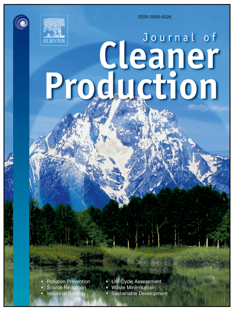

Carbon footprint assessment of water and wastewater treatment works in Scottish islands

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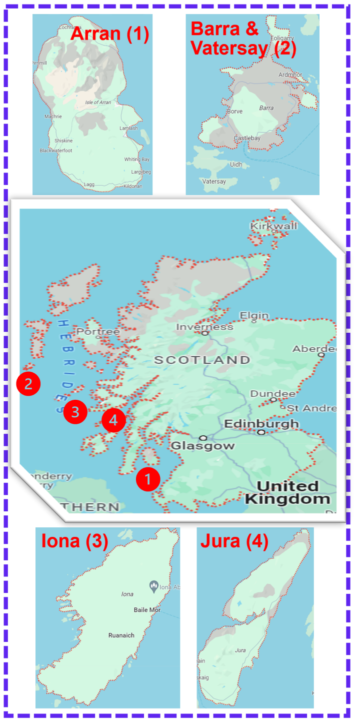
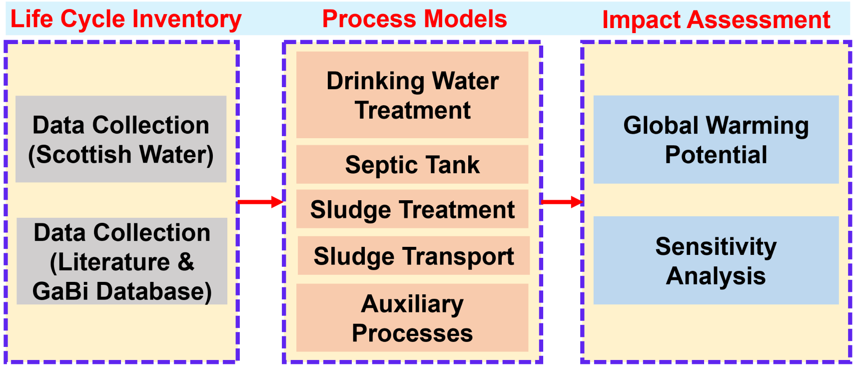




Life Cycle Inventory

Data Collection (Scottish Water)

Data Collection (Literature & GaBi Database)

Process Models

Drinking Water Treatment

Septic Tank

Sludge Treatment

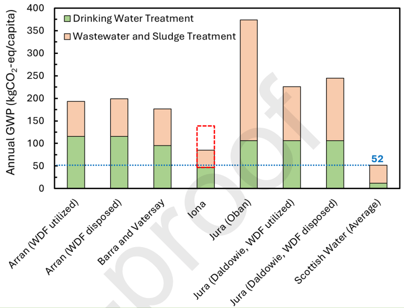
Sludge Transport

Auxiliary Processes

Impact Assessment

Global Warming Potential

Sensitivity Analysis



Scottish Water Commitment: '*Net-zero by 2040*'

Carbon Footprint Assessment of Water and Wastewater Treatment Works in Scottish Islands

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Abstract

Quantifying the global warming potential of existing water infrastructure is an important step in realising the water industry's commitment to net-zero carbon. Whilst there has been an improved understanding of the global warming potential of centralized urban water infrastructure, rigorous analyses of smaller-scale rural systems are rare. This work adopts a life cycle assessment to ascertain the global warming potential of existing drinking water treatment works and wastewater treatment works associated with five Scottish islands: Arran, Iona, Jura, Barra, and Vatersay. The water systems, from source to sink, along with the use of chemicals, transportation, energy, and the disposal of waste products from water infrastructure are considered. The global warming potentials of the island’s drinking water treatment works ranged from 0.18 to 0.79 $kgCO_2$-eq/m^3 of drinking water, while that for wastewater treatment works were 0.51 to 1.14 $kgCO_2$-eq/m^3 of wastewater. The global warming potential for water services on the islands can be as much as 7 times of that water services across Scotland as previously reported. Major global warming potential contributor in drinking water treatment works was the electricity consumed by the membrane bioreactor. The modelled direct emission of methane from sludge in septic tanks and landfill made the largest contribution to global warming potential. It was also highly sensitive to model parameters, which highlights the need for a comprehensive exploration of process emissions from septic tanks and sludge handling. This analysis of existing rural water infrastructure is a baseline against which potential alternative low-carbon technology configurations can be compared.

Keywords: Water; Community; Islands; Global Warming Potential; Net Zero; Life Cycle Assessment

1 Introduction

Water and energy are inextricably connected and managing the water-energy nexus has become an essential component of achieving carbon neutrality. The water sector's share of global electricity consumption is ~4% and the proportion of the world's population that still lack access to safe water and sanitation are 26% and 45% respectively [1]. Thus, unless we can reduce the energy expenditure in delivering high quality water services the absolute energy budget is set to grow. To achieve this, the water industry has recognised the need to reduce the energy demand and global warming potential (GWP) of existing and new infrastructures.

In countries with longstanding water infrastructure planning the route to net-zero may involve nuanced, location-specific trade-offs in appropriate process selection, control, and regulation. In Scotland, the publicly-governed water utility, Scottish Water (SW) treats 1.46 billion litre of drinking water and 996 million litres of wastewater per year [2], using approximately 442 GWh of electricity – enough to power nearly 144,000 homes [3]. The overall operational GWP of SW's facilities was 272,000 tCO_2-eq during 2018-2019, in which drinking water, wastewater, and sludge treatment works (STW) accounted for 23%, 41%, and 30%, respectively [2]. The consumer GWP per megalitre of water reported by SW during 2018-2019 was 0.11 tCO_2-eq for drinking water treatment works (DWTWs) and 0.23 tCO_2-eq for wastewater treatment works (WWTWs) [2]. The emission from an SW-operated system depends on the technological and energy selection, level of treatment, and geographical location. The type of DWTW varies with population density, where rural populations are served by small-scale membrane units and urban populations receive drinking water from five-stage treatment plants. For wastewater, the sophistication of treatment is also inversely proportional to population density: e.g., from septic tanks (STs) in remote areas, primary treatment followed by discharge and dilution, biofiltration in small municipal works, activated sludge with tertiary treatment, or advanced technologies like Nereda in cities. All of these, from off-grid to the highly centralised require sludge handling and treatment infrastructures.

In rural communities, the trade-offs between energy consumption, water footprint, cost, and effluent quality have been difficult to assess, because the systems are site-specific. Thus, comparisons are challenging and the received wisdom on the relative merits and costs of different technologies are driven by inconsistent metrics. Not only this, but the aspirations of local communities for their water services, demographic changes, regulatory changes, seasonal fluctuation in water resources, and climate change, all serve to make strategic planning of rural water services a complex, and sometimes contentious issue. A rural settlement is defined as comprising 3,000 or less people, which make up 17% of the population in Scotland [4]. This suggests that the overall environmental impacts of water facilities in rural communities can be non-trivial and associated knowledge is very limited, especially from a per-capita perspective.

SW have committed to being ‘net-zero by 2040’ and have ambitions to go beyond net-zero. Existing initiatives include the use of solar photovoltaic, biomass, hydropower, solar thermal, wind energy, anaerobic digestion, combined heat power (CHP), and wastewater heat harvesting [5]. SW’s targets are integral to the Scottish government's goal to make Scotland ‘net-zero by 2045’ [6]. The particular challenges facing rural and remote communities were recognised in an initiative to ensure that a group of six Scottish islands will become carbon neutral by 2040 [7]. If net-zero aspirations are to be met, whilst responding to customer demands, then it is imperative that an objective inventory of the environmental and energy cost of existing water infrastructure is constructed using methods that will allow for comparisons to be drawn with potential future alternative schemes [8]. Here we use life cycle assessment (LCA) to ascertain the environmental footprint of existing DWTWs and WWTWs associated with five Scottish islands: Arran, Iona, Jura, and Barra and Vatersay. The two-fold aim of this study include comparing the GWP per capita of water treatment works in rural Scottish communities to the reported SW average and identifying pathways to decarbonize the water industry in Scotland.

These islands water treatment systems comprise a wide variety of mass (chemical, sludge, and toxic materials) and energy (electricity, heat, and diesel) flows and LCA lends a high-level understanding of the interconnected systems. Our LCA is tailored for water technologies and uses GWP, which have been used in previous studies [9].

2 Methodology

2.1 Goal and scope

The framework provided by international standard ISO14040 to conduct LCA is adopted in this work and implemented in the GaBi software. The goal of the LCA is to evaluate the environmental footprints of existing DWTWs and WWTWs associated with the five Scottish islands. The functional units (FUs) are selected separately for the LCA of DWTWs and WWTWs since they have different functional attributes and flowrates. These flowrates further vary across different islands. The FU for WWTW is 1 m^3 of wastewater treated, while that for DWTW is 1 m^3 of drinking water supplied. The scope of the LCA is covers the indirect emissions associated to material and energy inputs as well as direct emissions from various processes such as STs and sludge landfills (i.e., cradle-to-gate). For some sludge management systems, re-utilization of resources derived from septic sludge is considered, which offers abatement of GWP. On these islands there exists a mix of SW-managed and privately managed water treatment assets. Due to a lack of data for several privately managed facilities, they are excluded from the baseline LCA. Where per capita metrics are calculated the proportion of the population on private water supplies and with private STs have not been included for Arran, Barra, and Vatersay. For Jura, the septage emptying for both private and SW-managed STs was considered for accounting for the transportation-related emissions. Iona does not have SW-managed STs, but to account for the direct emissions of private STs for more consistent comparison, the average value of direct emissions for the other islands was estimated and used.

2.2 Process descriptions and models

The process flow for DWTWs and WWTWs associated with various islands are obtained via internal communication with SW. Where unavailable, appropriate datasets and models are used to conduct the LCA.

2.2.1 Process description for Isle of Arran

The Isle of Arran is one of the largest islands located on the Firth of Clyde, being home to approximately 4600 people, where the DWTWs are managed by SW. The wastewater generated is treated via STs and ~86% of them are managed by SW, while 14% are privately owned. Due to the absence of STWs on this island, wet septic sludge is transported to the Scottish mainland via trucks and ferries for further treatment and disposal. The process flow schematic including DWTW, ST, and associated STW on the mainland is shown in Figure 1.

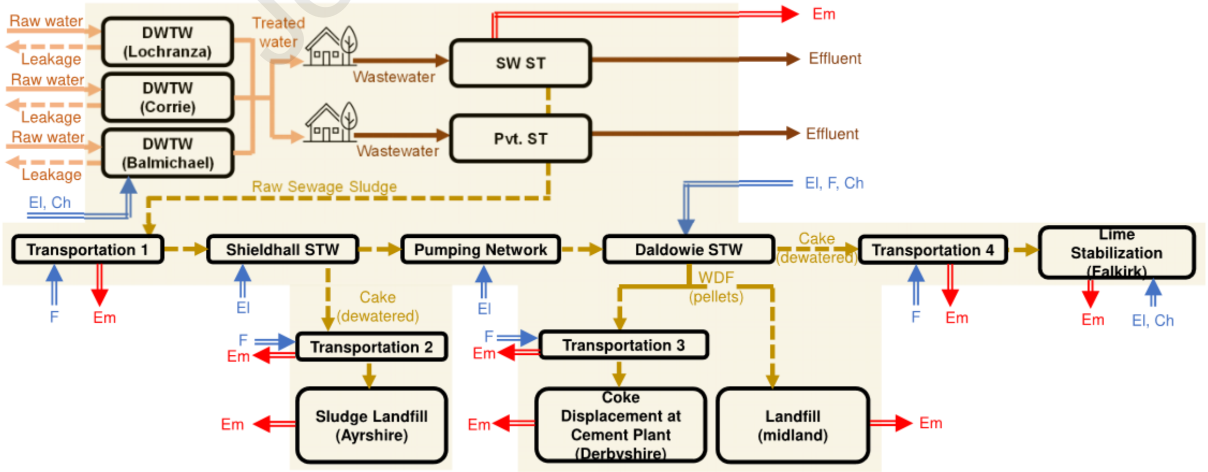

Figure 1. Process flow for DWTW and WWTW associated with Arran. The yellow shaded region denotes the system boundary for LCA. Legends – El: Electricity, Ch: Chemical, F: Fuel, and Em: Emissions.

2.2.1.1 Drinking water treatment

The drinking water in Arran is served by three DWTWs managed by SW: Balmichael, Lochranza, and Corrie. The plants utilize membrane technology for water treatment and are supplied with water from nearby boreholes or surface water. Coagulation chemicals are dosed and the resultant wastewater from DWTWs is discharged to nearby watercourses. As a result, the DWTWs do not require sludge to be transported away from the island.

The Balmichael DWTW has the largest capacity among all the DWTWs in Arran and intakes raw water from the borehole into ultrafiltration (UF) membrane units via an in-line strainer. In total there are 3 duty UF units, each with 6 duty membrane housings. Permeate water from the membranes subsequently flows to permeate/backwash tanks where water is abstracted to supply cyclic backwashes. Every 40 backwashes, a chemically enhanced backwash is initialized where sodium hypochlorite 15%, sodium hydroxide 25%, and sulphuric acid 30% are dosed to enhance the removal of absorbed materials. Waste from this process flows into a neutralization tank where pH is adjusted with sodium hydroxide 25% and sulphuric acid 30%, and residual chlorine is neutralized by sodium bisulphite 23% before being discharged into a nearby watercourse. Subsequently, permeate water moves to a static mixer where sodium hypochlorite is dosed for disinfection before entering a clear water tank. The plant has a flowrate of 3300 m^3/day.

The Lochranza DWTW uses tubular membranes for treating raw water fed via gravity. The raw water entering the plant is combined with a recycle flow and filtered through cellulose acetate UF membranes. There are two membrane module stacks, each consisting of 30 membranes providing a total area of 624 m^2. The treatment works use chemicals such as sodium hypochlorite 15%, sodium bisulphite 23%, and citric acid anhydrous. The plant has a flowrate of 261.1 m^3/day.

Similarly, the Corrie DWTW uses tubular cellulose acetate UF membrane and intakes raw water via gravity. There are two membrane module stacks, each consisting of 20 membranes giving a total membrane area of 416 m^2. The treatment facility uses chemicals such as sodium hypochlorite 15%, sodium bisulphite 23%, and citric acid anhydrous. The plant has a flowrate of 77.5 m^3/day.

2.2.1.2 Wastewater and sludge treatment

The wastewater generated in Arran's households is managed via STs which provide primary-level biological treatment. There are 17 STs that are managed by SW, 16 of which are currently operational. These collect the wastewater from 3954 people, which constitutes 86% of the total population. The remaining population is served by privately managed STs. The data for the SW-managed STs, which includes tank volume, population equivalent (PE), biological oxygen demand (BOD), suspended solids (SS), and wastewater flowrate are provided in the supplementary material (Table S1). The average annual sludge generation from privately managed STs is 645.5 m^3, which are disposed of by SW. However, operational data for BOD, SS, and wastewater flow are unavailable for the private STs. Therefore, direct emissions associated with them are excluded from the LCA.

The frequency of emptying STs is once a year where it is assumed that the entire volume of the tank is emptied. Hence, the total annual sludge yield for SW-managed STs is 916.25 m^3, whilst that for the privately managed STs is 645.5 m^3. The volume of the septic sludge is converted to mass by using the average density of sludge $\rho_{sludge} = 1025$ kg/m^3 from [10]. The wet sludge generated contains 2.06% dry solids (DS_{wet}) and is transported (33 miles by trucks and 13.1 miles via ferries) to the Shieldhall STW located in Glasgow for further treatment. At Shieldhall STW, a fraction of the sludge imported from Arran (15.7%) is dewatered forming sludge cakes with 26.73% dry solids (DS_{cake}), whilst the rest (84.3%) is pumped forward to Daldowie STW located in Glasgow. The sludge pumping process from the Shieldhall STW to Daldowie STW consumes electricity. In addition, the Shieldhall STW uses only electricity and does not require chemicals to carry out the centrifugation for producing sludge cakes. The sludge cakes produced at the Shieldhall STW are transported to Ayrshire (45.5 miles via truck) for landfill purposes.

At Daldowie the wet sludge is converted to dewatered sludge cakes (26.73% *DS*) and waste-derived fuel (WDF) pellets (91% *DS*). The plant requires chemicals (flocculant), electricity, and thermal energy (from natural gas) for the sludge dewatering/drying processes. The sludge cakes are transported to a plant located in Falkirk (21.4 miles via trucks) for further treatment via lime stabilisation. The lime stabilisation process requires chemicals and electricity (see Section 2.2.9). The WDF pellets are value-added products with high calorific value which can be sent to a cement plant located in Hope Valley, Derbyshire (239 miles via trucks). At the cement plant, the WDF pellets displace a fraction of coke usage and mitigate GHG emissions. When the WDF pellets are not used in the cement facility, they are disposed of at landfill sites near the Daldowie STW (see Section 2.2.10). Based on the different allocations of the pellets, two cases were considered for Arran. The first case considers that the WDF pellets displace cokes in the cement plant, while the second case assumes that the pellets are landfilled.

2.2.2 Process description for Isles of Barra and Vatersay

Barra and Vatersay are the two southernmost inhabited islands in the Outer Hebrides of Scotland and are home to 1264 people (587 households). The process flow schematic including DWTW, ST, and associated STW is shown in Figure 2.

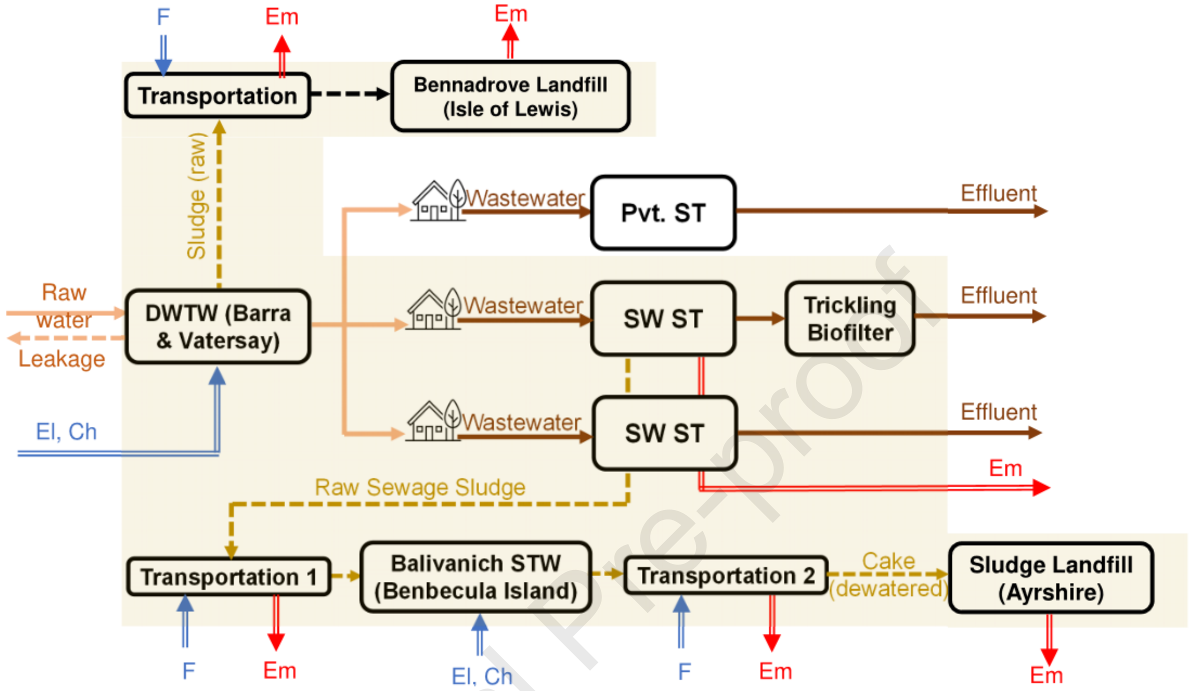

Figure 2. Process flow for DWTW and WWTW associated with Barra and Vatersay. The yellow shaded region denotes the system boundary for LCA. Legends – El: Electricity, Ch: Chemical, F: Fuel, and Em: Emissions.

2.2.2.1 Drinking water treatment

The drinking water in Barra and Vatersay is supplied by a centrally managed DWTW on the island, with a design flowrate of 430 m^3/day. The source water is taken from a reservoir and the plant utilizes sand filtration (SF) and chemical treatment mechanisms to remove impurities, adjust pH, and perform disinfection. Various chemicals are utilized including sodium carbonate (pH adjustment), ammonium sulphate (disinfection), sodium hypochlorite (disinfection), Magnafloc LT25 polyacrylamide (flocculant), and polyaluminum chloride hydroxide 18% (coagulant). The sludge generated from the chemical treatment process is transported once a year to a landfill site (Bennadrove landfill) located in the Isle of Lewis. The distance between the DWTW and landfill site is 137 miles: 120.2 miles by land and 16.8 miles by sea. The process consumes electricity and chemicals for treating raw water.

2.2.2.2 Wastewater and sludge treatment

The WWTWs of Barra and Vatersay predominately rely on STs to provide primary biological treatment to the wastewater. There are 17 sites with STs managed by SW, which treat wastewater for 669 people (53% population). Out of these 17 sites, 2 sites have a trickling biofilter following the ST, that provides secondary treatment to the wastewater. The supplementary material (Table S2) provides the parameters for the SW-managed ST such as tank volume, PE, BOD, SS, and wastewater flow. A large portion (47%) of the population utilizes privately managed STs. Details for these privately managed STs are unavailable and therefore excluded (see Figure 2).

The frequency for emptying ST sludge is once a year, and it is assumed that the entire volume of the tank is emptied. Hence, the total annual yield of sewage sludge is $V_{sludge} = 399$ m^3. The wet sludge containing 2.06% dry solids (DS_{wet}) from Barra and Vatersay is transported to the Balivanich sludge treatment works located in the Isle of Benbecula, where it is dewatered to form sludge cakes (26.73% dry solids (DS_{cake})). The STW uses electricity and a flocculant named Zetag 9019 (polyacrylamide) for the sludge dewatering process. The dewatering process is essential for mass reduction of sludge for ease of transportation and has typical losses up to 5%. The sludge cakes from Balivanich are then transported to Ayrshire for landfill purposes. The distance between Barra and Balivanich is 46.4 miles (40.4 miles by trucks and 6 miles by ferry), whilst that between Balivanich and Ayrshire is 317.7 miles (287 miles by trucks and 31 miles by ferry). Since the mass of the sludge cakes generated from Barra and Vatersay sludge was unknown, it was estimated using the following equation that accounts for 5% mass loss (Loss%).

$$M_{cake}=\rho_{sludge}\times V_{sludge}\times\frac{DS_{wet}}{DS_{cake}}\times(100\text{-Loss\%}) \quad (1)$$

2.2.3 Process description for Isle of Iona

The Isle of Iona is one of the sparsely populated islands located within the Inner Hebrides of Scotland. It is home to approximately 170 people, and the drinking water is supplied from a DWTW located on the nearby Isle of Mull. The wastewater generated on Iona is treated via STs, which are privately managed. Septic sludge from the island is transported to the Scottish mainland via trucks and ferries for further treatment and disposal. The process flow schematic including DWTW, ST, and associated STW is shown in Figure 3.

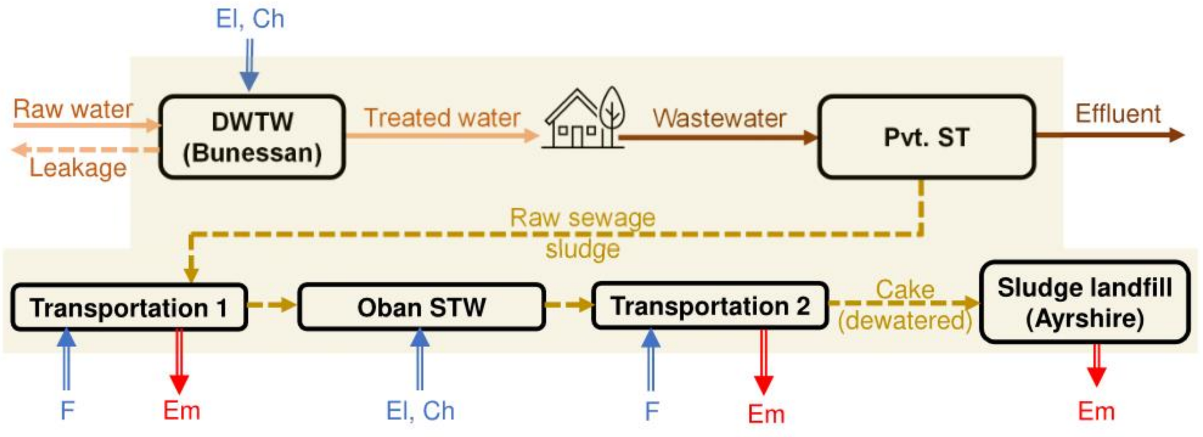

Figure 3. Process flow for DWTW and WWTW associated with Iona. The yellow shaded region denotes the system boundary for LCA. Legends – El: Electricity, Ch: Chemical, F: Fuel, and Em: Emissions.

2.2.3.1 Drinking water treatment

Due to the absence of an indigenous DWTW on Iona, drinking water is supplied by Bunessan DWTW located on the Isle of Mull. The plant supplies approximately 120 m^3/day to the Iona households. It uses pressure-based filtration and cellulose acetate membrane technology for water purification. The raw water is supplied from Loch Assapol, while the wastewater is discharged to nearby watercourses. The DWTW does not generate sludge. The chemicals used in the DWTW include sulphuric acid 96%, sodium carbonate, and sodium hypochlorite.

2.2.3.2 Wastewater and sludge treatment

The WWTWs of Iona rely on STs for primary level biological treatment to the wastewater. All the STs are privately managed, and it was not possible to retrieve the information about the PE, BOD, SS, and wastewater flow of the STs. Sludge from these private STs is disposed of by SW once a year, which enabled accounting for emissions associated with sludge transportation, treatment, and disposal. The average annual sludge generation from privately managed ST is 51.5 m^3. The wet sludge containing 2.06% dry solids (DS_{wet}) is transported (11 miles by ferry and 36.8 miles by truck) to the Oban STW where it is dewatered to form sludge cakes (26.73% dry solids (DS_{cake})). The STW uses chemicals (flocculant) and electricity for the sludge dewatering process. The sludge cakes are then transported to Ayshire (132 miles by trucks) for landfill purposes.

2.2.4 Process description for Isle of Jura

The Isle of Jura is another sparsely populated island, located in the Inner Hebrides of Scotland. It is home to approximately 200 people and the DWTW managed by SW is the main supply for drinking water. The wastewater on this island is treated via STs where approximately 25%

of them are managed by SW, while 75% are privately owned. Due to the absence of STWs on this island, wet septic sludge is transported to the mainland via trucks and ferries for further treatment and disposal. The process flow schematic including DWTW, ST, and associated STW is shown in Figure 4.

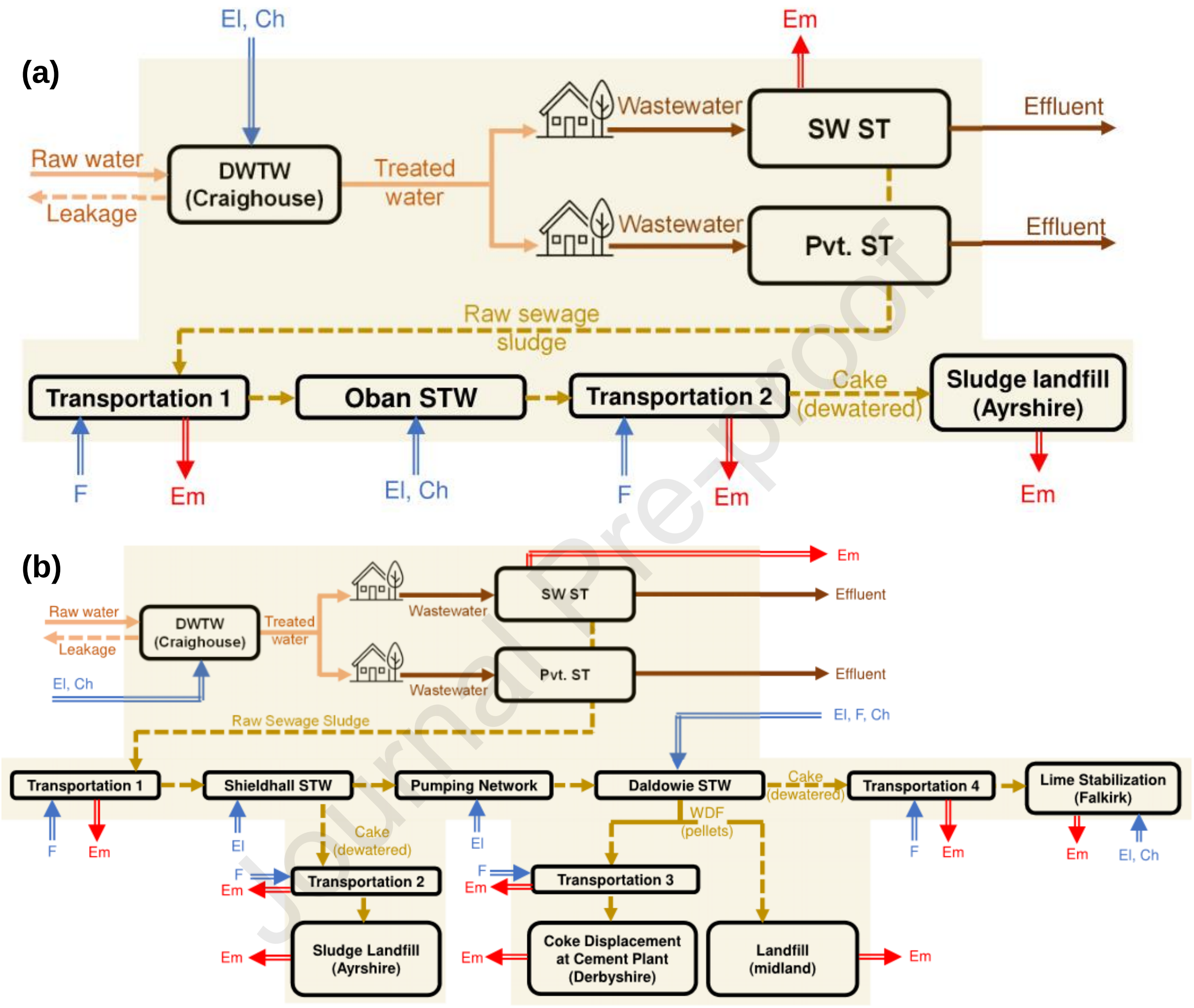

Figure 4. Process flows for DWTW and WWTW associated with Jura for two systems when the sludge is treated at (a) Oban STW and (b) Shieldhall STW. The yellow shaded region denotes the system boundary for LCA. Legends – El: Electricity, Ch: Chemical, F: Fuel, and Em: Emissions.

2.2.4.1 Drinking water treatment

The drinking water in Jura is supplied by the Craighouse DWTW on the island. The plant utilizes cellulose acetate membrane technology for water purification. The membrane modules undergo periodic cleaning to remove foulant material and restore pressure equilibrium. The effluent from this process is directed to a chemical spill tank, which avoids sludge transportation from the DWTW. The plant has a design flowrate of 114 m^3/day and uses chemical such as chlorine and citric acid.

2.2.4.2 Wastewater and sludge treatment

The wastewater treatment in Jura relies on STs providing primary-level biological treatment. There are 3 ST sites that are managed by SW, treating wastewater for 50 people (25% of the population). The parameters for the SW-managed STs including tank volume, PE, BOD, SS, and wastewater flowrate are shown in supplementary material (Table S3). The average annual sludge generation from privately managed STs is 47 m^3, which is annually disposed of by SW. Operational data for BOD, SS, and wastewater flow are unavailable for the private STs. Therefore, direct emissions associated with them are excluded from the LCA. However, we did ultimately augment the LCA with a crude estimate of the GWP from direct emissions based on the calculations from the other islands to facilitate the comparison among the islands.

The frequency of emptying STs is once a year and it is assumed that the entire volume of the tank is emptied. The total annual sludge yield for SW-managed STs is 25 m^3, whilst that for the privately managed STs is 47 m^3. The volume of the septic sludge is converted to mass by using the average density of sludge $\rho_{sludge} = 1025$ kg/m^3 from [10]. Depending on the availability of sludge tankers there are two options for STW: the wet septic sludge is sent to (a) Oban STW (Figure 4a) and (b) Shieldhall STW (Figure 4b). Therefore, the LCA conducted herein considers both sludge disposal pathways. The transportation distances between Jura and the Shieldhall STW is 137.8 miles (104 miles by truck and 33.8 miles by ferry), whilst that for Jura and the Oban STW is 98.2 miles (67.9 miles by truck and 30.3 miles by ferry).

The sludge treatment and residue disposal at Shieldhall and Oban are discussed in Sections 2.2.1.2 and 2.2.3.2, respectively. Consequently, the LCA for Jura considers three sludge management systems. The first case considers that sludge from Jura is treated at the Oban STW and the cakes are disposed of at the Ayrshire landfill. The second case considers that the sludge is treated at the Sheildhall STW, followed by Daldowie STW, and the WDF pellets produced at Daldowie displaces cokes in the cement plant. The third case considers that WDF produced at the Daldowie STW is disposed of by landfill.

2.2.5 Indirect emissions from electricity, chemical, heat, and diesel usages

The usage of various assets such as electricity, chemical, thermal energy, and fuel contributes GHG during their production. Various inbuilt processes in GaBi software are used to model the environmental footprint associated with the production of these assets. Emissions associated with several chemicals are not available in GaBi, which is resourced from the literature. The details for these processes are provided in the supplementary material (Table

S4). It is worth noting that EU-28 based (or other European country-based) GaBi processes were utilized when UK-specific GaBi processes were unavailable.

2.2.6 Direct emissions from sludge transportation processes

Transportation modelling is required to quantify GHG emissions that occur during sludge transport processes via land and ferry routes. The amount of direct GHG emissions is estimated based on the mode of transportation (truck or ferry), the total sludge loading, and transportation distance. The LCA simulation with GaBi adopted “US: Truck – Dump Truck/52000 lb payload” as the truck process and “GLO: Bulk commodity carrier, 1500 to 20000 dwt payload capacity, coastal” for all the ferry transportation. Based on the sludge loading and transportation distance, the inbuilt GaBi models calculate the diesel consumption and its associated environmental footprint.

2.2.7 Direct emissions from septic tanks

STs are biological reactors and produce GHGs such as CH_4, CO_2, and N_2O, which increases the emissions of the overall system. The emission models based on a report by RTI International and US Environmental protection agency (US EPA) are utilized [11] and their details are provided in the supplementary material (Table S5).

2.2.8 Direct emissions from landfill sludge disposal

Landfill sludge disposal models are required to quantify the GHG (CH_4 and CO_2) emissions that occur during the disposal of wet sludge (2.06% *DS*), dewatered sludge cakes (26.73% *DS*), and WDF pellets (91% *DS*). This work utilized the first-order sludge decay model for CH_4 and CO_2 generation, developed by US EPA [11] to estimate the emissions from landfill sludge disposal (see supplementary material, Table S6).

2.2.9 Direct and indirect emissions from lime stabilization of sludge

Lime stabilization is a promising means of reducing GHG emissions from wet and dry sewage sludge. The dewatered sludge cakes (with 26.73% *DS*) produced at the Daldowie STW is sent to a lime stabilization plant located in Falkirk for further treatment. The lime stabilization process requires electricity and chemical (lime), causing direct GHG emissions. As indicated in [12], the total electricity consumption is 4.41 kWh/t sludge cake, and the consumption for lime is 10% of the mass of sludge cake to be treated. These two processes are implemented via “GB: Electricity grid mix” and “EU-28: Lime (CaO; quicklime lumpy)” processes in GaBi.

To quantify the direct emissions from lime stabilization of sludge cake, it is important to understand the chemical reactions involved. The hydration reactions shown below indicate that the process does not involve CH_4 and N_2O emissions.

$$\mathrm{CaO} + \mathrm{H_2O} = \mathrm{Ca(OH)_2} + \text{heat} \uparrow$$

$$\mathrm{Ca(OH)_2} + \mathrm{CO_2} = \mathrm{CaCO_3} + \mathrm{H_2O} + \text{heat} \uparrow$$

Due to absorbing CO_2 from the environment as shown in the second step of the reaction, a negative GHG is expected. Based on [12] the emission component is -0.0786 kgCO$_2$-eq/kg sludge cake treated, which is implemented in GaBi via a custom-built process.

2.2.10 Direct emissions displaced by waste-derived fuel utilization

The WDF pellets generated at the Daldowie STW are utilized in cement production to reduce the usage of coke. The net calorific value of coke (NCV_{coke}) in the UK is 30 MJ/kg (published by BEIS [13]), while that for WDF (NCV_{WDF}) produced at Daldowie is 15.5 MJ/kg (published by Scottish Power [14]). The GWP abatement via WDF utilization at cement plant is therefore [15],

$$GWP_{WDF} = r \times M_{WDF} \times \frac{NCV_{WDF}}{NCV_{coke}} \tag{2}$$

where $r = 1.61$ kgCO$_2$-eq/kg WDF is the specific emission reduction factor obtained from [15] and M_{WDF} is the annual mass of WDF produced at Daldowie.

2.3 Life cycle inventory

The LCI is provided in the supplementary material (Table S7), contains essential parameters of the DWTW and WWTW to conduct the LCA. The table includes annual values of electricity, fuel, thermal energy, chemicals, water flows, and sludge yields.

2.4 Life cycle impact assessment and data interpretation

The work evaluates GWP as the life cycle impact assessment (LCIA) category following the CML 2001 – Aug 2016 methodology [16]. The emissions are measured in terms of GWP over 100 years following the IPCC norms and are expressed in terms of kgCO$_2$-eq/FU [16]. For this study, biogenic carbon is not included in the LCA [16]. The stagewise breakdown of GWP for different islands associated with DWTWs and WWTWs are shown in Sections 3.1 and 3.2, respectively. The GWP for each island is further compared to the GWP reported in SW 2019 sustainability report [2] and several literatures [8, 17-24] in Section 3.3. The influence of uncertainty in the input datasets and choice of model parameters is examined through one-way sensitivity analysis in Section 3.4. The sensitivity ratio (SR) was used to quantify the relative influence of different parameters [25]:

$$\mathrm{SR} = \frac{\left|\frac{\mathrm{GWP}^{i}_{\mathrm{baseline}} - \mathrm{GWP}^{i}_{\mathrm{changed}}}{\mathrm{GWP}^{i}_{\mathrm{baseline}}}\right|}{\left|\frac{\Phi^{i}_{\mathrm{baseline}} - \Phi^{i}_{\mathrm{changed}}}{\Phi^{i}_{\mathrm{baseline}}}\right|} \quad (3)$$

where $\mathrm{GWP}^{i}_{\mathrm{baseline}}$ and $\mathrm{GWP}^{i}_{\mathrm{changed}}$ are the baseline and altered GWPs corresponding to $\Phi^{i}_{\mathrm{baseline}}$ and $\Phi^{i}_{\mathrm{changed}}$, where Φ^{i} being the i^{th} parameter of the LCA. Higher the value of SR, stronger the influence of i^{th} towards the environmental footprint.

3 Results and discussion

3.1 Global warming potential of drinking water treatment works

The stagewise GWP breakdowns associated with DWTW for different islands are shown in Figure 5. The total annual GWPs for DWTWs in different islands in terms of $\mathrm{kgCO_2\text{-}eq/m^3}$ drinking water are (a) Arran – 0.4, (b) Barra and Vatersay – 0.79, (c) Iona – 0.18, and (d) Jura – 0.51. This means that DWTW at Barra and Vatersay is the most GWP-intensive, due to their higher GWP contribution from electricity and chemical usage, and the sludge landfill requirement. Barra and Vatersay use a comparatively old SF-based treatment architecture, while the other islands use modern UF-based membrane technologies. For all the islands electricity usage from the grid accounts for a major portion (60-98%) of their respective GWP. Therefore, one possible way to decarbonize and make rural DWTWs self-resilient is to install on-site electricity generation using renewable energy systems (e.g., solar, wind) [5] or waste-to-resource systems (e.g., anaerobic digestion) [26]. Since for Arran (Figure 5a), Iona (Figure 5c), and Jura (Figure 5d), the DWTWs do not generate sludge, the GWP is only contributed by electricity and chemical usage. For Barra and Vatersay additional GWP is caused (~12%) by the sludge transportation and landfill stages. The GWP results are comparable to the ones reported in the literature for various UF-, FS-, and microfiltration-based DWTWs, ranging between 0.23-0.42 $\mathrm{kgCO_2\text{-}eq/m^3}$ drinking water [21].

According to Figure 5a, the GWP contributions for Arran comprise 96.3% from electricity and 3.7% from chemical usage, among which the largest facility Balmichael contributes the most. Similarly, for the DWTW in Jura, the emissions from electricity and chemical usage accounts for 98% and 2%, respectively (Figure 5d). Figure 5c reveals that the GWP for Iona has 58% contribution from electricity and 42% from chemical usage. Figure 5b shows the GWP contributions for the DWTW at Barra and Vatersay are due to (a) electricity – 74.8%, (b) chemicals – 13%, (c) transportation – 1.8%, and (d) sludge landfill – 10.4%. The LCA results calculated per FU are converted to per capita for a comparison with the average GWP associated with SW operations (see Section 3.3).

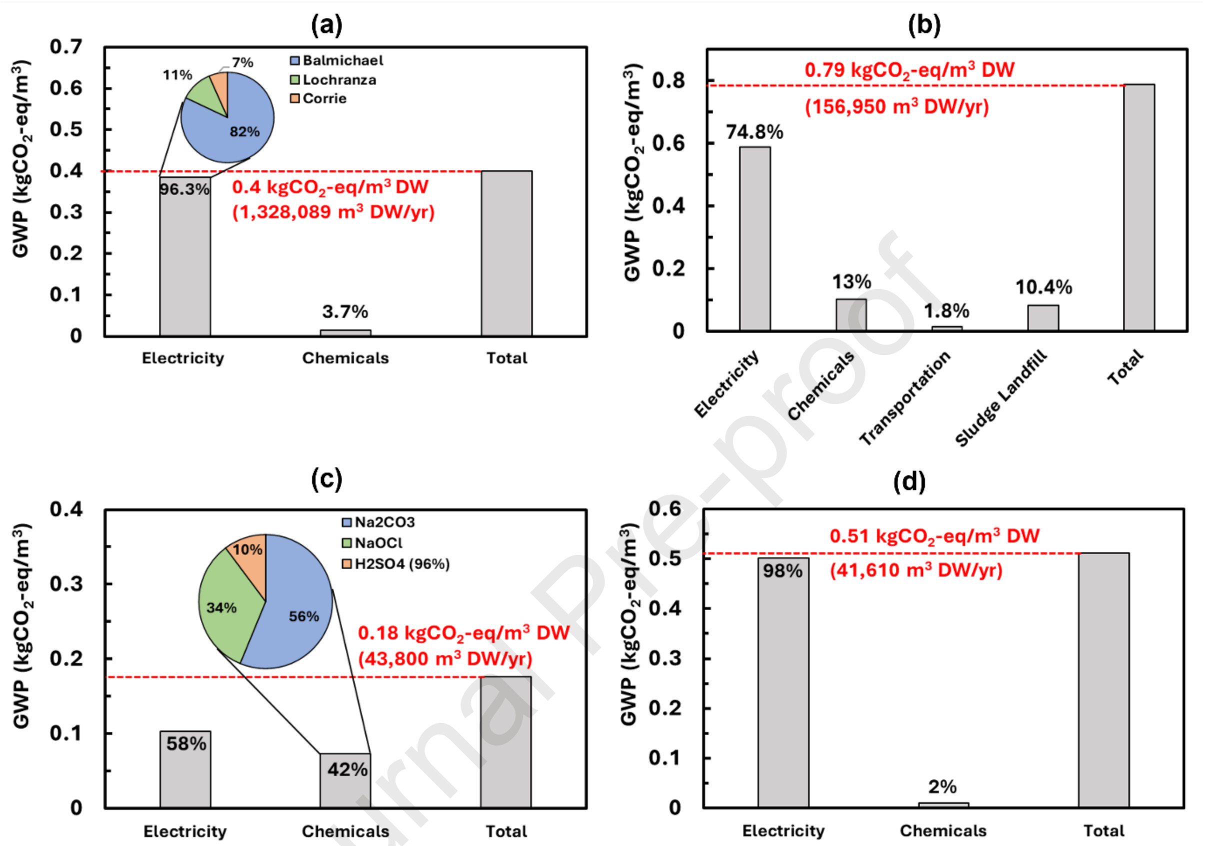

Figure 5. GWP breakdown of DWTW for (a) Arran, (b) Barra and Vatersay, (c) Iona, and (d) Jura.

3.2 Global warming potential of wastewater treatment works

The GWP breakdowns for WWTW and STW processes for various islands are shown in Figure 6. The annual GWPs in $kgCO_2$-eq/m^3 wastewater are (a) Arran with WDF utilization - 0.55, (b) Arran (WDF disposed) - 0.59, (c) Barra and Vatersay - 0.58, (d) Iona - 0.3, (e) Jura with Oban STW - 1.14, (f) Jura with Shieldhall STW (WDF utilized) - 0.51, and (g) Jura with Shieldhall STW (WDF disposed) - 0.59. These results are comparable to the GWPs of frequently used wastewater treatment technologies (e.g., activated sludge, constructed wetland, membrane bioreactor, moving bed bioreactor, and sequence batch bioreactor), falling within a range of 0.28-1.33 $kgCO_2$-eq/m^3 wastewater [8, 17-20, 22, 23]. Figures 6a and 6b compare two systems associated with the Arran WWTWs and consider the utilization and disposal of WDF generated at the Daldowie STW, respectively. Reutilization of WDF in a cement plant to displace usage of coke reduces the annual GWP by 0.04 $kgCO_2$-eq/m^3. The direct GHG emissions from STs contribute >85% of the overall GWP associated with Arran WWTWs. A similar trend was observed for Barra and Vatersay WWTWs in Figure 6c, where ST emissions constitute >83% of the overall GWP. Since the data for private STs on Iona were unavailable, a crude estimation of direct emissions from STs is made by averaging the ST emissions estimated for the other islands, which gives 0.42 $kgCO_2$-eq/m^3. The total GWP for Iona including and excluding the ST emission are 0.3 and 0.72 $kgCO_2$-eq/m^3. Hence, the ST emission component could significantly affect the outcome of LCA.

Other significant GWP components are electricity consumption during septic sludge processing and direct emissions from sludge landfills. Figures 6e, 6f, and 6g correspond to different sludge treatment and re-utilization systems for Jura. It is shown that treating the Jura sludge at Shieldhall/Daldowie STWs offers more than 2 times GWP abatement than treating sludge at the Oban STW. This is primarily due to significant emissions associated with high electricity consumption for the Oban STW and the sludge cake disposal to the Ayrshire landfill. Figures 6g and 6f indicate that by converting a large portion of the wet septic sludge generated at Jura to WDF pellets, significant mass reduction is achieved and the value-added WDF pellets have the potential to displace the usage of coke in a cement plant (offering 14% GWP reduction). Comparing the WDF utilization case for Arran (Figure 6a) and Jura (Figure 6f) reveals that the emission abatement effect is more pronounced for Jura (17.4% reduction) than for Arran (6.9% reduction). The direct emissions from SW-managed STs located in Jura contribute ~58% of the GWP. As a future pathway to decarbonize the GWPs associated with sludge handling and treatment, installing low-carbon waste-to-resource technologies e.g., anaerobic co-digestion integrated with a heat pump [26, 27], high solid anaerobic digesters [28], or biochar production using sewage sludge pyrolysis systems [29, 30] can be promising.

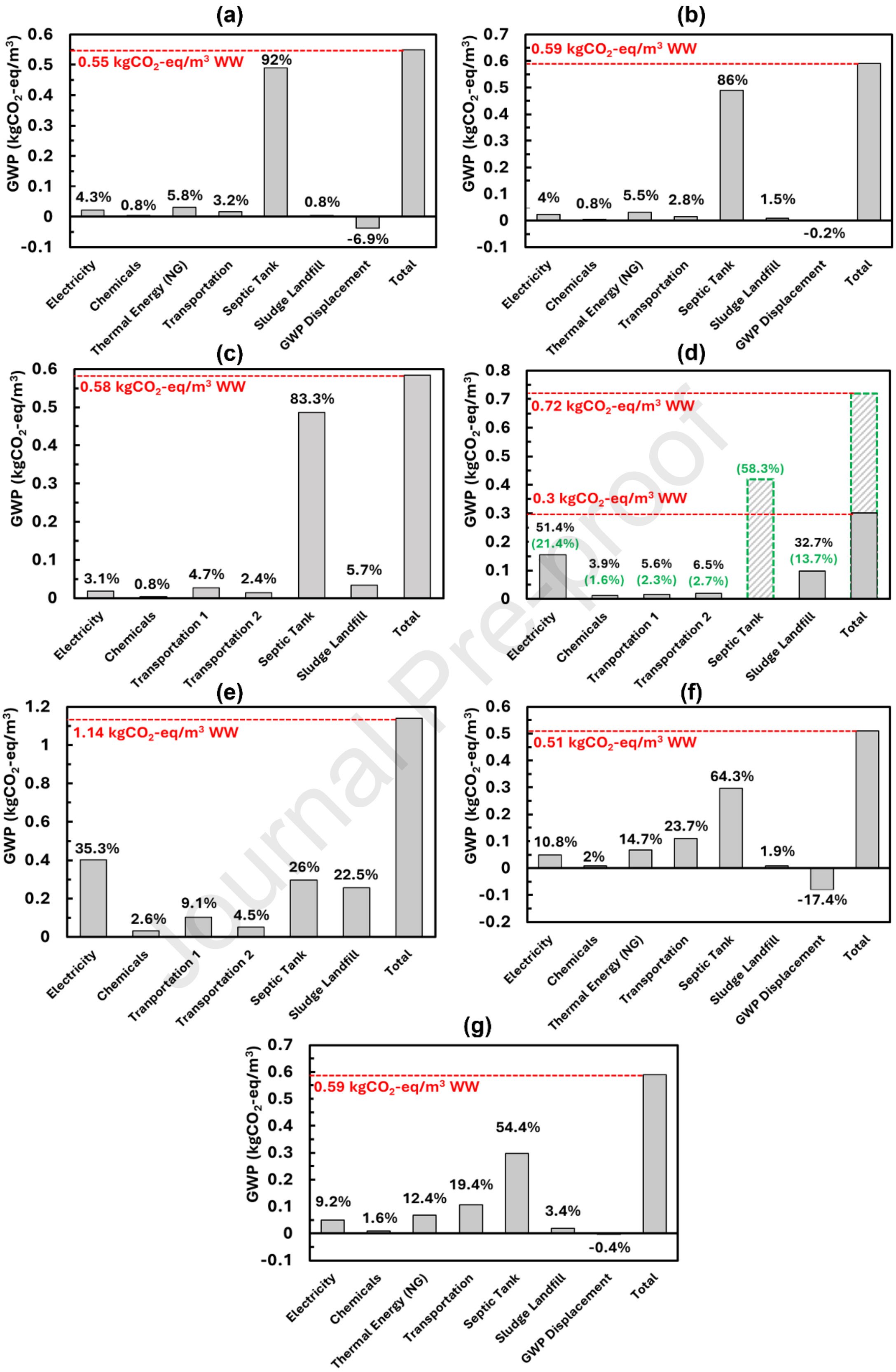

Figure 6. GWP breakdown of DWTW for different islands and sludge management systems. (a) Arran with Shieldhall STW (WDF utilized), (b) Arran with Shieldhall STW (WDF disposed), (c) Barra and Vatersay with Balivanich STW, (d) Iona with Oban STW, (e) Jura with Oban STW, (f) Jura with Shieldhall STW (WDF utilized), and (g) Jura with Shieldhall STW (WDF disposed). The dotted green bar in Figure 6d corresponds to the direct emissions

of private STs located in Iona, which is estimated as the average of ST emissions for the three other islands.

3.3 Comparison of global warming potential with Scottish Water sustainability report

The annual values of GWP per capita across different islands are compared to the ones reported in the SW 2019 sustainability report [2] (see Figure 7). The SW sustainability report provides an average GWP/capita for the whole Scotland, while our analysis focuses on the water facilities in remote island communities. The total operational GWP for SW during 2019 was reported to be 272,000 tCO_2-eq, of which 99% was attributed to DWTWs, WWTWs, and pumping services [2]. This corresponds to the facilities serving approximately 5.2 million people in Scotland, which is approximately 96.3% of the Scottish population. Therefore, the operational GWP of SW per annum can be calculated as $\left(0.99\times272000\times10^{3}\right)/\left(5.2\times10^{6}\right)\approx52$ $kgCO_2$-eq/capita.

Figure 7 reveals that the total GWP per capita (including both DWTW and WWTWs) for Arran, Barra and Vatersay, Iona (ST emissions considered), and Jura are between 3- to 7-folds higher than the average value reported by SW. This suggests that the DWTWs and WWTWs located within rural communities would likely have higher GWP than their urban counterparts. However, it is worth noting that the SW-reported GWP might be based on an environmental accounting protocol which is different than the one adopted in this work. Hence further research based on the same LCA is recommended to develop a like-for-like GWP comparison between rural island and urban mainland Scottish communities.

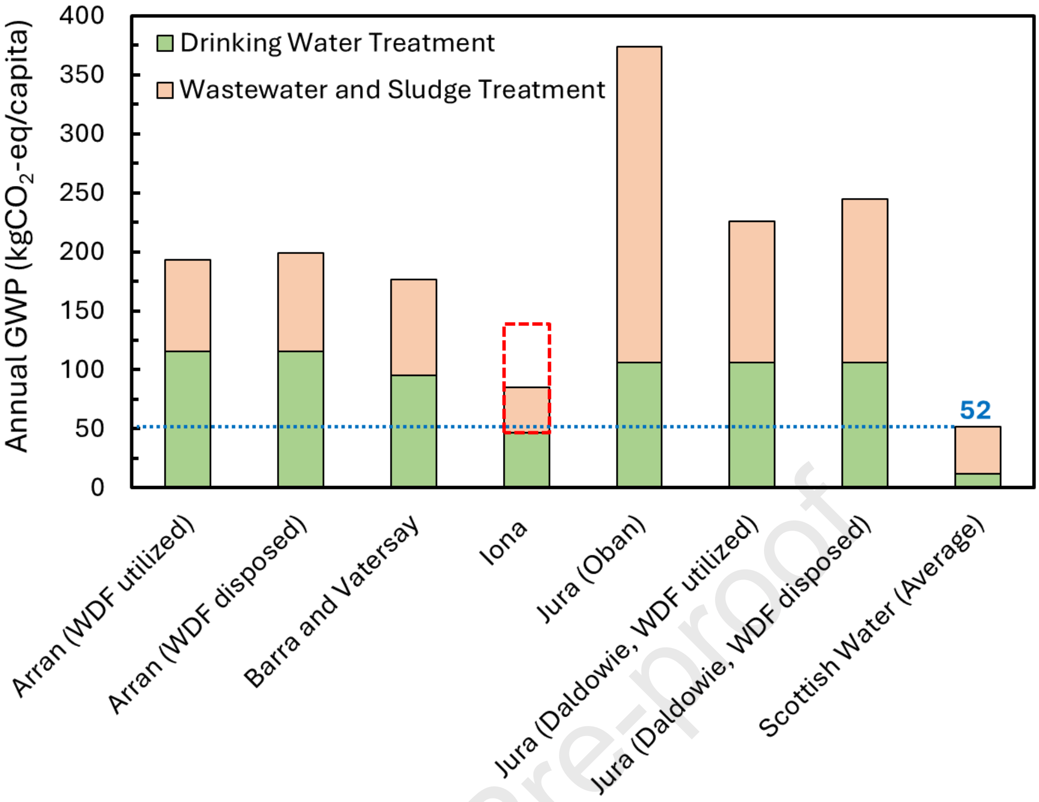

Figure 7. Comparison of annual GWP/capita for different islands with SW 2019 Sustainability report [2]. The dotted red bar for Iona corresponds to the GWP when direct emissions for private STs located in Iona are also included. Due to lack of data, this component was estimated as the average of ST emissions for the three other islands.

3.4 Sensitivity analysis

A one-way sensitivity analysis is performed as shown in Figures 8 and 9 for DWTW and WWTW, respectively. Each parameter was changed by 30% whilst keeping all the other parameters constant [25, 26, 31]. The SR (Eq. 3) reveals the relative importance of a parameter in changing the overall GWP. Consistent with IPCC norms for sensitivity analysis in LCA, SR = 0.2 (corresponding to a 6% change in GWP) was selected as a cut-off threshold to designate a change as ‘significant’ [31]. A high-level inspection of Figure 8 suggests that for three out of the four DWTWs i.e., Arran, Barra and Vatersay, and Jura, the GWP value is largely dictated by the electricity consumption. For the case of Iona (Figure 8c), one of the chemicals i.e., sodium carbonate shows significant influence towards regulating the GWP. Therefore, it is instructive to carefully account for uncertainties associated with the parameters mentioned above.

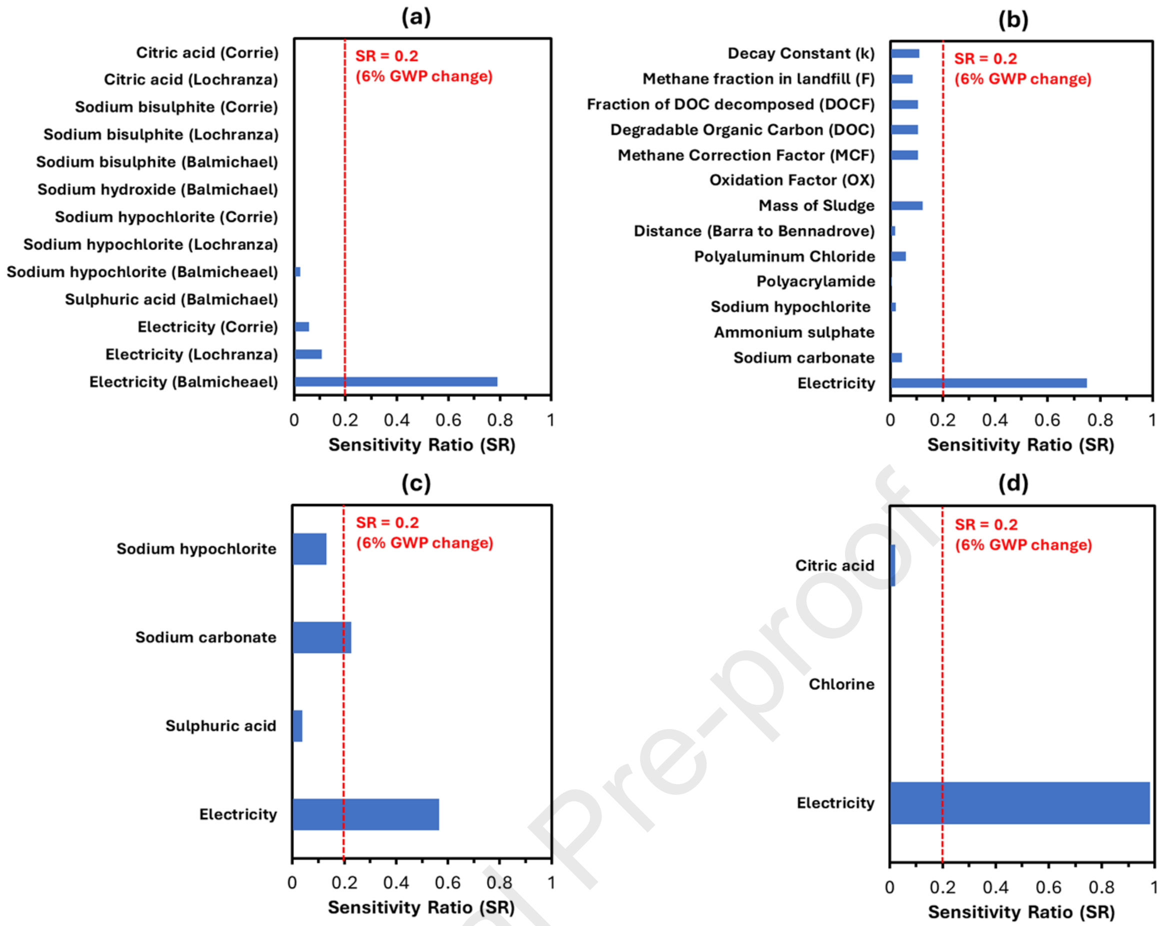

Figure 8. Sensitivity maps showing influences of parameters towards altering the GWP for DWTWs: (a) Arran, (b) Barra and Vatersay, (c) Iona, and (d) Jura. The parameters with SR values above 0.2 are designated to have significant influence on the GWP.

Figure 9 shows the sensitivity maps for WWTWs across different islands. For S-1A, S-4B, and S-2, the GWP is highly sensitive to ST emission model parameters such as biological oxygen demand (BOD), efficiency of biological treatment unit (Eff_{BOD}), methane correction factor (MCF_{WW}), and fraction of carbon as methane in biogas (BG_{CH_4}) (see supplementary material, Table S5). The parameter BOD is provided by SW, which is estimated based on the size of ST and population. The Eff_{BOD} is the oxygen demand removal efficiency of ST, which is in the range of 30% to 50% [32]. This work utilized an average value $Eff_{BOD} = 40\%$. MCF_{WW} indicates the fraction of the influent oxygen demand that is converted anaerobically in STs. The documentation for the emission model [11] suggested $MCF_{WW} = 0.8$ for the anaerobic wastewater treatment process, which is adopted in this work. BG_{CH_4} signifies the fraction of carbon as CH_4 in the biogas generated from ST, which is taken as 0.65 as per literature [11]. The high dependency sensitivity of GWP results to the ST model parameters also calls for further research for more accurate accounting of case-to-case variations.

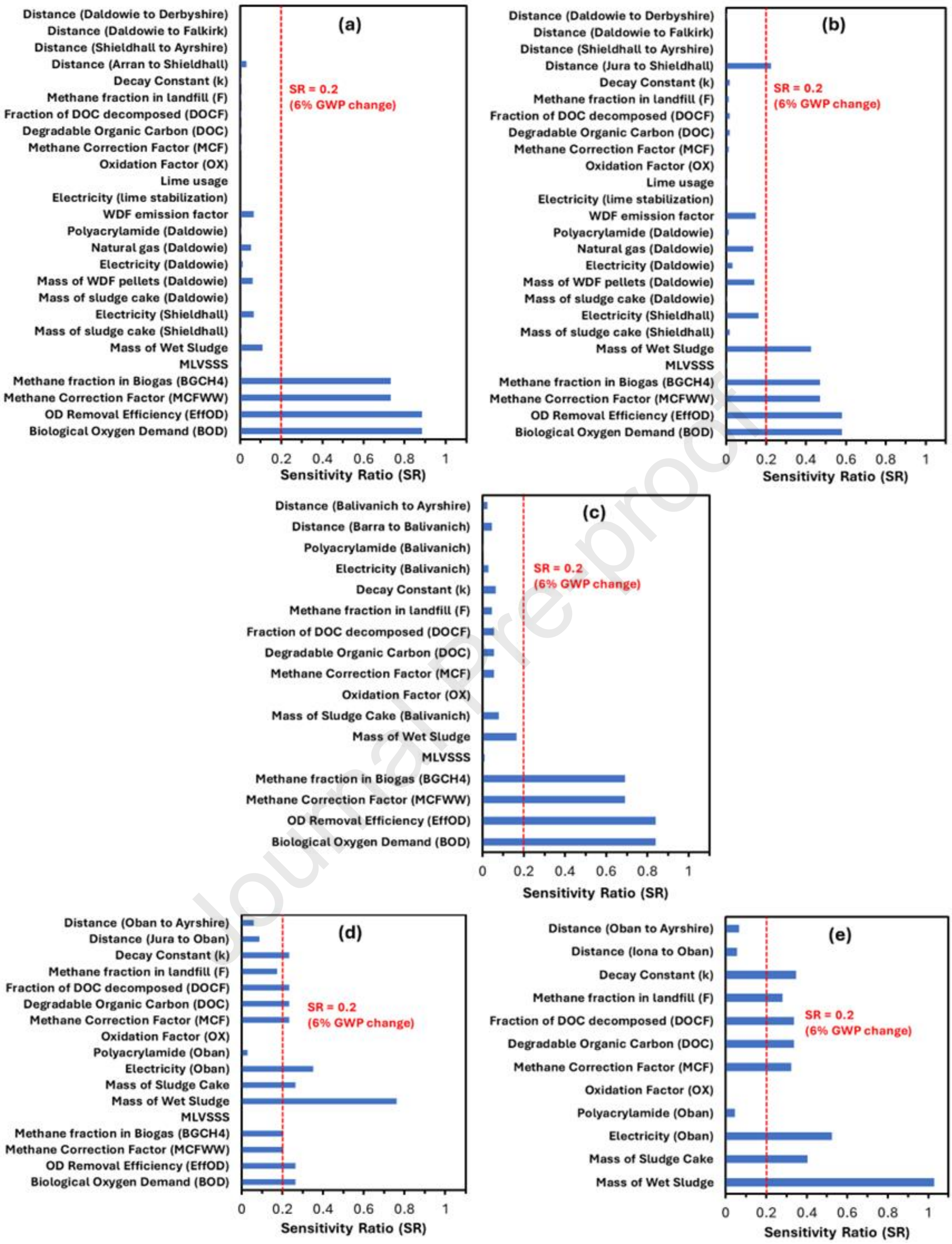

Figure 9. Sensitivity maps showing influences of parameters towards altering the GWP for WWTWs: (a) Arran with Shieldhall STW (WDF utilized), (b) Jura with Shieldhall STW (WDF utilized), (c) Barra and Vatersay with Balivanich STW, (d) Jura with Oban STW, and (e) Iona with Oban STW. The parameters with SR > 0.2 are designated to have significant influence on the GWP.

4 Conclusions and Implications

The value of the LCA and data collection methods for water system studies comes from identifying the GWP hotspots and allowing the exploration of alternative low-carbon technologies. These results can effectively contribute to policymaking and construct business models for facilitating net-zero technologies. Whilst we have used the ISO14040 guidelines to perform the LCA we still need to be cautious in drawing comparisons with other previous studies published by other research groups. The vagaries of data reporting and differences in system boundaries can cast doubt on whether comparisons are like-for-like. Thus, the fact that our detailed study of the rural water infrastructures in Scotland yielded higher GWPs than previous values reported for larger centralised technologies requires some further investigation. Indeed, to draw a more accurate comparison we need to apply the same method to a centralized DWTW and WWTW, which is our future intention. Nonetheless, the fact that the GWP of the water infrastructure on the selected Scottish Islands is between 3-7 times higher than that reported by SW for their business gives pause for thought. Given that, 17% of the Scottish population lives in rural areas and the GWP of rural water infrastructures is higher compared to urban ones, decarbonising rural water infrastructure should be a very important component of efforts to decarbonise the water industry.

From our analysis, because we have carefully applied the same methods using the same data sources, we can be confident in the comparison between the five islands. Furthermore, any consistent high emissions process in these decentralized water systems should be identifiable. The GWPs of the islands' DWTWs ranged from 0.18 to 0.79 kgCO_2-eq/m^3 and the GWPs of the islands' WWTWs ranged from 0.51 to 1.14 kgCO_2-eq/m^3. For DWTWs, electricity demand causes a major portion (between 75% to 98%) of the GWP. In contrast, GWP for WWTWs was affected by indirect emissions from electricity usage at STWs and direct emissions from ST, sludge landfills, and sludge transportation. Indeed, we had not anticipated that direct emissions from STs would contribute the majority of the GWP. There have been suggestions in the past that the emissions from STs may make a significant contribution of methane to the atmosphere, for example, the IPCC estimates based on STs functioning like anaerobic lagoons [29]. The assumptions made by the IPCC have been called into question. Here we use the US EPA model for ST emissions to similarly estimate the direct emissions and thus similar criticism may apply. We also found that the estimated GWP for the islands was most sensitive to the parameters used in the ST emissions model. There is a paucity of direct measurements of ST emissions [30], so the empirical components of the model are from alternate WWTWs.

Given the prevalence of STs globally and the suggestions from this and previous modelling studies that direct emissions are substantial and have been largely neglected, it is imperative that an extensive study that directly measures ST emissions is conducted. This will either verify existing models or allow more accurate models of this important process to be created. Whilst there are more direct measurements of methane emissions from larger systems of municipal wastewater treatment, sewer and water resource recovery facilities, the variations appear to be very large [33] even between very similar processes [34].

Our study did show that adopting circular economy approaches, for example, generating WDF pellets from septic sludge for Arran and Jura islands could reduce their overall GWPs by 6.6% and 15.8%. The result of the analysis highlights that alternative, environmentally friendly methods of handling septage ought to be explored for decarbonising the water facilities on the islands. In this realm, one potential approach is to install on-site anaerobic digestors to treat septic sludge (and food waste) generated in rural communities for bioenergy production. This will serve to mitigate the environmental impact associated with long-distance sludge transportation while powering the rural community (including its DWTW(s) that consume(s) electricity) with a low-carbon energy source.

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Declaration of Competing Interests

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.

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Highlights

- The carbon footprint of water infrastructure on Scottish islands was quantified
- The carbon footprint of drinking water treatment works ranged between 0.18-0.79 kgCO_2-eq/m^3
- The carbon footprint of wastewater treatment works ranged between 0.51-1.14 kgCO_2-eq/m^3
- Sludge-derived fuel pellet production and rerouting septage disposal lower the footprint
- The footprint was sensitive to septic tank emission and sludge decay model parameters

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: