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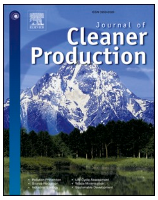

What drives the viability of waste-to-energy? Modelling techno-economic scenarios of anaerobic digestion and energy generation for the Scottish islands

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ABSTRACT

Anaerobic digestion, a technology which converts biowaste into biogas, can address issues of waste utilisation, energy security and reducing emissions. Co-digestion of waste could improve biogas yields and synergies between sectors but requires transport of waste. To improve on existing biowaste-to-energy models which consider simple transport costs, this work combines a techno-economic model with a capacitated vehicle routing problem (CVRP) solver to consider detailed waste transport costs with actual Open Street Map (OSM) road networks. This addresses whether biowaste-to-energy techno-economic modelling is improved with more specific transport costs and more broadly how factors of resource availability, generation technology and transport costs influence the viability of anaerobic digestion and generation plants. The levelised cost of energy (LCOE) is used to compare scenarios of these aspects. The Scottish islands have been modelled as a case study due to high biowaste potential and varied topographies, which both influence transport costs. Number of waste vehicles required is improved by 42.8% and the unit cost of collection varies from £0.1–1670.0/tonne. Local topographies and waste availability significantly affects the viability of individual facilities, which might not be considered by simpler collection cost metrics. Between 14.0 and 20.6% of the regions electricity demand could be met by biogas. While industrial facilities co-located with demand have the cheapest LCOE, this can in some cases be improved with other waste streams, highlighting the need for further research on and policies supporting co-digestion, as well as improving household and business participation rates. Incentives and avoided costs are crucial to supporting biowaste-to-energy if more isolated regions are to benefit from improved waste utilisation.

1. Introduction

Meeting climate change goals and carbon reduction targets will require changes to energy systems and resource utilisation. Waste from domestic, commercial and industrial sectors could be better utilised with wide ranging benefits: reducing costs for companies, local government and consumers; reducing CO_2 emissions; and improving the security, flexibility and resilience of local energy systems (Ricardo Energy, 2019). All of these factors could contribute towards meeting mid-century net zero goals, which for Scotland have been brought forward to 2045 (Scottish Parliament Climate Change, 2019). For wetter, organic biowaste types, anaerobic digestion (AD) is the best suited technology for conversion into energy via biogas. Substrates with a high organic load are introduced into a digestor where they are degraded by microorganisms anaerobically (i.e. in the absence of oxygen) which produces biogas (Lora Grando et al., 2017). It is one of the only technologies which can address waste management, increase dispatchable renewable energy production and reduce greenhouse gas emissions (Al Seadi et al., 2008). The US Inflation Reduction Act of 2022 extended renewable energy tax credits to biogas, as well as $1.7 billion of grants for agricultural anaerobic digestion (Clean Energy Building a Clean, 2023). The REPowerEU action plan targets an increase to 35 billion cubic metres by 2030 (European Commission REPow erEU: Affordable, 2019)- just over double current production (European Biogas Association Delivering 35, 2022). Challenges the plan highlights for the sector include the need for increased collaboration between waste sectors, greater understanding of regional resources and assessment of investment challenges (European Commission REPow erEU: Affordable, 2019). Better understanding of how these challenges can be addressed requires waste-to-energy modelling: considering the available resource, how the waste is converted into energy, the generation type and assessment via metrics of

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Acronyms

AD	Anaerobic digestion
BB	Biogas boiler
CAPEX	Capital expenditure
CHP	Combined heat and power
COD	Chemical oxygen demand
CVRP	Capacity Vehicle Routing Problem
LCOE	Levelised cost of energy
OPEX	Operational expenditure
OSM	Open Street Map
OSMnx	Open Street Map Network Python package
REG	Reciprocating engine generator
VS	Volatile solids

cost or other environmental impacts.

Generally, analysis considering available biomass resources have focused on one specific industry or waste stream (Lora Grando et al., 2017), considering a single resource or industry in detail (Duguid and Strachan, 2016; Xiong et al., 2016). Others models have included a range of waste types to consider synergies between sectors (Keller et al., 2019; Hoo et al., 2020; Song et al., 2016). There is growing recognition of the importance of co-digestion (i.e. digestion with more than one type of waste) (Lora Grando et al., 2017) which can increase biogas yields (Karki et al., 2021; Bong et al., 2018; Zhang et al., 2022). Unlike other waste streams, such as domestic refuse for incineration, the wetness of materials used for AD prevent it being imported or stored for any length of time (Lü et al., 2016). Transport of waste is therefore crucial, but these costs in the reviewed biowaste-to-energy literature were largely either calculated as an average per tonne or considered as an exogenous cost input (Luz et al., 2015; Kassem et al., 2020; Balcioglu et al., 2022; El Ibrahimi et al., 2021). In the UK, collection makes up about two-thirds of the operational costs of domestic waste processing, mainly being made up of vehicle costs and staff fees (WRAP Newcastle, 2015), with difficulties highlighted for food waste (WRAP Household Food Waste Collection, 2021). Transport modelling costs will therefore have a significant effect on modelling of the synergies of co-digestion.

Various methods have been developed to minimise cost or distance by routing vehicles between locations of waste production and collection depots given constraints of vehicle capacity, referred to as the capacitated vehicle routing problem (CVRP). Using a backtracking search algorithm and the concept of a threshold waste level (the fullness of each waste node prior to collection) at which reductions of 37% travel distance were found for 91% of routes compared with a simplified model (Akhtar et al., 2017). Similarly, a particle swarm optimisation algorithm was used to optimise routes, finding the optimal costs, travel distance, fuel efficiency and waste collection efficiency at 70–75% of the threshold waste level (Hannan et al., 2018). Using the OR-tools CVRP solver developed by Google and a recursive-DBSCAN algorithm to reduce the problem size via node clustering, a 61% runtime improvement was achieved for problems of up to 5000 nodes (with the basic solver managing up to 2000) with a 7% reduction in accuracy (Bujel et al., 2018). In these cases, through consideration of local topography, CVRP solvers can provide much more accurate and specific estimates of waste collection costs than simpler flat-rates or heuristics.

A matrix of distances (which can be any metric of cost, time, distance, etc.) between nodes is used to optimise CVRP for that metric, which for some studies is approximated as the straight-line, Euclidean distance (Bujel et al., 2018; Edwards et al., 2016). In modelled cases for major cities, this was found to be an acceptable compromise by using a factor of 1.3 to adjust the distance, but it was highlighted that this holds mainly when a lower proportion of nodes are served in the network (i.e. less so for household food collection) (Boyacı et al., 2021). To improve on this method, Open Street Map Network (OSMnx) is a Python package developed using Open Street Map data to providing actual road networks for distance and travel time calculations (Boeing, 2017). It has been used to compare waste collection route optimisation methods for the topography of Salvador, Brazil (Oliveira and Garcia, 2021), assessment of the potential of heat from waste water for Göttingen, Germany (Pelda and Holler, 2018) and develop a genetic algorithm waste collection optimisation tool based on Lisbon, Portugal (Da and Mendonça, 2018).

This detailed modelling of transport costs could be integrated with other optimisation decision making frameworks, which generally feature comparison of technology types and facility configurations. The technology type is critical to the impacts and benefits of waste to energy, affecting the amount of useful energy and the overall cost significantly. Rankings of outcomes also depend on the chosen assessment metric, which varying depending on the desired outcome or end-user (Duguid and Strachan, 2016; Hoo et al., 2020). Availability of resource (which is affected by transport costs) is one of the main factors affecting the sizing and available energy of AD projects (Luz et al., 2015; Kassem et al., 2020; Balcioglu et al., 2022; Castley et al., 2022). A range of models have been identified in the literature but modelling of transport costs could be improved with more specific road-network data.

(i) *Stochastic programming* has been utilised for municipal solid waste in Singapore, where the authors demonstrated that an optimised hybrid waste-to-energy system could be more practical than the current incineration system (Xiong et al., 2016);
(ii) *Input-output modelling* of multiple waste-streams and five waste-to-energy technologies found wastewater biogas and solid waste incineration were the most suitable technologies, mitigating up to 18 million tonnes of CO2 emissions (Song et al., 2016)
(iii) *Life-cycle assessment and life-cycle cost models* have demonstrated the waste streams with higher biogas yields and their impact on natural gas in different cases for in Turkey for agricultural waste. Waste streams with higher biogas yields improved on the impacts of natural gas in almost all cases, but that lower biogas yielding materials had more limited benefits (Balcioglu et al., 2022).
(iv) *Bio-inspired optimisation algorithms*, such as particle swarm optimisation algorithm (PSOA) for energy saving metrics, cost saving and carbon reduction ratios for CCHP (combined heating, cooling and power). This found an integrated AD and biogas boiler resulted in the greatest savings, but highlighted that results were dependent on metric weightings which would vary by end-user (Castley et al., 2022).
(v) *Techno-economic models* have been used to assess various processes. Modelling of a centralised AD and energy facility for distillery waste on the Scottish island of Islay compared biogas boilers and combined heat and power (CHP), finding the optimal technology varied with considerations such as availability of demand (Duguid and Strachan, 2016). Analysis of MSW gasification for power generation in Brazilian municipalities found larger plants with higher installed power were more economically viable (Luz et al., 2015). A diary waste-to-energy model for New York state found AD and hydrothermal liquefaction with averaged collection costs to be feasible with a net present value of \$0.4–1.5 billion (Kassem et al., 2020).

The importance synergies between biogas waste sectors is highlighted in the REPowerEU plan (European Commission REPow erEU: Affordable, 2019), which necessitates the transport of waste (Lü et al., 2016). From the range of models identified, many only considered transport costs as an exogenous input (Luz et al., 2015; Kassem et al., 2020; Balcioglu et al., 2022; El Ibrahimi et al., 2021). Studies have done more detailed modelling of transport costs (Boeing, 2017; Oliveira and Garcia, 2021; Pelda and Holler, 2018; Da and Mendonça, 2018), but not incorporated it with technology decision-making optimisation frameworks. Transport costs will vary significantly with local road networks-including these in techno-economic modelling will improve the understanding of what factors influence viability of biowaste-to-energy and the subsequent evidence-based policy recommendations.

2. Methodology

To consider the availability of waste, transport costs, facility configurations and suitability of generation technologies, a model has been developed in Python (Python Software Foundation Python Version, 2022) combining three sub-models of collection, resource and techno-economics (Fig. 1). All data and code used is available on Mendeley Data (Matthew, 2023). This integrated model will allow synergies between sectors to be more fully considered, highlighting what factors influence the viability of waste-to-energy plants. Integration of a detailed transport cost model improves on other works with simpler cost calculation methodologies.

A resource database (Section 2.1) has been developed for six waste types considering volumes, energy potential and locations of waste. The collection model (Section 2.2) uses a CVRP solver to optimise collection routes of waste in the bioresource database, based on the recursive-DBSCAN clustering algorithm (Bujel et al., 2018). The techno-economic model (Section 2.3)takes the energy potential, technology costs and collection costs to calculate the levelised cost of energy (LCOE). The scenarios-based assessment (Section 2.4) will consider variability of modelled inputs, with three scenarios each for facility configuration, generation technology type and resource availability.

The model has been developed for the case study of the Scottish islands. Scotland has pledged to be carbon neutral by 2045, which will require changes in domestic, commercial and industrial sectors (Scottish Parliament Climate Change, 2019). Studies have highlighted the contribution of bio-energy to this target (Ricardo Energy, 2019; Shaiith Sector Study on Beer, 2015). The islands have an excellent energy potential from biowaste, which has been highlighted for several sectors (Ricardo Energy, 2019; Duguid and Strachan, 2016; Scottish Enterprise Biorefinery Roadmap for, 2019; Zero Waste Scotland Biorefining Potential, 2017; Kang et al., 2020; Ruiz, 2021) but not assessed as a combined resource. The dispersed and irregularly connected islands will highlight the impact of more detailed modelling of transport costs.

2.1. Resource database

The resource database was collated from the most representative dataset, which for fish farm was directly reported but, in all others, had to be approximated from multiple sources using Equations (1) and (2). Waste was categorized as either liquid or solid to inform how it could be transported. A summary of the total waste and data sources for each sector modelled is given in Appendix A with supporting calculations in Appendix B where direct data was not available.

$$Local\ Production\ (tonnes) \times Waste\ Factor\ (\%) = Waste\ (tonnes) \qquad \text{Eq. 1}$$

$$Waste\ (tonnes) \times AD\ Energy\ Factor (MWh\ /\ tonne) = Energy\ (MWh) \qquad \text{Eq. 2}$$

2.1.1. Food waste

Household and business food waste data sets were developed by combining local household and business data with national estimates of waste per property (WRAP UK Progress against Courtauld, 2020), to give an annual food waste matched to specific buildings and locations. The household and business database (used to locate resources in the farm, food processing, distilleries and breweries waste databases) was developed from Open Street Map (OSM) (OpenStreetMap contributors Planet Dump Retrieved, 2021) and UKBuildings (Geomni UKBuildings

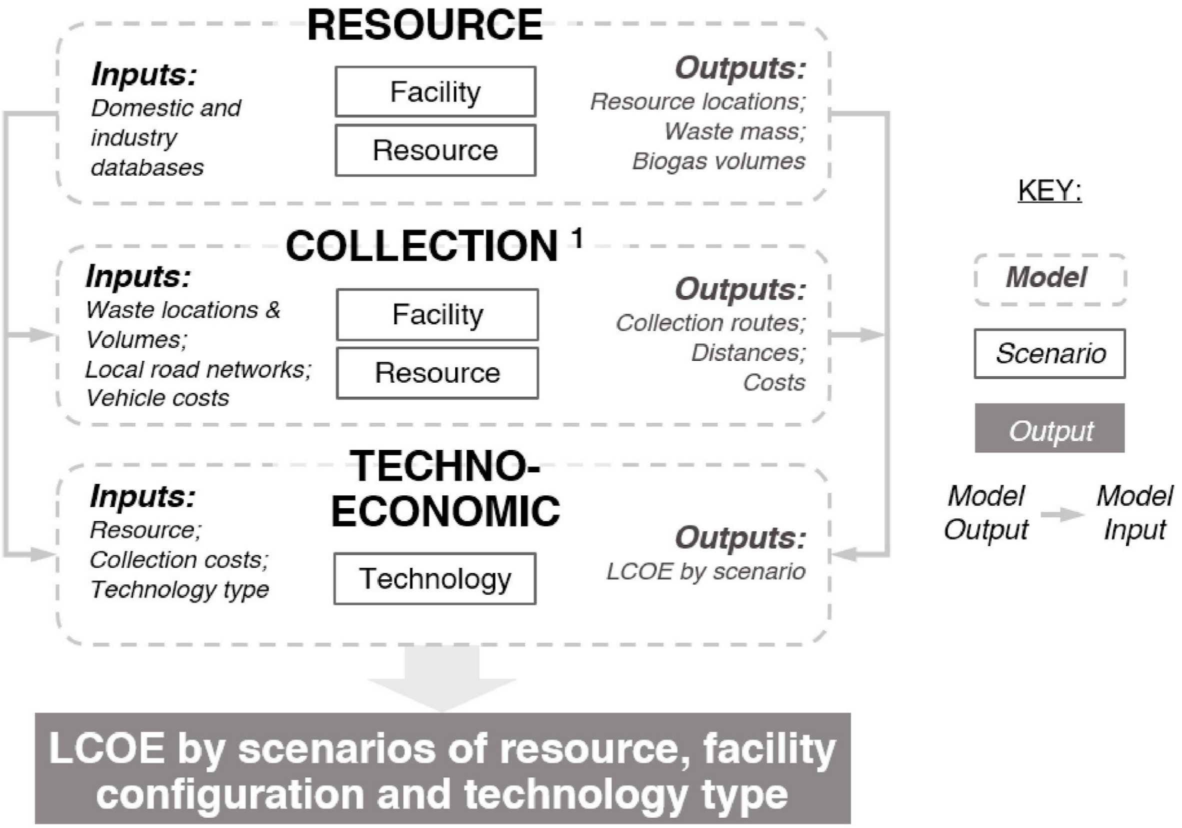

Fig. 1. Configuration of the three models and scenarios, illustrating how scenarios impact each model the overall results. ^{1} The collection model is adapted from the recursive DBSCAN-clustering methodology of (Bujel et al., 2018)- all other models are the authors own work.

Database, 2020, 2020) databases. By assigning synthetic households based on census demographic data (National Records of Scotland, 2011, 2016) to a database of actual building polygons (Geomni UKBuildings Database, 2020, 2020), household waste can be assigned to actual property locations. For non-domestic food waste, business occupancy types were assigned to specific buildings using the Open Street Map (OSM) database. Average annual food waste values for each property type (WRAP UK Progress against Courtauld, 2020; Tesco Tesco Annual Report and Financial Statements, 2017) were matched with average business footprints (BEIS, 2015) to get an average annual food waste per square meter (see Appendix B for values and references). This factor was combined with local floor areas gave an annual waste per year specific to each property.

2.1.2. *Fallen stock farm waste*

Waste directly from farms was considered as the on-farm mortalities from natural causes (termed 'fallen stock') of the local livestock-sheep and cows. Farm waste data came from agricultural census data (EDINA National Agricultural Census Data, 2022) and national average fallen stock rates (On Farm Cattle Deaths in, 2002). The Agricultural Census data contained livestock density values, which combined with national proportion of fallen stock per year and weight of livestock (550 kg for cattle and 54 kg for sheep) (On Farm Cattle Deaths in, 2002), this gave average weights of fallen stock per year for each OSM farm (OpenStreetMap contributors Planet Dump Retrieved, 2021).

2.1.3. *Fish farm waste*

Fish farm waste was considered as farmed mortalities, which was the only modelled waste type with a directly recorded dataset (Scotland's Aquaculture Fish Farms Monthly, 2022). The data contained locations of fish farms with monthly reports of the total biomass onsite and monthly mass of mortalities. As >97% of the total recorded biomass was Atlantic Salmon, for simplicity it was the only species considered. Fish farm locations were offshore, so it was assumed that the resource would be brought to the nearest port to be collected.

2.1.4. *Food processing waste*

To avoid conflicting resource demands, only wastewater from fish, meat, and dairy processing was considered. The local production and a conversion factor were used to get the wastewater for each sector (see Appendix B for values and references). Food processing facilities were identified from the register of Scottish food processing sites (Food Standards Scotland Approved Establishments, 2022).

Statistics for annual fish landing by port (Marine Management Organisation United Kingdom, 2016) and fish farm biomass (Scotland's Aquaculture Fish Farms Monthly, 2022) were grouped by port and apportioned to the nearest fish processing facility. It was assumed 70% of the local catch is exported without processing (Tetley, 2016). The waste water proportion was directly available (Chowdhury et al., 2009)-the potential energy content was calculated from other values (see Appendix B for values and references).

For dairy processing, the number of dairy cows (EDINA National Agricultural Census Data, 2022) was combined with an estimated yield per cow (WRAP UK Progress against Courtauld, 2020) to get local production which was assigned to the nearest food processing facility. The fraction of wastewater and estimated energy content is calculated in Appendix B. Similarly for meat processing, number of cows was used to estimate the annual production (EDINA National Agricultural Census Data, 2022), but unlike dairy, a proportion of cattle will be exported live from the islands, assumed as 70% as for fish processing (Tetley, 2016).

2.1.5. *Distilleries waste*

Waste from distilleries came in three forms (draff, spent lees and pot ale) which occur in differing proportions and potential biogas yields (Ricardo Energy, 2019). The amount of each waste stream produces was estimated from known proportions and the production of each distillery. Distillery production was estimated using the production capacity of each facility (Gray, 2020) and a production factor based on the annual Scottish production of whisky compared with total production capacity (Gray, 2020; Bell et al., 2019). The waste and energy potential for each distillery was assigned by location.

2.1.6. *Breweries waste*

Beer brewing is a much smaller industry than whisky distilling on the islands but was included for completeness. Brewery locations were available from the OSM (OpenStreetMap contributors Planet Dump Retrieved, 2021). Production relative to building floor area were estimated (see Appendix B for values and references). A factor of 50% was applied in calculating the production to account for other building uses. Brewery waste arose in three forms – spent grain, spent hops and spent yeast, with differing energy potentials (Appendix B).

2.2. *Resource collection model*

The Capacitated Vehicle Routing Problem (CVRP) solver, developed using Google's OR-tools (Perron, Furnon), was used to optimise the collection routes for the varying resources-the main input of this being a nodal distance matrix and nodal demands from the bioresource database. The actual distance from OSM road networks (Boeing, 2017) was used to calculate the distance matrix. Resource collection was considered to occur once every two weeks. The main outputs of this to be used for the economic model are the number of vehicle days required per facility, the fuel costs and the ferry costs.

2.2.1. *Distance matrix*

The main CVRP solver input is a matrix of the shortest distances (which can be any metric-distance, time, cost, etc.) between every node, calculated using the OSMnx Python package (Boeing, 2017). By requesting the OSM road shapes from the polygon of an area, network theory is used to calculate the distance matrix for a given set of nodes.

OSMnx graphs contained distance and road type information, which were converted to metrics of costs and time taken. Data on ferry routes was manually collected and added to the graphs for the 80 ferry routes connecting the islands from the main ferry operators (Orkney Islands Council Ferry Service, 2022; Shetland Islands Council Ferry Fares, 2022; Caledonian MacBrayne Ferries Summer Timetables, 2022). As the length of a working day could limit collection routes, with some ferries taking more than 2 h, time was used to optimise the routes and constrain the length of a working day to 8 h. The road type information included in the OSM graphs was used to approximate the travel speed (Appendix C) and time taken.

2.2.2. *Scenario waste collection areas*

Collection areas would vary with the facility configuration scenarios (Section 3.4.1). For the Islands scenario, the catchment area would be each island. For the Industrial scenario, the waste closest by travel time on each island to each facility was considered as belonging to that facility. For the Centralised scenario (Fig. 2), catchment areas were manually assigned to the approximate area of a day's travel.

To site non-industrial AD facilities, the Local Development Plans of each local authorities was used (EDINA National Agricultural Census Data, 2022). These classify land area based on its suitability for development-existing housing, protected area, economic development, etc. Potential locations were identified by considering land classifications suitable for economic or industrial development. For the Centralised Facilities and Individual Island Facilities scenarios, the best location for each catchment area was assumed to be the one the closest to the waste centre of gravity of each resource collection area, calculated using equation (3):

$$Centre\ of\ mass_{x,y} = \frac{\sum_0^n c_n m_n}{\sum_0^n m_n} \qquad \text{Eq. 3}$$

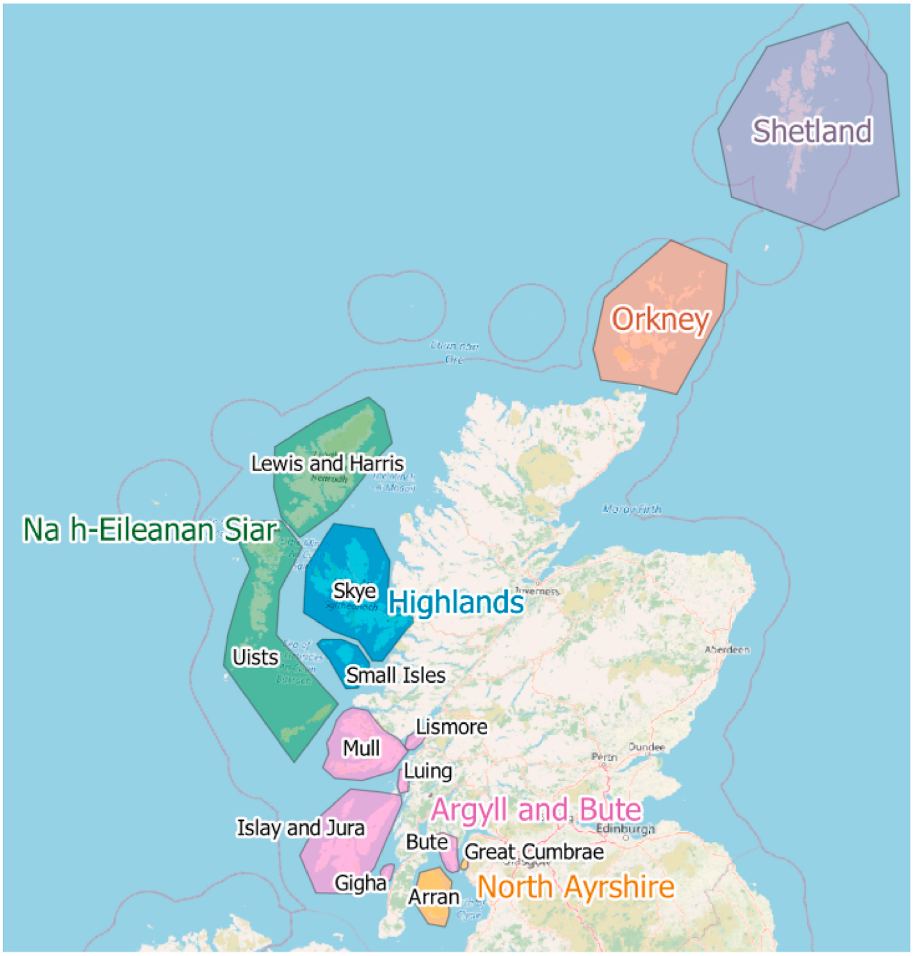

Fig. 2. Modelled resource collection areas noted in black text, with local authority (LA) areas grouped by colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Where Centre of $\text{mass}_{x,y}$ = x/y coordinates of centre of mass; n = number of coordinates; c = nth x/y coordinate; m = nth mass.

2.2.3. *Capacitated vehicle routing problem (CVRP) solver*

To optimise the collection of each waste stream, Python and Google's OR-Tools solver (Perron, Furnon) was used, which required the distance matrix, vehicle capacities, vehicle number and collection facility location. A 2.5T vehicle was assumed for solid waste, with 18,000L for liquid waste (Duguid and Strachan, 2016). The main outputs are the time required for each collection route, the volume of waste collected, the distance travelled and the ferry costs. The lengths of trips were grouped into the minimum number of collection days to minimise vehicle costs. The number of vehicles required would be this divided by ten, the number of working days in the two-week collection period. The OR-tools solver can handle all waste streams except for food waste, where the node count of up to 5000 exceeded the computing power of the available 2019 Dell laptop with 2.60 GHz Intel i7-9850H CPU and 16 GB RAM. To deal with these larger problems, the recursive DBSCAN algorithm was used (Bujel et al., 2018), which recursively cluster nodes into groups with similar numbers of collection points, which the CVRP is then applied to. Smaller areas of demand compared with the recursive DBSCAN algorithm found a discrepancy of 7% between the CVRP solver and recursive DBSCAN, as for the study describing the method (Bujel et al., 2018).

2.3. *Techno-economic model*

The resource modelling and the transport costs was used as inputs to the techno-economic model. The technical and economic characteristics used to model the AD and generation technologies will be described. Each of the three facility configurations (Section 3.4.1) were modelled with an AD plant and each of the three generation technologies-reciprocating engine generator (REG), combined heat and power (CHP) and biogas boiler (BB).

The outputs of the resource model were used to size the AD plant, depending on the waste available from each facility configuration. The mass of waste, density (assumed as 1000 kg/m^3 or 500 kg/m^3 for food waste and animal remains) and a retention time of 3 days was used to determine an AD volume (m^3) capacity which was used to calculate the cost. It is not clear from the literature if co-digestion would be feasible for all waste types but as AD costs were modelled without a fixed element, this would not affect results in terms of cost. The energy available from biogas production was used to size the generation technology by technical characteristics (Table 1). The sizes of AD (m^3) and generation technology (MW) was then used to calculate the cost of each technology and facility configuration.

Other economic analyses of the region or sectors have calculated payback times or the net present value (NPV) using average fuel, heat and electricity prices and highlighting the extreme sensitivity of results to energy prices (Duguid and Strachan, 2016; Kassem et al., 2020; Kang et al., 2020), which can be volatile. By considering the LCOE, assumptions about energy prices can be separated from the results. Rather than assume what outcomes (i.e. CO_2 reduction, avoided landfill, cost

Table 1
Modelled technical characteristics (Duguid and Strachan, 2016).

Aspect	Biogas boiler	Combined heat and power	Reciprocating engine generator
Capacity Factor	50%	90%	6%
Thermal Efficiency	80%	41%	–
Electrical Efficiency	–	39%	39%
Parasitic AD Demand	20%	5%	10%

savings, etc.) would be most desirable, the LCOE will be compared to analyse what factors influence the cost of waste-to-energy and ways of addressing this will then be discussed. The LCOE was calculated using equation (4), with a discount rate of 7.5% and the economic lifetime of 20 years (IRENA Renewable Power Generation Costs, 2018). Capital expenditure (CAPEX) and operational expenditure (OPEX) was calculated as the sum of each facility cost aspect (Table 2). To compare the potential viability of individual schemes, the LCOE of each technology type can be compared to benchmark costs. These are considered as £130/MWh for heat (the current heat cost from a feasibility study of using hydrogen for an Orkney distillery) (EMEC Hydrogen Title, 2019), £313/MWh for REG and £135/MWh for CHP (BEIS, 2020).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t + O_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad \text{Eq. 4}$$

Where t = the year; C = CAPEX; O = OPEX; E = electricity generated; r = discount rate; n = economic life of project.

Where waste disposal on the islands currently has a cost, these avoided costs are modelled as current rate producers of waste pay to have waste removed (Table 3). The LCOE will be compared with and without these avoided costs (as well as the capital incentives) to understand the impact on results.

Heat network costs would be considered depending on the facility. Centralised and island facilities would be standalone AD and generation plants, not co-located with significant heat demand and so would require a heat network. Industrial demand would depend on the industry-distilleries were modelled without heat network costs as the majority of demand is heat (Ricardo Energy and Environment Scotch, 2020), but other facilities with negligible heat demand included heat network costs. These vary by up to a factor of 4 depending on the proximity and nature of local heat demand (Department of Energy, 2015), therefore the model will be considered for the average costs with variability discussed.

Table 2
Summary of costs considered in the model.

Aspect	Type[a]	Description	Source
AD	C&O	CAPEX- £300/MWh OPEX- £25/MWh	Duguid and Strachan (2016)
REG	C[b]	£44,908 + (£372.43 x capacity)	Allardyce et al. (2022)
Biogas boiler	C[b]	£57,484 + (£13.97 x capacity)	Allardyce et al. (2022)
CHP	C[b]	£54,968 + (£475.62 x capacity)	Allardyce et al. (2022)
Biogas storage	C[b]	£3000/tonne	Rural Futures Economic Viability of (2010)
Waste collection (per vehicle)	C&O	CAPEX - £50,000 OPEX - £6250 OPEX (per driver)[c] - £28,000 Fuel costs – £0.96/km	(WRAP Newcastle, 2015); fuel costs (Madden et al., 2022)
Grid connection	C&O	Connection *(if <250kWh: £938; else £2556)* Annual charge *(£6.43 per day – £0.75 x annual generation)*	Connection (Scottish and Southern Electricity Networks, 2022); annual charge (Scottish and Southern Electricity Networks, 2020)
Heat network connection	C&O	CAPEX - £923/MWh OPEX - £26/MWh	Department of Energy (2015)
Capital incentives	C	50% capital costs	Scottish Government The Low Carbon (2021)
Avoided costs	O	See Table 3	

[a] C = capital costs; O = operational costs.
[b] OPEX calculated as 5% of CAPEX.
[c] Assumed two drivers/operators for food waste; one driver for liquid and animal waste.

Table 3
Avoided costs by waste type.

Fee description	Applicable waste	Rate (£/tonne)	Source
Fallen stock disposal	Farm (cow)	200	Robinson Mitchell Price List Available (2020)
	Farm (sheep)	155	Robinson Mitchell Price List Available (2020)
Fish farm mortalities disposal	Fish farm	36.5	Zero Waste Scotland Finfish Mortalities (2016)
Landfill tax	Food waste	98.6	Scottish Government The Scottish Landfill (2022)
Wastewater disposal rate	Food processing and distilleries (spent lees)	1.6	Scottish Water Metered Charges (2022) (2022)

2.4. Modelled scenarios

Scenarios of facility sizing, location, technology types and resource availability have been modelled. The topography and distribution of waste types varies significantly between regions, which will affect the availability of resource, subsequent facility configuration and generation technology suitability. AD plants co-located with waste generation and demand will minimise transport costs for waste and energy. For other islands with less significant industrial sites, it may be more efficient to minimise transport costs for a wider range of waste streams. To compare the range of these possibilities (Fig. 3), three options will be modelled for resource and generation type scenarios.

2.4.1. Facility configuration scenarios

This and the generation technology will have the most significant impact on the of cost per unit energy. It is dictated by the number of facilities and their catchment areas), which dictates the facilities CAPEX and OPEX (Section 3.3). To model the regional capacity, the facility location will affect the waste transport (Section 3.2) and energy export (Section 3.3). Both are connected as the location relative to other facilities will dictate the catchment area of available waste. To understand the dynamic between the economies of scale, collection costs and energy distribution costs, three scenarios of facility sizes will be modelled, for a total of 122 facilities:

- **Centralised Facilities:** the 75 inhabited islands have been clustered into 14 collection areas (Fig. 2), the size of which are dictated by ferry connection and the area which could be served within an 8-h working day. Each of these areas will have a facility. This scenario will have the largest AD and heat/electricity generation capacity, therefore the lowest facility costs per MW, but also the highest transport costs.
- **Island Facilities:** each group of the 35 road connected islands will have an AD facility, eliminating the cost of ferries to transport waste and reducing road transport costs. This will be traded off against more numerous, smaller facilities having higher CAPEX and OPEX.
- **Industrial Facilities:** each of the industrial facilities with a potential capacity biogas boiler capacity of >10 kW will have a facility, with

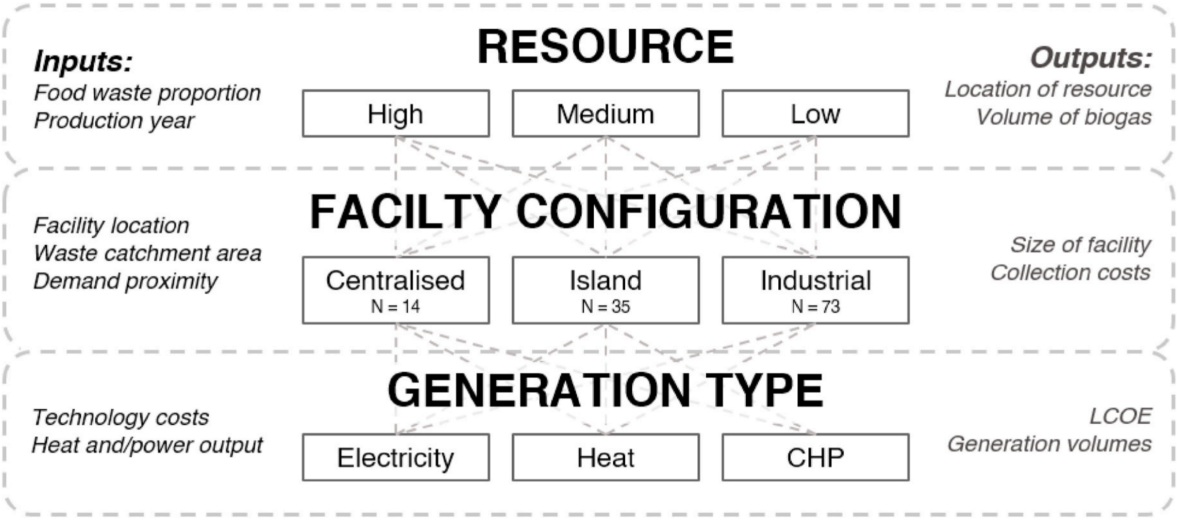

Fig. 3. Diagram of the inputs and outputs for each modelled scenario.

island groups without industrial facilities assumed to have a facility each, for a total of 73. Waste for other locations will be assigned to the nearest facility, eliminating transport costs for 94.4% of the waste by weight.

o **Industrial Facilities Only:** to further understand the impacts of reduced transport costs, a sub-scenario of Industrial Facilities was considered where only waste from the major producers was considered. This reduces the available biogas to 85% of the total but will eliminate transport costs.

2.4.2. *Generation type scenarios*

Review of literature identified AD as the most suitable technology to generate biogas from the available (wet) waste streams. Studies of distillery waste have also considered pre-treatment to improve AD biogas yields, but this does not alter the result in terms of technology suitability, merely highlighting the difference between with and without pre-treatment (Kang et al., 2020; Ruiz, 2021; Gunes et al., 2019; Weber and Stadlbauer, 2017). Given the mixed waste streams and reduced impact on the end use of the biogas, only AD will be considered in this analysis. In utilising the biogas from AD, the model will consider the generation of electricity (REG), heat (BB) and both (CHP). A cut-off of 2.5 MW (the smallest UK grid connected generator) (BEIS, 2019) was applied to REG.

2.4.3. *Resource scenarios*

For all resources, data was collected for as many years as was available between 1990 and 2021 (available years varied by dataset) to understand annual variability and obtain more representative average values. Availability of waste, which dictates waste-to-energy plant sizing, is generally controlled by external market or behavioural demands which supersede demand for waste as energy. For example fish farming biomass has increased by 80% in the last 15 years (Scotland's Aquaculture Fish Farms Monthly, 2022), whereas cattle numbers in the islands and across Scotland have declined by ~0.7% annually since the 1970s, following the trend across Scotland (EDINA National Agricultural Census Data, 2022).

Three scenarios of High, Medium and Low waste have been modelled to capture this. For industrial waste streams (farms, fish farms, food processing, breweries and distilleries), the factors influencing waste production have been modelled as market demand based (Section 3.1). While the modelled factors influencing production for some industries were separate, others were based on the same datasets (e.g. the Agricultural census for food processing and farm mortalities). To capture this, specific years for each aggregated LA were identified for the High, Medium and Low scenarios.

Food waste collected is more significantly influenced by the household participation rate. Research in the UK has shown that this varies significantly, with participation rates of <35% being poor, 35–55% average and >55% being good (WRAP Household Food Waste Collection, 2021). For the High, Medium and Low scenarios therefore, bands of 30%, 45% and 60% participation rate were used.

3. Results

3.1. *Waste generated*

The annual modelled waste by category is shown in Fig. 4. Although distilleries produce the most waste (plotted on a second axis to make the other waste types more visible), this is dominated by the whisky region of Islay and Jura (the LA of Argyll and Bute)- in other areas, other waste types form a greater proportion of the mix. The discrepancy between scenarios varies significantly across regions (Fig. 4). For Na h-Eileanan Siar, the Low scenario is 37% of the High, driven by the preponderance of fish farm mortalities waste, where the rate of mortalities varies annually. For North Ayrshire, the Low scenario is 78% of the High, caused by the larger share of food waste which has lower interannual variability.

The spatial distribution of biogas potential by resource is separated into solid and liquid waste (Fig. 5). Clusters in some locations are clear

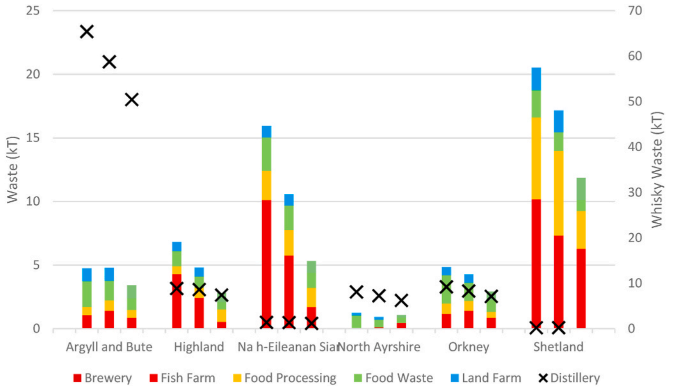

Fig. 4. Modelled annual waste produced by LA area (see Fig. 2 for map of LA regions) and waste type, with the waste scenarios of High, Medium and Low from left to right for each LA.

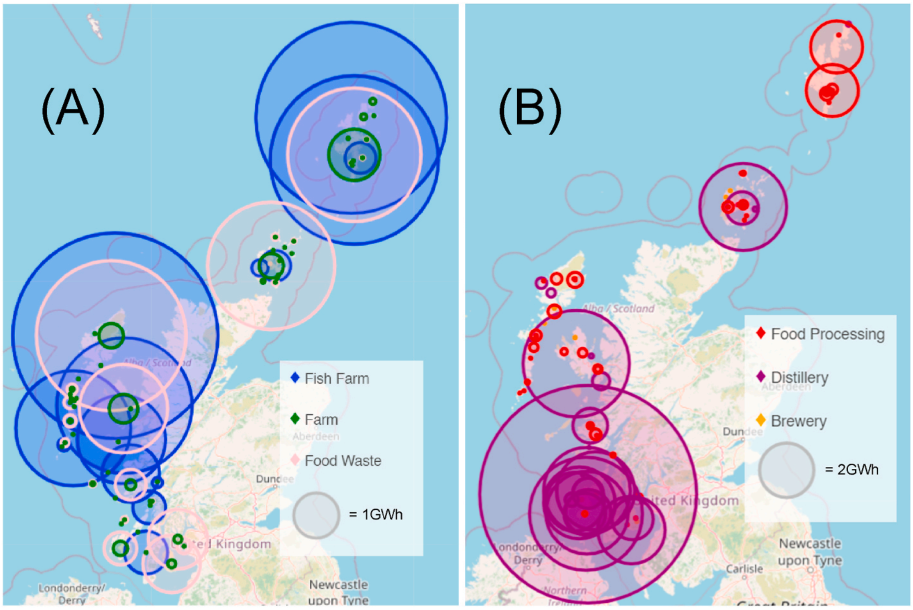

Fig. 5. Solid (A) and liquid (B) waste for the Scottish islands, noting the difference in scales. Food and farm waste have been clustered by island.

as identified by another study (Ruiz, 2021)- that of Shetland, Orkney, Islay and Jura, Skye and Mull.

By weight, liquids make up a much higher proportion of the overall resource than solid waste (Table 4). The changing proportions of liquid/solid waste between scenarios also indicates the changes driven by the markets of each sector, with solid waste reducing much more relative to liquid as the number of and rate of mortalities for salmon, sheep and cow farms varies annually, with food waste collection rate varying from 30 to 60%. The modelled industrial output of distilleries, food processing and breweries varies much less and the waste factors are constant.

3.2. Collection route optimisation results

Modelled collection costs for food waste are compared with the actual budget for each LA (Scottish Government Scottish Local Government, 2022) (Fig. 6- actual budget shown in bold). The actual budget listed considers waste collection for all types and households, therefore the modelled results (considering one waste stream and <60% of households) are a proportion of this total. The proportion of the modelled costs for each scenario remains constant across each LA, indicating that the model consistently captures the road-network aspects which defines collection costs.

3.2.1. OSM and straight-line distance comparison

Two of the CVRP outputs, the number of vehicle days and distance travelled have been compared for routes optimised using the straight line and OSM distance between nodes. The straight-line distance underpredicts the average collection distance for each collection area by 21.5% compared to the model (Table 5), indicating that the non-uniform lengths and shapes of roads had a significant impact on the optimised routes.

Table 4
Comparison of the mass and energy potential of the solid and liquid waste types.

	High		Medium		Low	
%	Solid	Liquid	Solid	Liquid	Solid	Liquid
Mass	29	71	25	75	21	79
Energy Potential	43	57	38	62	32	68

3.2.2. Scenario collection costs

The net present value of collection costs can be compared by facility configuration and resource scenarios (Fig. 7). For the larger island groups, the impact of facility configuration is clear: Centralised facility collection costs are 10.6 times larger than the Industrial facility and 3.0 times larger for the Island facility scenario. Transport costs vary from £0.1–1670/tonne. By co-locating industrial facilities with waste production, only 5.6% of the biowaste requires transport. This is particularly clear for Shetland and Orkney, which being composed of numerous smaller islands (Fig. 2) makes the difference in costs much clearer between a single and individual facility for each island. The trend is not entirely uniform though: the Island facility costs for Lewis and Harris are much higher at 74.7% of the Centralised facility due to the larger size of the single island.

3.3. Comparison of LCOE by scenario

The LCOE grouped by collection area demonstrates scenarios impact on costs and variability between regions (Fig. 8). The clearest and only consistent trend is that the LCOE of REG (where capacity is greater than 2.5 MW, excluding six regions) is significantly higher than BB or CHP, driven by the much lower peaking capacity factor (500 h per year). This does not necessarily mean REG would be unprofitable, as peak electricity generation receives a higher price baseload. CHP appears the cheapest option by the averaged LCOE, followed closely by BB, but this will be assessed in more depth subsequently.

3.3.1. Facility cost and viability

The LCOE of individual facilities can be compared with the technology benchmark costs (£130 for BB, £135 for CHP and £313 for REG) to determine which facilities could be economically viable for the medium resource scenario (see Section 4.3.2 for impacts of the resource scenarios).

Looking at the spread of cost for the viable facilities (Fig. 9), again the cost clearly decreases Centralised to Island to Industrial-as facility catchment area decreases, reduction of collection costs generally outweighs the increase in facility costs relative to the capacity. The consistency of the trend across generation technology types indicates that for areas with high transport costs, minimising transport costs has more benefits than of economies of scale. This preponderance of industrial waste on the islands (85% of the energy potential)- encourages co-

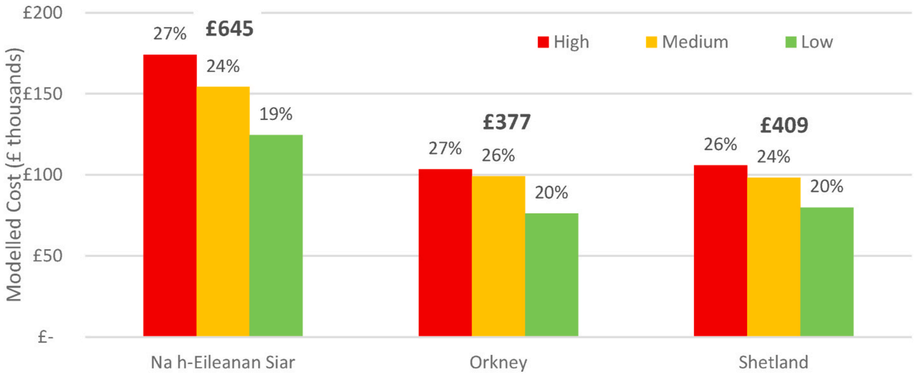

Fig. 6. Comparison of food collection costs with the actual whole budget allocated to each LA for waste collection (shown in bold-the proportion of households served by the high, medium and low scenarios is 60%,45% and 30% respectively) (Scottish Government Scottish Local Government, 2022). The percentage on each bar indicates the proportion of modelled cost against actual total waste collection costs.

Table 5
Summary of the CVRP results comparing the modelled OSMnx distances with straight line distances.

	Sum of Errors	Mean Error	MAPE
Straight line distance	−594,802 km	−21.5%	27.7%
Corrected straight line distance	0 km	−3.3%	16.4%
Number of vehicles	5	−7.0%	20.3%
Rounded number of vehicles	22	−29.5%	42.8%

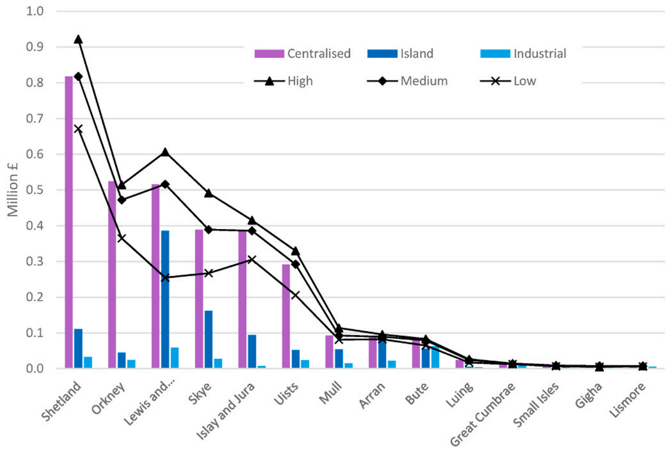

Fig. 7. NPV (as a cost) of collection CAPEX and OPEX costs per scenario and grouped by collection area. Facility configuration costs are shown for the medium resource scenario and the resource scenarios for the Centralised facility configuration.

location of supply and demand to eliminate transport costs. To consider this further, the model was also run considering only industrial facilities and excluding other waste which would require transportation to the facility (Industrial Only in Fig. 9).

The impacts of neglecting the additional energy and transport costs from non-site-specific industrial waste are less clear, with costs reduced on average by 0.8%. for all technology types. For BB and CHP, costs are reduced slightly on average, but to a lesser extent than the main scenarios, whereas the cost appears to increase slightly for REG. In some cases, additional energy from external waste streams seems to provide cost effective energy, but in others, transport costs increase overall costs per energy.

Plotting the change in biogas potential (the proportion of waste excluded by not collecting it) against the change in LCOE (the reduced transport costs and energy produced) between the Industrial and Industrial Only scenarios further demonstrates this (Fig. 10). There is no trend, indicating that the value of off-site waste is highly context specific.

3.3.2. *Impact of resource scenarios on cost*

Having considered the impacts of facility configuration and generation technology on LCOE for the medium resource scenario, the impact of the resource scenarios is considered separately (Fig. 11). The cost clearly decreases with increased availability of resource for all facility and technology scenarios, with the average LCOE for all facilities decreasing by 6.1% from the Low to High scenarios. The utilisation of resource used by viable facilities also decreases with the resource across nearly all other scenarios (Table 6).

3.4. *Sensitivity analysis*

Other aspects not considered in scenarios were identified as impacting results: avoided costs, incentives and heat network costs. Variability of these has been considered separately.

The model has been developed considering avoided costs and incentives, which will both impact results. Avoided costs are considered as the cost per tonne which waste producers currently pay for processing. For the medium resource scenario, these avoided costs range from 28 to 42% of OPEX including facility costs. Incentives have been considered as 50% of CAPEX, which has been assumed to automatically apply to all facilities.

With avoided costs and incentives, an average of 87% of the resource could be utilised across all facility scenarios. This decreases to an average of 51% for incentives only and 26% for avoided costs only. The incentive of 50% of CAPEX costs encourages CHP and REG to greater extent than BB, likely due to the higher heat network CAPEX costs. Again, the importance of co-locating heat generation with demand is clear. For the Centralised and Island scenarios, including avoided costs overtakes transportation costs, with the CAPEX incentive making more facilities viable. For the Industrial scenario, avoided costs have more impact-combined with the benefits of mixed waste identified in Section 4.3.1, indicating that industrial facilities could pay below current waste processing charges and benefit from increased biogas yields from more energy dense waste located nearby.

Where not co-located with demand (i.e. non-distilleries), heat network costs were modelled using the average (£923/MWh) of a range of surveyed costs (£410–1496/MWh) (Department of Energy, 2015). At the lower end, heat network costs make up 13–47% of total CAPEX, increasing to 36–76% at the upper end, impacting the facility viability. With reduced heat and network capacities, CHP facilities are insulated from these increased costs, with a minimal change in the viable resource. This would indicate that CHP would be preferable in instances

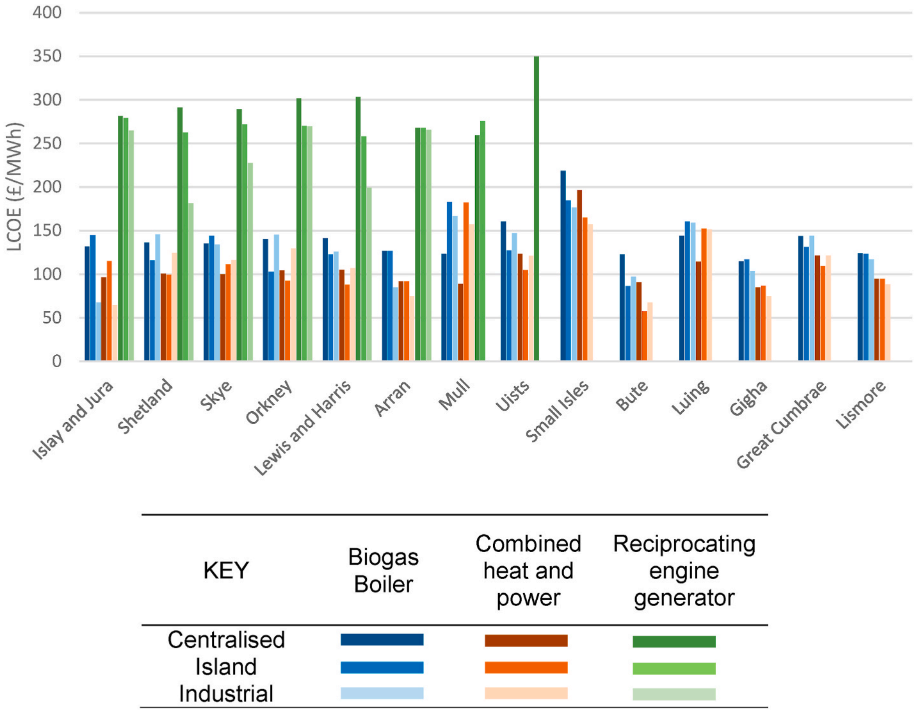

Fig. 8. Total LCOE for each facility type and technology- Island and Industrial scenarios have been aggregated by collection areas. Islands are ordered with the highest energy potential on the left. The LCOE of CHP has been calculated using the heat and electricity output.

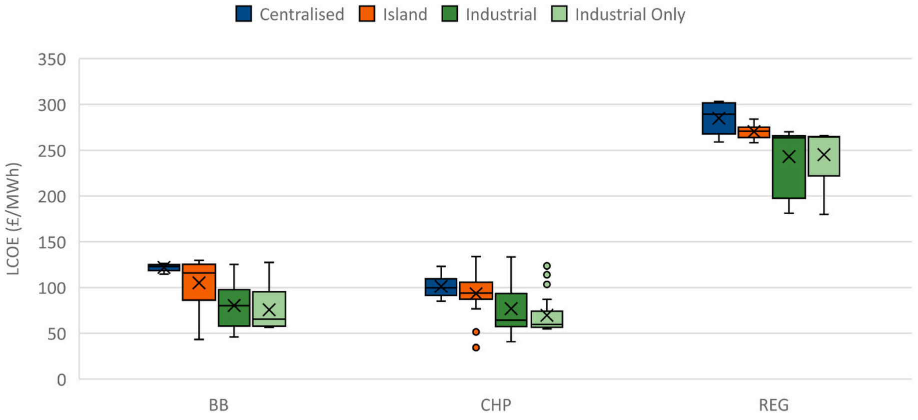

Fig. 9. LCOE of economically feasible facilities by facility and technology scenario, where Industrial Only shows the industrial scenario without any waste not produced on-site.

where heat networking is required. BB is most sensitive to heat network costs, which would make the larger Centralised and Island facilities unviable with higher heat network costs.

Household participation rates in food waste collection is a major driver of waste collection volumes (WRAP Household Food Waste Collection, 2021). This was varied independently to understand the impact of efforts to improve the collection rate. For the medium resource scenario and waste collection facilities for each fourteen collection areas, the variation of collection costs with participating households can be considered (Fig. 12). Fuel costs, being directly proportional to the distance travelled increase linearly with household participation rate. The linear approximation for ferry costs is less clear, with increase household proportions slightly reducing ferry costs in some cases (80–90% participation) where collection volumes are better optimised for journeys.Where C = collection costs (£/tonne); k = constant (£/tonne); P = participation rate (−); α = exponent (−).

The levelised costs of collection per (calculated using Equation (4) with tonnes of waste instead of energy E_t) follows a power law (Equation (5) and shown in Fig. 12) with an R-squared score >0.99. The constant k (372.15) and exponent α (−0.634) could be related to the unit costs and topography of the islands. Observation of this relationship was not identified in literature. If the exponents are related to road network connectedness (or other aspects), collection costs could be estimated based on this relationship rather than specific modelling. This would allow cost-benefit analyses to trade off the costs of greater collection with measures to increase participation rates. Further work comparing regions would be needed to determine the consistency of this power relationship between road networks and the collection costs.

4. Discussion

Techno-economic modelling of biogas facilities has highlighted the influence of waste availability; vehicle routing and collection costs; and generation technology. The potential of biogas in replacing fossil fuels,

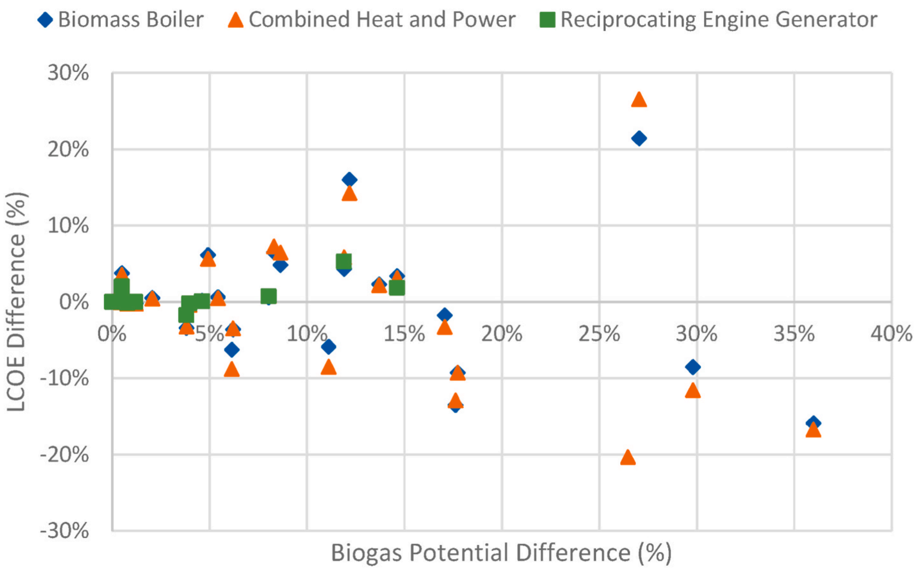

Fig. 10. Comparison of the change in biogas potential and LCOE between the Industrial and Industrial Only scenarios.

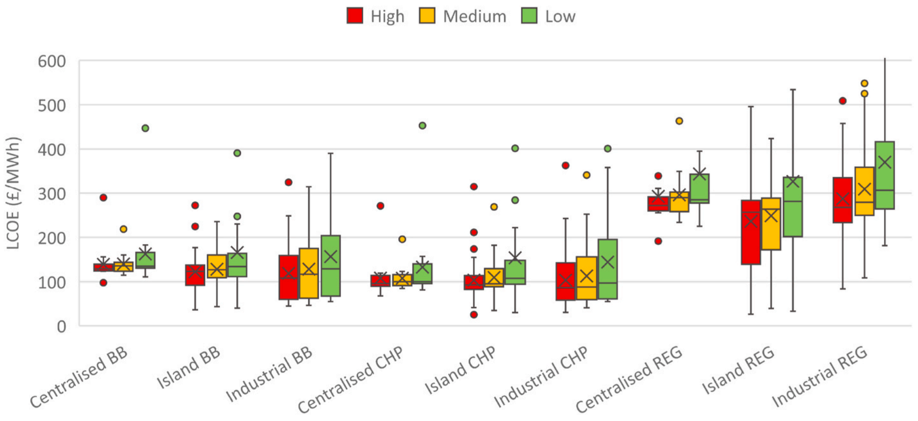

Fig. 11. Comparison of the LCOE of all facilities by resource scenarios.

Table 6
Proportion of the total resource utilised by viable facilities in each Resource scenario.

		High	Medium	Low
Centralised	BB	36%	11%	8%
	CHP	100%	100%	97%
	REG	95%	94%	93%
Island	BB	92%	91%	74%
	CHP	99%	99%	99%
	REG	96%	92%	86%
Industrial	BB	96%	94%	89%
	CHP	98%	97%	95%
	REG	70%	68%	59%

highlighted in the REPowerEU plan, is reinforced by the model, with a potential energy of 14–20.6% of the total electricity demand for the islands (BEIS, 2022). Although industry waste makes up two thirds of the total by weight, regional solutions differ depending on the waste type availability and location. The influence of greater resource in reducing costs through economies of scale highlights the importance of policies encouraging participation in biowaste collection. Household collection rates were varied, demonstrating a relationship which, adapted for local road networks, could be used to assess the cost-effectiveness of these policies. Business participation was assumed at 100%, but this likely over-estimates the actual rate-existing waste collection arrangements will constrain this. Maximising participation of individuals and business clearly reduces the cost of energy. Although variability of resource is considered on a scenarios basis, interannual variability of high or low years is not considered for the same facility, which could have a significant impact on its viability if there were years with insufficient waste to meet demand. Further research would be needed to identify the influence of this. Although intra-annual variability is not considered, biogas could be stored at a cost to better match supply with demand.

Detailed modelling of collection costs using the CVRP solver and OSM street networks demonstrates that travel distance can be approximated to within 3.3% by a straight-line approximation adjusted by a correction factor. Cost estimates for distance travelled are less sensitive to imprecise calculation, as the error averages out or could be adjusted over time. Estimation of the number of vehicle collection days and therefore number of vehicles required is more sensitive, with an absolute error of 42.8%. The error in the recursive DBSCAN-clustering CVRP method of 7% matched previous work (Bujel et al., 2018), demonstrating it provides a reasonable approximation with solving problems which would otherwise be computationally prohibitive. Depending on the cost estimation required, an adjusted straight-line calculation could therefore be appropriate or greatly mis-represent waste transport costs-facility could either have underutilised assets or not enough

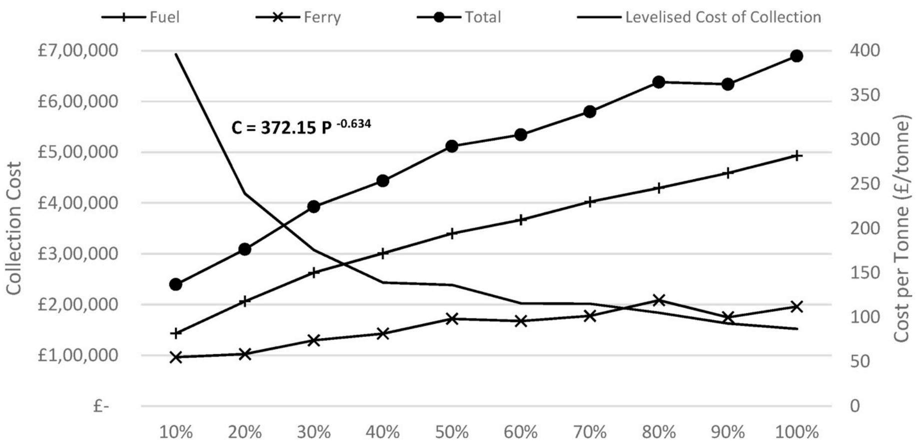

Fig. 12. Proportion of participating households and food waste collection costs, where the levelised cost of collection per tonne includes CAPEX and OPEX.

$$C = kP^{\alpha} \tag{Eq. 5}$$

collection capacity.

Through modelling of local topographies and road-networks, there is a clear impact on the viability of biogas facilities which would not be captured using a simple cost per tonne metric, with modelled costs varying from £0.1–1670/tonne. For larger, dispersed regions connected by ferries, vehicle costs per tonne are reduced to a limited extent with increased resource availability, but for the larger non-ferry connected islands, the reduction is much more pronounced. For the smallest, most remote areas, far fewer facilities are viable due to relatively higher collection costs. This demonstrates that under the modelled framework, isolated communities could miss out on opportunities to utilise biowaste to reduce emissions without additional incentives or financial support. Alternatively, smaller-scale, bespoke solutions not considered in this analysis could be more feasible depending on the local context.

17 out of 36 scenarios with the cheapest biogas potential are those with a high concentration of industrial waste (85–97% by energy potential; mainly from distilleries, which also have significant heat demands), which minimises or eliminates transport costs. The cost of energy for 39% of these industrial cases was reduced by excluding non-industrial waste, but in 36% of cases it was increased (the remaining 24% was unchanged). For more regions geographically dispersed regions with lower proportions of industrial waste (26–73% by energy potential), centralised facilities collecting domestic, commercial and industrial waste are more economically viable. This demonstrates that no "one-size-fits-all" approach can be taken with waste-to-energy modelling-the optimal solution is highly dependent on the local resource, transport costs and generation technology.

A simple biogas production model based on production factors for individual waste streams. Further work with this model could be improved with a more detailed AD model. Other research has demonstrated though that co-digestion can improve biogas yields (Karki et al., 2021; Bong et al., 2018; Zhang et al., 2022), which would only further reduce the cost of energy with multiple waste streams. Further research is needed into the dynamics of co-digestion to understand the synergies between specific waste sectors, reinforcing the conclusions of other work (Karki et al., 2021). The transport model using OSM road network data to capture local topographical impacts on costs demonstrates the potential importance of co-digestion- if with this worst case biogas production scenario (assuming no improved biogas yields), co-digestion can reduce the cost of energy for facilities, then with increased co-digestion yields the impact would be more significant. If further research can quantify the benefits of co-digestion in theory and in practice for specific waste types, it would be expedient to minimise any potential regulatory barriers and to encourage cooperation between waste producers. A governmental organisation could help facilitate this through sharing of best co-digestion practices and providing a forum for local businesses, farmers, local household waste collection and industry to collaborate and maximise the benefits of waste-to-energy. Whilst the sensitivity analysis demonstrated that CAPEX incentives can be crucial in supporting schemes (particularly for isolated regions as discussed), 51% of the resource could in theory be economically utilised without, indicating that economic factors alone are not the only factor limiting the uptake of waste-to-energy.

To focus on waste-to-energy and limit the number of scenarios under consideration, this analysis considered only AD and the three generation technologies (biogas boiler; combined heat and power; and reciprocating engine generator). Whilst this presents a comparative assessment of these technologies, it could also be considered in a wider resource nexus framework (Bleischwitz et al., 2017). Focusing solely on the energy-materials nexus excludes impacts on water, land use and food, for which there could be significant impacts not considered here (Spataru, 2019). Increasing the geographic coverage would improve the reliability of the conclusions but require significant additional data collection.

5. Conclusions

Biowaste-to-energy and AD can play an important role in reducing emissions and improving resource utilisation. To demonstrate the context specific impacts of collection costs on the viability of biowaste-to-energy facilities, a techno-economic model has been developed with sub-models for bioresource, transport costs using OSMnx road networks and facility techno-economic characteristics. The Scottish islands were modelled for their high biowaste density and geographic dispersion-for the area, 14–20.6% of local electricity demand could be met by biowaste from domestic, services and industrial sectors. Comparison of modelled transport costs with a straight-line model demonstrate that distance related costs can be approximated to within 3.3%, but vehicle costs have a much higher error of 42.8%. Industrial AD sites co-located generally have the lowest cost of energy (particularly when co-located with heat demand), collection of additional waste can increase or decrease the cost of energy depending on the local biowaste and road networks. Using a simple AD model, it was demonstrated that multiple waste streams can reduce the cost of energy. Improved biogas yields through co-digestion would only improve this and so stresses the importance of further research and policies to encourage cooperation between parties, minimise barriers to entry and maximise the benefits from biowaste. Modelling of waste availability and collection participation demonstrated a power law which could be used to model transport costs and allow policy makers to trade-off additional costs with increased energy availability. Higher transport costs for more isolated regions demonstrates that additional support, beyond the modelled incentives and avoided costs are needed if these areas are to benefit from increased waste utilisation. Inclusion of a more detailed transport model has demonstrated how understanding of factors influencing the viability of biowaste-to-energy can be improved with such models. The model could be improved with a more detailed AD model and further consideration of other nexus elements, such as land and water use.

Code repository

The bioresource database and code written in Python used in this paper are hosted on Mendeley Data (Matthew, 2023).

CRediT authorship contribution statement

Chris Matthew: Conceptualization, Methodology, Data curation, Formal analysis, Validation, Writing – original draft, and, Project administration. **Catalina Spataru:** Conceptualization, Methodology, Supervision, Writing – review & editing, and, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is available at the Menedeley Data repository referenced in the paper.

Acknowledgements

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Appendix A

Table A1
Summary of the total biomass production, waste fraction and energy potential for the Scottish islands. References are provided throughout the table.

Sector	Resource Type	Production (kT)	Waste Conversion Factor	Waste (kT)	Biogas Yield (GWh/kT)	Energy Potential (GWh)
Food waste	Domestic	–	–	11.5 (WRAP UK Progress against Courtauld, 2020; National Records of Scotland, 2011, 2016)	1.1 (Ricardo Energy, 2019)	12.7
	Non-domestic	–	–	5.4 (WRAP UK Progress against Courtauld, 2020; OpenStreetMap contributors Planet Dump Retrieved, 2021)	1.1 (Ricardo Energy, 2019)	5.9
Farm Fallen Stock	Cows	75.8 (EDINA National Agricultural Census Data, 2022)	0.004 (Alba et al., 2015)	0.3	1.66 (Williams et al., 2008)	0.5
	Sheep	45.2 (EDINA National Agricultural Census Data, 2022)	0.065 (Alba et al., 2015)	2.9	1.66 (Williams et al., 2008)	4.9
Fish Farm Mortalities	Atlantic Salmon (Demersal)	–	–	17.1 (Scotland's Aquaculture Fish Farms Monthly, 2022)	1.5 (Ricardo Energy, 2019)	25.7
Distilling	Draff	37.2 (Gray, 2020)	2.5 (White et al., 2016)	93.0	1.1 (Ricardo Energy, 2019)	102.3
Distilling	Spent Lees	37.2 (Gray, 2020)	1.4 (White et al., 2016)	52.1	0.003 (Ricardo Energy, 2019)	0.2
	Pot Ale	37.2 (Gray, 2020)	7.9 (White et al., 2016)	293.9	0.1 (Ricardo Energy, 2019)	29.4
Brewing	Grain (solid)	0.4 (OpenStreetMap contributors Planet Dump Retrieved, 2021; Brew Plants Estimate Your Brewery, 2022)	0.2 (Zero Waste Scotland Biorefining Potential, 2017)	0.0800	1.51	0.1208
	Hops	0.4 (OpenStreetMap contributors Planet Dump Retrieved, 2021; Brew Plants Estimate Your Brewery, 2022)	0.002 (Zero Waste Scotland Biorefining Potential, 2017)	0.0008	0.84	0.0007
	Yeast	0.4 (OpenStreetMap contributors Planet Dump Retrieved, 2021; Brew Plants Estimate Your Brewery, 2022)	0.015 (Zero Waste Scotland Biorefining Potential, 2017)	0.0060	0.01	0.0001
Seafood Processing	Pelagic	39.4 (Scotland's Aquaculture Fish Farms Monthly, 2022; Marine Management Organisation United Kingdom, 2016)	9.9 (Chowdhury et al., 2009)	390.5	0.0241	9.5
	Demersal	6.4 (Scotland's Aquaculture Fish Farms Monthly, 2022; Marine	9.9 (Chowdhury et al., 2009)	64.2	0.0241	1.6

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Table A1 (*continued*)

Sector	Resource Type	Production (kT)	Waste Conversion Factor	Waste (kT)	Biogas Yield (GWh/kT)	Energy Potential (GWh)
		Management Organisation United Kingdom, 2016)				
	Shellfish	0.6 (Scotland's Aquaculture Fish Farms Monthly, 2022; Marine Management Organisation United Kingdom, 2016)	9.9 (Chowdhury et al., 2009)	6.0	0.0241	0.1
Meat Processing	Cows	13.2 (EDINA National Agricultural Census Data, 2022; DEFRA Latest Cattle, 2022)	0.067 (WRAP UK Progress against Courtauld, 2020; DEFRA Latest Cattle, 2022)	0.9	0.0315	0.0279
Dairy Processing	Dairy	44.3 (EDINA National Agricultural Census Data, 2022; DEFRA Latest Cattle, 2022)	0.029 (WRAP UK Progress against Courtauld, 2020; EDINA National Agricultural Census Data, 2022)	1.3	0.0345	0.0455
					TOTAL	**192.9**

Appendix B

Table B1
Description of non-domestic food waste floor space factors. References are provided throughout the table.

	National			Scottish Islands	
	Annual waste	Floor area	Waste factor	Floor area	Annual waste
	(tonnes/year)	(m^2)	(tonnes/m^2/year)	(m^2)	(tonnes/year)
	WRAP UK Progress against Courtauld (2020)	BEIS, 2015	–	OpenStreetMap contributors Planet Dump Retrieved (2021)	–
Restaurant/café	4.59	128	0.0358	214	7.66
Supermarket	13.70 (Tesco Tesco Annual Report and Financial Statements, 2017)	1053	0.0130	1076	13.99
Pub	5.09	350	0.0145	205	2.97
Hotel	6.38	387	0.0175	454	7.95

Table B2
Calculation of the energy content of fish processing and brewery waste. Brewery references (identical for grain, hops and yeast) are shown for grain only. References are provided throughout the table.

	Name	Values				Units	Calculation
	Industry	Fish processing (Chowdhury et al., 2009)	Brewery				
	Resource	Wastewater	Grain	Hops	Yeast		
A	Wastewater per unit production	9.9	0.2 (Shaiith Sector Study on Beer, 2015)	0.00176	0.015	litres/kg	–
B	Chemical oxygen demand (COD) per unit wastewater	0.005	0.33 (Gunes et al., 2019)	0.37	0.032	kg COD/L	–
C	Methane per unit COD	0.35	0.5 (Gunes et al., 2019)	0.25	0.04	kg CH4/kg COD	–
D	Methane production per unit waste	0.00175	0.1084	0.0608	0.0008	kg CH4/L	B x C
E	Energy content of methane (Gunes et al., 2019)	0.0139	0.0139	0.0139	0.0139	MWh/kg CH_4	
F	Energy potential per unit production	0.0241	1.51	0.84	0.01	MWh/tonne	A x D x E x 1000

Table B3
Calculation of the energy content of meat and dairy processing wastewater. References are provided throughout the table.

Name	Values		Units	Calculation
Industry	Meat processing (Hamawand, 2015)	Dairy processing (Shi et al., 2021)		

(continued on next page)

Table B3 (*continued*)

	Name	Values		Units	Calculation
	Industry	Meat processing (Hamawand, 2015)	Dairy processing (Shi et al., 2021)		
	Resource	Wastewater	Wastewater		
	Resource	Wastewater	Wastewater		
A	Wastewater per unit production	0.067	0.029	litres/kg	–
B	Volatile solids (VS) per unit wastewater	0.07	0.01103	kg VS/L	–
C	Methane per unit VS	0.049	–	m^3 CH4/kg VS	–
D	Methane density	0.657	–	kg/m^3	–
E	Methane per unit VS	–	0.22535	kg CH4/kg VS	–
F	Methane per unit wastewater	0.0023	0.002486	kg CH_4/L	B x C x D (meat); B x E (dairy)
G	Energy content of methane (Gunes et al., 2019)	0.0139	0.0139	MWh/kg CH_4	–
H	Energy potential per unit production	0.0315	0.0345	MWh/tonne	F x G x 1000

Table B4
Calculation of the waste proportion for dairy and meat processing. References are provided throughout the table.

Ref	Name	Year	Value		Units	Calculation
			Dairy	Meat		
A	UK waste water (WRAP UK Progress against Courtauld, 2020)	2015	423	370	kT	–
		2018	429	422		
B	UK production (DEFRA, 2022)	2015	14,882	5739	kT	–
		2018	14,874	6121		
C	Mean proportion of waste	–	0.029	0.067	kg/kg production	A x B

Table B5
Calculation of the production for breweries from floor space factors. References are provided throughout the table.

Ref	Name	Value	Units	Calculation
A	Production factor per cycle	10 (Brew Plants Estimate Your Brewery, 2022)	HL/m^2	–
B	Number of cycles per year	20 (Brew Plants Estimate Your Brewery, 2022)	–	–
C	Production per year	200	HL/year/m^2	A x B

Appendix C

Table C1
Types of OSM road types from OSMnx and assumed travel speeds.

OSM road type	Count	Suitable for vehicles	Speed (km/h)
Primary	11757	TRUE	80
Track	23460	TRUE	20
Residential	13823	TRUE	30
Service	52825	TRUE	50
unclassified	21479	TRUE	50
Tertiary	7866	TRUE	50
Footway	10120	FALSE	–
Path	8067	TRUE	30
Steps	498	FALSE	–
Secondary	7426	TRUE	51
Pedestrian	124	TRUE	5
primary_link	21	TRUE	60
living_street	2	TRUE	10
secondary_link	2	TRUE	40
Corridor	2	FALSE	–
Trunk	572	TRUE	40
trunk_link	1	TRUE	40
cycleway	114	FALSE	–
bridleway	14	FALSE	–
Road	2	TRUE	80

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