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Optimising sustainability: Circular pathways for Scotch Whisky distillery co-products

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ABSTRACT

The use of co-products for animal feed can potentially have a higher greenhouse gas (GHG) emission and water scarcity offset compared to bio-energy (bio-electricity/fuel) production. We cluster 136 Scotch Whisky distilleries and evaluate the co-product pathways for the production of animal-feed and/or bio-energy at centralised processing facilities. Production of animal feed, and the subsequent displacement of imported animal feed, offered the most significant GHG offset, which was between a factor of c.a. 2.5 to 8 times greater than the bio-electricity/fuel and bio-energy/feed scenarios. This offers significant potential from a global net-zero carbon emissions perspective. However, this comes at a cost to local energy security potential. Bio-electricity produced in the electricity intensive scenarios was 481 GWh per year. This would significantly increase Scotland's bio-energy production and equates to c.a. 5% of Scotland's non-commercial electricity needs.

1. Introduction

According to a recent United Nations Environment Programme (UNEP) (2019) report, natural resource extraction and processing comprise 50% of greenhouse gas (GHG) emissions and account for up to 90% of biodiversity loss. Higher income regions import resources and materials while "off-shoring" production related environmental impacts to middle and lower income regions (UNEP, 2019). Evidence (Steffen et al., 2015) suggests that anthropogenic activities are impacting the functioning of the earths systems to such a large degree that the stability of ecosystem service functions, and the persistence of a "Holocene like" state, are under threat. The continuation of a linear model of production (take-make-dispose) is not sustainable (Gallego-Schmid et al., 2020) and as such, circular, sustainable and resilient solutions must be introduced wherever possible.

The Circular Economy (CE) model of production, defined by Geissdoerfer et al. (2017) as: "*a regenerative system in which resource-input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling*", offers an alternative approach. However, there are significant technical, political and social challenges to implementing CE models that vary in complexity depending on the context and model examined. In the Scottish context, there has been firm commitment to systemic change and a just-transition toward sustainability (Scottish Government, 2020a).

Scotland is one of over a 100 countries that have committed to, or are considering, net-zero targets, which allow for a clear vision of sustainability and solidifies long-term ambition in terms of climate policy (van Soest et al., 2021). The Scottish government aims to reduce GHG emissions by 75% by 2030 and a net-zero target by 2045 (Scottish Government, 2020a). The plan acknowledges the need for further investment in renewable energy infrastructure. Bio-energy production, where it will have the greatest value in reducing GHG emissions, is a key aim (Scottish Government, 2021a). Further, the Scottish government has also committed to reducing food waste by 33% by 2025 (Scottish Government, 2016). Addressing the potential for circularity in the Scottish food and drink (F&D) sector, in a manner that maximises the

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environmental and economic benefits, will be a key component in the achievement of net-zero, bio-energy, and food waste reduction targets.

The production of spirits in Scotland in 2018 was valued at ~ £2.5bn GVA (Gross Value Added), which makes up about 60% of the food and drink processing sector (Scottish Government, 2021b). The production of malt and grain whisky in 2017 was over 550 million litres (mL) of pure alcohol (mLPA) (Gray, 2018). In terms of co-products, this translates to over 7758 mL of pot ale (The product remaining in the still from the first (wash) distillation of a malt distillery (EU, 2022)) and 1.34 million tonnes (mT) of draff (solid (wet) product from whisky production (EU, 2022)) produced annually. There are 136 distilleries across Scotland, with several areas being considered as densely populated (Gordon, 2020) offering the potential for a coordinated approach to the handling of co-products. However, some distilleries are relatively isolated, meaning circular pathways for co-products are less feasible, resulting in co-products being spread directly on the land or discharged to the sea (ZWS, 2015).

1.1. Distillery Co-products

Both pot ale and draff have several, potentially competing uses as fresh or processed animal feed, or in the production of bio-energy (Bell et al., 2019; ZWS, 2015). Moist draff can be fed to animals, mainly beef and sheep, in a relatively unprocessed state (Bell et al., 2019; Schestak et al., 2021). However, the demand for fresh draff as feed locally can be insufficient, leading to a surplus (Bell et al., 2012). Pot ale on the other hand requires evaporation to pot ale syrup (PAS), which can be sold as cattle feed (as the copper content may be too high for sheep) (Russell and Stewart, 2003; ZWS, 2015), or combined with draff for additional processing into dried distiller grains with solubles (DDGS) (Bell et al., 2019; Russell and Stewart, 2003; ZWS, 2015). Processing co-products (PAS and DDGS) increases the shelf-life and lowers transportation costs of co-products (Bell et al., 2012). The European Food Manufacturers' Federation (FEFAC) distinguishes between protein sources based on percentage of protein content, with medium and high protein content being sources that contain between 15 to 30 and 30–50% protein, respectively (FEFAC, 2021). An estimate from the FEFAC (2021) European Union (EU) and United Kingdom (UK) balance sheet show self-sufficiency gap in high and medium protein content (72 and 88% on average) feed sources. The crude protein content of wheat and malt distiller grains, and PAS is 34, 27 and 36%, respectively (Bell et al., 2019), offering an opportunity to reduce the self-sufficiency gap.

However, more recently, the use of co-products as animal feed has begun to decline in favour of their use in bio-energy production. Between 2012 and 2019, use of co-products as animal feed reduced by up to 57% (Bell et al., 2019). According to White et al. (2020), there are currently only 10 facilities in Scotland producing PAS for animal feed, this number includes DDGS production facilities. Reliance on imported protein sources for animal feed increases indirect land use change (iLUC), which occurs when a production system in one region triggers expansion of production in another region (Arima et al., 2011). In Latin America, "new agricultural land" has largely come from formerly forested lands (Gibbs et al., 2010). Argentina, the UK's largest supplier of imported soybean based feed (Chatham House, 2021), was second, behind Brazil, in terms of largest area of net tree cover loss during 1982–2016 (Song et al., 2018). In the UK, between 2013 and 2020, purchase of imported soybean based feed increased by an average of 8%, while importation of barley has increased by an average of 23%, relative to 2012 (Chatham House, 2021). The decline in utilisation of co-products for animal feed is, in part, due to the incentivisation of renewable energy technologies by UK and Scottish Governments (Bell et al., 2019), which highlights the significant potential of policy drivers aimed towards incentivisation of greener action. This case study considers the potential opportunity cost of various potential CE pathways.

Previous studies, focusing on the environmental impacts of alcohol production at the distillery level, have shown that the use of co-products for animal feed can potentially have a higher GHG emission and water scarcity offset compared to bio-energy production (Leinonen et al., 2018; Schestak et al., 2021). The aim of this paper is to illustrate the potential CE pathways for Scotland's distillery co-products, examining routes for the production of bio-energy (bio-fuel and bio-electricity) and animal feed. Illustration and discussion of potential CE pathways serve to highlight the opportunity cost of investment from various perspectives. This discussion will be vitally important to policymakers and other stakeholders as they strive to meet environmental, social, and economic objectives. Here, we firstly cluster distilleries based on population density, with the assumption that co-products would be transported to centralised processing facilities. Consequential Life Cycle Assessment (cLCA) allows us to account for the indirect impacts of systemic changes incurred through market signals (Weidema et al., 2018; Weidema and Schmidt, 2010). The cLCA methodology is employed here to examine the wider environmental outcomes associated with system change scenarios as may be incurred by market forces and/or policy decisions. For both, bio-energy and feed production pathways, we quantify environmental impacts alongside the effect of displacing imported fossil-fuels and animal feeds. This includes the potential impacts of iLUC resulting from the displacement of imported animal feeds.

2. Materials and methods

The aim of this study was to develop and assess prospective sustainable utilisation pathways for whisky distillery co-products that contribute to valorisation and circularity. The study utilised co-product output data from the 136 (n = 136) Scotch Whisky distilleries. Production data were sourced from Gordon (2020), while estimates of pot ale and draff output were derived from the Zero Waste Scotland report on the circular economy potential of beer, fish and whisky (ZWS, 2015) and Akunna and Walker (2017). The distilleries were clustered to form regional groupings, and scenarios were developed for the production of bio-energy (bio-electricity and bio-fuel) and animal feed (DDGS and PAS). The key bio-energy technology modelled for the production of bio-electricity and bio-fuel is anaerobic digestion (AD). The study involved the development and application of the Co-products CIRCular pathways (Co-CIRC) tool, which is based upon the LCAD (Life Cycle Assessment of Anaerobic Digestion) EcoScreen tool developed by Styles et al. (2016). A cLCA approach was taken to evaluate the environmental balance of animal feed production, the altered demand for imported animal feed products and AD. GHG emissions were calculated as carbon dioxide equivalents (CO_2e), according to 100-year global warming potentials of 1, 25 and 298 kg^{-1} CO_2, CH_4 and nitrous oxide (N_2O) emitted, respectively (IPCC, 2006).

2.1. Functional unit

The effective functional unit (FU) for this study is the management of annual co-product arisings from Scotch Whisky distillery operations (n = 136), 7758 mL of pot ale and 1.34 mT of draff. Total (net) environmental burdens are related to this FU. However, results are also related to distinct co-product components (pot ale and draff), following dedicated processing steps such as energy and feed processing, via intermediate reference flows of one tonne of dry matter or fresh matter (as

Table 1
Cluster Processing facility summary details.

Cluster Name	Processing Facilities	Fresh Matter (FM) Input	Avg Distance to Cluster Centre
Fife	13	1760 kt FM	5.96 km
Glasgow	8	984 kt FM	13.09 km
Hebrides	2	259 kt FM	12.62 km
Highlands	7	925 kt FM	8.61 km
Speyside	20	2773 kt FM	13.44 km

appropriate to the stage of the chain). Table A1 provides the full inventory for co-product use in all scenarios.

2.2. Clustering distilleries

The 136 Scottish whisky distillers were clustered into six groupings (Fig. 1) using DBSCAN (density-based spatial clustering of applications with noise) (Schubert et al., 2017) implemented using the programming language Python. DBSCAN is a density-based clustering algorithm that takes two parameters, ε and MinPts. The ε parameter relates to the maximum distance between two points that exist in the same cluster, while MinPts refers to the minimum size of the cluster. The optimum value for ε was determined based on methods derived from Rahmah and Sitanggang (2016). The minimum number of distilleries required to form a cluster was six. The six groupings consist of five regional groups (Fife, Glasgow, Hebrides, Highlands and Speyside), with a sixth group classified as “independent” outliers (Fig. 1). For the purposes of scenario development, five of the Scottish regional clusters were assumed to be delivering co-products to purpose-built centralised processing facilities for the production of either bio-energy and/or animal feed. Centralised facility capacities (Table 1) were based on the existing Rothes CoRDe Ltd plant in Speyside (Technik Aalborg Energie, 2015; ZWS, 2015). Independent distilleries (blue) have fewer feasible co-product valorisation pathways. It was assumed that as much draff as possible was utilised to satisfy the available “fresh market” requirements for livestock (dairy and beef cattle) within the distiller’s unitary authority. The remaining co-products were then utilised for bio-electricity production. As there is only one valorisation pathway explored, the bio-electricity outputs of independent distilleries are included in the final outputs for each of the scenarios developed for cluster pathways.

2.3. Attributional vs consequential LCA

A fundamental paradigm in environmental management systems is the recognition that actors should be responsible for the consequences of their production and consumption (Weidema et al., 2018). The difference between attributional LCA (aLCA) and cLCA can be seen by defining the questions that they aim to answer. The aim of aLCA is to describe the environmentally relevant physical flows to and from a life cycle and its subsystems (Ekvall et al., 2016). In contrast, the aim of cLCA is to describe how environmentally relevant physical flows will change in response to possible decisions (Ekvall et al., 2016). Weidema et al. (2018) defines a product cLCA as a system of interlinked activities that are expected to change as a consequence of a change in demand for a product. In this context, cLCA is employed to estimate the potential consequential impacts of investment in various circular pathways for Scottish distillery co-products, including iLUC resulting from the displacement of imported animal feeds.

2.4. Scenario development

Fig. 2 presents a conceptual framework for development of co-product-use scenarios. In line with the European Commission’s (EC) hierarchy for prioritisation of food surplus, by-products and food waste (FW) prevention strategies (EC, 2020), independent distilleries would first attempt to meet local fresh feed demand for local cattle, with remaining co-products utilised for bio-electricity production. Clustered groups would utilise centralised facilities in the production of either

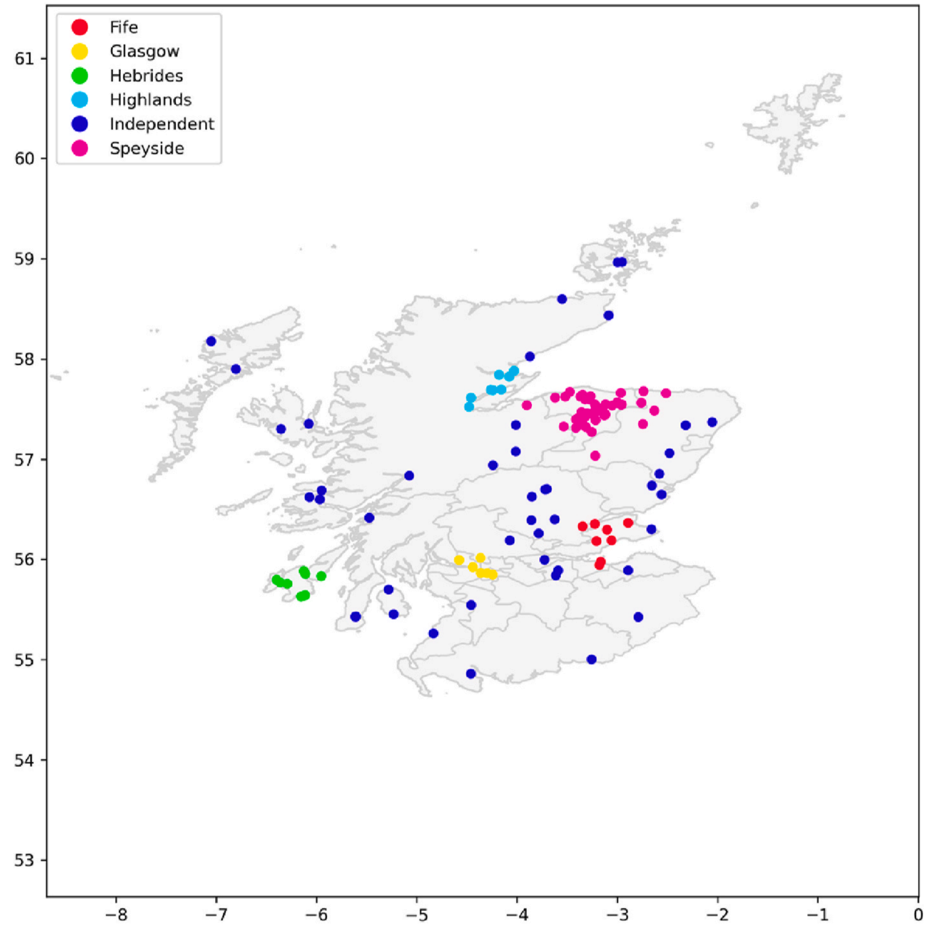

Fig. 1. Scottish whisky distillers grouped by clusters, with outlier distilleries treated as a single cluster. Clusters comprise: Fife, Glasgow, Hebrides, Highlands, Speyside, and Independent.

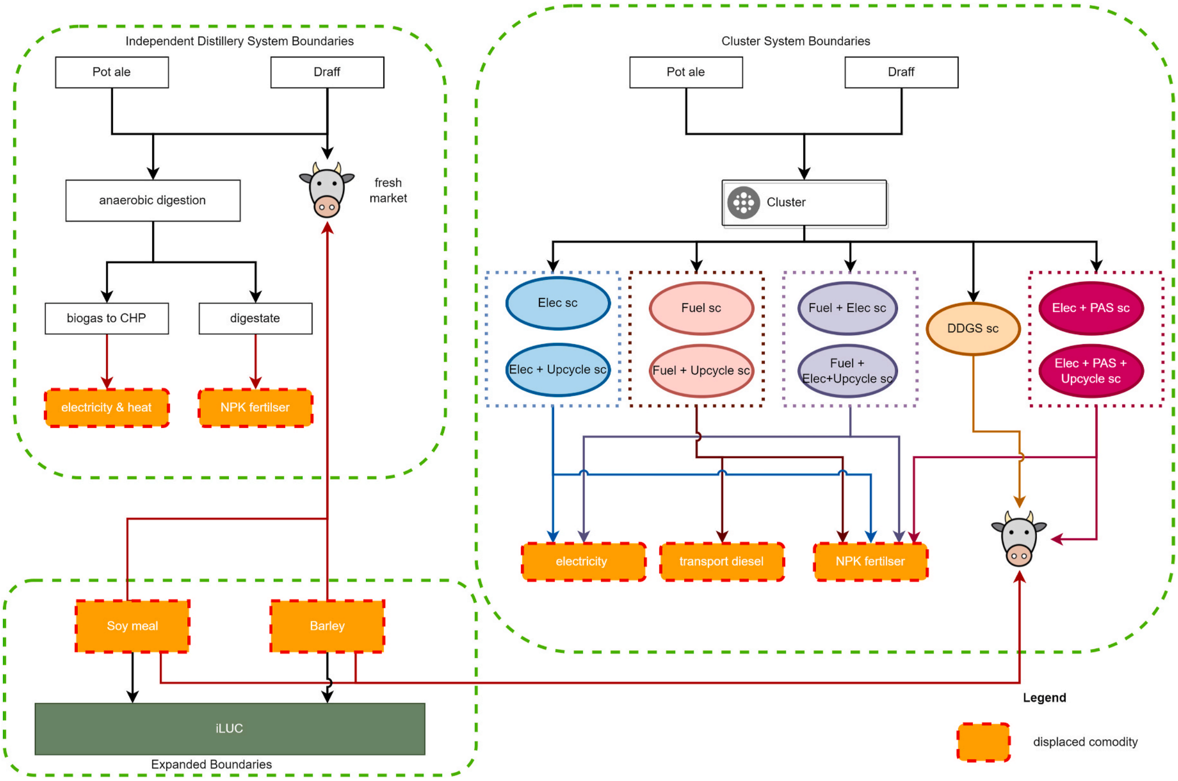

Fig. 2. Simplified conceptual framework for development of co-product utilisation pathways
* Elec = bio-electricity; Fuel = bio-fuel; Upcycle = Upcycled digestate.

processed animal feeds and/or bio-electricity/fuel production. Feed production displaces imported barley and soy feeds, as the dominant energy- and protein-feed commodities, respectively, on a matching digestible energy and protein basis. The most recent available trade data (Chatham House, 2021) illustrates that the majority of soy imported into the UK is sourced from Argentina (46%) with additional imports coming from Paraguay, Brazil and India (including indirectly from Ireland and the Netherlands). Barley imports are sourced from various European countries including Sweden, Finland, Denmark, Lithuania, Poland, Germany, Netherlands, France, Portugal, and Ireland.

There is significant protein and energy content in draff and pot ale, which makes them suitable replacements for imported animal feed. According to Bell et al. (2019), co-products utilised for animal feed are fed largely to dairy- and beef-cattle. These co-products can be fed directly to animals as 'fresh feed' or processed into either DDGS or PAS. DDGS are produced by combining draff and pot ale (in the form of PAS) to create a dried product (Russell and Stewart, 2003). PAS can be utilised as a feed product in its own right via evaporation, which is used to produce a concentrated liquid (ZWS, 2015).

Processing feeds in dried forms allows for longer storage periods and a reduction in weight, expanding the potential life-span of co-products (Russell and Stewart, 2003). To replace crude protein and metabolizable energy from barley and soy, the open-source optimisation tool Python library for linear programming (PuLP) was utilised. This was done by keeping protein and digestible energy content constant between replaced crops and co-products, while maximising the amount of feed replaced based on the DM content of the co-product.

Scenarios assumed that the displacement of imported soy indirectly reduces land-use change (iLUC), leaving spared area under the dominant natural land cover, thus avoiding emissions associated with land clearing for cultivation. Argentina was utilised as a proxy for iLUC, with the dominant natural land cover being shrubland. Scenarios displacing imported animal feed were given an avoided iLUC credit. Equations and parameters for the estimation of carbon sequestration in native shrubland was completed utilising IPCC (2006) guidelines. A value of 4 t dry matter (dm) ha^{-1} in shrubland <20 years old was used, with a root ratio of 0.4 and carbon fraction of 0.5. C values were then converted to CO_2e based on a molecular ratio of 3.67 kg CO_2 per kg C. Avoided iLUC area was calculated by estimating the dm content of soybean yield per ha for Argentina (FAO, 2020) and calculating the number of ha of cultivation avoided by the processed distillery co-products.

A total of nine scenarios (Table 2) were considered, with clustered facilities producing bio-electricity only (Electricity sc), bio-fuel only (Fuel sc), bio-electricity and bio-fuel production (Fuel + Electricity sc),

Table 2
Scenario summary details.

Scenario	% FS used for AD	% FS input used for animal feed	% biomethane for bio-electricity	% biomethane upgraded for transport fuel
Electricity sc	100	0	78	0
Electricity + Upcycled Digestate sc	100	0	78	0
Fuel sc	100	0	0	78
Fuel + Upcycled Digestate sc	100	0	0	78
Fuel + Electricity sc	100	0	39.5	39.5
Fuel + Electricity + Upcycled Digestate sc	100	0	39.5	39.5
Electricity + PAS sc	50	50	78	0
Electricity + PAS + Upcycled Digestate sc	50	50	78	0
DDGS sc	0	100	0	0

FS= Feed Stock; AD = Anaerobic Digestion.

the production of DDGS (DDGS sc) and the production of bio-electricity and PAS (Electricity + PAS sc). In addition, for scenarios producing bio-electricity/fuel, the additional upcycling of digestate to bio-fertiliser was also considered (Electricity + Upcycle sc, Fuel + Upcycle sc, Fuel + Electricity + Upcycle sc and Electricity + PAS + Upcycle sc). Fig. 3 shows the Co-CIRC model flows. The facilities are first clustered, being designated to a cluster or as independent. For independent facilities, a fresh market is established, and the proportion of draff required to meet fresh market is calculated. The remaining draff and pot ale are utilised to produce bio-electricity. The results are added to each of the scenario totals. The clustered groups are then aggregated into the aforementioned scenarios, and the total bio-energy (bio-electricity and bio-fuel), off-sets (displaced fossil fuel, animal feed imports and iLUC) and emissions are calculated for each scenario in addition to the independent distillery calculations.

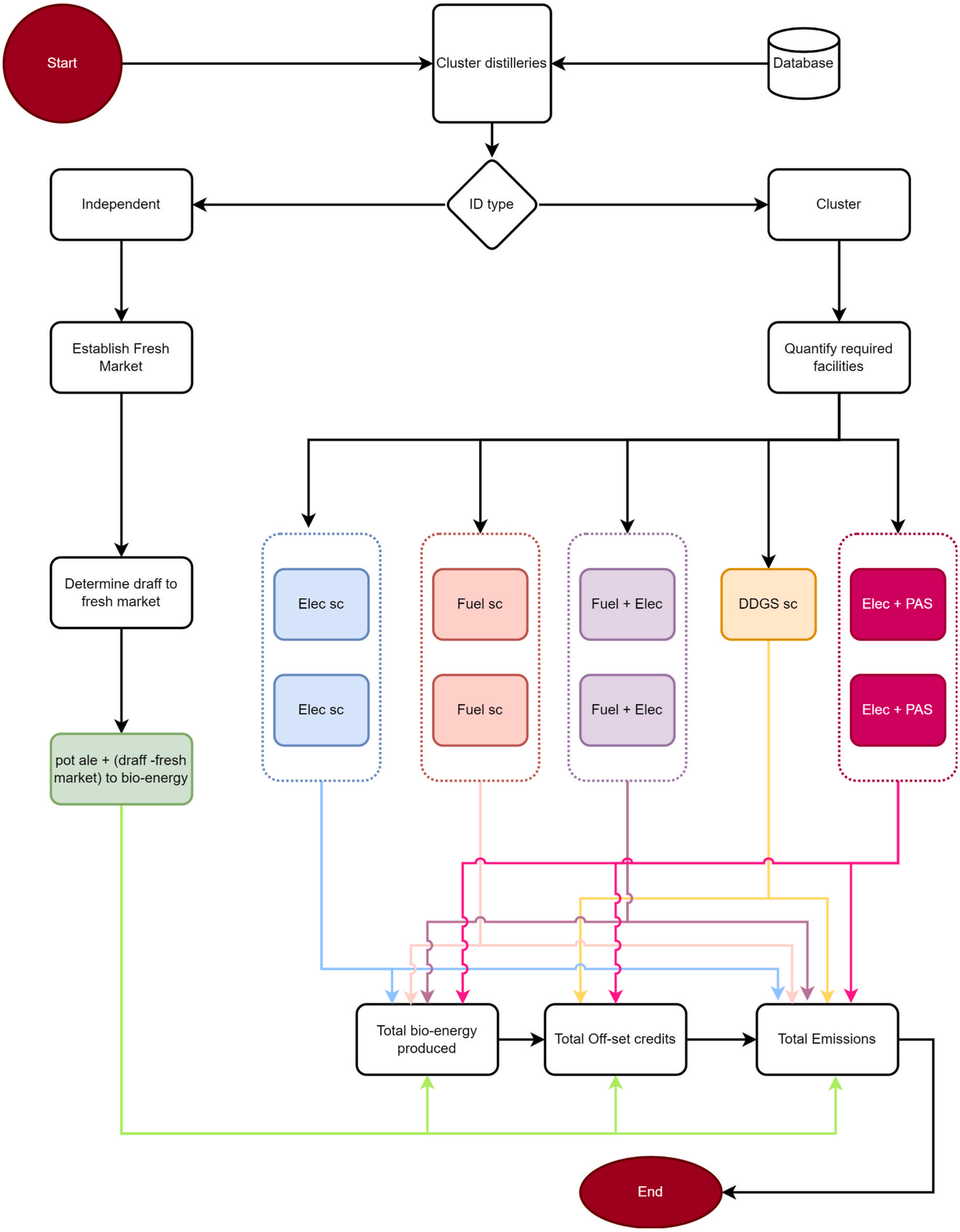

Fig. 3. Co-CIRC model flow depicting cluster development and scenario contributions to total bio-energy (electricity & fuel) produced, off-set credits and emissions * Elec = bio-electricity; Fuel = bio-fuel; Upcycle = Upcycled digestate.

2.5. Bio-electricity & bio-fuel production

The production of bio-energy in the scenarios fall into the categories of bio-electricity, bio-fuel, or a mix of the two categories. The production of bio-electricity involves the AD of co-products to bio-gas, which is then combusted in a combined heat and power (CHP) generator. In relation to bio-fuel production, the bio-gas produced is upgraded and scrubbed to produce "clean" biomethane that can be used as a transport fuel. In both cases, the digestate output from the AD process is utilised as an organic fertiliser on local fields that can replace inorganic fertiliser inputs.

Transport of inputs to the cluster processing facilities were calculated based on a weighted average distance of distilleries to the cluster centre (utilising the proportion of total co-product output for each distillery in a cluster as weights, and assuming facilities would be located centrally). Emissions related to transport were based on Ecoinvent data (see Table A1 for comprehensive list of inventory values). As with previous studies (Schestak et al., 2021; Styles et al., 2016), independent distilleries operating smaller AD facilities were considered to be "on-site", and thus, no transport burdens for inputs were calculated.

An emissions factor of 1% was applied to account for methane leakage from the digesters. The "parasitic load", which represents otherwise useful heat and electricity necessary to run the facility, was conservatively estimated to be 22% of output. This factor was uniformly utilised regardless of plant size. Both methane leakage and parasitic load are based on previous research by Styles et al. (2016). Scenarios that upgrade biomethane for use as transport fuel apply an additional "methane slippage" emissions factor of 1.4% Styles et al. (2016) as additional methane can leak during the upgrading process (Adams and McManus, 2019). Downstream CO_2e credits were calculated as vehicle-km burdens for Euro 5 cars powered by diesel, replaced by Euro 5 biomethane cars, taken from Ecoinvent v3.8, and assuming 1 MJ of biomethane replaces 0.75 MJ diesel (VVT, 2012). Emissions related to the storage, transport and application of digestate were also calculated. During storage of digestate, CH_4, ammonia (NH_3) and N_2O are released. Emissions may vary based on the type of storage facility. Based on research from Styles et al. (2016), we assume open tank storage and an NH_3–N emission factor of 10% of ammonium-N. Emissions related to NH_3, N_2O and nitrate (NO_3) and NPK fertiliser replacement values were modelled using MANNER NPK (Nicholson et al., 2013). Application assumptions were based on those utilised by Styles et al. (2016), assuming a weighted average February and April application to spring crops, and June and September applications to autumn crops, on sandy-clay-loam soils. In all scenarios, the application method was assumed to be a broadcast spreader. For digestate transport emissions, a distance of 5 km, using a tractor and trailer was assumed for independent distilleries (Styles et al., 2016). This distance was also used in relation to the clusters, however, given the location of processing facilities at the centre of clusters, it was assumed that the application of digestate would take place beyond the boundary of the cluster. As such, the distances for transportation of digestate from cluster processing facilities includes the static 5 km (as assumed with independent distillers) plus the average distance to cluster centre (distance to the cluster edge). The mode of transport for digestate was assumed to be a 28 t tanker. Ecoinvent data was utilised in both cases.

2.6. Bio-fertiliser production

The upcycling of digestate to bio-fertiliser is based on previous research conducted by Styles et al. (2018). Digestate from the production of bio-electricity and bio-fuel are separated into a solid fraction and a liquid fraction. The solid fraction is subject to the same assumptions regarding storage, transport and application as previously detailed. However, the liquid fraction is subject to a four-stage process involving the flocculation of suspended solids, struvite extraction, ammonium sulphate crystallization final fertiliser blending, with various heat, electricity, and chemical inputs. Electricity requirements are assumed to be met via the parasitic load (22%), while the heat requirements are assumed to be met via excess heat produced from CHP units. The chemical inputs and burdens are detailed in Table A1. The remaining effluent, which has been largely stripped of nutrients, is assumed to be waste water. However, additional uses for effluent, such as crop-irrigation or constructed wetlands, have been modelled by Styles et al. (2018), but were beyond the scope of this study. The final bio-fertiliser product can substitute chemical fertilisers directly. As such, displacement of chemical fertiliser production and transport emissions for bio-fertiliser are included. The bio-fertiliser is a relatively dry product which can be transported more widely. Bio-fertiliser from processing facilities includes a static 50 km transport distance, plus the average distance to the cluster centre.

2.7. DDGS and PAS production

Draff and pot ale are both used in the production of DDGS. The ratios of draff and pot ale to DDGS output are 2.7:1 and 9.1:1, respectively (ZWS, 2015). The production of PAS has a 10:1 pot ale to PAS ratio (ZWS, 2015). Electricity (UK grid) and thermal (as natural gas) energy inputs for DDGS and PAS production were derived from Murphy and Power (2008) and Russell and Stewart (2003). Thermal energy requirements for DDGS production were 5.96 MJ kg^{-1} dry matter, while electricity requirements were 0.129 kWh kg^{-1} dry matter. The final concentration of PAS is approximately 45–50% solids, the electricity requirements, assuming the use of a mechanical vapour recompression evaporator, is 0.139 kWh kg^{-1} dry matter (Russell and Stewart, 2003). Transportation of DDGS and PAS from processing facilities also includes a static 50 km transport distance, plus the average distance to the cluster centre.

2.8. Establishment of a fresh feed market

Distilleries classed as independent supply as much draff as possible to the local fresh feed market. Local fresh feed market size is derived from the total number of animals (dairy and beef cattle) in the same regional constituency as the distillery. Animal data were collected from the 2020 agricultural census (RESAS, 2020). The feed inputs required for animals were established based on concentrate feed consumption per head produced by Bell et al. (2019).

2.9. Uncertainty and sensitivity

To assess uncertainty in the inventory inputs, a post-hoc error propagation was implemented. The approach allows for the aggregation of uncertainty, which is expressed as the square root of the sum of squares of estimated uncertainty ranges for the major contributing categories (Casey et al., 2022). In this case, to reflect lower levels of uncertainty in relation to emissions from digestate and facility operation emissions, an uncertainty range of between 5 and 10%, respectively, has been implemented. Where uncertainty is greater, in relation to transport distances and emissions credits, an uncertainty range of 15–30%, respectively, has been implemented. Further, additional sensitivity analysis has been conducted, for emissions related to processing facilities, in regard to the potential improvements in electricity and gas infrastructure and potential electrification of transportation. In the case of electricity and gas infrastructure, a 50% reduction in emissions has been assumed for increased Carbon Capture and Storage (CCS), and an 80% emissions reduction has been assumed for increased electrification of transportation.

3. Results and discussion

The GHG emissions and potential avoided emissions (reductions), including those from iLUC (removals), for each of the scenarios are summarised in Fig. 4. The emissions, reductions and removals for

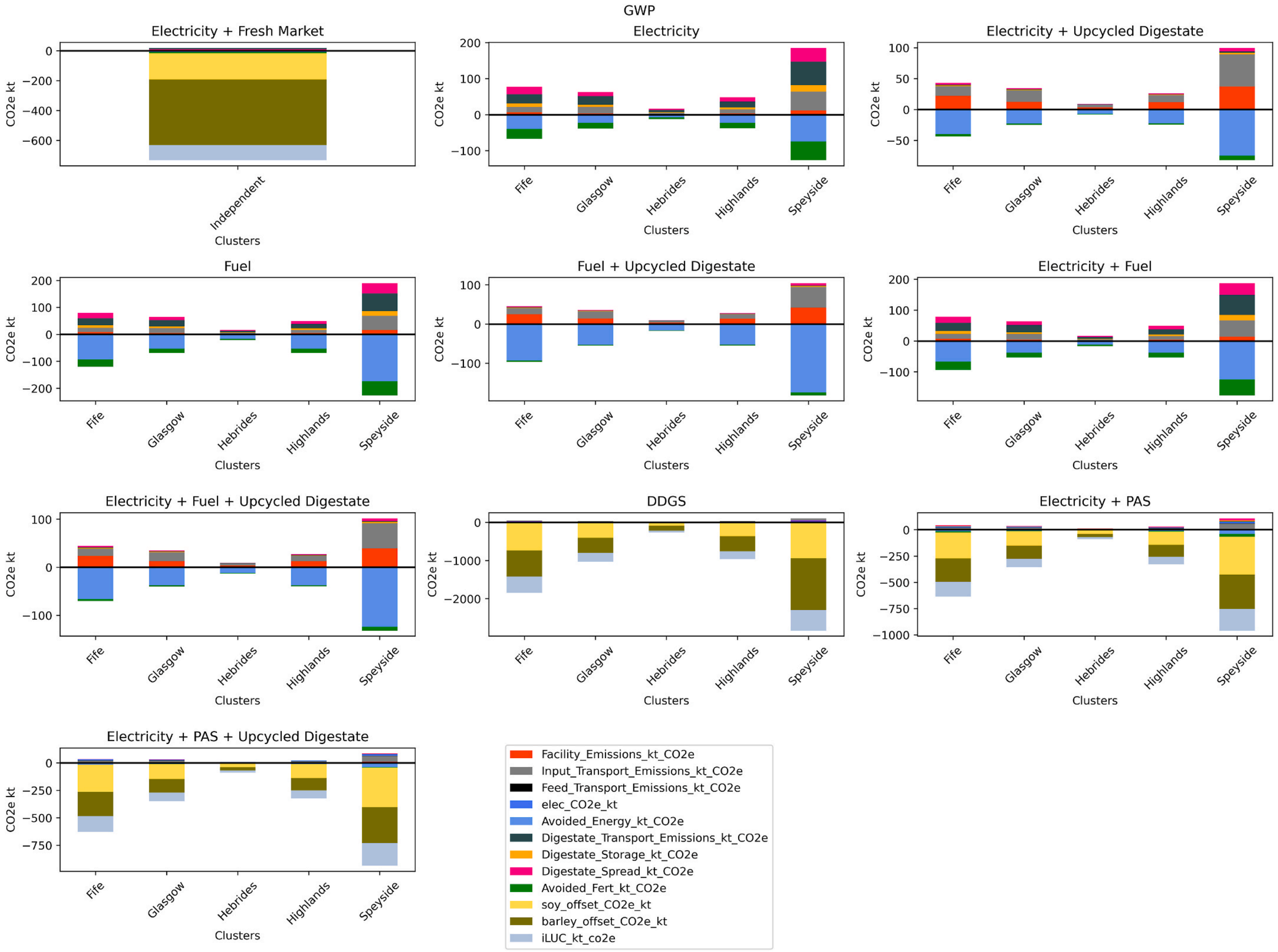

Fig. 4. Total emissions and reductions of each scenario alongside Electricity + Fresh Markets (Independent)
* Fuel = bio-fuel for transport; Upcycled Digestate = Bio-fert production; DDGS = Dried Distiller Grains with Solubles; PAS = Pot Ale Syrup; iLUC = avoided land use change.

independent distilleries (electricity + fresh market) are treated separately in Fig. 4. Examining the emissions, reductions and removal breakdown, we can see that the electricity production scenarios (Electricity sc and Electricity + Upcycled Digestate sc) result in a net emission for cluster groups. This is driven by the heavy penalty for both the transport of inputs to the cluster facilities and, in the case of the Electricity sc, the transport of digestate for spreading. The upcycling of digestate for bio-fertiliser reduces net cluster emissions by 72%. These reductions are related to digestate management, especially transport. However, there are significant additional emissions associated with the production and use of chemicals for bio-fertiliser production. The Fuel (bio-fuel upgraded for transport) scenarios (Fuel sc and Fuel + Upcycled Digestate sc) result in a net credit, which is due to the more effective emissions mitigation achieved from the displacement of imported diesel fuel. Again, the upcycling of digestate to bio-fertiliser increases the net credit by 78%. The Electricity and Fuel production (Electricity + Fuel sc and Electricity + Fuel + Upcycled Digestate sc) scenarios (evenly split between electricity production and bio-fuel upgraded for transport) result in a net emission for the Electricity + Fuel sc, however, the upcycling of digestate yields a net credit, with emissions reduced by a factor of 17. In all scenarios (excluding the independent distilleries), transport is one of the key emission hot-spots. This is especially true for electricity and fuel production scenarios, particularly where digestate has not been upcycled. Where digestate has been upcycled, there is less storage, spreading and transport emissions, as the separated solid fraction is relatively small. The bio-fertiliser produced is also relatively small (about 11 kg t^{-1} digestate), resulting much lower transport burdens, even with greater distances assumed. The assumption that independent distilleries will have their facilities sited close to the distillery eliminates the emissions from transport of inputs, however, there are still modest transport emissions related to the removal of digestate. The emissions related to the DDGS sc and Electricity and PAS production (Electricity + PAS sc and Electricity + PAS + Upcycled Digestate sc) scenarios also have the same transport emission burdens (for inputs), however, there are much less (none in the case of DDGS) transport emissions related to digestate output, and the lower weight of processed feeds reduces emission burdens for the transport of DDGS and PAS. The majority of emission mitigation related to DDGS and PAS is due to the displacement of imported soy and barley for animal feed. There is an additional credit allowed for a reduction of iLUC for soy production. However, this is relatively modest, due to the carbon storage assumptions in Argentinian shrubland, in comparison to the removals from displaced (off-shored/imported) soy and barley production. Given the magnitude of removals resulting from feed displacement and iLUC, the overall difference in fluxes between the Electricity + PAS sc and Electricity + PAS + Upcycled Digestate sc is <1%.

The total electricity and fuel production, disaggregated CO_2e emissions and removals are presented in Fig. 5 for each scenario. In addition,

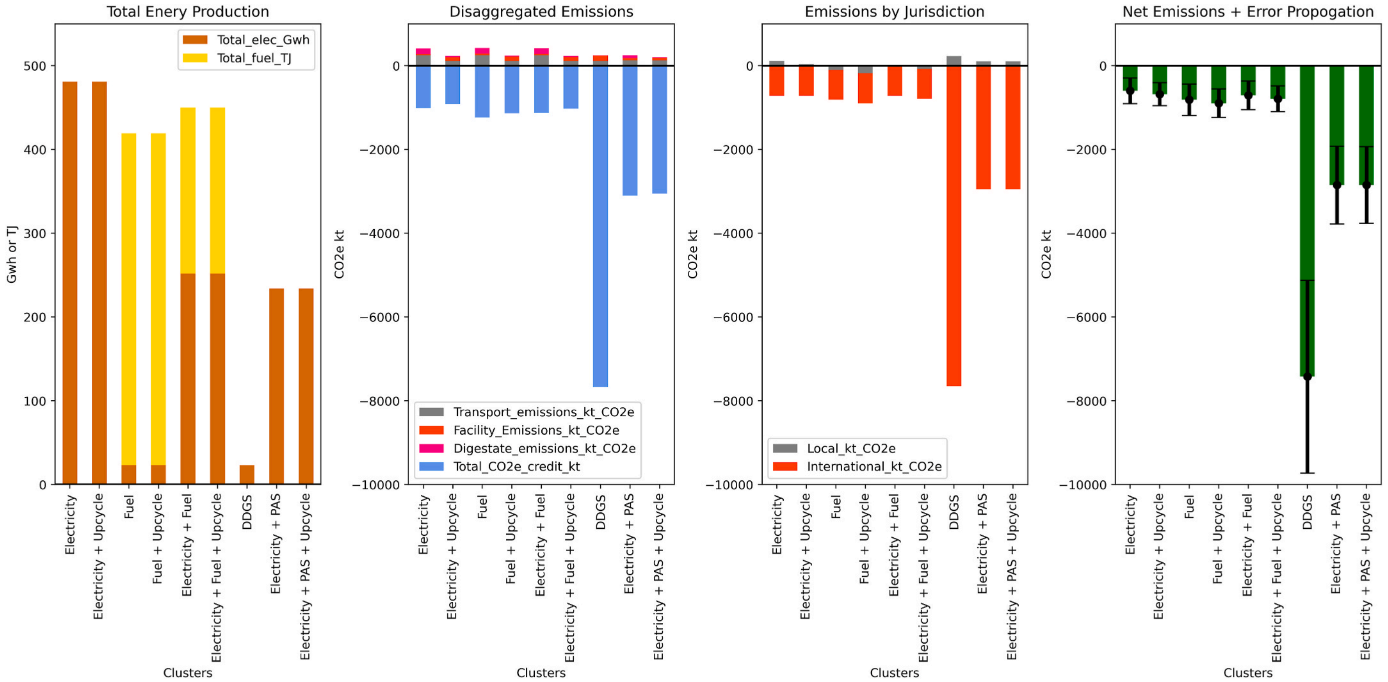

Fig. 5. Total energy output, disaggregated emissions, emissions by jurisdiction, and net emissions by scenario. Outputs for independent distillers are included in each scenario.
* Fuel = bio-fuel for transport; DDGS = Dried Distiller Grains with Solubles; PAS = Pot Ale Syrup.

Fig. 5 also presents the emissions output per scenario categorised by jurisdiction. Finally, Fig. 5 presents the net emissions for each scenario. Energy, emissions, and removals for independent distilleries are included in each of the scenarios.

Energy outputs are represented as GWh in relation to electricity production and TJ for transport fuel production. In terms of bio-electricity, the Electricity, Electricity and Fuel, and Electricity and PAS scenarios output 481, 252 and 234 GWh, respectively. The remaining scenarios output 23 GWh, due to the inclusion of the independent distilleries. In terms of bio-fuels, the Fuel and the Electricity and Fuel scenarios output 396 and 198 TJ, respectively. Scenarios that produce bio-fertiliser are assumed to have the same outputs in relation to bio-energy, given the conservative parasitic load factor utilised.

The addition of independent distilleries to each scenario results in a net removal in all scenarios. The Electricity, Fuel, and Electricity and Fuel scenarios, including those scenarios with digestate upcycled to bio-fertiliser, result in 1075 (±160) kt of CO_2e removed. However, the Electricity and PAS scenarios have the potential for removals of >3000 kt CO_2e. This is dwarfed by removals from the DDGS sc of >7500 kt CO_2e.

The vast majority of removals are categorised as “international”, meaning the credit for this removal would not be accounted for in the local inventory. However, the penalty for any additional emissions is accounted for in the local inventory. Finally, the highest levels of

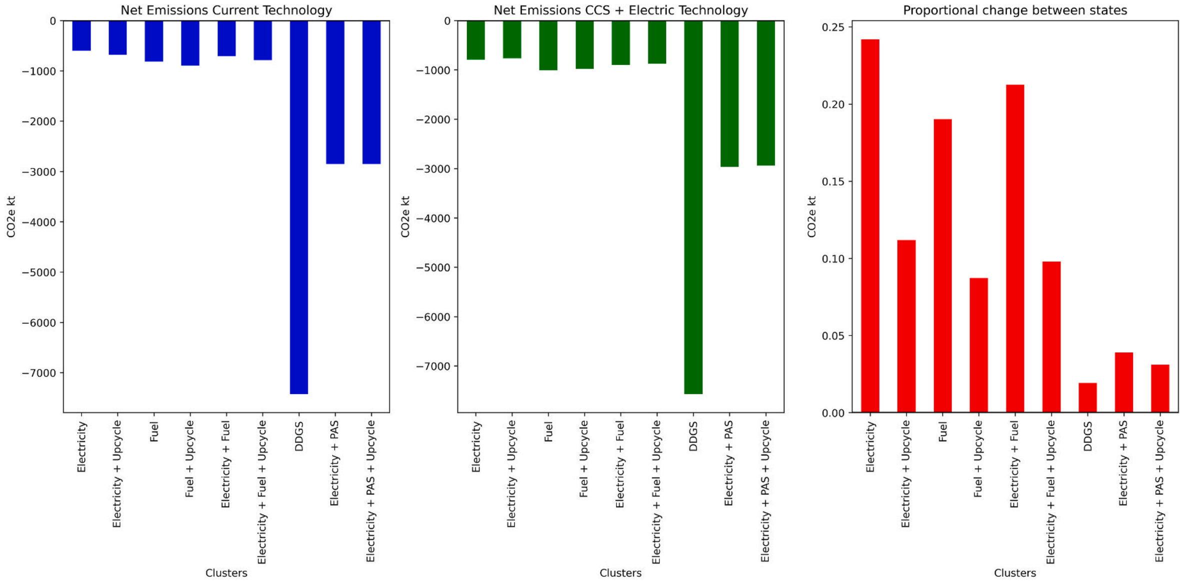

Fig. 6. Sensitivity analysis examining the impact of increased utilisation of Carbon Capture and Storage (CCS) and increased share of electrified vehicles.
* CCS implementation assumes a 50% reduction in emissions, while transportation emissions reduction assumes and 80% decrease.

uncertainty are observed in the production of animal feeds. Additional sensitivity analysis has been conducted and presented in Fig. 6, which illustrates net emissions from scenarios with current technologies, net emissions from scenarios with the implementation of future mitigating technologies in both energy supply systems and transportation, and the proportional change between current and future technologies. The most significant impact of potential future technology assumptions is had on the bio-fuel and bio-electricity production scenarios, with an increase in removals by up-to 25%. However, the feed production scenarios still outperform bio-energy (fuel and electricity) only scenarios.

Finally, Fig. 7 displays the total bio-energy output in GWh and TJ for all clusters, and independent distilleries for each scenario. Clusters with the largest potential for bio-energy production are the Speyside, Fife, Glasgow, and Highland clusters. The Hebrides cluster has significantly lower potential, however, clustering and centralised processing still provides a route for co-products that does not require transportation back to the mainland.

3.1. *Optimising sustainability*

The clustering of facilities into coherent groups provides the opportunity for joint-infrastructural investment. However, which of these outlined scenarios makes the greatest impact on sustainability is up for debate. Adhering to the “three pillar” concept of sustainability (Purvis et al., 2019), which places sustainability as the cross-section between the environment, society and the economy, there is a potential argument as to the merits of each of these scenarios and their contribution to Scottish and global sustainability. On the one hand, addressing the ‘climate emergency’ appears to be the most pressing global concern given the increasingly pressing temporal considerations. However, recent global events have driven home the need for increased national sustainable-energy security.

Though the production of processed animal feeds (DDGS and PAS) comes with an environmental burden in terms of energy consumption (Bell et al., 2019; Schestak et al., 2021), the potential offset in terms of reduced barley and soy imports, along with the additional credit received from iLUC assumptions, would make the production of DDGS the best option from a global climate mitigation perspective. Although there are uncertainties regarding the inclusion of iLUC effects (Hjulström, 2019), the sequestration impact on the scenarios is relatively modest, ranging from 8 to 20% of the total offset. This is greatest for scenarios displacing large quantities of animal feed. The DDGS sc has a total offset of 7669 kt CO_2e, the more balanced Electricity PAS scenarios have an offset of ~60% less relative to DDGS sc. The bio-energy/fuel scenarios have, on average, >86% less mitigation potential than the DDGS sc. Even with the most pessimistic view of the 30% uncertainty range (Fig. 5), the net emission reduction credit for DDGS and PAS scenarios is significantly higher than even the most optimistic bio-energy scenarios from a climate mitigation perspective.

From a local perspective however, the optimum pathway for global climate stability may not be the most attractive pathway for policy-makers. The majority of emissions, though relatively few, are credited to local inventories, while removals are largely credited internationally (Fig. 5), which is unlikely to motivate policymakers when faced with the opportunity to pursue more tangible local benefits. The contribution of the DDGS sc to energy security is limited to the contribution of the independent distillery category, which are assumed to operate their own AD facilities. In contrast, the scenarios focused on bio-electricity/fuel production can generate between 252 and 481 (Fuel + Electricity and Electricity sc’s, respectively) GWh annually, providing a significant amount of renewable energy, while bio-fuel scenarios can generate between 198 and 396 TJ (Fuel + Electricity and Fuel sc’s, respectively). In 2019, the Scottish domestic (non-commercial) electricity consumption was 9625 GWh (Scottish Government, 2020b), i.e. increasing capacity by an additional 481 GWh would equate to about 5% of domestic consumption. The more balanced Electricity + PAS scenarios offer the potential to increase offsets by a factor of >3 via reductions in iLUC and imported feed. Though, this comes at a cost to bio-electricity output, which would equate to >2% of domestic consumption in 2019. However, this does offer a potential compromise pathway where local energy security needs are balanced with the pressing global need for climate mitigation.

Examining the case for bio-fuels, relative to 2005, the consumption of diesel for private cars and for light goods vehicles has increased 53 and 45% (Scottish Government, 2020b), respectively. Data for bio-fuel consumption is not disaggregated from the UK. According to the Scottish Government (2020b), the approximate proportion of bio-fuels used in road vehicles is 5.4%. In 2019, the total diesel consumption for private cars and light goods vehicles was 63,579 TJ (Scottish Government, 2020b), with approximately 3433 TJ being bio-fuels. The Fuel and Fuel + Electricity scenarios would increase this share by 11.5% and 5.7%, respectively. The Fuel + Electricity scenarios also outputs considerable bio-electricity (252 GWh), >7% higher than the Electricity + PAS scenarios.

However, bio-electricity/fuel scenarios come with a significant transportation and digestate management burden. Transportation of

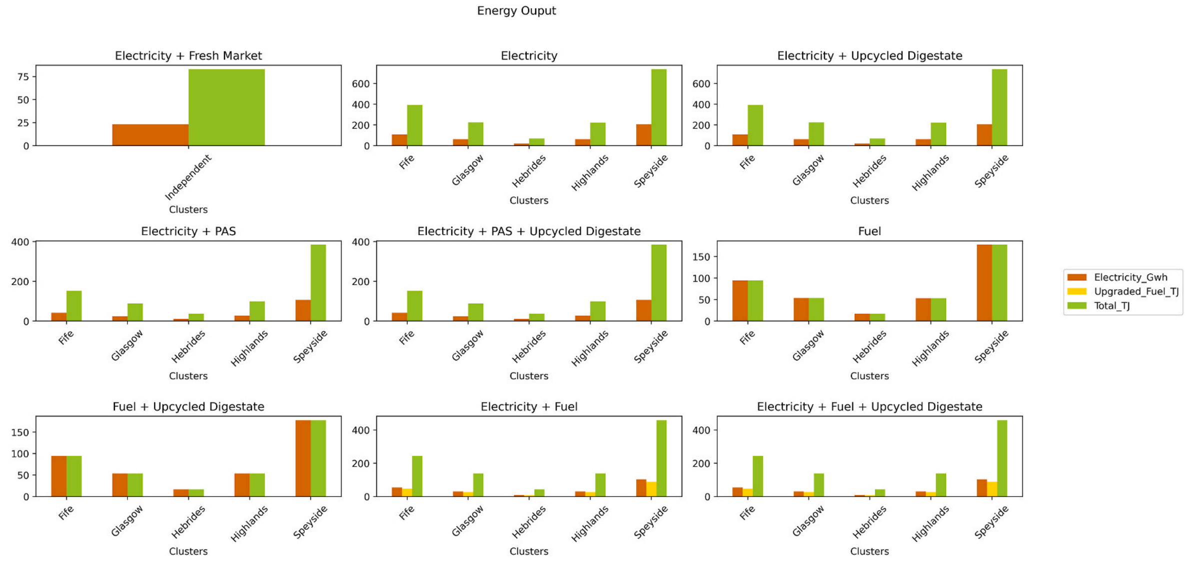

Fig. 7. Bio-electricity, bio-fuel and total bio-energy outputs for each cluster. Electricity presented in GWh, fuel and total bio-energy output presented in TJ.

inputs to processing facilities result in considerable emissions due to volume. Further, the management, in terms of storage, transportation and spreading of digestate further increases environmental burdens. Scenarios that upcycle digestate to bio-fertiliser mitigate this burden for the most part, however, they also add an additional burden in relation to the production and use of chemical inputs in the upcycling process. Transportation burdens for DDGS and PAS have also been included, though, given the much lower volumes of co-product outputs, burdens are relatively small.

Current transport burdens may not carry such a grave penalty as transport and energy infrastructure is upgraded and emissions burdens reduced. The sensitivity analysis (Fig. 6) illustrates the potential implications of an increase CCS and electrification of transportation. The proportional change between current and future technologies shows the largest benefit for the bio-electricity, bio-fuel and bio-electricity + fuel scenarios. This is followed by the upcycled scenarios in the same category. However, even with these assumed large gains in efficiency, the climate mitigation benefit is still much less than that of the animal feed production scenarios.

As with studies conducted by Schestak et al. (2021) and Leinonen et al. (2018), objectively, the conclusion here, in terms of a globally optimal pathway for sustainability in the face of pressing need for climate mitigation, must be that feed processing pathways provide the greatest global climate stabilisation benefits.

3.2. Policy drivers

According to the Scottish Government's (2020a) Climate Action Plan, in 2019, over 30 TWh of renewable electricity was generated in Scotland, and the continued investment in renewable energy sources to reduce GHG emissions, create employment and contribute to a "green recovery" is a central part of Scotland's longer-term energy transition ambition. The climate action plan (2020a) outlines goals to increase development of energy capacity up to 16 GW to 2032. This pressing need is fuelled by anticipated increased demand due to the expected role of heat pumps and electric vehicles across Scotland. Bio-energy alone is not expected to fulfil this increase, but is expected to play a significant role in the transition to "net-zero" (Scottish Government, 2021a). Potential pathways illustrated here could support that argument. Incentives provided for renewable energy technologies have spurred investment within the distilling industry, leading to a decline in co-product utilisation for animal feed (Bell et al., 2019). It is clear that these incentives provoke the desired response by policymakers, however, the policy signals sent do not reflect the level of nuance required to achieve optimised sustainability solutions in the context of climate change. Policy, incentives, plus public and private investment will play a key role in delivering sustainable regenerative economy. However, global, long-term, sustainability must be given at least equal weighting in investment decisions. Despite the potential of bio-electricity/fuel outlined in these illustrative pathways, policy that incentivises only bio-electricity prioritises pathways that may not be the most desirable from a global climate stabilisation perspective. Displacement of imported emission intensive animal feeds can potentially have a much greater impact on overall/global sustainability. Transportation requirements associated with centralised bio-energy production have a sizeable effect on bio-energy outcomes. Even when this has been somewhat mitigated via digestate upcycling, feedstock transport is still a significant burden. Addressing these hotspots would increase the feasibility of bio-energy scenarios. However, even with improved technology, the climate stabilisation benefits will still be less than that of the feed processing scenarios.

A compromise pathway, that attempts to balance the pressing needs for long-term climate stabilisation with local energy security needs, offers policymakers a potential route forward. The more balanced pathways offer considerable renewable energy increases and displacement of imported animal feeds, while mitigating the environmental costs of additional transportation burdens. However, this comes with a significant energy generation trade-off. Considering the fact that most of the climate mitigation potential falls into the international jurisdiction, while any increase in emissions, though small, largely falls into the local jurisdiction in regard to national inventory accounting. Will policymakers be willing to pass up more tangible local gains for the greater global good?

In short, careful consideration must be given when incentivising potential sustainability pathways. At best, a lack of nuance in terms of prioritisation of sustainability pathways may result in sub-optimal outcomes from a global net-zero perspective. At worst, local trade-offs in terms of energy gains and jurisdictional accounting credit may disincentivise local policymakers from prioritising outcomes that will considerably slow the global achievement of net-zero carbon emissions.

3.3. Limitations and further research

One of the key hotspots in terms of emission trade-offs between the scenarios is transport of both inputs and digestate. Additional research into the feasibility and impact of pre-transport processing, or transport alternatives, such as electric trucks (beyond what is theoretically modelled here), which are being seen as an increasingly viable option (Liimatainen et al., 2019), is warranted. In addition, this research has focused on the aggregate impact of circular pathways for distillery co-products, as such, we have not attempted to discern the impact at the level of the individual distiller. However, this is an important area of future research, as support for potential sustainability pathways will also be necessary at the individual level. The socio-economic impacts of the outlined scenarios are beyond the scope of this paper, however, given the increasing importance of national energy security, the impacts of this study warrant further examination in this regard. Lastly, there are alternative pathways that could be considered for distillery co-products, such as processing for aquaculture or human consumption, which could potentially have significant sustainability impacts, and as such, warrant additional research. One such example is the potential impact of current research on high purity protein extraction and energy recovery from remaining carbohydrates, with protein being targeted for use by aquaculture feed companies (ZWS, 2015).

4. Conclusion

Scotland has set ambitious emissions and waste reduction targets. There is political recognition that further investment is needed to increase infrastructure related to renewable energy production to meet anticipated future demand. Bio-energy generation is likely to play a key role in the future energy landscape of Scotland. The Scotch Whisky industry, given its socio-economic importance, and the resulting level of potentially valuable co-products produced, could, and arguably should, play a significant role in the generation of bio-electricity/fuel. There has already been a move towards the generation of bio-electricity at the distillery level given the current policy incentives. However, this paper illustrates the potential climate opportunity cost that can result from over investment in pathways that seek to maximise local benefit at the expense of global climate mitigation. In the most bio-electricity intensive scenario, bio-electricity output was 481 GWh per year, which equates to ~5% of Scotland's non-commercial electricity needs. However, transportation of inputs and outputs to and from processing facilities increases the environmental burdens associated with bio-energy production considerably. This can be somewhat mitigated by maximising circularity via upcycling of digestate to bio-fertiliser. In terms of the overall environmental burdens considered, the displacement of imported animal feeds offers a much greater global climate stabilisation benefit. The processed animal feed-only scenario had an offset between a factor of c.a. 2.5 to 8 times greater than the bio-electricity/fuel and bio-energy/feed scenarios. These results illustrate the importance of carefully planned sustainability pathways that maximise the potential circularity. Further, the study shows the potential opportunity cost of prioritisation of local realised benefits at the expense of global mitigation potential. Failure to assess the potential trade-offs in CE pathways risks increasing the lag time in achieving global net-zero carbon emissions.

Declaration

The authors confirm that this study has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

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CRediT authorship contribution statement

Colm Duffy: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **David Styles:** Conceptualization, Methodology, Validation, Writing – review & editing. **Isabel Schestak:** Conceptualization, Validation, Writing – review & editing. **Kenneth Macgregor:** Investigation, Writing – review & editing. **Frances Jack:** Writing – review & editing. **Daniel Henn:** Validation, Writing – review & editing. **Kirsty Black:** Validation, Writing – review & editing. **Pietro P.M. Iannetta:** Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kenneth Macgregor and Frances Jack are both employed by the Scotch Whisky Research Industry.Kirsty Black is employed by Arbikie Distillery.

Data availability

Data will be made available on request.

Appendix

Table A1
Inventory for co-product use in scenarios

Process/Material	Quantity	Reference/comment
Anaerobic Digestion		
Specific methane yield	295 Nm^3/t VS	FNR (2010)
Pot Ale dm	5%	Schestak et al. (2021)
Draff dm	23%	Bell et al. (2019)
Digester methane leakage	1%	Styles et al. (2016)
Parasitic load	22%	Share of electricity/heat output required to run AD
Biomethane Upgrade		
Upgraded methane slip	1.4%	Styles et al. (2016)
Biomethane (1 MJ)	replaces 0.75 MJ diesel	VVT (2012)
Digestate Storage		
CH_4 leakage rate	1.5%	Styles et al. (2016)
N content digestate	0.62	Average crop available N factor (Nicholson et al., 2013)
Digestate total N as NH_4–N	59%	Wellinger et al. (2013)
NH_3–N leakage rate (fraction of NH4– N)	10%	Styles et al. (2016)
Digestate Application		
Digestate output	90%	Digestate output assumed to be 90% of throughput (NNFCC, 2022)
NH_3–N emission factor (fraction of NH_4–N)	7.8%	Nicholson et al. (2013)
NO_3–N emission factor (fraction of NH_4–N)	9.5%	Nicholson et al. (2013)
Digestate Upcycling		
$MgCl_2 \cdot 6H_2O$	0.85 kg/t digestate	Styles et al. (2018)
NaOH 50%	10 kg/t digestate	Styles et al. (2018)
H_2SO_4 96%	11 kg/t digestate	Styles et al. (2018)
Sodium hydroxide production	0.94 kg CO_2e/kg	Ecoinvent v3.8 burdens for production of sodium hydroxide NaOH 50%
Sulfuric acid production	0.19 kg CO_2e/kg	Ecoinvent v3.8 burdens for production of sulfuric acid H_2SO_4 96%
Potassium chloride (used as proxy for $MgCl_2 \cdot 6H_2O$)	0.46 kg CO_2e/kg	Ecoinvent v3.8 burdens for production of potassium chloride
Avoided Fertiliser		
Digestate N content	34 kg/t DM	DEFRA (2010)
Digestate P content	6.2 kg/t DM	DEFRA (2010)
Digestate K content	0.4 kg/t DM	DEFRA (2010)
Avoided NH_3–N emission factor	1.7%	Misselbrook et al. (2012)
NO_3–N emission factor	10%	Duffy et al. (2014)
Avoided AN fertiliser upstream	8.56 kg CO_2e/kg N	Ecoinvent v3.8 burdens for production of ammonium nitrate
CHP Specifications		
CHP Leakage rate	0.5%	Styles et al. (2016)
CHP electricity conversion efficiency (small)	35%	Styles et al. (2016)
CHP electricity conversion efficiency (medium)	40%	Styles et al. (2016)
CHP electricity conversion efficiency (large)	40%	Styles et al. (2016)
CHP thermal efficiency (small)	50%	Styles et al. (2016)
CHP thermal efficiency (medium)	45%	Styles et al. (2016)
CHP thermal efficiency (large)	45%	Styles et al. (2016)

(*continued on next page*)

Table A1 (*continued*)

Process/Material	Quantity	Reference/comment
Transportation		
Pot ale transport	0.09 kg CO$_2$e/tkm	Ecoinvent v3.8 burdens for liquid tanker transport 28t
Draff transport	0.08 kg CO$_2$e/tkm	Ecoinvent v3.8 burdens for >20t truck EURO5
Independent distillery digestate transport	0.36 kg CO$_2$e/tkm	Ecoinvent v3.8 burdens for tractor and trailer
Cluster digestate transport	0.09 kg CO$_2$e/tkm	Ecoinvent v3.8 burdens for liquid tanker transport 28t
Cluster solid digestate transport	0.08 kg CO$_2$e/tkm	Ecoinvent v3.8 burdens for >20t truck EURO5
Cluster upcycled digestate (bio-fert) transport	0.08 kg CO$_2$e/tkm	Ecoinvent v3.8 burdens for >20t truck EURO5
Feed Characteristics		
Soybean meal dm	88%	Feedipedia (2020)
Soybean meal crude protein	55%	Feedipedia (2020)
Soybean meal rME	13.4 MJ/kg DM	Feedipedia (2020)
Barley DM	87%	Feedipedia (2020)
Barley crude protein	11.8%	Feedipedia (2020)
Barley rME	12.4 MJ/kg DM	Feedipedia (2020)
Draff crude protein	20%	Bell et al. (2019)
Draff rME	11.1 MJ/kg DM	Bell et al. (2019)
Wheat DDGS dm	90%	Bell et al. (2019)
Wheat DDGS crude protein	34%	Bell et al. (2019)
Wheat DDGS rME	13.5 MJ/kg DM	Bell et al. (2019)
Barley DDGS dm	90%	Bell et al. (2019)
Barley DDGS crude protein	26%	Bell et al. (2019)
Barley DDGS rME	12.2 MJ/kg DM	Bell et al. (2019)
PAS DM	45%	Bell et al. (2019)
PAS crude protein	36%	Bell et al. (2019)
PAS rME	14.2 MJ/kg DM	Bell et al. (2019)
Feed Production processing inputs		
DDGS thermal energy inputs	5.96 MJ/kg DM	Input values based on Murphy and Power (2008) environmental burdens for natural gas based on Ecoinvent v3.8
DDGS UK grid electricity inputs	0.12 KWh/kg DM	Input values based on Murphy and Power (2008) environmental burdens for electricity (UK country mix) based on Ecoinvent v3.8
PAS UK grid electricity inputs	0.13 KWh/kg DM	Input values based on Russell and Stewart (2003) environmental burdens for electricity (UK country mix) based on Ecoinvent v3.8
PAS digestate transport	0.09 kg CO$_2$e/tkm	Ecoinvent v3.8 burdens for liquid tanker transport 28t
DDGS solid digestate transport	0.08 kg CO$_2$e/tkm	Ecoinvent v3.8 burdens for >20t truck EURO5
iLUC Characteristics		
Soy yield	2.9 t/ha	FAO (2020)
Above ground biomass	4 t dm/ha	IPCC (2006)
Carbon fraction	0.5	IPCC (2006)
Root ratio	0.4	IPCC (2006)

Table A2
Aggregated emissions and reduction specific quantities of all scenarios

Cluster Name	Total Emissions (kt CO$_2$e)	Total offset (kt CO$_2$e)	Total electricity output (GWh)	Total Fuel (TJ)
Electricity sc	409	−1013	481	0
Electricity + Upcycled Digestate sc	230	−914	481	0
Fuel sc	420	−1235	23	396
Fuel + Upcycled Digestate sc	241	−1137	23	396
Electricity + Fuel sc	414	−1124	252	198
Electricity + Fuel + Upcycled Digestate sc	236	−1026	252	198
Electricity + PAS sc	247	−3098	234	0
Electricity + PAS + Upcycled Digestate sc	202	−3052	234	0
DDGS sc	244	−7669	23	0

*Fuel = bio-fuel for transport; DDGS = Dried Distiller Grains with Solubles; PAS = Pot Ale Syrup.

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