the so-called "soybean loop" (Dalgaard et al., 2007b), but in the current study, the assumed effect was in an opposite order (Parajuli et al., 2017a). Instead of an increased demand of soybean meal, it was for the reduced demands of soybean meal and soybean. It was assumed that avoiding 1 kg soybean meal production would decrease the production of soybean by 1.005 kg; the sign convention of which is in an opposite flow compared to Dalgaard et al. (2007b). It resulted to compensate the demand of soy oil by palm oil, but also induce additional production of palm kernel meal (approx. 23 g per 1 kg soymeal displaced). The palm kernel was again assumed to substitute the marginal meals, such as soymeal and spring barley. Hence, finally the induced impact resulted in the following forms:

- 1 kg avoided soymeal production, resulted to add the burdens equivalent to 0.86 kg of fresh fruit bunches (due to induced impact on palm oil value chain) and avoid 0.012 kg of spring barley production (Dalgaard et al., 2007b). Fresh fruit bunches are the product delivered from the palm planation and are transferred to the palm oil mills for sterilisation, whereupon the palm fruits are enzyme-deactivated and separated from the palm bunches (Saeed *et al.*, 2012).
- The avoided land use due to the co-productions of feed protein and fodder silage was 0.26 and 0.83 ha respectively. The stated land use would have been otherwise occupied to maintain the conventional demand (Fig. 2).

GHG emissions related to fresh fruit bunches and spring barley, as covered in the "soybean loop" was adapted from Dalgaard et al. (2007b). Table 7 summarizes the calculated GHG emissions induced due to iLUC for the integrated system.

Table 7. Induced GHG emissions due to iLUC, all data are per 1000 kg_{LW}-Pigs and SCC each. Impact per FU is shown at the bottom most row of this table.

2.10 Sensitivity analysis

The variations made on the basic assumptions to compare with the alternative scenarios are as follows.

2.10.1 Variations on the basic assumptions

a. Senst.-1: It assessed carbon footprint, with SOC change in 20 years. Emission reduction potential in 20 years was assumed as 19.8% of net C-input to soil (Petersen et al., 2013).
b. Senst.-2: Soil C assimilation due to crop residues and manure incorporation to the soil was excluded. The results on the carbon footprint thus exclude the contribution due to soil C sequestration.
c. Senst.-3: It jointly considered the below variations in the feed supply:
    - outdoor feed: grass-clover (grazed) was excluded, and the stake of it was covered by grass grown in permanent grassland (Table 2).

- rapeseed meal not accounted: source of protein was assumed to be supplied only from the imported soybean meal. Hence, the additional demand of feed protein to be produced was also proportionately calculated along with the increased demand of grass-clover to be supplied. Green biomass demanded was estimated to be 47% higher than in basic scenario (Table 5).

2.10.2 Variations in the integration scenarios

The features of the alternative scenarios assumed for the system integration are shown in Table 8. Scenarios with the different manure management practices were S_2-conv and S_3-conv, which were aimed to represent the conventional mixed crop-livestock systems, respectively without and with biogas conversion facility. Manure was assumed to be applied directly as fertilizer in S_2-conv. Hence, N_2O-N emissions during the application of manure was assumed to be 64% and 60% higher for cattle and pigs respectively, compared to the case of applying the digestate (Sommer and Birkmose, 2007). In contrast to S_1-GBR, in S_3-Conv and S_4-GBR, biogas was considered as a fuel to a combined heat and power (CHP) plant. Electricity and heat (outputs) were assumed to substitute the corresponding marginal productions (Table 1). Energy input and output was thus varied accordingly in S_3-Conv and S_4-GBR (Table 8).

Table 8. Alternative scenarios assumed for the mixed crop-livestock system.

3 Results

The characterised results obtained per FU are summarized in Table 9. Net and gross impacts are the environmental footprints, calculated with and without avoided impacts respectively. The detailed breakdown on the impact pattern for each livestock product and of the entire system can be found in SI-4.

3.1 Carbon footprint

Results on the carbon footprint obtained per FU for S_1-GBR are summarized in Table 9. The major contribution to the impact was from Sys-I (indoor and outdoor feed productions), covering 27% of the gross impact. It was mainly due to N_2O emissions, which covered 20% of the gross impact (i.e 2.68 kg CO_2 eq per FU). GHG mitigation due to SOC change was -3.17 kg CO_2 eq per FU. Among the crops produced, direct N_2O emissions during the production of grass-clover (grazed) was higher than rest of the biomasses (3.48 kg N_2O-N per ha); hence compared to other crops it relatively had a higher contribution to the total GHG emissions. Despite grass-clover production had higher N_2O emissions (both in rotation and in the grazed land), it was characterized with a higher soil C sequestration and thus possess GHG mitigation potential (Table 2).

Emissions from Sys-II contributed 0.8% of the gross carbon footprint obtained per FU, primarily due to energy input to produce feed protein and to process the fodder silage. Emissions from Sys-III contributed 62% of the gross impact. On this, CH_4 emissions due to the enteric fermentation contributed 55%, and the rest was related to energy input to livestock production units (Table 9, and detailed in SI, Table S4.1). In the same manner, Sys-IV contributed 9% of the gross impact, which was mainly due to energy input (5%) and CH_4 emission

(4%). CH_4 emissions was covering the both, fugitive losses during the biogas conversion process and the losses during the upgrading process.

The avoided products displaced 27% of the gross carbon footprint (Table 9). Displacement of LNG and synthetic fertilizers covered respectively, 40% and 42% of the total avoided impact (i.e. -7.2 kg CO_2 eq per FU). Of the total amount of biomethane production within S_1-GBR, the stake of decanted juice was however only 7%, thus proportionally had similar share during the substitution of LNG. Rest was covered by the manure recirculated back as fertilizer collected from the Sys-III. The substitutions due to feed protein and fodder silage contributed, respectively with 7% and 11% to the total avoided impact (SI-4, Table S4.1).

Furthermore, the carbon footprint (with iLUC) obtained per FU was 25% higher than excluding it (Table 9). The relative contribution related to iLUC in the respective value chains is shown in Table 7.

Table 9. Potential environmental impacts obtained per FU.

3.2 Non-renewable energy use

NRE use obtained per FU is shown in Table 9. Negative values for NRE use were due to higher abatement potential of fossil fuel consumption, which was induced due to the substitution of the marginal products (Table 9). The total avoided impact per FU was -211 MJ eq per FU, hence the main products were credited by displacing 258% of the gross impact (Table 9). Of the total avoided impact, the contribution from biomethane production was 84%, followed by recovered digestate-nutrients (10%), and the rest covered by feed protein and fodder silage (7%) (detailed in SI-4, Table S4.2).

Primary energy input to Sys-I contributed with 55% to the gross NRE use (Table 9), followed by energy input to: Sys-IV (24%), Sys-III (17%) and Sys-II (4%). Production of grass-clover (both as rotational crop and from the grazed land) and grasses (from permanent grassland) contributed 32% of the gross NRE use, including the demand of grass-clover in Sys-II. Rest of the contribution to the obtained NRE use was from cereals (13%), followed by imported soymeal (3%) and the remaining was from mineral feeds and rapeseed cake. The contribution from Sys-IV was mainly due to energy input for the conversion of biogas and for the upgrading process, covered 8% and 17% respectively of the gross NRE use.

3.3 Other impact categories

The undesired N and P emissions contributing to EP are shown in Table 2. Feed production system covered 97% of the gross EP (Table 9). The stake of ammonia was 38% of the gross EP, followed by nitrate (20%), phosphate (12%), nitric-oxide (5%) and N_2O (2%). Rest of the eutrophication potential was from the background system, particularly related to energy input considered within Systems-II and IV. Detailed contribution patterns on the selected environmental impact categories are shown in SI-4, Table S4.3. Regarding PFWTox, the feed production system covered 66% of the gross impact (Table 9). Emissions were related to imported soymeal (43%), followed by grass-clover (10%), cereals (8%) and the rest was covered by the other feeds. Grass-clover had the lowest impact at the field level, but the net impact was elevated due to the emissions from the production of agro-chemicals at the background level (mainly chemical fertilizers and energy, which were consumed higher than other crops). In the same manner, at the field level, spring barley and winter wheat contributed the most to the impact. Relatively, higher contribution was from winter wheat production, and was partly due to higher emissions at the farm level, depending on the types of a.is considered in the evaluation (Parajuli et al., 2016). Example, for the common types of herbicides considered for winter wheat and maize, such as fluroxypyr, iodosulfuron, pendimethalin, epoxiconazole, pyraclostrobin and cypermethrin, the calculated CTUe for winter wheat was two-fold higher than maize. This was mainly due to different emission distribution fractions, as was varied between these two crops, depending on the climatic parameters and the application seasons of the respective pesticide (Parajuli et al., 2016). Likewise, impact obtained for cereal crops was also higher compared to grass-forages, which was partly due to higher application rate assumed for growing cereals (Parajuli et al., 2016). The total avoided impact obtained per FU was -22 CTU_e (Table 8). It was due to displaced products, such as soymeal substituted 51% of the total avoided impacts, followed by LNG (35%), marginal fertilizers (10%) and Ukrainian barley (energy-feed) (3%) (SI-4, Table S4.4).

3.4 Environmental consequences of integrating GBR in the mixed crop-livestock system

The integration of Sys-II to the mixed crop-livestock system was articulated with the following variations in the resource use (i) production and the processing of grass-clover to meet the demand of livestock protein in Sys-III (Table 2), (ii) utilization of decanted juice to produce upgraded biogas in Sys-IV. The benefit was thus the co-productions of feed protein, fodder silage and biomethane. Environmental consequences of such were: additional demand of biomasses and their processing added the impacts, e.g. it was 1.8% of the overall GHG emissions calculated for the entire system. Likewise, specific amount of energy input and CH_4 losses related to the processing of decanted juice during the biogas conversion contributed with 2% to the total GHG emissions. Hence, approximately 4% of the impact was added to the system, whilst the products delivered from it avoided 7% of the impact (Fig. 3). Likewise, consequences of integrating Sys-II, with respect to the other impact categories are shown in Fig. 3, and are detailed in SI-4.

Fig. 3. Environmental burdens added and credited due to the integration of GBR (Sys-II) to a mixed crop-livestock system. Contributions of each sub-system are calculated with respect to the gross impact of S_1-GBR.

3.5 Sensitivity analysis

3.5.1 SOC change and variations on carbon footprint

Carbon footprint obtained for the different assumptions, as considered for within the faming system is shown in Fig.4. Results showed that when SOC change was calculated with a temporal scope of 20 years (Sens.-1), net carbon footprint was 24% lower than in the basic scenario. SOC change was almost double in 20 years compared to 100 years, inferring that less CO_2 is released to atmosphere in 20 years (Parajuli et al., 2017b; Petersen and Knudsen, 2010). In the same manner, when SOC change was excluded (Sens.-2), the impact was 21% lower in the basic scenario.

When feed crop such as, grass-clover (grazed) was replaced by grass (from permanent grassland) and rapeseed cake was replaced by soybean meal (Sens.-3), the carbon footprint was 3% higher compared to the basic scenario. The increment on the impact was in accordance to the additional demand of grass-clover, as required to produce feed protein also covering the demand which was covered by rapeseed cake in the basic scenario. The carbon footprint (with iLUC), as obtained per FU for the basic scenario was 17 and 7% lower than Sens.2 and Sens.3 respectively, but was 17% higher than Sens.1 (Fig. 4).

Fig. 4. Carbon footprint obtained under different scenarios of considering SOC change and the feed supply. The figure shows how the results on the carbon footprint varied under different assumptions compared to the main integrated system (S_1-GBR).

3.5.2 Environmental impacts under different scenarios of the mixed crop-livestock system

Fig. 5 shows the results obtained within the different alternative scenarios considered for the mixed crop-livestock system. Detailed results of each scenario are reported in SI-4. Key factors influencing the results were primarily due to SOC change and N_2O emissions. With regard to carbon footprint, the impact obtained per FU in S_1-GBR was 16% lower than S_2-conv, but was higher by 17% and 31% compared to S_3-conv and S_4-GBR. Results also revealed that the impact was largely influenced by the environmental credits, as induced due to the co-products. Example, the avoided impact for S_1-GBR was 141% higher than S_2-conv. In S_2-conv, manure was assumed to be directly applied as fertilizer, hence the avoided impact was only due to the recovered nutrients from the digestate. A higher carbon footprint in S_2-conv was also due to higher N_2O emissions, due to the assumption that manure was directly applied to the field (see section 2.10.2). On contrary, the avoided impact in S_3-conv and S_4-GBR were respectively, 17% and 36% higher than in S_1-GBR. Reason for a higher avoided impact in S_2-conv was mainly due to the assumptions on the biogas conversion pathways (Table 8). Higher avoided impact was due to displacement of marginal heat and electricity production, which was in addition to the utilization of the recovered nutrients (digestate). Likewise, in S_4-GBR, the main product was credited jointly by the substituted heat and electricity produced from the biogas conversion process, which was in addition to the impacts displaced due to recovered nutrients and the substituted feed protein source. Furthermore, net GHG emission was higher in S_1-GBR compared to S_4-GBR, which was due to emissions from the additional energy input and methane losses during the upgrading process. The contribution due to energy input for biogas processing in S_1-GBR and S_4-GBR was 9% and 7% of the respective gross impact. Other studies on biomethane conversion also reported a higher GHG emission profile compared to other conversion pathways of biogas (Steubing *et al.*, 2012; Tonini et al., 2016b).

The study showed a higher fossil fuel savings for S_1-GBR compared to the other alternative scenarios (Fig. 5). It was partly due to higher avoided impact in S_1-GBR, due to the substitution of LNG compared to the case of substituting the marginal energy mix, as considered in S_3-conv and S_4-GBR (detailed in SI-4, Table S4.2). In the same manner, net EP ranged from 0.09 to 0.11 kg PO_4 eq per FU; on which slightly higher impact was for S_1-GBR and S_4-GBR compared to the conventional systems (Fig. 5). This was mainly due to the emissions from the production of grass-clover required to cope the additional demand in Sys-II. Lastly, net PFWTox was lowest in S_4-GBR among all the alternative scenarios (Fig. 5), which was mainly due to a relatively higher avoided impact compared to the other alternative scenarios (see for detail in SI-4, Table S4.4). The uncertainties however also exist due to the consideration of the different emission distribution fractions, particularly at the foreground and background systems. In the current study, at the foreground level, use of Pest LCI tool was considered to differentiate the boundaries between the technosphere and the biosphere (Birkved and Hauschild, 2006), which is often improperly done in the current practice of pesticide emission modelling. However, at the background level it was based on the Ecoinvent database. The production of pesticides and other chemicals included in the Ecoinvent database are considered with emissions to agricultural soil, e.g. taking 100% of the applied active ingredients and letting the characterization model deal with their fate (Nemecek et al., 2007; Weidema et al., 2013).

Fig. 5. Results obtained for the potential environmental impacts within different scenarios of mixed-crop livestock system. Nomenclatures for S_1-GBR, S_2-conv, S_3- conv and S_4-GBR are detailed in Table 8.

4 Discussions

4.1 Comparison with other studies

At the time of preparing this study, no any similar kind of LCA study was found, particularly as modelled for S_1-GBR. In order to compare the environmental impacts and to check with the details obtained for emissions, primarily at the feed production level, the results obtained for producing LW of pigs and SCC under scenarios: S_2-conv and S_3-conv were considered. Comparison with other studies, based on these scenarios is relevant, because: (i) they represent the conventional mixed crop-livestock system and (ii) the variations on the results were found mainly due to the different assumptions made for feed production, livestock production and the biogas conversion systems (Dalgaard et al., 2007a; Kool *et al.*, 2009; Nguyen et al., 2010a). This was also revealed through the results discussed in section 3.4.

In the current study, within the pig production unit, NH_3 emissions was 21 kg NH_3-N per 1000 kg_{LW} (i.e. per 0.55 ha, Table 2), which was close to the values reported in Dalgaard et al. (2007a). NH_3 emission, as estimated per FU if was to calculated per 1 ha of land, then it would be 38 kg NH_3-N, which was also within the range, as reported for a typical Danish pig farms (27-44 kg NH_3-N) (Dalgaard, 2007). The calculated nitrate emissions (53 kg NO_3-N per ha) was also close to the range reported for a typical Danish pig farm (63-95 kg NO_3-N). P-leaching was calculated to be 1.5 kg P per ha (estimated from 0.81 kg P per 1000 kg_{LW}-Pigs, Table 2), and it was also within the Danish range (1.2-2.2 kg P per ha) (Dalgaard, 2007). N_2O-N emission per ha was 1.4 kg N_2O-N, which as lower than the range reported in the same study (i.e. 4.5-5.1 kg N_2O-N per ha). In the case of manure, directly applied to field (as assumed in S_2-conv), calculated N_2O emission was 2.2 kg N_2O-N per ha. The differences on the results for the specific emissions might be due to the types and numbers of crops that have been considered in the current study, which would otherwise vary if whole crop sequence grown in a full rotation in a typical farm is considered. The presented emissions were due to the production of winter wheat and spring barley covering the demand accounted for the pig production unit (Table 2). Likewise, with regard to the comparison of the specific emissions for the feed production in cattle farm, the related N-emissions (as shown in Table 2) were also close to the values reported in Nguyen et al. (2010a).

Carbon footprint calculated within S_3-conv and S_2-conv was found ranging from 1.56 to 2.07 kg CO_2 eq per kg_{LW}-Pigs (Fig. 4), which was equivalent to 2.1-2.8 kg CO_2 eq per kg meat (slaughter weight, see section 2.2) respectively. Detailed on the impact obtained for pig production is reported in SI-4 (Table S4.1). The carbon footprint of a typical conventional pork production in the countries, including Denmark, Sweden, France, Germany, the Netherlands and England ranged from 2.6 to 3.7 kg CO_2 eq per kg pork (Basset-Mens and van der Werf, 2005; Cederberg *et al.*, 2012; Dalgaard et al., 2007a; Kool et al., 2009).

Likewise, the carbon footprint obtained for SCC within S_2-conv and S_3-conv (Table 9) was equivalent to 40 and 32 kg CO_2 eq per kg slaughter weight (see section 2.2) respectively. This was equivalent to 21 and 15 kg CO_2 eq per kg_{LW}). Average CF per kg of beef meat for the countries, including Japan, Ireland, England, Canada and Brazil ranged from 25-40 kg CO_2 eq (Casey and Holden, 2006a; Casey and Holden, 2006b; Cederberg *et al.*, 2009; Dick *et al.*, 2015; Jacobsen *et al.*, 2014; Ogino *et al.*, 2007; Vergé *et al.*, 2008; Williams *et al.*, 2006). In the case of beef, average carbon footprint in EU-27 in 2004 was reported to be 10 and 17 kg CO_2 eq per kg_{LW} respectively, including and excluding emissions from land use change (Desjardins *et al.*, 2012). In the current study, the carbon footprint for SCC, as obtained after excluding SOC change was 18-24 kg CO_2 eq per $kg_{LW.}$ Likewise, the average carbon footprint (including SOC change) estimated per kg beef meat produced in Denmark was approximately 28 kg CO_2 eq (Mogensen *et al.*, 2015). In the same study, EP was reported as 0.17 kg PO_4 eq per kg meat (the conversion factor for kg NO_3 eq to kg PO_4 eq = i.e. 0.095) (Environdec, 2013). In the current study, it was approximately 0.15 kg PO_4 eq per kg slaughter weight of SCC. Likewise, net NRE use (excluding the avoided impact) was 42 and 47 MJ eq per kg_{LW}-SCC in S_2-Conv and S_3-conv respectively, which was 28 MJ eq per kg meat in Mogensen et al. (2015). Differences on the results between these two studies might be mainly due to the different LCA approaches considered for the evaluation. Detailed on the impact obtained for SCC is reported in SI-4 (Table S4.1).

With regard to the 'environmental hotspot', alike to the other studies, the current study also showed similar contribution patterns. Feed production was the main contributor to most of the impact categories. Example, for the production of pigs and SCC individually, the contribution from feed production was respectively, 44-52% and 25-35% of the gross carbon footprint obtained for S_3-conv and S_2-conv (SI-4, Table 4.1). Furthermore, results for S_2-conv showed that the total GHG emission, including the emissions due to feed production system and enteric fermentation contributed 93% of the total impact obtained for pig production unit. The contribution from the similar value chain was reported as 96% of the total GHG emissions for a typical Danish pig production system (Hermansen and Kristensen, 2011; Nguyen et al., 2011). Likewise, within the beef production cycle (within S_2-conv) the livestock production unit alone accounted 65% of the gross GHG emissions (SI-4, Table S4.1), which was 80% in Beauchemin et al. (2010). The contribution from the enteric fermentation was 58% of the gross GHG emissions obtained for SCC, which was reported as 49% for a bull/heifer system (Clarke *et al.*, 2013).

The results showed mixed pattern when comparing with other studies, and the minor variation compared to the above stated studies were partly due to the different feed production scenarios and composition of feed considered to fulfil the dietary requirement of the selected livestock system. Clarke et al. (2013) also suggested that SCC system since is very extensive, great variation on the results can be expected due to the difference between farms.

4.2 Other aspects of biogas conversion pathways and the extent of material processing

Here we discussed the potential avenues of considering the alternative ways of handling the raw materials (i) produced manure in a biogas conversion pathway and (ii) other potential means of utilizing the available chemicals in the press cake, e.g. to produce high value biobased chemicals.

4.2.1 Biogas conversion pathways

The current study showed that for most of the selected environmental impact categories, systems integration resulted with lower environmental burdens for producing livestock products compared to the conventional livestock farm. One of the important concerns identified from this study was on the part of utilizing biogas, i.e. whether it should be prioritized as a fuel to CHP or should be upgraded to be used as transport fuel. Results showed that the conversion of biogas to biomethane performed better in terms of fossil fuel savings and a reduction of the eco-toxicological measures, but it had higher carbon footprint compared to the scenarios where biogas was considered as fuel to a CHP plant. Most of the LCA studies also concluded with a higher GHG emission profile for the biomethane conversion pathway compared to other conversion pathways of biogas (Gallagher and Murphy, 2013; McEniry *et al.*, 2011; Smyth *et al.*, 2009; Tonini *et al.*, 2016a). Börjesson and Ahlgren (2012), however also concluded that from a techno-economic perspective utilization of biogas was better if it was considered as vehicle-gas in the transport sector than as fuel in the district heat sector. It was also argued that replacement of oil based transport fuel is an effective measure for meeting the objective of energy security of supply. Furthermore, Murphy et al. (2004) argued that in order to save GHG emissions, the only sustainable option could be using the most of the biogas for upgrading and using minor part for a small scale CHP generation on site.

4.2.2 Extent of material processing

Likewise, with regard to the extent of material processing, the sugar content in the press cake and partial fractions of the press juice can be further processed to produce fermentable products, e.g. lysine or lactic acid (Kamm et al., 2009). The further processing of the intermediate raw materials, however demand additional material inputs (e.g. energy and chemicals), but can add new values in the biomass conversion chains (Parajuli et al., 2017a). Parajuli et al. (2017a) reported that in the case of processing alfalfa to produce biobased lactic acid, there were net environmental gains, e.g. in terms of reducing GHG emissions and fossil fuel consumption, particularly compared to the conventional lactic acid production. Hence, expanding the system boundary of assessment, as for utilizing such intermediate materials, can further reduce the environmental footprints of the livestock products. The complexities of the industrial processing and technological know-how for it, are however could be an issue, particularly if they have to be facilitated at the farmers' level.

In the case of the biomethane conversion, variations on the obtained results may further occur if the methane loss factor is considered differently. Methane loss was found significantly varying with the different upgrading technologies (0.15% to 3% of the produced biogas) (Bailón and Hinge, 2012). A reduction of biomethane loss by 0.5% would reduce the GWP by 14–18% depending on the utilization route (Moghaddam *et al.*, 2016). Amine scrubber technology, which was assumed in the current study (with losses approximately 0.1-0.15%) is one of the recommended option to minimize GHG emissions in the biomethane conversion routes (Starr *et al.*, 2012). If alternatively, PSA technology was considered, the demand of heat for the upgrading process can be neglected, which can reduce the impact, but the methane loss reported for this technology was very high (around 3%), thus increasing the burden. Hence, innovations on the biogas upgrading technologies with lower loss level (Tonini et al., 2016a) and its commercial availability are demanded. Development of biomethane industry for a low carbon transport sector further relies on public policies and commitment at the national and regional levels (Smyth *et al.*, 2010).

In addition, the above discussed perspective also highlights on the need of judicious selection of the biogas conversion pathways, and whether there are other alternative sustainable energy options particularly to meet the demand of heat and power, besides utilizing biomethane. Furthermore, in future there could also be different energy pathways and diversified productive uses for the large quantities of other forms of energy, including power generation and use of electric vehicles (Weber and Clavin, 2012). It can also be argued that the different utilization, pathways may be not necessarily mutually exclusive but can simultaneously expanded. It has also been argued that "any natural gas used to displace coal will not be available to potentially displace oil in the transportation sector". It is also relevant to identify domestic opportunity costs of exporting natural gas rather than consuming it through domestic combustion or in other utilization pathways (Abrahams *et al.*, 2015). Furthermore, sustainable energy management is guided by numerous variables such as whether there exists optimal use of available resources, consideration of energy savings and efficiency measures, which are particularly relevant to meet a long-term sustainability goals that a country sets (Lund *et al.*, 2010b).

5 Conclusions

The study showed that with the inclusion of green biorefinery to produce feed protein and the integration of the biogas conversion facility to produce biomethane in a mixed crop-livestock system resulted in reduced environmental impacts, particularly compared to the livestock production system with no biogas facilities and GBR. Net environmental impacts obtained per FU for the main integrated system (S_1-GBR) considered in the current study were: 19.6 kg CO_2 eq for global warming potential; 0.11 kg PO_4 eq for eutrophication, - 129 MJ eq for non-renewable energy use and -3.9 CTUe for potential freshwater ecotoxicity. It indicated that due to substantial avoided undesired emissions, freshwater ecotoxicity was abated significantly and abatement of the fossil fuel depletions. Rest of the impacts were also lower than the conventional system. Like in the other similar studies, primarily related to a conventional rearing of pigs and SCC, the current study also revealed that the highest contribution to carbon footprint was from the production of feed and handling of manure. Similar value chains were the major contributors to the eutrophication potential and for the freshwater ecotoxicity. With regard to the fossil fuel consumption, it was again the feed production and the biogas conversion processes contributing the most to the impact. The environmental consequences of integrating biorefinery, with biomethane conversion facilities (along with manure collected from Sys-III), e.g. in terms of GHG emissions can be described in two-fold (i) increased the environmental burden by 12% of the gross carbon footprint, which was jointly due to the additional demand of the grass-clover required in Sys-II and energy input to Sys-II and Sys-IV, and (ii) displaced 27% of the gross impact due to co-products substituting the alternative conventional products. Furthermore, the specific impact of integrating Sys-II to a mixed crop-livestock system, was more or less balancing the environmental burdens, e.g. the added impact was 4%, whilst the avoided impact due to the products delivered from it was 7%. In the entire integrated system, the induced GHG emissions due to iLUC increased the carbon footprint by 25% compared to excluding it. With regard to NRE use, the consequence of the system integrations were: (i) 28% of the gross impact was added due to additional demand of grass-clover (Sys-II) and energy input to process biomass in Sys-II and produce upgraded biogas (Sys-IV), (ii) but, 258% of the gross impact was credited to the main product due to the displacement of the alternative products. A similar tendency was articulated for eutrophication potential and freshwater ecotoxicity.

The livestock products were credited in terms of their environmental footprints due to the utilization of manure and decanted juice to produce biomethane. The products arrived with higher fossil fuel savings, lower eutrophication potential and freshwater ecotoxicity, but the carbon footprint was higher, particularly compared to if biogas was treated as a fuel to CHP. The current study also suggested that the impact was mainly influenced by energy input and methane losses during the upgrading process, but further development of the conversion technologies was deemed potential to further mitigate the related environmental burdens. Considering the results obtained for S_1-GBR and S_4-GBR, the best integration approaches was for S_4-GBR, as it was with relatively lower environmental impacts compared to the main integration scenario. This was however due to the assumption of methane losses in the upgrading processes and more environmental credits gained in the S4-GBR due to the displacement of marginal electricity heat. However, in section 4.3.2, it was argued that endues of biogas may be not necessarily mutually exclusive but can simultaneously expanded. Furthermore, it is uncertain to claim on any of options, until and unless rest of the energy systems are also evaluated in a broader perspective, e.g. how the rest of the energy system could be a driving tool for sustainable energy management, such as interventions through the optimal use of available resources, combination of energy savings and efficiency measures, particularly to meet a long-term sustainability goals that a country sets. It is within this broader scope of systems issues that the real impacts of such a large energy shift must be analysed. Finally, assessing economic viability, institutional and societal aspects of operating the proposed integrated mixed crop livestock systems with a green biorefinery are inevitably relevant to support in the decision-making process.

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List of Tables:

Table 1. Basic assumptions considered for the substitutions of the alternative products.

Products	Substitution factor	Alternative products
LW-SCC		
LW -Pig		Assumed as the main products
Feed protein	1.58[a]	Soymeal[a]
Fodder-silage	0.91[b]	Ukrainian barley[b]
Biomethane	1	LNG [c]
Electricity	1	Danish marginal electricity mix[d]
Heat	1	Natural gas fired district heat[e]
Recovered nutrients (digestate)	NPK	Marginal fertilizer [f]

Assumptions:

[a] Marginal source of livestock protein was assumed to be soymeal (Dalgaard et al., 2007b). Substitution ratio was calculated based on the CP of the respective products: feed protein (65% per kg DM press cake) O'Keeffe et al. (2011) and soymeal (41% per kg DM) (NorFor, 2017). CP of the produced feed protein = 31% of CP (fresh biomass) (see SI-3, Fig. S3.1).

[b] Ukrainian barley as marginal feed (Muñoz et al., 2014; Schmidt and Brandao, 2013). Feed energy value and the equivalent mass were calculated as 15.2 and 13.9 MJ per kg DM for barley and grass-clover respectively (Møller et al., 2005; NorFor, 2017).

[c] LNG was decided based on the fuel properties (Fatih Demirbas, 2009).

[d] Marginal electricity = Danish electricity mix (Lund *et al.*, 2010a; Mathiesen *et al.*, 2009).

[e] Marginal heat = natural gas fired heat production (Mathiesen et al., 2009).

[f] Marginal synthetic fertilizers: Calcium Ammonium Nitrate (CAN), Triple super phosphate (P_2O5), Potassium Chloride (K_2O) (Hamelin *et al.*, 2011; Tonini *et al.*, 2012).

Table 2. Materials input and outputs related to feed production system (Sys-I); all data are per 1000 kg_{LW}-Pigs and suckler cow calves (SCC) respectively.

Items	Pigs		SCC	
	Feed (kg DM)[b]	Land occupation (ha)[c]	Feed (kg DM)[b]	Land occupation (ha)[c]
A. Total feed required (Sys-I)[a]	3098	0.55	20851	3.26
i. Indoor feeding				
Cereal grains	2460	0.55	2254	0.47
- *Barley*	*1230*	*0.31*	*564*	*0.14*
- *Winter wheat*	*1230*	*0.24*	*1691*	*0.33*
Grass-clover (in rotation)	-	-	5446	0.71
Maize silage	-	-	2404	0.24
Straw[d]	-	-	1726	-
ii. Outdoor feed			9021	1.83
- *Grass-clover (grazed)*	-	-	*4511*	*0.58*
- *Grass (permanent grassland)*	-	-	*4511*	*1.25*
B. Imported feed	431	-	143	-
- *Soymeal*	*364*	-	*12*	-
- *Rapeseed cake*	*273*	-	-	-
- *Mineral feed*	*6*	-	*131*	-
- *Vegetable Oil*	*31*	-	-	-
- *Fishmeal*	*30*	-	-	-
Net fertilizer input				
N[e]	111	-	904	
P[f]	23	-	132	
K[f]	54	-	528	

SON change (kg N)[g]	8	-	70	-
Emissions				
due to SOC change ($kg\ CO_2\ eq$)[g]	- 132	-	- 3040	-
NH_3-N (kg) [h]	21	-	90	-
N_2O-N (kg)[h]	1	-	11	-
NO_3-N (leaching) (kg)[h]	29	-	221	-
NOx-N (kg)[h]	3	-	12	-
P losses (kg)[i]	0.81	-	4	-

Assumptions:

[a] Total feed production from Sys-I (Fig. 1) included both indoor and outdoor feeding, data partly based on Nguyen et al. (2010a) and Nguyen et al. (2010b).

[b] Mass of each individual feed was calculated based on the feed to LW ratio, feed composition (Kjeldsen, 2016; Kristensen et al., 2015) and the nutrient composition in each feed (Kristensen et al., 2015; NorFor, 2017) (see SI-2, Table S2.1-2.4).

[c] Land occupation (ha) = Feed required divided by DM yield per ha of respective feed crops (DM yields are reported in SI-1, Table 1.1).

[d] Straw was based on winter wheat.

[e] Net N input = N-digestate + N-syn + N-seeds + N-deposition + N-fixation. $N_{fixation}$ (for grass-clover) = 80 kg N/ha/y (Høgh-Jensen and Kristensen, 1995). N deposition = 15 kg Nha^{-1} (Ellermann *et al.*, 2005). N_{seed} (kg N/ha/y) = 0.16 (maize); 0.17 (grass-clover); 2.42 (winter wheat), 1.88 (spring barley), 0.08 (permanent grassland), calculated based on the crude protein content of the respective seeds (see SI-1, Table S1.2).

[f] Net P and K = P and K-digestate + P and K-syn. For nutrients available from the manure-digestate, see SI-1, Table S1.5.

[g] Emissions due to SOC change = SOC change * 9.7% (emission reduction potential in 100 years) * mol. weight of CO_2 to C (44/12). Negative values indicate the soil C sequestration.

[h] Emission factors (EF) and assumptions on the emissions are reported in SI-1, Tables S1.2- S1.3.

[i] P losses = 5% of P surplus (Nielsen and Wenzel, 2007). P surplus = P-input from fertilizer + P manure minus P uptake by plant (Parajuli et al., 2017b; Parajuli et al., 2016).

Table 3. Digestate available as the source of crop nutrients, all values are per 1000 kg_{LW}-Pigs and SCC respectively.

	Pigs	SCC	Total (Pigs +SCC)
Total N-digestate (kg, demanded)[a]	94	550	644
Total N-digestate (kg, produced)[b]	45	425	470
- Sys-III[±]	41	424	465
- Sys-II[±±]	4	0.13	4
N-digestate (kg, deficit/surplus)[c]	49	126	174
Total digestate mass (demanded)[d] (t)	20	95	114
Total digestate mass (produced)[e] (t)	9	73	82.54
- Sys-III	*8.60*	*73.10*	*81.70*
- Sys-II[β]	*0.81*	*0.03*	*0.84*
Digestate mass (deficit/surplus)[f] (t)	10	22	32

Assumptions:

[a] N-digestate (demanded) = 75% and 70%, respectively for cattle and pig slurry with respect to N-synthetic.

[b] N-available was assumed to be N content in manure (ex-animal) (See Table S1.5). [±] Values based on the manure flow characteristics. [±±] N-content in decanted juice (digestate) = fresh mass * 50% total solid loss (Drosg *et al.*, 2015; Lebuf *et al.*, 2013) * N,P,K content per kg decanted juice. N, P and K (g per kg decanted juice) = 5, 0.9 and 2.8 respectively (Drosg et al., 2015; Parajuli et al., 2017a).

[c] N-digestate (deficit) = Total N-digestate (demanded) minus N-digestate (produced). Negative value indicates deficit amount.

[d] Mass of digestate, assumed based on N-content per t manure (ex-storage) = 4.76 kg N and 5.81 kg N per t manure of pig and cattle respectively (Hamelin *et al.*, 2012; Poulsen, 2009). Similarly, assumed for decanted juice.

[e] Total digestate mass (available) = Mass of residues from Sys-II and manure from Sys-III, i.e. after the digestion. [β]Wet mass (decanted juice) (Table 5), considering 6% DM (O'Keeffe et al., 2011).

[f] Negative mass indicate deficit wet mass in cattle farm. Total deficit mass of the digestate (32 t) was assumed to be covered by transporting from another farm (at 10 km distance). Only the environmental burdens of transporting it was accounted.

Table 4. Materials input and outputs of the livestock system (Sys-III), all data are per 1000 kg_{LW}-Pigs and SCC respectively.

Items		Pigs	SCC
Feed input		Table 2	Table 2
Energy input (housing)[a]			
- Electricity	kWh_e	195	1070
- Heat	MJ_h	239	-
Manure pumping and stirring[b]	kWh_e	36	336
Crop processing[c]	kWh_e	-	640
Output			
Live weight (LW)	kg	1000	1000
Manure fresh (ex-animal)[d]	kg	$7.9*10^3$	$73*10^3$
Manure flow (ex-housing)[e]	kg DM	551	$8.3*10^3$
Manure (ex-storage)[e]	kg DM	525	$7.5*10^3$
Volatile substance (VS) (ex-storage)[f]	kg DM	413	$6*10^3$
Emissions			
CH_4			
- Enteric fermentation[g]	kg	6	418
- Manure management[h]	kg	39	130

Assumptions:

[a] Pig: heat and electricity inputs = 240 MJ_h and 190 kWh_e per 1000 kg_{LW}-Pigs respectively (Nguyen et al., 2010b); SCC: electricity (used in stables) = 1.07 kWh_e per kg_{LW}-SCC (Nguyen et al., 2010a).

[b] Energy for pumping and stirring slurry (in-house to outside storage) = 4.6 kWh per 1000 kg slurry ex-housing (Wesnæs et al., 2009).

[c] Electricity (for crop processing) = 0.6 kWh_e per kg_{LW}-Pigs (Nguyen et al., 2010b).

[d] Total weight based on manure flow characteristics for pig and cattle slurry (see SI-1 Table S1.5).

[e] DM of the manure for pig and cattle, respectively: ex-animal (77, 126), ex-housing (70, 113), ex-storage (61, 103). Losses during the storage and during housing = 5% of ex-housing values and 10% of ex-animal values respectively (Poulsen, 2009).

[f] VS (ex-storage) for pig and cattle = 48 and 82 kg per t total mass, assumed after 80% of DM ex-storage. Losses were assumed the same, as reported above for DM in the footnote ‘e’.

[g] Pig: 1.5 kg/head/year (default factor for swine in developed countries) * 10 heads * 145 days * (365 days/year)$^{-1}$; Cattle: 0.06 * kg DM feed intake * 18.45 MJ/kg DM * (55.65 MJ/kg CH4)$^{-1}$ (IPCC, 2006).

[h] CH_4 (kg) (manure management) for pig = 0.45 m^3 CH_4 per kg VS * 0.67 (kg CH_4 per m^3 CH_4) *17% (for slurry in-house storage more than 1 month); for cattle = 0.17 m^3 CH_4 per kg VS * 0.67 (kg CH_4 per m^3 CH_4) *10% (for slurry outside storage with natural crust cover) (IPCC, 2006).

Table 5. Material flows considered for the production of feed protein and fodder silage in the GBR system (Sys-II), all data are per 1000 kg_{LW}-Pigs and SCC respectively.

Items/Livestock units	Units	Pigs	SCC
Total CP required (based on soymeal)[a]	kg DM	364	12
Total feed protein required and produced from GBR[b]	kg DM	231	8
Total fodder silage production[c]	kg DM	2720	90
Total grass required to fulfil the protein demand[d]	kg DM	5032	166
Decanted juice available for the biogas conversion[e]	kg DM	1336	44
VS of the decanted juice[f]	kg DM	1099	36
Energy input [g]			
- Electricity	kWh_e	144	5
- Heat	MJ_h	1456	48

Assumptions:

[a] From Table 2. CP content (soymeal) = 41% of DM (soymeal) (NorFor, 2017).

[b] CP content (feed protein) = 2.6% of total green biomass (O'Keeffe et al., 2011), or, 65% per kg DM of the CP product (see SI-3, Fig. S3.1) (O'Keeffe et al., 2011).

[C] Total grass-fibres production (fodder silage) = Total green biomass required (DM) * % of grass fibres per t DM of green biomass (54%), calculated after O'Keeffe et al. (2011) (see SI-3, Fig. S3.1, Block 4).

[d] Total green biomass required = CP content (soymeal)/CP (feed protein).

[e] Residues available for biogas conversion = 27 t (with 6% DM). It was calculated as 32% per t DM green-biomass (or, volatile dry solids (VDS, in kg t^{-1} DM) was 5% of the decanted press juice, wet mass) (O'Keeffe et al., 2011) (see SI-3, Fig. S3.1, Block 9).

[f] VS = 82% of the DM of decanted juice (O'Keeffe et al., 2011), see SI-3, Fig. S3.1, Block 9.

[g] Electricity = 29 kWh_e per t DM green biomass; heat = 289 MJ_h per t DM green biomass. Energy inputs were calculated based on Kamm et al. (2009) and O'Keeffe et al. (2011). Detailed in SI.3, Table S3.1.

Table 6. Conversion of the residues to biogas and upgrading to biomethane, all data are per 1000 kg_{LW}-Pigs and SCC respectively.

Items	Unit	Pigs	SCC
Input			
VS[a]	kg DM	1512	6060
Energy input			
a. Biogas conversion[b]			
- Electricity	kWh_e	20	146
- Heat	MJ_h	465	3423
b. Biogas upgrading[c]			
- Electricity	kWh_e	74	293
- Heat	MJ_h	1580	6277
Output			
Potential biogas production[d]	m^3 CH_4	704	2824
Net potential biogas production[e]	m^3 CH_4	702	2790
Output from the biogas conversion			
Biomethane[f]	m^3 CH_4	694	2759
Digestate (available)[g]	kg	$7*10^3$	$73*10^3$
Emissions			
CH_4 loss during biogas production[h]	m^3 CH_4	13	51
CH_4 loss during upgrading[i]	m^3 CH_4	1.1	4.2

Assumptions:

[a] VS in S_1-GBR = VS of manure (ex-housing) (Table 4) + VS of liquid residues of GBR (Table 5). VS of liquid residues from GBR = 82% of DM of the substrate (i.e. decanted juice) (O'Keeffe et al., 2011). See Table 5 for the VS (decanted juice).

[b] Energy input for the biogas conversion = 2 kWh_e and 49 MJ_h per tonne manure (ex-housing) (Nielsen *et al.*, 2003).

[c] Energy consumption for biogas upgrading: electricity (0.105 kWh_e) and heat (2.25 MJ_h) per m^3 net biogas production (Bailón and Hinge, 2012).

[d] Biogas yield, 85% efficiency = 0.85 * 0.356 m^3 CH_4/kg VS (Møller etal.,2004) *(0.65 m^3 CH_4/m^3 biogas)$^{-1}$ =0.466 m^3 biogas/kg VS.

[e] Net biogas production = Potential biogas production minus fugitive losses from the biogas plant (see footnote ‘h’).

[f] Recovery of biomethane = 99% of the net biogas production. Value averaged from Bailón and Hinge (2012).

[g] Digestate includes both processed manure plus digested generated after the digestion of the decanted juice (Table 3).

[h] CH_4 fugitive losses = 1.8 % of the potential biogas production (Pugesgaard *et al.*, 2013).

[i] CH_4 losses (upgrading) = 0.15% of net biogas production, value averaged from Bailón and Hinge (2012).

Table 7. Induced GHG emissions due to iLUC, all data are per 1000 kg_{LW}-Pigs and SCC each. Impact per FU is shown at the bottom most row of this table.

Items	Unit	Pigs	SCC
Impact per 1000 kg_{LW} of each livestock			
- iLUC, induced due the land use change[a]	kg CO_2 eq	2089	5670
- iLUC avoided[b]	kg CO_2 eq	- 1086	- 36
- Net iLUC[c]	kg CO_2 eq	1003	5634
Net iLUC per kg_{LW} of each livestock unit[d]	kg CO_2 eq	1	5.63
Net iLUC per FU[e]	kg CO_2 eq	6.64	

Assumptions:

[a] Calculated for the total land occupied for producing 1000 kg_{LW}-Pigs and SCC each = iLUC factor per ha * total land occupation (Table 2). iLUC factor = 1.73 t CO_2 eq ha^{-1} (Denmark) (Schmidt and Muños, 2014).

[b] Avoided iLUC covered the consequences in the form of "soybean loop" (Dalgaard et al., 2007b). See text in section 2.9.

[c] net iLUC = iLUC induced due to the land occupation minus iLUC avoided.

[d] iLUC per kg_{LW} of each livestock.

[e] Net iLUC of the whole system divided by the FU.

Table 8. Alternative scenarios assumed for the mixed crop-livestock system.

Variables/Scenarios	S_1-GBR (basic scenario)	S_2-conv	S_3- conv	S_4-GBR
Models of system integrations	Sys-I + Sys-II + Sys-III + Sys-IV-energy (biomethane)	Sys-I + Sys-III	Sys-I + Sys-III + Sys-IV-energy (heat and power)	Sys-I + Sys-II + Sys-III + Sys-IV-energy (heat and power)
Manure + residues management	Biogas + digestate (fertilizer)	Manure (fertilizer)	Biogas + digestate (fertilizer)	Biogas + digestate (fertilizer)
Biogas conversion	Biomethane	-	Combustion in CHP [a]	Combustion in CHP [a]

Assumptions:

[a] Energy output for biogas as fuel to CHP: electricity = 1.12 kWh/kg VS; heat = 5.22 MJ/kg VS (Nguyen et al., 2010b; Nielsen et al., 2003). VS for S_3-conv and S_4-GBR shown in Table 4 and Table 5, respectively.

Table 9. Potential environmental impacts obtained per FU.

Contributions	Carbon footprint ($kg\ CO_2$ eq)	EP ($kg\ PO_4$ eq)	NRE use (MJ eq)	PFWTox (CTU_e)
Sys-I	7.38	$1.2*10^{-1}$	45	12
Sys-II	0.22	$1.9*10^{-4}$	3.1	0.4
Sys-III	16.73	$2*10^{-3}$	14	4
Sys-IV	2.52	$8.8*10^{-4}$	20	2
Gross impact	26.86	$1.2*10^{-1}$	82	18
Avoided impact	- 7.25	$- 9.8*10^{-3}$	- 211	- 22
Net impact	19.6	$1.1*10^{-1}$	- 129	- 3.9
Net impact (with iLUC)	26.24	-	-	-

List of Figures:

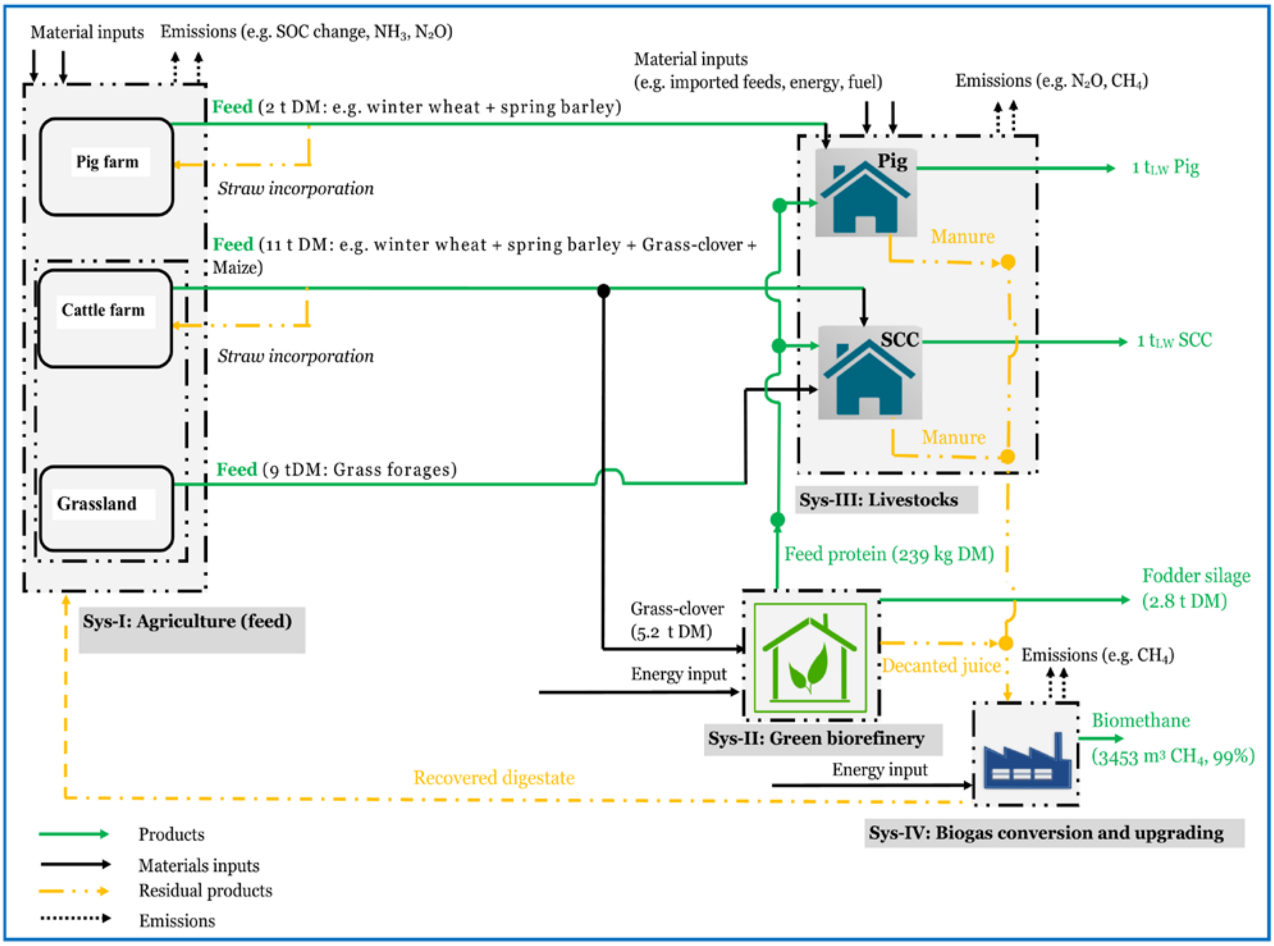

Fig. 1. Overall assessment framework considered for accounting the resource use in the integrated system (S_1-GBR).

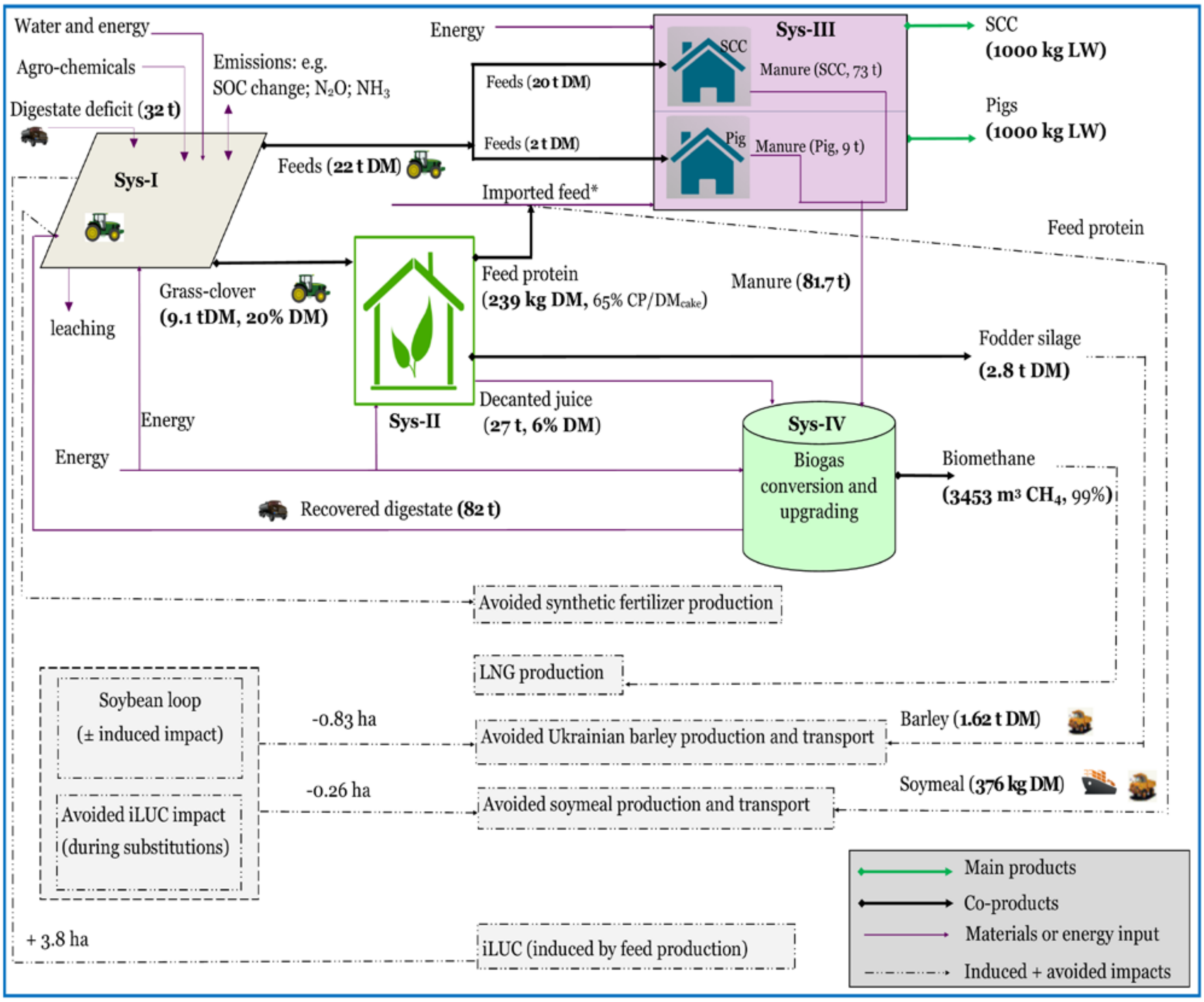

Fig. 2. System boundary considered for S_1-GBR**.** Values not shown for the materials are described in the respective sections. * Feed protein, produced and assumed to be supplied to the livestock system (Sys-III) substitutes the marginal protein supply. Utilization of fodder silage and recovered digestate also substitute the corresponding marginal products.

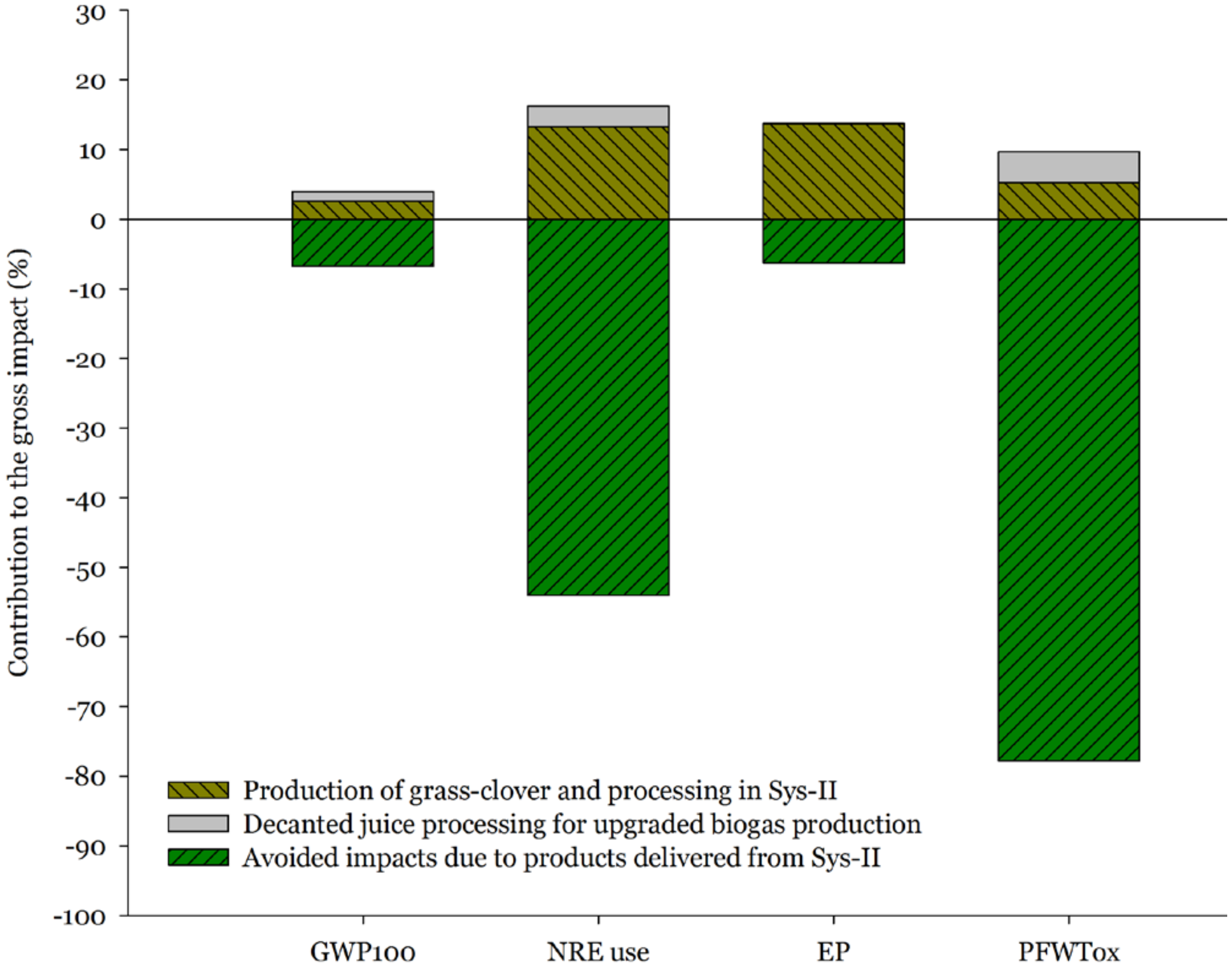

Fig. 3. Environmental burdens added and credited due to the integration of GBR (Sys-II) to a mixed crop-livestock system. Contributions of each sub-system are calculated with respect to the gross impact of S_1-GBR.

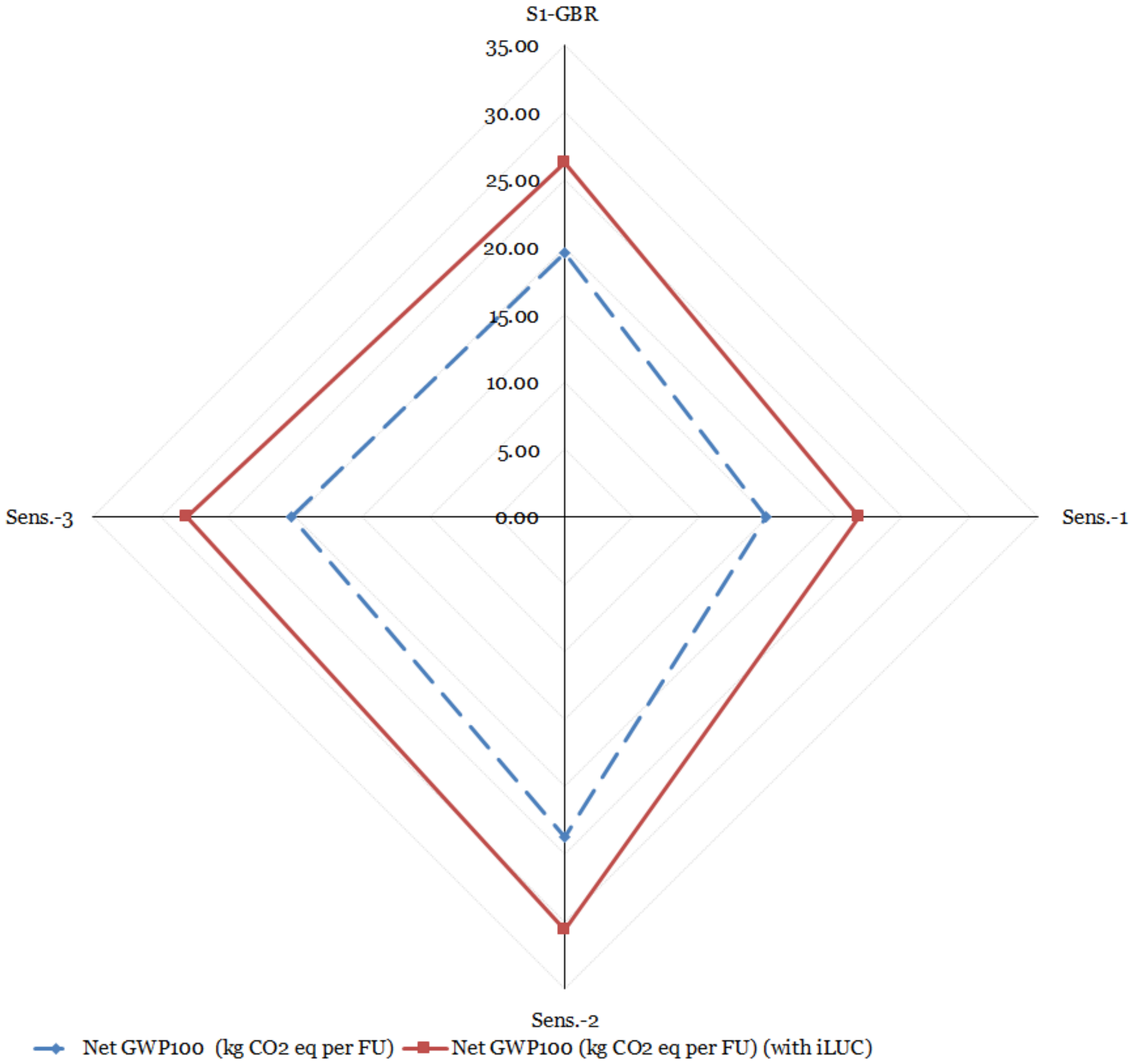

Fig. 4. Carbon footprint obtained under different scenarios of considering SOC change and the feed supply. The figure shows how the results on the carbon footprint varied under different assumptions compared to the main integrated system (S_1-GBR).

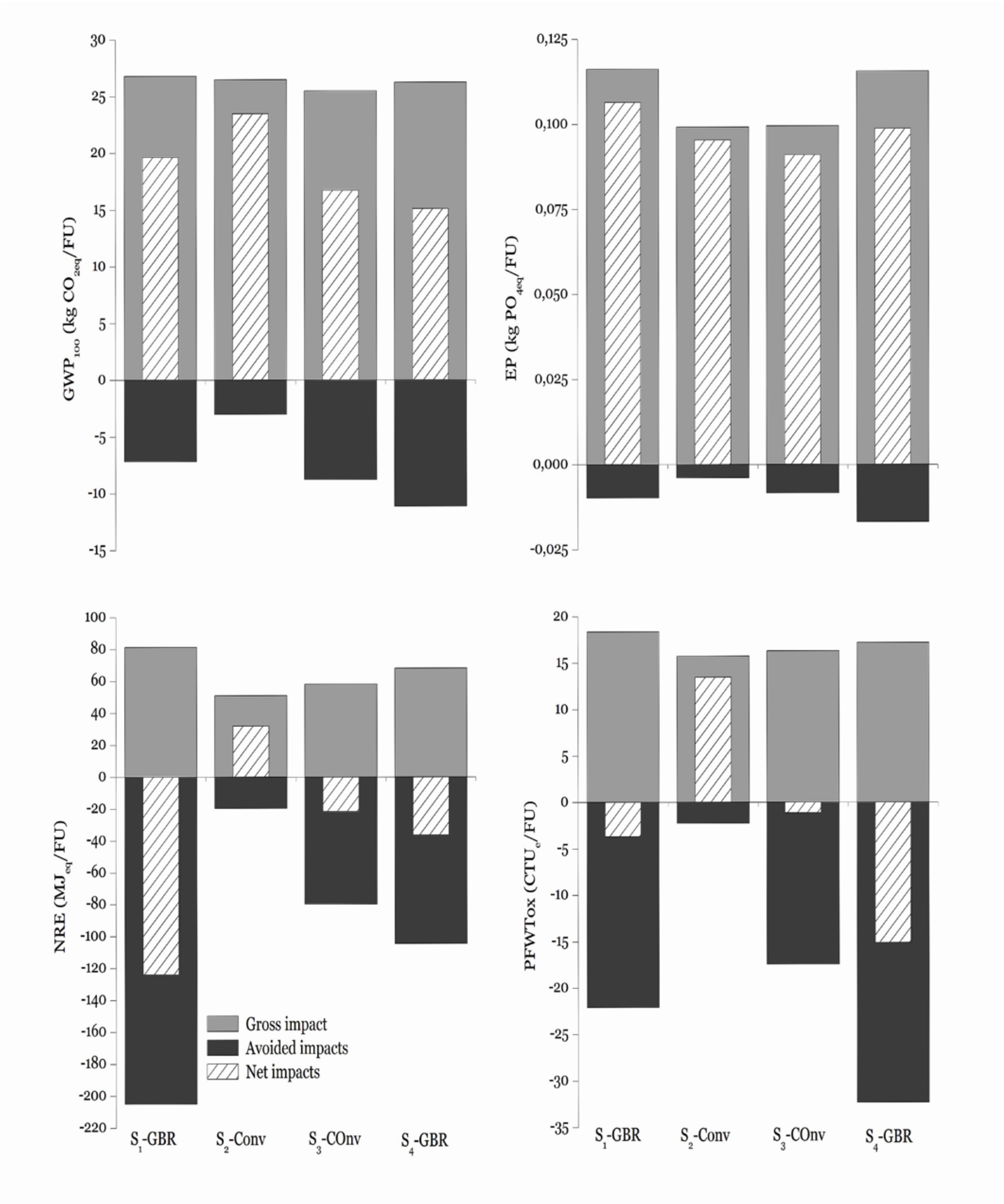

Fig. 5 Results obtained for the potential environmental impacts within different scenarios of mixed-crop livestock system. Nomenclatures for S_1-GBR, S_2-conv, S_3- conv and S_4-GBR are detailed in Table 8.

Appendix-A: Supporting data and information

Can farmers mitigate environmental impacts through combined production of food, fuel and feed? - a consequential life cycle assessment of integrated mixed crop-livestock system with a green biorefinery

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Contents

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1 SI-1: Data used in the feed production system (Sys-I)

Table S1.1. Calculation for SOC change during the production of the selected livestock feed (all data are per 1 ha).

Parameters/Crop types	Unit	MZ[ℓ]	GC[ℓ]	WW[ℓ]	SB[ℓ]	GC-gr[ℓ]	PP-gr[ℓ]
DM from residues							
Yield of removed roughage & grain	t DM $ha^{-1}y^{-1}$	9.91	7.71	5.07	3.94	7.71	3.62
Straw	t DM $ha^{-1}y^{-1}$			2.79[a]	(2.16)[a]		
Total non-harvestable residues	t DM $ha^{-1}y^{-1}$	13.72	20.04	14.99	10.07	20.04	9.40
Root[b]	t DM $ha^{-1}y^{-1}$	2.06	9.02	3.75	1.71	9.02	4.23
Stubble, chaff, straw left in the field[c] etc.	t DM $ha^{-1}y^{-1}$	1.75	3.31	3.38	3.43	3.31	1.55
Total crop residues[d]	t DM $ha^{-1}y^{-1}$	3.81	12.32	7.13	5.14	12.32	5.78
SOC change							
C input from reference crop[e]	kg C $ha^{-1}y^{-1}$	2924	2924	2924	2924	2924	2924
C input from the main crops[f]	kg C $ha^{-1}y^{-1}$	1751	5668	3281	1368	5668	2660
C input from digestate/manure[g]	kg C $ha^{-1}y^{-1}$	1391	1391	1391	1391	2621	1771
Total SOC change (including C from digestate)[h]	kg C $ha^{-1}y^{-1}$	-218	-4135	-1748	165	-5365	-1507
Emissions due to SOC change (100 y)	kg CO_2 eq $ha^{-1}y^{-1}$	-77	-1471	-622	59	-1908	-536

[ℓ] MZ = maize, GC = grass-clover, WW = winter wheat, SB = spring barley, GC-gr = grass-clover (grazed) and PP-gr = permanent pasture (grazed).

Assumptions:

[a] 100% of the straw from winter what is removed, whilst straw from spring barely (given in parenthesis) 100% of straw assumed incorporated to soil.

[b] Harvest index (alpha) and root mass (beta) of the selected crops are based on Taghizadeh-Toosi *et al.* (2014).

[c] Calculated as: Total plant residues - Root residues.

[d] Total Plant residues = Crop yield * Parameter[†] for stubble + root/(net yield). Parameter[†] are derived from Mikkelsen *et al.* (2011).

[e] Spring barely was assumed as the reference crop (Parajuli *et al.*, 2017b; Parajuli *et al.*, 2016).

[f] Calculated from the total C assimilation (Taghizadeh-Toosi et al., 2014).

[g] C input from digestate/manure based on the DM of manure flow (from SI4 Table S4.4). Digestate from the pig manure was considered for producing winter wheat and spring barley (for the pig production unit). C content of manure (averaged 39% per manure DM) (C-tool) (Taghizadeh-Toosi et al., 2014) was considered for the calculation.

[h] SOC change = C input from the selected crops +manure minus C input from the reference crop.

[i] 9.7% of the SOC change (Petersen *et al.*, 2013) * mol. weight of CO_2 to C (44/12). Negative value here indicates the soil C sequestration.

Table S1.2.a N and P flows during the production of the livestock feed crops (all data are per 1 ha)

		MZ	GC	WW[£]	SB[£]	GC-gr	PP-gr
N-balance							
Total N-input[a]	kg N ha^{-1}y^{-1}	209	339	217 (208)	187 (186)	411	243
- *N-syn*		*25*	*75*	*31 (22)*	*1 (0)*	*227*	*59*
- *N-digestate*		*169*	*169*	*169 (169)*	*169 (169)*	*169*	*169*
- *N-others*		*15*	*95*	*17 (17)*	*17 (15)*	*15*	*15*
Output[b]	kg N ha^{-1}y-^{1}	125	204	103 (103)	68 (68)	272	84
Field balance[c]	kg N ha^{-1}y^{-1}	84	136	114 (105)	118 (118)	139	159
N losses	kg N ha^{-1}y^{-1}						
Total NH_3-N[d]		30	29	31 (38)	30 (38)	28	25
NOx-N[e]		4.1	4.1	4.2 (5.2)	4.1 (5)	3.5	3.1
Denitrification[f]		7.9	11.5	1.4 (1.4)	1.2 (1.2)	11.54	9.86
Total N_2O-N losses (direct + indirect)[g]	if, manure	2.75	3.14	3.35 (3.21)	4.05 (1.88)	7.39	6.26
	if, digestate	1.67	2.06	2.27 (2.13)	2.97 (0.8)	5.23	4.1
Soil change, N[h]	kg N ha^{-1}y^{-1}	1	44	17 (17)	12 (12)	51	1
Potential leaching[i]	kg N ha^{-1}y^{-1}	41	47	60 (43)	71 (61)	45	119
P-balance							
Pinput[j]		45.04	40.26	40.74	40.63	40.26	40.25
P-uptake[k]	kg P ha^{-1}y^{-1}	25.76	20.06	13.18	10.24	20.06	9.41
P-surplusk[l]	kg P ha^{-1}y^{-1}	19.28	20.21	27.55	30.39	20.21	30.84
P-losses[m]	kg P ha^{-1}y^{-1}	0.96	1.01	1.38	1.52	1.01	1.54

Assumptions:

[£] Values given in the parentheses for winter wheat and spring barely are for the feeds grown on pig farm, where the pig based manure/digestate application is considered. Emission factor for NH_3 due to pig manure application (at housing) thus was set to 0.16 * kg N-manure, other factors remaining the same (see emission factors in Table S1.3). Plant uptake efficiency (pig manure) assumed at 75% (Wesnæs et al., 2009).

[a] Total N-input = N-digestate + N_{syn} + N-others. N others = $N_{fixation}^{\rho}$ + $N_{deposition}^{\dagger}$ + $N_{seed}^{\pm}$. $^{\rho}$ $N_{fixation}$ for grass-clover = 80 kg N/ha/y (Høgh-Jensen and Kristensen, 1995). †N deposition = 15 kg Nha^{-1} (Ellermann *et al.*, 2005). ± N_{seeds} calculated from the crude protein content of the respective seeds, assumed as: 9.6, 15, 10, 10.8, 15, 14.5% per kg DM seeds respectively, maize, grass-clover, winter wheat, spring barley, grass-clover (grazed) and permanent pasture (grazed) (Møller *et al.*, 2005). N_{norms} considered for the crops are shown in Table S1.2.b.

[b] Calculated based on crude N and the DM yield. Crude N content (% DM)= maize =7.9; grass-clover (average of 2000-2013, based on (Møller et al., 2005; Thøgersen and Kjeldsen, 2015); winter wheat= 10.9 and straw= 3.3; spring barley = 10.82, average of years 2007-2013 (Møller *et al.*, 2012; Møller and Sloth, 2013; Møller and Sloth, 2014; Vils and Sloth, 2003); grass-clover (grazed) and permanent grass land (grazed) = 22 and 14.5 respectively (Møller et al., 2005; Thøgersen and Kjeldsen, 2015).

[c] Field balance = N-input minus N-output.

[d] NH_3 emission shown in Table S1.3.

[e] NO_x-N = (NO+NO_2), where NO_2 is assumed to be negligible, and calculated as NO_x-N: NH_3-N = 12:88 (Schmidt and Dalgaard, 2012).

[f] Based on Vinther (2005).

[g] See section 2.5 in the main document. Emission factors shown in Table S1.3. N_2O losses are shown both for the cases, if manure or digestate are applied.

[h] See section 2.5 in the main document

[i] N-leaching = N-balance minus N-losses

[j] See texts in section 2.5 in the main document

[k] Emission factors shown in Table S1.3.

[l] P surplus = P-input from fertilizer minus P uptake by plant (Nielsen and Wenzel, 2007).

[m] P losses = 5% of P-surplus (Nielsen and Wenzel, 2007).

Table S1.2.b. N,P,K fertilization norms considered for the selected feed crops production (all data are per 1 ha).

	MZ	GC	WW[1]	SB[1]	GC-gr	PP-gr
		N-balance				
N-norms[a]	143	194	149	119	345	177
P-norms[a]	45	38	32	18	21	19
K-norms[a]	137	275	407	86	54	230

Assumptions:

[a] Norms for Fertilizer input were based on NaturErhvervstyrelsen (2013) and NaturErhvervstyrelsen (2015). For grass-clover (rotational): N-norm - reduced quota (40.5 kg $ha^{-1}y^{-1}$) in the crop following the grasses. Grass-clover (grazed) and grass (permanent grass land) also included N-quota (under-sown crops) (i.e. 111 kg N $ha^{-1}y^{-1}$).

Table S1.3. Emission factors considered during the manure management.

Emissions	Amount	Emission factor (EF)	Source for EF
N_2O-N_{direct} (kg)			(IPCC, 2006)
Housing	kg N in manure ex-animal		
- Slurry		0.002	
Storage	kg N in manure ex-housing		
- Slurry		0.005	
Application	kg N in manure ex-storage		
- Slurry		0.01	
At pasture (grazing)		0.02	
N-synthetic		0.01	
Crop residues	kg N $ha^{-1}y^{-1}$	0.01	(IPCC, 2006)
N_2O-$N_{indirect}$ (kg)			(IPCC, 2006)
from NH_3 losses	NH_3-N	0.01	
From N-leaching	NO_3-N	0.0075	
NH_3-N (kg)			(Mikkelsen *et al.*, 2006; Poulsen *et al.*, 2001)
Housing	kg N in manure ex-animal		
- Slurry	0.16 (pig) 0.08 (cattle)		
Storage	kg N in manure ex-housing		
- Slurry		0.022	
Application	kg N in manure ex-storage		
- Slurry		0.12	
At pasture (during grazing)		0.07	
N-synthetic		0.022	
Crop residues			(Sommer *et al.*, 2004)
- Grasses		0.5 $kgha^{-1}$	
- Cereals and other arable crops		2 $kgha^{-1}$	

Table S1.4. Manure flow characteristics assumed in the study.

		Pigs			Cattle		
Manure flow		ex-ani	ex-hou	ex-sto	ex-ani	ex-hou	ex-sto
Total mass	kg	7900	7900	8600	73101	73101	73101
DM[a]	kg	612	551	525	9194	8274	7529
VS[b]	kg	507	446	413	7622	6702	6024
Assumptions (unit for below materials are per t total mass)							
[a]DM	kg	77	70	61	126	113	103
VS[b]	kg	64	56	48	104	92	82
N[c]	kg	6.56	5.45	4.77	6.89	6.36	5.81
P	kg	1.09	1.09	1.00	1.02	1.03	0.99
K	kg	2.85	2.85	2.62	5.82	6.09	5.83

Assumptions:

[a] DM ex-storage (ex-sto) from Poulsen (2009). Losses during the storage: 5% of the ex-housing (ex-hou) values. Losses during the housing: 10% of the ex-animal (ex-ani) (Hamelin *et al.*, 2012).

[b] VS-ex-storage = 80% of the DM ex-storage (Hamelin et al., 2012).

[c] Based on Poulsen (2009).

Table S.1.5. LCI data considered for the assumed substitutable products, adapted from Ecoinvent v3 (Weidema *et al.*, 2013).

Co-products	Marginal products	Source/data
Feed protein	Soymeal	Protein feed, 100% crude (GLO)| soybean meal to generic market for protein feed
Electricity	Danish electricity mix (in sensitivity analysis)	Electricity, high voltage (DK) market for | Conseq, U)
Heat	Natural gas fired heat production (in sensitivity analysis)	Heat, central or small-scale, natural gas (Europe without Switzerland)| market for heat, central or small-scale, natural gas | Conseq, U)
Fertilizers	CAN	CAN = Nitrogen fertiliser, as N (RER)| CAN| Conseq, U
	P_2O_5	P_2O_5 = Phosphate fertiliser, as P_2O_5 (RER)| triple superphosphate production | Conseq, U
	K_2O	K_2O = Potassium chloride, as K_2O (RER)| potassium chloride production | Conseq, U

2 SI-2: Data used in the livestock production system (Sys-III)

Table S2.1. Feed compositon assumed for the pig production.

	Reported values[a]	Used Values
Barley	39%	24.4%
Wheat	39%	45.6%
Vegetable oil	1%	1.6%
Soybean meal	12%	12%
Rapeseed cake	9%	9%
Fish meal	1%	5%

Assumptions:

[a] Values based on Kjeldsen (2016).

Table S2.2. Feed distribution assumed for the livestocks production

Feeds	Pigs[a]	Cattle[b]
	100%	100%
Cereals	79%	11%
Protein feed	21%	0.06%
- *Soy*	*11.6%*	*0.06%*
- *Rapeseed cake*	*9%*	-
- *Fish meal*	*1%*	-
Maize-silage	-	12%
Grass and grass-clover	-	68%
- *Grass-clover (rotation)*	-	*27%*
- *Grass-clover (grazed)*	-	*18%*
- *Grass (permanent grassland)*	-	*22%*
Other roughages (straw)	-	9%
Mineral feed	-	1%

Assumptions:

[a] Based on ingredients (% of dry matter intake) (Kristensen *et al.*, 2015) and average norms of nutrients in each feedstocks, based on NorFor (2017) and Feedipedia (2017).

[b] Distributed based on the total feed required (Nguyen *et al.*, 2010) and dietary characteristics for cattle feed (see Table S2.3) and nutrient contents (Table S2.4).

Table S2.3. Dietary characteristics for cattle feed (Kristensen et al., 2015)

Nutrients	unit	Quantity
CP	g/kg DM	165
Crude fat	g/kg DM	31
NDF	g/kg DM	331
Starch	g/kg DM	170
Sugar	g/kg DM	59

Table S2.4. Nutrients content in the assumed feed for SCC (considered for distributing the feedsstuffs). Values based on *NorFor (2017).*

	CP	Crude fat	NDF	Starch	Sugar
Barley grain	101	31	180	609	20
Winter wheat grain	104	26	117	680	32
Grass-clover	159	44	438	10	71
Grass	156	44	434	0	67
Maize	75	22	363	307	17
Soybean meal	410	81	-	55	-
Rapeseed cake	385	40	-	62	-
Straw	33		820	-	-
Fishmeal	92.1	-	-	-	

3 SI-3: Data used in the feed protein production system (Sys-II)

Table S3.1. Energy consumption in Sys-II, values are per t DM of the green biomass

	Processes	Units	Value
1	Pumping/water energy[±]	kWh_e	2.27
2	Fiber processing to silage fodder[Δ]	kWh_e	16.88
3	Protein extraction		
3.1	Steam coagulation[Δ]	MJ_h	284
3.2	Skimming[Δ]	kWh_e	0.19
3.4	Decanting[±]	kWh_e	3.36
3.5	Dehydration and drying[Δ]	MJ	5.88
	Total electricity	kWh_e	29
	Total heat	MJ_h	289

Assumptions:
Energy inputs per t fresh matter of the green biomass reported in [±]O'Keeffe *et al.* (2011) and [Δ]Kamm *et al.* (2009) were considered for pressing. Calculated energy inputs in the Table above are per t DM of the biomass, estimated also considering the differences in the DM fractions, as reported in O'Keeffe et al. (2011) (i.e. 22%) and in the current study (i.e. 20%). DM assumption was similar to Kamm et al. (2009).

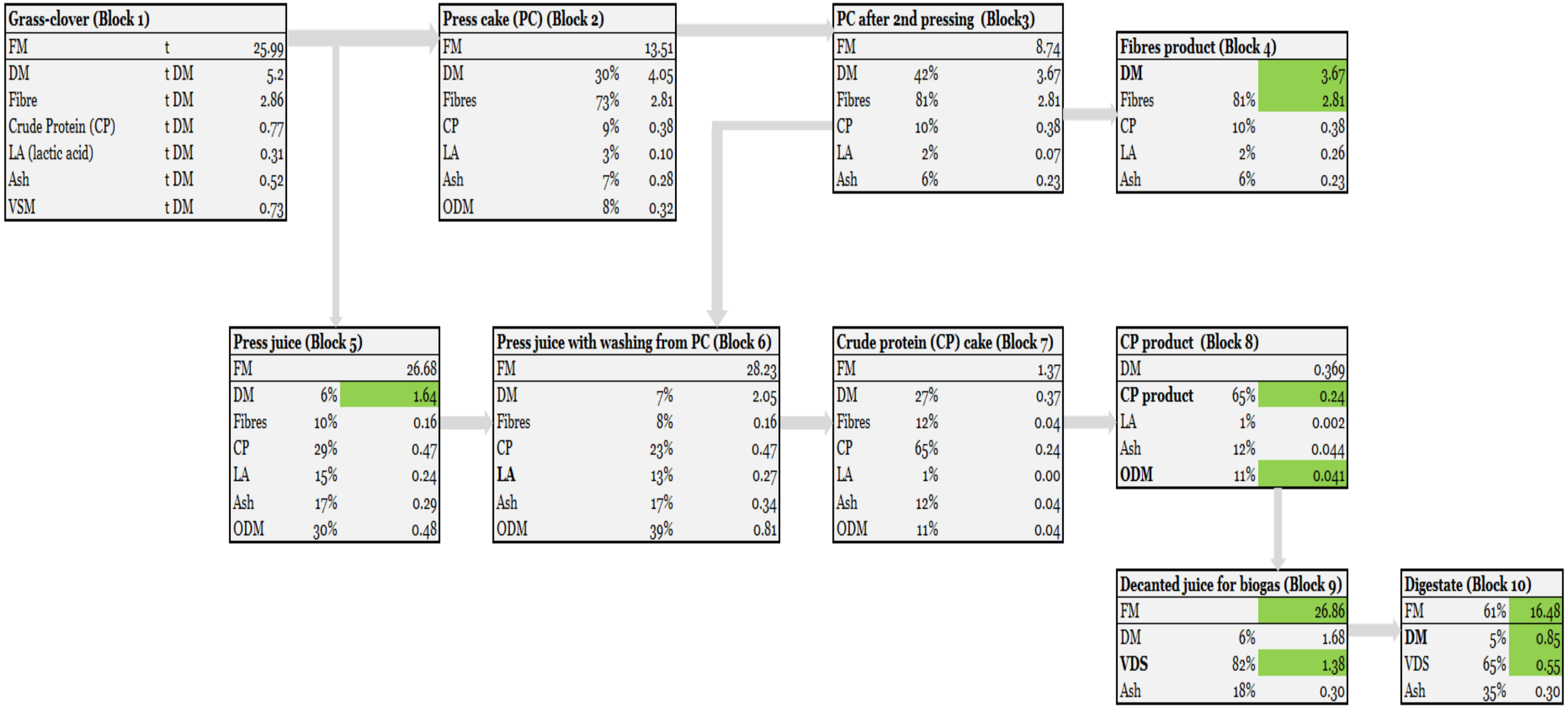

Fig.S-6.1: Mass flow considered for the conversion of 5.2 t DM grass clover to produce feed protein (CP product, Block 8) and fodder silage (Fibres, Block 4). Data on the conversions were partly adapted from O'Keeffe et al. (2011) and Parajuli *et al.* (2017a). DM content of the green biomass at harvest is assumed to be 20%. 'Green' shaded parts represent the mass of the depending intermediate materials and the final products considered in the evaluation. All data presented are in DM basis, calculated from the fresh matter (FM) and the compositions of each material are calculated with respect to the DM mentioned in each block. ODM = organic dry matter, LA = lactic acid, VDS = volatile dry solids (kg t^{-1} DM), volatile solids expressed as a fraction of the stillage DM.

4 SI-4: Detail results on the environmental footprints for basic scenarios and the alternative scenarios.

Table S4.1. Details on the estimated carbon footprints for Pigs and SCC production per 1000 kg_{LW} each (impact per FU and per kg_{LW} of each livestock, shown at the bottom of the Table).

	S_1-GBR			S_2-conv			S_3-conv			S_4-GBR		
	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC
Feed (Sys-I)	**1616**	**5765**	**7381**	**1428**	**8326**	**9754**	**1147**	**5750**	**6896**	**1616**	**5765**	**7381**
Maize	-	365	365	-	488	488	-	365	365	-	365	365
Grass-clover	-	509	509	-	867	867	-	509	509	-	509	509
Winter wheat	305	440	745	428	609	1037	305	440	745	305	440	745
Barley	290	133	423	449	206	654	290	133	423	290	133	423
Rapeseed cake	1.21E+02	-	1.21E+02	-	-	1.21E+02	1.21E+02	-	1.21E+02	1.21E+02	-	1.21E+02
Soymeal	356	12	368	356	12	368	356	12	368	356	12	368
Grass-clover grazed	-	1646	1646	-	2238	2238	-	1646	1646	-	1646	1646
Permanent grassland	-	2388	2388	-	3650	3650	-	2388	2388	-	2388	2388
Fishmeal	1.38E-02	-	1.38E-02	-	-	1.38E-02	1.38E-02	-	1.38E-02	1.38E-02	-	1.38E-02
Straw	-	257	257	-	257	257	-	257	257	-	257	257
Vegetable oil	49	-	49	49	-	49	49	-	49	49	-	49
GBR (System II)	**215**	**7**	**222**	**-**	**-**	**-**	**-**	**-**	**-**	**215**	**7**	**222**
Grass-clover production	471	16	486	-	-	-	-	-	-	471	16	486
Energy input	215	7	222	-	-	-	-	-	-	215	7	222
Electricity	*102*	*3*	*105*	-	-	-	-	-	-	*102*	*3*	*105*
Heat	*113*	*4*	*117*	-	-	-	-	-	-	*113*	*4*	*117*
Livestock housing (System III)	**1300**	**15428**	**16728**	**1300**	**15428**	**16728**	**1300**	**15428**	**16728**	**1300**	**15428**	**16728**
Bedding material (straw removal)	-	301	301	0	301	301	-	301	301	-	301	301
Energy	182	1448	1630	182	1448	1630	182	1448	1630	182	1448	1630
Electricity	*164*	*1448*	*1612*	*164*	*1448*	*1612*	164	1448	1612	*164*	*1448*	*1612*
Heat	*19*	-	*19*	*19*	-	*19*	19	-	19	*19*	-	*19*
Emissions												
CH_4 (enteric + manure management)	1118	13679	14797	1118	13679	14797	1118	13679	14797	1118	13679	14797
Biogas conversion (System IV)	**524**	**2000**	**2524**	**-**	**-**	**-**	**135**	**1739**	**1874**	**401**	**1579**	**1980**
Energy input (for biogas production)	52	370	422	-	-	-	41	370	411	52	370	422
Electricity	*14*	*104*	*118*	-	-	-	12	103	116	*14*	*104*	*118*
Heat	*37*	*267*	*304*	-	-	-	29	266	295	*37*	*267*	*304*
Energy input (biogas upgrading)	203	697	900	-	-	-	-	-	-	-	-	-
Electricity	*60*	*208*	*268*	-	-	-	-	-	-	-	-	-

Heat	*142*	*490*	*632*	-	-	-	-	-	-	-	-	-
Emissions												
CH_4 Emissions (biogas plant + upgrading)	266	923	1189	-	-	-	93	1359	1452	346	1199	1545
N_2O	3	10	13	-	-	-	1	10	11	3	10	13
Avoided impact	**-2629**	**-4626**	**-7255**	**-655**	**-2350**	**-3005**	**-1023**	**-7730**	**-8753**	**-3554**	**-7807**	**-11362**
Soymeal	-528	-12	-540	-	-	-	-	-	-	-528	-12	-540
Energy feed (by grass-fibres)	-757	-25	-782	-	-	-	-	-	-	-757	-25	-782
Displaced LNG	-651	-2238	-2889	-	-	-	-	-	-	-	-	-
Total fertilizer	-693	-2351	-3045	-655	-2350	-3005	-655	-2350	-3005	-693	-2351	-3045
Manure	-655	-2350	-3005	*-655*	*-2350*	*-3005*	-655	-2350	-3005	-655	-2350	-3005
Decanted residues	-38	-1	-40	-	-	-	-	-	-	-38	-1	-40
Energy	-	-	-	-	-	-	-369	-5380	-5748	-1576	-5419	-6996
Electricity	-	-	-	-	-	-	-323	-4710	-5033	*-1380*	*-4745*	*-6125*
Heat	-	-	-	-	-	-	-46	-670	-716	*-196*	*-675*	*-871*
Gross impact	**3655**	**23200**	**26856**	**2728**	**23754**	**26482**	**2582**	**22917**	**25499**	**3533**	**22779**	**26312**
Net impact (per 1000 kg$_{LW}$) and per system	**1026**	**18574**	**19601**	**2073**	**21404**	**23477**	**1558**	**15187**	**16746**	**-22**	**14972**	**14950**
per kg$_{LW}$ (product based)	**1.03**	**18.57**	**-**	**2.07**	**21.40**	**-**	**1.56**	**15.19**	**-**	**-0.02**	**14.97**	**-**
per FU		**19.60**			**23.48**			**16.75**			**14.95**	
per kg$_{LW}$ (with iLUC) (product based)	**2.03**	**24.21**	**-**	**3.03**	**27.04**	**-**	**2.52**	**20.82**	**-**	**0.98**	**20.61**	**-**
per FU (with iLUC)		**26.24**			**30.07**			**23.34**			**21.59**	

Table S4.2. Details on NRE use for Pigs and SCC production per 1000 kg_{LW} each (impact per FU and per kg_{LW} of each livestock, shown at the bottom of the Table).

	S_1-GBR			S_2-conv			S_3-conv			S_4-GBR		
	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC
Feed (Sys-I)	**14645**	**30229**	**44874**	**8212**	**29984**	**38196**	**8212**	**29984**	**38196**	**14645**	**30229**	**44874**
Maize	-	2248	2248	-	2248	2248	-	2248	2248	-	2248	2248
Grass-clover	-	8061	8061	-	8061	8061	-	8061	8061	-	8061	8061
Winter wheat	2195	3016	5211	2195	3016	5211	2195	3016	5211	2195	3016	5211
Barley	1872	858	2730	1872	858	2730	1872	858	2730	1872	858	2730
Rapeseed cake	1.00	-	1.00	1001.16	-	1001.16	1001.16	-	1001.16	1.00	-	1.00
Soymeal	2333	77	2409	2333	77	2409	2333	77	2409	2333	77	2409
Grass-clover grazed	-	10008	10008	-	10008	10008	-	10008	10008	-	10008	10008
Permanent grassland	-	5440	5440	-	5440	5440	-	5440	5440	-	5440	5440
Fishmeal	3E-04	-	3E-04	3E-04	-	3E-04	3E-04	-	3E-04	3E-04	-	3E-04
Straw	-	275	275	-	275	275	-	275	275	-	275	275
Vegetable oil	456	-	456	456	-	456	456	-	456	456	-	456
GBR (System II)	**2960**	**97**	**3058**	**-**	**-**	**-**	**-**	**-**	**-**	**2960**	**97**	**3058**
Grass-clover production	7449	245	7694	-	-	-	-	-	-	7449	245	7694
Energy input	2960	97	3058	-	-	-	-	-	-	2960	97	3058
Electricity	*965*	*32*	*997*	-	-	-	-	-	-	*965*	*32*	*997*
Heat	*1995*	*66*	*2060*	-	-	-	-	-	-	*1995*	*66*	*2060*
Livestock housing (System III)	**1881**	**11803**	**13684**	**1881**	**11803**	**13684**	**1881**	**11803**	**13684**	**1881**	**11803**	**13684**
Bedding material (straw removal)	-	322	322	-	322	322	-	322	322	-	322	322
Energy	1881	11481	13362	1881	11481	13362	1881	11481	13362	1881	11481	13362
Electricity	*1553*	*11481*	*13034*	*1553*	*11481*	*13034*	*1553*	*11481*	*13034*	*1553*	*11481*	*13034*
Heat	*327*	-	*327*	*327*	-	*327*	*327*	-	*327*	*327*	-	*327*
Biogas conversion (System IV)	**3757**	**16251**	**20008**	**-**	**-**	**-**	**613**	**5668**	**6280**	**738**	**5672**	**6410**
Energy input (for biogas production)	738	5672	6410	-	-	-	613	5668	6280	738	5672	6410
Electricity	*128*	*982*	*1110*	-	-	-	*106*	*982*	*1088*	*128*	*982*	*1110*
Heat	*611*	*4689*	*5300*	-	-	-	*506*	*4686*	*5192*	*611*	*4689*	*5300*
Energy input (biogas upgrading)	3019	10579	13598	-	-	-	-	-	-	-	-	-
Electricity	*562*	*1969*	*2531*	-	-	-	-	-	-	-	-	-
Heat	*2457*	*8610*	*11066*	-	-	-	-	-	-	-	-	-
Avoided impact	**-57126**	**-153573**	**-210699**	**-4328**	**-15438**	**-19766**	**-7882**	**-71899**	**-79781**	**-34058**	**-72724**	**-106782**
Soymeal	-3457	-77	-3534	-	-	-	-	-	-	-3457	-77	-3534

Energy feed (by grass-fibers)	-9771	-322	-10093	-	-	-	-	-	-	-9771	-322	-10093
Displaced LNG	-39297	-137727	-177024	-	-	-	-	-	-	-	-	-
Total fertilizer	-4600	-15447	-20047	-4328	-15438	-19766	-4328	-15438	-19766	-4600	-15447	-20047
Manure	-4328	-15438	-19766	*-4328*	*-15438*	*-19766*	*-4328*	*-15438*	*-19766*	-4328	-15438	-19766
Decanted residues	-272	-9	-281	-	-	-	-	-	-	-272	-9	-281
Energy	-	-	-	-	-	-	-3554	-56461	-60015	-16229	-56878	-73107
Electricity	-	-	-	-	-	-	*-2813*	*-44686*	*-47499*	*-12844*	*-45016*	*-57860*
Heat	-	-	-	-	-	-	*-741*	*-11775*	*-12516*	*-3385*	*-11862*	*-15247*
Gross impact	**23243**	**58381**	**81623**	**10093**	**41787**	**51880**	**10705**	**47455**	**58160**	**20224**	**47802**	**68026**
Net impact (per 1000 kg$_{LW}$) and per system	**-33884**	**-95192**	**-129076**	**5764**	**26349**	**32113**	**2823**	**-24444**	**-21622**	**-13834**	**-24922**	**-38756**
per kg$_{LW}$ (product based)	**-34**	**-95**	**-**	**6**	**26**	**-**	**2.82**	**-24**	**-**	**-14**	**-25**	**-**
per FU		**-129.08**			**32.11**			**-21.62**			**-38.76**	

Table S4.3. Details on EP for Pigs and SCC production per 1000 kg_{LW} each (impact per FU and per kg_{LW} of each livestock, shown at the bottom of the Table).

	S_1-GBR			S_2-conv			S_3-conv			S_4-GBR		
	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC
Feed (Sys-I)	**35.05**	**85.20**	**120.25**	**21.03**	**84.69**	**105.72**	**21.03**	**84.69**	**105.72**	**35.05**	**85.20**	**120.25**
Maize	-	5.60	5.60	0.00	5.60	5.60	0.00	5.60	5.60	0.00	5.60	5.60
Grass-clover	-	16.69	16.69	0.00	16.69	16.69	0.00	16.69	16.69	0.00	16.69	16.69
Winter wheat	6.62	9.10	15.71	7.11	9.10	16.20	7.11	9.10	16.20	6.62	9.10	15.71
Barley	8.61	3.95	12.56	9.51	3.95	13.46	9.51	3.95	13.46	8.61	3.95	12.56
Rapeseed cake	1.3E+00	-	1.3E+00	1.3E+00	0.0E+00	1.3E+00	1.3E+00	-	1.3E+00	1.3E+00	-	1.3E+00
Soymeal	2.80	0.09	2.89	2.80	0.09	2.89	2.80	0.09	2.89	2.80	0.09	2.89
Grass-clover grazed	-	13.52	13.52	-	13.52	13.52	-	13.52	13.52	0.00	13.52	13.52
Permanent grassland	-	35.62	35.62	-	35.62	35.62	-	35.62	35.62	0.00	35.62	35.62
Fishmeal	-	-	-	-	-	-	-	-	-	-	-	-
Straw	-	0.12	0.12	-	0.12	0.12	-	0.12	0.12	-	0.12	0.12
Vegetable oil	0.22	-	0.22	0.22	0.00	2.20E-01	0.22	0.00	0.22	0.22	-	0.22
GBR (System II)	**0.18**	**0.01**	**0.19**	**-**	**-**	**-**	**-**	**-**	**-**	**0.18**	**0.01**	**0.19**
Grass-clover production	15.42	0.51	15.93	-	-	-	-	-	-	15.42	0.51	15.93
Energy input	0.18	0.006	0.19	-	-	-	-	-	-	0.18	0.006	0.19
Electricity	*0.13*	*0.0044*	*0.14*	-	-	-	-	-	-	*0.13*	*0.004*	*0.14*
Heat	*0.05*	*0.002*	*0.05*	-	-	-	-	-	-	*0.05*	*0.0015*	*0.05*
Livestock housing (System III)	**0.22**	**1.73**	**1.96**	**0.22**	**1.73**	**1.96**	**0.22**	**1.73**	**1.96**	**0.22**	**1.73**	**1.96**
Bedding material (straw removal)	-	0.15	0.15	-	0.15	0.15	-	0.15	0.15	0.00	0.15	0.15
Energy	0.22	1.59	1.81	0.22	1.59	1.81	0.22	1.59	1.81	0.22	1.59	1.81
Electricity	*0.21*	*1.59*	*1.80*	*0.21*	*1.59*	*1.80*	*0.21*	*1.59*	*1.80*	*0.21*	*1.59*	*1.80*
Heat	*0.01*	-	*0.01*	*0.01*	*0.00*	*0.01*	*0.01*	*0.00*	*0.01*	*0.01*	-	*0.01*
Biogas conversion (System IV)	**0.17**	**0.71**	**0.88**	**-**	**-**	**-**	**0.03**	**0.24**	**0.27**	**0.03**	**0.24**	**0.28**
Energy input (for biogas production)	0.03	0.24	0.28	-	-	-	0.03	0.24	0.27	0.03	0.24	0.28
Electricity	*0.02*	*0.14*	*0.15*	-	-	-	*0.01*	*0.14*	*0.15*	*0.02*	*0.14*	*0.15*
Heat	*0.01*	*0.11*	*0.12*	-	-	-	*0.01*	*0.11*	*0.12*	*0.01*	*0.11*	*0.12*

Energy input (biogas upgrading)	0.13	0.47	0.60	-	-	-	-	-	-	-	-	-
Electricity	*0.08*	*0.27*	*0.35*	-	-	-	-	-	-	-	-	-
Heat	*0.06*	*0.20*	*0.25*	-	-	-	-	-	-	-	-	-
Avoided impact	**-8.04**	**-1.77**	**-9.82**	**-0.76**	**-3.09**	**-3.85**	**-1.17**	**-7.21**	**-8.38**	**-9.66**	**-7.45**	**-17.11**
Soymeal	-4.15	-0.09	-4.24	-	-	-	-	-	-	-4.15	-0.09	-4.24
Energy feed (by grass-fibers)	-2.85	-0.09	-2.95	-	-	-	-	-	-	-2.85	-0.09	-2.95
Displaced LNG	-0.24	-0.82	-1.06	-	-	-	-	-	-	-	-	-
Total fertilizer	-0.81	-0.76	-1.57	-0.76	-3.09	-3.85	-0.76	-0.76	-1.52	-0.81	-0.76	-1.57
Manure	-0.76	-0.76	-1.52	*-0.76*	*-3.09*	*-3.85*	*-0.76*	*-0.76*	*-1.52*	-0.76	-0.76	-1.52
Decanted residues	-0.05	-0.002	-0.05	-	-	-	-	-	-	-0.05	0.00	-0.05
Energy	-	-	-	-	-	-	-0.41	-6.45	-6.86	-1.85	-6.50	-8.35
Electricity	-	-	-	-	-	-	*-0.39*	*-6.18*	*-6.57*	*-1.78*	*-6.23*	*-8.00*
Heat	-	-	-	-	-	-	*-0.02*	*-0.27*	*-0.29*	*-0.08*	*-0.27*	*-0.35*
Gross impact	**35.62**	**87.65**	**123.27**	**21.25**	**86.42**	**107.67**	**21.25**	**86.42**	**107.67**	**35.49**	**87.18**	**122.67**
Net impact (per 1000 kg$_{LW}$) and per system	**27.58**	**85.88**	**113.45**	**20.49**	**83.33**	**103.82**	**20.11**	**79.45**	**99.56**	**25.82**	**79.73**	**105.56**
per kg$_{LW}$ (product based)	**0.03**	**0.09**	**-**	**0.02**	**0.08**	**-**	**0.02**	**0.08**	**-**	**0.03**	**0.08**	**-**
per FU		**0.11**			**0.10**			**0.10**			**0.11**	

Table S4.4. Details on PFWTox for Pigs and SCC production per 1000 kg LW each (impact per FU and per kg_{LW} of each livestock, shown at the bottom of the Table).

	S_1-GBR			S_2-conv			S_3-conv			S_4-GBR		
	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC	Pigs	SCC	Pigs+SCC
Feed (Sys-I)	**9477**	**2710**	**12121**	**8988**	**2694**	**11682**	**8988**	**2694**	**11682**	**9477**	**2710**	**12187**
Maize	-	121	121	-	121	121	-	121	121	-	121	121
Grass-clover	-	532	532	-	532	532	-	532	532	-	532	532
Winter wheat	297	409	706	297	409	706	297	409	706	297	409	706
Barley	371	170	540	371	170	540	371	170	540	371	170	540
Rapeseed cake	1022	-	1022	1022	-	1022	1022	-	1022	1022	-	1022
Soymeal	7587	250	7837	7587	250	7837	7587	250	7837	7587	250	7837
Grass-clover grazed	-	834	834	-	834	834	-	834	834	-	834	834
Permanent grassland	-	346	346	-	346	346	-	346	346	-	346	346
Fishmeal	-	-	-	-	-	-	-	-	-	-	-	-
Straw	-	32	32	-	32	32	-	32	32	-	32	32
Vegetable oil	-358	0	-358	-358	-	-358	-358	-	-358	-358	-	-358
GBR (System II)	**385**	**13**	**397**	**-**	**-**	**-**	**-**			**385**	**13**	**397**
Grass-clover production	492	16	508	-	-	-	-	-	-	492	16	508
Energy input	385	13	397	-	-	-	-	-	-	385	13	397
Electricity	*297*	*10*	*307*	-	-	-	-	-	-	*297*	*10*	*307*
Heat	*87*	*3*	*90*	-	-	-	-	-	-	*87*	*3*	*90*
Livestock housing (System III)	**493**	**3573**	**4066**	**493**	**3573**	**4066**	**493**	**3573**	**4066**	**493**	**3573**	**4066**
Bedding material	-	38	38	-	38	38	-	38	38	-	38	38
Energy	493	3536	4029	493	3536	4029	493	3536	4029	493	3536	4029
Electricity	*478*	*3536*	*4014*	*478*	*3536*	*4014*	*478*	*3536*	*4014*	*478*	*3536*	*4014*
Heat	*14*	-	*14*	*14*	-	*14*	*14*	*0*	*14*	*14*	-	*14*
Biogas conversion (System IV)	**336**	**1492**	**1827**	**-**	**-**	**-**	**55**	**508**	**563**	**55**	**508**	**563**
Energy input (for biogas production)	55	508	563	-	-	-	55	508	563	55	508	563
Electricity	*33*	*302*	*335*	-	-	-	*33*	*302*	*335*	*33*	*302*	*335*
Heat	*22*	*205*	*228*	-	-	-	*22*	*205*	*228*	*22*	*205*	*228*
Energy input (biogas upgrading)	281	984	1265	-	-	-	-	-	-	-	-	-
Electricity	*173*	*607*	*780*	-	-	-	-	-	-	-	-	-

Heat	*108*	*377*	*485*	-	-	-	-	-	-	-	-	-
Avoided impact	**-14077**	**-8247**	**-22324**	**-434**	**-1823**	**-2257**	**-1332**	**-16101**	**-17434**	**-16426**	**-16478**	**-32904**
Soymeal	-11246	-250	-11495	-	-	-	-	-	-	-11246	-250	-11495
Energy feed (by grass-fibers)	-614	-20	-634	-	-	-	-	-	-	-614	-20	-634
Displaced LNG	-1756	-6153	-7908									
Total fertilizer	-462	-1824	-2286	-434	-1823	-2257	-434	-1823	-2257	-462	-1824	-2286
Manure	-434	-1823	-2257	*-434*	*-1823*	*-2257*	*-434*	*-1823*	*-2257*	-434	-1823	-2257
Decanted residues	-29	-1	-30							-29	-1	-30
Energy	-	-	-	-	-	-	-899	-14278	-15177	-4104	-14384	-18488
Electricity	-	-	-	-	-	-	*-866*	*-13762*	*-14628*	*-3956*	*-13864*	*-17819*
Heat	-	-	-	-	-	-	*-33*	*-516*	*-549*	*-148*	*-520*	*-668*
Gross impact	**10690**	**7788**	**18412**	**9481**	**6267**	**15748**	**9481**	**6267**	**15748**	**10409**	**6804**	**17213**
Net impact (per 1000 kg$_{LW}$) and per system	**-3387**	**-459**	**-3912**	**9048**	**4444**	**13492**	**8204**	**-9326**	**-1123**	**-6017**	**-9674**	**-15691**
per kg$_{LW}$ (product based)	**-3.39**	**-0.46**	**-**	**9.05**	**4.44**	**-**	**8.20**	**-9.33**	**-**	**-6.02**	**-9.67**	**-**
per FU		**-3.91**			**13.49**			**-1.12**			**-15.69**	

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