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An evaluation of feedstocks for sustainable energy and circular economy practices in a small island community

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A R T I C L E I N F O

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A B S T R A C T

Maximising the use of anaerobic digestion to generate power from waste feedstocks is becoming a practical way to use waste contributing to the transition from a linear to a circular economy and reducing the carbon footprint. In addition to harnessing the production of biogas generated from anaerobic digestion plants, there are a stream of potential bioresources such as fertiliser, chemicals, gases and bioplastics which may provide sustainable alternatives to petroleum-based products. Island communities are constantly faced with waste management challenges often shipping waste off the island, which increases the 'islands' carbon emissions. This study investigated Orkney Islands as a model example, focusing on establishing whether an anaerobic digestion plant is a feasible sustainable waste management solution through analysis of waste quantities and composition, available technology, community buy-in, environmental impacts and economics. A survey of waste revealed 76,000 tonnes/annum of waste on Orkney over a variety of organic, textile and plastic categories which could generate 5 M m^3 biogas and 11 M kWh electricity per year. Four scenarios of producer clusters for anaerobic digestion plant operations were modeled and showed an average of 19 years for investment pay back, demonstrating that significant investment would be required to make the project economically viable for the business. A life cycle analysis was performed, and the project found that anaerobic digestion produces the greatest environmental benefits for processing waste compared to landfill or producing animal feed. This study demonstrates the contributions of anaerobic digestion in the community and represents a blueprint on how communities can reduce waste and develop a circular economy. The benefits of implementing a combined heat and power plant were explored and the study found that the community would profit. The anaerobic digestion plant will provide a constant base load of energy to help fill the gaps created with other intermittent energy supplies (wind and tidal). The inclusion of a waste disposal system on the island significantly reduces the communities carbon footprint due to removing the need to ship waste to the Shetland Island for disposal. The energy produced in the combined heat and power plant can supply many end users, such as 97% of energy needs for the largest distillery on the island, 4 compressed natural gas trucks for the island or a 1-acre greenhouse. However, individual efforts will not be enough to create the change that is needed, community and regulatory collaborations are essential to create a circular economy in Orkney and significantly reduce the carbon footprint.

1. Introduction

The use of waste as a renewable energy source and its substantial efforts has many economic, social and environmental advantages. The utilisation of waste from a process as part of a solution, in this case, renewable energy, demonstrates that sustainability can be incorporated

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into the operations of businesses and organisations [1]. The traditional linear approach of extract-produce-use-dump as an economic and environmental system to material and energy flows is unsustainable. Furthermore, the waste-to-resource approach allows business operations to be more cost-efficient and minimises adverse environmental impacts. The transformation of operations to include the waste-to-energy processes may be costly; however, having the ability to produce energy will reduce business operational costs and contribute to the circular economy model.

The circular economy (CE) concept is interlinked with industrial symbiosis and Eco-city developments concept widely popularised in Denmark, the USA, Germany, and many Asian countries, particularly China and Japan [2]. According to Yu et al. [2]; the evolution of circular economy practices is shaped by the cultural drivers within the social and political systems they are developed in. Sakai et al. [3] discuss several examples that depict the disparities between global circular economy practices. For example, Germany favours an environmental policy route to address raw material and resource use issues for sustained economic growth. In contrast, the circular economy underpinning Chinese development and steady growth is far more focused on mechanisms for profitable product development, technology, and industry developments [4]. The UK and Scandinavian countries take an alternative approach; the concept has been applied for waste management, focusing on business models that reuse, repurpose, and recycle materials [53]. An example of extremely influential industrial symbiosis developments can be found in Kalundborg (Denmark), which exemplifies natural physical linkages of material flows and exchanges between localised industries. Industrial symbiosis is a business-focused collaborative approach towards resource efficiency and sustainability by recovering by-products and waste from one entity for the use of another. Most recently, Maroušek and Gavurová [5] recently reported novel methods of recovering phosphorous from biogas fermentation residues indicates that the novel fertiliser competitive to the markets. They proposed a method to activate the charred fermentation residues using the calcium chloride typically used in fertilisers for fertilization and using the resulting sorbent to capture phosphorus out of the fermentation residues liquid fraction. The study reported that the activated char is capable of capturing up to 37.5 kg P/tonne whereas the phosphorus availability for plant nutrition outperforms fermentation residues as well as struvite. In addition, the char demonstrated the potential to improve soil characteristics and the metabolism of soil biota.

Despite the consensus that governments, policy makers and industry partners lead circular economy practices, much of the concept is largely unexplored [49]. According to Huppes and Ishikawa [6]; ecological economics are potentially the most productive source for new practical, policy, and business orientated circular economy concepts. Consistent with this view, Jiao and Boons [7] identify different policy instruments and approaches as regulatory and economic tools to achieve significant effects that would not occur without governmental intervention. Eco-industrial parks and networks are a government initiative to reduce energy and raw material use, minimise waste and support sustainable economic, ecological, and social relationships. Approaches such as Eco-industrial parks and industrial symbiosis are grouped together in literature; however, there are significant differences between the operations, such as scale, the scope of objectives, actors involved and differences in practices.

Practices of optimisation models, sustainable decision making, and island development are becoming more important [8]. Islands are considered vulnerable due to the regular challenges they face. These include relative isolation, a sensitive environment, high dependency on seasonal activities and external inputs, demographic imbalances, and insufficient public structures. Due to the limited number of resources available, energy planning is essential in Island energy systems. Of particular interest to this study is the community of the Orkney Islands that possess the principles of a circular economy whilst performing sustainable practices that have been embedded within its culture. In Orcadian culture, 'bruck' contains a possible future and a new beginning. This word describes what outsiders would normally perceive as ''waste'; however, in Orcadian culture, items termed 'bruck' are a potential resource that can be re-utilised.

From an economic point of view, Orkney Islands are a low carbon island economy driven by innovation, achieving ambitious carbon reduction targets, and providing global energy system solutions. The community is maturing into a globally recognised region for innovation in their efforts to develop solutions for the 'world's energy challenges. Orkney's sustainable strategy suggests that their global connections will be continually exploited to further develop the research and development activities and position Orkney within the global energy market and knowledge economy [9].

However, like many other islands of similar settings, the Orkney Islands, face a very specific challenge in waste management due to their location, size and total volumes of waste being generated. Orkney is located over 15 km away from the Scottish mainland, with a size of 990 km^2 and an estimated population of 22,400 [51]. Although waste production figures aren't publicly available, it can be calculated from the population size that waste levels aren't significantly high however there are waste management issues. Waste is generated at such a small scale that it is extremely difficult to attract waste management firms at reasonable and commercially viable rates. Consequently, nearly all of Orkney's waste has been put to land, deposited historically in landfills around the islands, and in the last twenty years waste has been regularly shipped to the Shetland Isles for incineration in the energy from waste scheme; an increasingly expensive and unsustainable exercise. The geographic and climate benefits of the Orkney Islands support a wide range of industries, such as drinks distilleries, breweries, fish and shellfish businesses, agriculture, horticulture and a strong hospitality sector. On the contrary, the agricultural industry and brewing/distilling industry, the largest producers of waste in Orkney, mainly put their waste straight to land under The Scottish Environment Protection Agency (SEPA) regulations. This practice has the potential to produce and recover significant amounts of biogas through Anaerobic Digestion processes.

Therefore, the aim of this study is to evaluate the feasibility of a community-driven anaerobic digester (AD) Plant Installation in Orkney to address specific waste management challenges faced by remote, rural and island communities/local authorities. The goal is to identify the most appropriate AD system and recommend a waste management strategy involving an anaerobic digester plant(s) in Orkney. The findings of this study will serve as an input into an integrated waste system that processes organic materials from wastes largely produced by households, local businesses and the agricultural sector.

2. Study area

It is considered that there is scope for recycling of organic waste from agricultural, horticultural and food operations on Orkney Islands, and this project seeks to provide a detailed assessment of the feasibility of using these wastes, together with possible crop supply as feedstock for the anaerobic digestion (AD). The sustainable Orcadian culture has led to the innovation of 'green' practices in Orkney. The future of the island's sustainability is embedded within its culture, although the common high windspeeds make Orkney a wind energy production hotspot and the 917 km of coastline provide access to tidal energy potential. These opportunities allow the community to produce over 120% of their electricity needs through renewable sources [10]. However, Orkney export significant amounts of the energy produced to the electricity network, therefor the community is required to pay high prices for energy produced on the island. Despite high production levels it is estimated that 80% of Orkney are still in 'energy poverty'.

The population saw a 10% rise between 2001 and 2012 due to the take-off of the renewable energy generation market. From 2008 the presence of wind technology snowballed and began peaking in 2011. At

Table 1
Total Waste available, Survey Data 2020.

Type of waste	Total t/annum
Mixed Ordinary waste	70
Green Waste	100
Plastic Waste	12
Brewing and distilling waste	57,156
Vegetable waste	~2
Food processing waste	12,050
Slurry	3811
Animal manure	1100
Abattoir waste	3500
Textile waste	~1
TOTAL	**77,800**
Alternative sources	
Fish Waste	10,790
Food Waste	2200
Sludge	950
TOTAL	**13,940**
OVERALL TOTAL	**91,740**

this point, the main energy supplier reduced the number of grid applications. By 2014, the grid was over-saturated with wind technology supply. Many organisations, such as European Marine Energy Centre (EMEC), provided an opportunity for alternative renewable energies to be explored such as tidal and wave.

3. Materials and methods

The study was designed to identify the most appropriate AD options and recommend a strategy for running the plant(s) as part of an integrated system for processing organic material from wastes. An online questionnaire was designed and curated specifically for the project to collect relevant data. The questionnaire was divided into two sections: the available waste streams and the current waste management systems.

3.1. Data

The survey data provided an insight into the potential waste streams available in Orkney and estimated totals. The total amount of wastes available are outlined in Table 1 below. Due to the COVID-19 pandemic creating difficulties in data collection, the totals seen below may not be representative of the total available waste across Orkney. Brewery and distillery waste estimations were based on alcohol production levels [11]. Table 1 includes waste data from alternative sources, Zero Waste Scotland [12] and Orkney Island Council [9] to provide a full data set. The economic analysis completed, uses the figures in the Table 1 as a basis of feedstock inputs.

Waste producer clusters were formed, and potential AD plant locations were outlined (Fig. 1). Clusters were formed by analysing regions for the concentration of resources, producing three micro sources. Fig. 1 shows the area with the greatest waste output and the most viable location in the central area of the Orkney mainland. The consideration of grid connection and baseload capacity was not prioritised due to the project's aim of collaborating with an end user to take on the energy produced, whether that be heat and power for running a local or neighbouring distillery, CNG for vehicle use on the island or providing community heat to combat the energy poverty. Consistent with the adopted practice on the island, the question regarding the current waste management systems revealed that most of the waste from agricultural and brewing industries is being put to land under Scottish Environment Protection Agency (SEPA) regulations.

4. Economic assessment

4.1. Conceptual framework

In this study, assumptions were made in the surrounding parameters. The project was assumed to be an investment activity, with the capital resources expended to generate a profit providing asset over an extended period (30+ years), i.e., the financial viability of the project was based on the cash flow. The project was also assumed to be a community benefiting asset, with the project providing a sustainable solution to waste management issues within the islands. Therefore, the social viability of the project was based on the potential circular economy benefits. The conceptual framework is outlined below (Fig. 2). The total cost, income and benefits were identified and valued based on a technological design of a continuous stir reactor in a CHP plant. This plant design was justified by the types of waste available for AD in Orkney. The financial viability of the project was estimated using a financial decision criterion, these included net present value, internal rate of return and payback period, to conclude the feasibility of the investment opportunity.

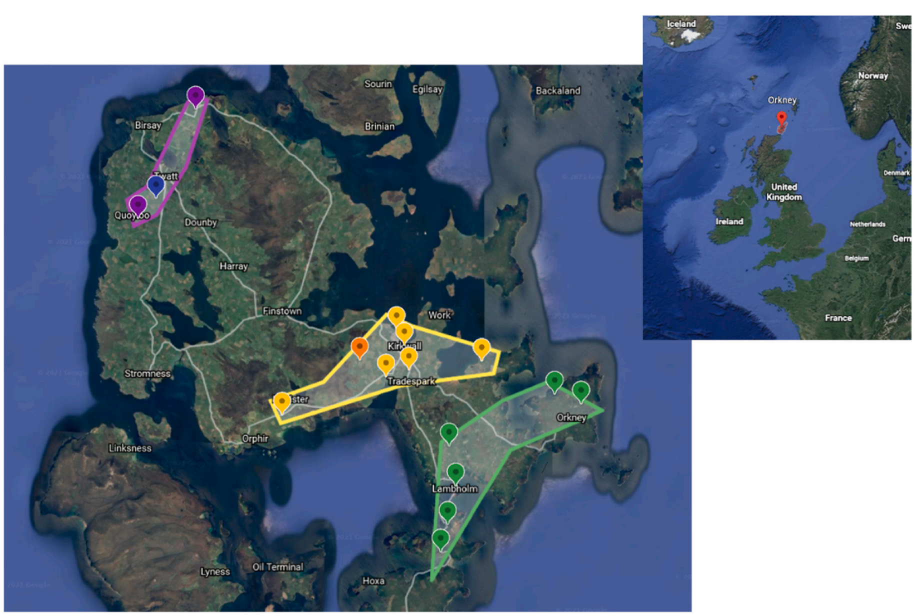

Fig. 1. Map of mainland Orkney, potential clusters and locations outlined.

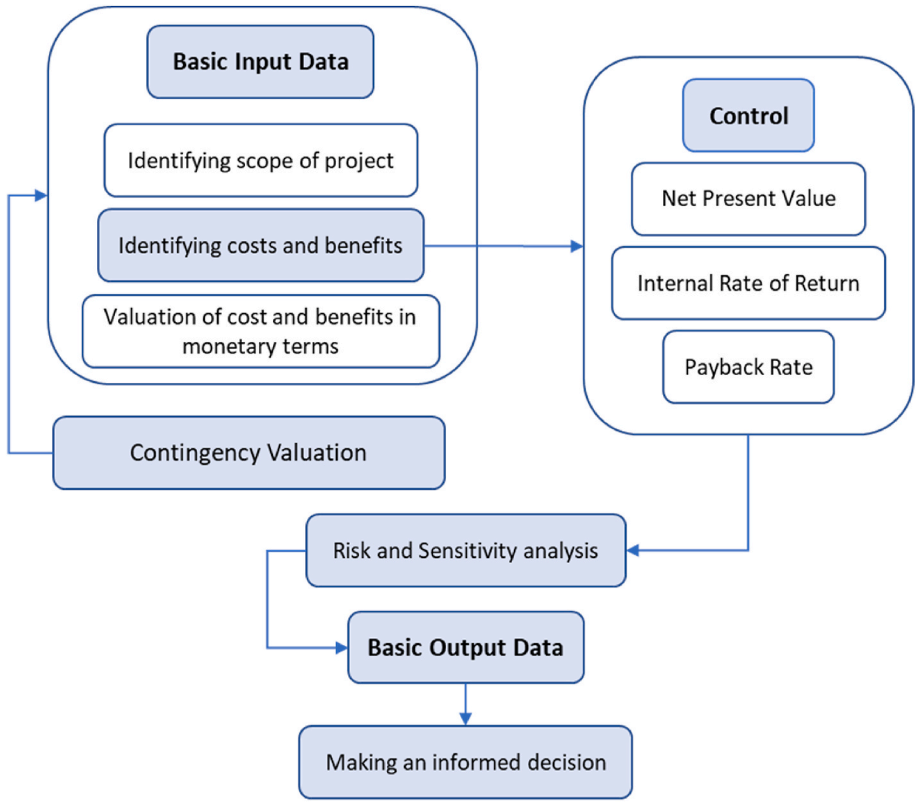

Fig. 2. Conceptual framework.

4.1.1. Estimating the cost of the biogas plant

The cost estimation was made based on market values from 2018 to 2020 using project partner Strathendrick Biogas and academic literature for reference. To simplify the estimations, many values were based on percentages rather than the actual figures. The cost elements were grouped into pre-production expenditures, operational costs, and business rates. Research suggests that the capital costs associated with biogas plants vary with the size; therefore, this study used a percentage assumption for adequate maintenance and insurance costs. The capital costs were assumed to be $3400/kW of potential energy produced, including administrative fees, installation, and all other consultancy fees. A figure of 2% of capital costs was assumed for maintenance costs and 1% of capital costs were assumed for insurance [13].

4.1.2. Plant installation costs

The capital cost varies depending on the type of reactor and tanks used. The cost generally comprises of feasibility studies, permits, design, legal fees, license fees, health and safety costs, environmental impact assessment (EIA), planning permission, plant machinery and equipment, contingencies and pre-construction costs, construction of the plant and accessory buildings. The use of underground pipes and tanks will increase the capital cost of construction; however, it will reduce the amount of heat needed to maintain temperatures within the tanks, therefore reducing the operational costs. This also allows for more heat to be sold, increasing income. In this study, the capital costs were accounted as $3400/kW, estimating roughly around $4.1 million for the simplest option.

The inclusion of a pasteurisation unit suitable for abattoir waste would increase the capital cost by around $680,000. However, the cost of a new built micro abattoir catering for cattle, pigs, and sheep is similar. This will take the total capital expenditure up to $5.4million and increase annual running costs by around $81,000. The inclusion of an abattoir may not be the best scenario in terms of economic returns. However, it would fill a gap in the local infrastructure with the potential to generate business opportunities, not to mention the money saved by keeping the animal by-products local rather than shipping them off the island [14].

The options for financing the capital costs of installations of the CHP plant are based on the degrees of risk and benefits associated with the project. The options for an upfront capital purchase provide a higher NPV; however, the initial cash flow will be negative. In the case of Orkney, the possibility of an upfront capital cost is not available to purchase the CHP plant. This is due to the lower return on investment of the project; however, a positive cash flow will be experienced from the offset. This will result in a 15–18-year payback period; however, there will be a positive cash flow from the first year of operations [15].

4.1.3. Storage, spreading and transport costs

One of the biggest costs to the operations is the storage, spreading and transporting of the digestate. Due to the nature of the material, the storage costs are a significant expenditure. For this economic assessment, the storage cost is assumed at $3.50 per tonne of digestate stored. This storage, however, is not required all year due to the seasonality of the agricultural community; only 6 months of the year require storage of digestate [16]. In terms of spreading costs, this is a flat rate of $4.20per m^3 of digestate spread. With a total of around 45,000 tonnes of digestate to spread, a costing of around $190,000 a year is expected. This is included in the operational costs as a yearly figure; however, spreading is required 4 times a year, within 6 months [17].

The transport costs were considered on the outgoing digestate, not the incoming feedstocks. The digestate produced provides significant micro-nutrients and is used as a bio-fertiliser, providing an economically and environmentally suitable way to utilise any by-products produced by the CHP plant. The suggested cost of transport is $0.18/km. When analysing the suggested location options, the central option (Kirkwall) provided the most feedstock in the shortest distance. Having said this, the market for the digestate would be across the Orkney Islands and not just from local producers near the AD plant site. Average farm size 141

Table 2
Distance from suggested location to local waste producer.

Participant	Waste produced	Amount of waste produced (t/a)	Distance (Km) (Location A)
Location A	Beef Slurry	1300.00	0.00
1	Distillery	11333.90	2.57
2	Distillery	33800.00	5.47
3	Beef Slurry	2503.00	9.81
4	Manure	100.00	12.80
5	Beef Slurry	288.00	22.36
6	Beef Slurry	720.00	22.85
7	Brewery	152.00	23.97
8	Brewery	79.00	29.12
	BULK	**50275.90**	129.06
	AVERAGE		14.33

Table 3
Feedstock costs estimates.

Feedstock	Cost to CHP/Price received	Total based on resources
Fish Waste	$7	$73,500.00
Food Waste	$14	$30,000
Sludge	$61	$58,000
Abattoir	-$136	-$7400
Spent Lees and Pot Ale	$7	$155,000
Draff	-$27	-$188,000
Spent grain	-$40	-$7650
'Brewer's yeast	-$40	-$1300
Slurry	FOC	$0.00
Manure	FOC	$0.00
Mixed Ordinary Waste	-$40	-$2800
Vegetable Waste	-$40	-$86
Whey	-$7	-$82,000
Textile	-$40	-$10
Total Feedstock Costs		**$212,260.00**

ha (Scotland); the amount of digestate produced requires around 900 ha to spread. This suggests that the AD plant will provide digestate for around 6 farms. Using the 4 suppliers closest to the suggested location, an average of 17 km is calculated. The total digestate costs are estimated between $10–14/tonne, including the costs of storage, spreading and transport. This provides a total cost ranging from $430,000 to $610,000.

4.2. *Estimating the cost of the biogas plant operation*

Operational costs will be roughly around $580,000 per annum, primarily for labour, digestate processing and maintenance costs. A breakdown of all operation costs is included in the economic assessment as follows.

4.2.1. *Maintenance budgets*

When budgeting maintenance costs for an AD plant, roughly 2% of the capital cost is suggested. However, it is slightly different when it comes to CHP plants. The cost should be no more than $1.9/kWh, with efficient plants costing as little as $1.02/kWh. A CHP plant is expected to run for 30 years with regular maintenance. This should be budgeted into maintenance costs. The plant will require little to no maintenance within the first few years of operation and will require significantly more in the final 10 years of operation. This budget allowance will balance out over the 30 years of operational life.

4.2.2. *Labour costs*

When it comes to the labour costs for the running of an AD plant, it is not based on output capacity, but the type of system in place and the complexity of the operating processes. However, for the purposes of this assessment, labour costs are based on 4 full-time members of staff, at an annual rate of $38,000-$40,000, depending on the level of operational knowledge and experience. The type of work undertaken requires a specific set of skills and knowledge due to the complex nature of the operation. The total budget for staffing of the AD plant is between $156,000 and $164,000 per year.

4.2.3. *Land lease*

A rough land lease estimate has been made at $34,000. However, this can be negotiated or even removed depending on the nature of the relationship with the landowner. For example, the use of on-farm facilities will allow for a smaller lease requirement and a drop in initial capital costs.

4.2.4. *Feedstock costs*

In terms of local feedstock costs a breakdown can be as follows. The cost of feedstock depends on the calorific value of each. Table 3 outlines all feedstock costs. Some feedstock requires the plant operator to pay as supplying an AD plant might not be their cheapest or most beneficial waste management system.

4.2.5. *Insurance budget*

Once running, an AD plant is reliable and a safe energy production method, therefore it is suggested that there should be a rough budget of 1% of capital for insurance until a more detailed estimate can be provided at a later stage. This estimate is subject to changes within the procurement phase.

4.2.6. *Inflation and interest rates*

The basis of the following economic assessment was assumed to have an inflation rate of 2%, in line with current UK figures [18]. No interest rate has been considered on the capital costs [13] due to the potential of grants and sponsored funding being considered at a later date.

4.3. *Estimation of benefits of the biogas plant*

The benefits from energy production through a CHP plant are achieved from the first year of operations. The inclusion of Orkney Cheese waste could significantly increase to the energy production levels of the CHP plant. Understandably, the increased capital costs incurred with installing a pasteurisation unit to treat the waste beforehand would increase the payback period significantly. However, the addition of this waste could provide 1800 MWh of energy.

A similar situation can be seen with the inclusion of abattoir waste. The Orkney community requires an abattoir, and the potential waste available (867 tonnes a year) could provide the energy income with an increase of around $20,500 with the potential production of 99 MWh. This inclusion of abattoir waste also incurs an increase in capital and operational costs with the inclusion of licence fees. The initial capital costs for the required animal by-products processing licence are $15,000, and the cost of the pasteurisation unit would increase the capital costs by $696,300, with an annual subsistence charge of $10,244 (SEPA 2021).

Due to previous complications with energy production using AD technology on Orkney, the governing body (OIC) currently transfers all food waste collected to Shetland for incineration through the Energy from Waste (EfW) scheme. The inclusion of community food waste will provide an alternative to the current waste management system in use. The inclusion of food waste in the AD plant poses some waste contamination risks, as food waste can contain microplastics even after separation, severely affecting the AD process.

4.4. *Energy production*

Annual income has been calculated according to the annual expenditure, the sale of digestate and potential annual earnings. It can be assumed that the plant will maintain a payback period of 15–18 years. A cash flow model was developed for 30 years based on the lifespan of the technology used. A discounted rate of 2% was estimated in line with the current inflation rates. Revenue is received through the sale of electricity, heat, digestate and biofuel for the collection of Renewable Transport Fuel Obligation certificates.

The unit sale of electricity is at a rate of $0.20/kWh. Whereas heat energy is sold at a lower rate of $0.04/kWh. The digestate produced is sold at the rate of $3.40/t. The CHP plant will provide energy at a ratio of 50:50 in terms of heat and power. The table below shows the minimum output and income available.

4.5. Partner distillery

The potential energy production could provide a significant amount of heat and electricity to local businesses. In terms of distillery energy needs, roughly 7.5 kWh of energy is required per litre of alcohol produced. This is broken down into 97% heat and 3% electricity.

One of the main distilleries supplying the potential AD plant with pot ale, spent lees and draff is Highland Park distillery. As the main supplier of feedstock, it is logical to include them in the potential energy output options. This local distillery would require 15,200 MWh of heat and 470 MWh of electricity. The main benefit of supplying energy directly to an end-user is avoiding connecting to the grid. In terms of the location, Orkney's electricity needs are met by producing energy through wind power, which is supplied at a better rate than biogas. This creates competition in the market for grid connectivity, and the possibility of being unable to access the grid completely. The benefit of AD production is that there is no fluctuation in energy production as a baseload is generated 24/7. The direct connection to an end-user can provide the usage required from a reliable and renewable energy source.

4.6. Biofuel/incentives

There is a significant lack of governmental incentives in 2021 to produce renewable energy, specifically biogas. Previously there have been the Renewable Heat Incentive (RHI) and Renewable Obligation Certificates (ROCs). In the past, these have provided renewable energy producers with a significant income; however, currently, there is only one incentive that applies to the production of biogas.

The UK Governments Renewable Transport Fuel Obligation applies to the production of biogas in the form of transport fuel. This incentive requires a minimum production of 450,000 L of fuel a year. This would provide an income of a minimum of $184,000 at $0.40/kg of biofuel produced. The standard cost of RTFO's is roughly $0.19/kg, however the production of such fuel through renewable energy (feedstock dependant, anaerobic digestion included) means producers will receive double the amount, encouraging the production of transport and CNG fuel through renewable means. The biogas plant in question has the capacity to provide CNG for at least 4 trucks in Orkney.

4.7. Digestate

In terms of creating a complete circular economy, the methods of waste disposal need to change. Although putting lots of waste to land can be beneficial to the soil with the contents of the waste, it could be better utilised through the AD process. The use of local waste means that there is significantly less disposal to land. The provision of digestate will create significant benefits to the land through the high nitrogen content. Current research shows that N-fertiliser negatively affects the environment and contributes towards combating climate change. The use of digestate proves to be a beneficial bio-fertiliser for the land and the agricultural industry.

A rule of thumb is used to suggest that digestate is produced at a rate of 90% of the feedstock input. For example, if 1000 tonnes of feedstocks were input, 900 tonnes of digestate would be produced as an output. This is another method of income for the AD plant; however, the economic viability of the AD plant relies on the market for digestate sales in Orkney to be fruitful. Digestate contains nitrogen, potassium and phosphorous and the current price for digestate sales depends on the nitrogen contents per tonne. The estimated breakdown of digestate for this scenario are shown in Table 6.

In terms of land requirements for the digestate dispersal, roughly 50 tonnes of digestate are required per hectare. This means that there is a need for 900 ha of farmland to spread the digestate produced, roughly 2% of the total agricultural land in Orkney. According to OIC data, in 2018, there was around 40,000 ha of agricultural land in Orkney. The division of this farmland was split into different types of agricultural land, crops, vegetables, grazing and other grassland.

With the current rate at $3.40/t, the production of 45,000t/a of digestate would generate an income of around $154,000 annually. The costs of digestate cover the costs of spreading but not transport. This is an expensive cost to the operations of the AD plant.

Contractual agreements may be put in place between the feedstock supplier and the AD plant. This may be utilised by suppliers with free of charge feedstocks, as it will encourage them to provide their waste. For most farmers on the island, a system is already in place for the storage, and spreading of their own farm produced slurry. From the data collection we can see that there is roughly 5000 tonnes of slurry and manure available. The removal of $17,000 will take the digestate income down to $137,000.

Table 4
Summary of operational costs.

Operational Costs	
Feedstock Costs	-$212261.00
Maintenance	-$136242.00
Labour	-$159403.00
Land lease	-$34,000.00
Insurance	-$68,000.00
Licences (feedstock dependent)	-$15,700.00
Total Opex	**-$625,800.00**

Table 5
Potential income.

	MWh/Tonnes	Price	Income
Heat	1900	$0.04/kWh [19]	$77,700
Power	1900	$0.20/kWh [19]	$388,300
Digestate	45,000	$3.40/t (SBL 2021)	$153,300

Table 6
Digestate breakdown.

	Feedstock (t/a)	Digestate (t/a)
Digestate production	50,000	45,000
Digestate contents	kg/tonne	k/tonne
Nitrogen	4.00	180,000
Potassium	2.00	90,000
Phosphorous	2.00	90,000

4.8. Sensitivity analysis

A sensitivity analysis using estimated financial values has been conducted to systematically test what would happen to the potential cash flow of the biogas plant if a number of factors changed from that used in the original economic projections. A sensitivity analysis was performed to assess the ability of the business plan to deal with any uncertainty about future events and values, as there are many based around the assumptions made in the economic analysis. This was achieved by varying the input variables such as the price of heat, electricity and digestate, inflation rate and interest rate to identify the effect on the outcome of the project worth. The parameters of the analysis were as follows in Table 7. The results were then presented in tables and tornado

Table 7
Factors investigated in sensitivity analysis.

Factor Investigated	Base Value	% of base value (NPV)	% of base value (IRR)
Power Price	$0.20/ kWh	−50 to +50	−25 to +25
Inflation Rate	2%	−50 to +50	−25 to +25
Digestate Price	$3.40/t	−50 to +50	−25 to +25
Heat Price	$0.04/ kWh	−50 to +50	−25 to +25
Interest Rate	2%	−50 to +50	−25 to +25

charts (see Fig. 3).

4.9. Cost benefit analysis

The internal rate of return, net present value and the payback period were used to assess the financial viability of the biogas plant. The Net Present Value (NPV) was calculated as $NPV = \frac{R_t}{(1+t)^t}$ where R_t = Net cash flow at time t and i = Discount rate.

The IRR was calculated as $NPV = \sum_{n=0}^{N} \frac{Cn}{(1+r)n}$ where N = total number of periods, n = non-negative integer, Cn = Cash flow and r = internal rate of return.

The Payback Period (PBP) was calculated as $PBP = 1/\sum_{t=0}^{n} En = 1$ where I = initial investment of the project, E = the project net cash flow, n = number of periods and t = time.

5. Results and discussion

5.1. Scenarios

Four waste input scenarios were analysed, combining the inclusion of a baseload feedstock and alternative sources based on community benefits. All four scenarios are broken down into A and B where A includes the sale of heat and power with B includes the sales of heat, power and CNG.

In terms of the profitability of the suggested AD plant, all scenarios provide a positive NPV and IRR. The least profitable feedstock combination is outlined in scenario 3 due to the low biogas yield in the food waste whereas scenario 2 provides the most profit when including the sale of CNG. Scenario 2 provides an NPV of over $13.5 million and an IRR of over 14% with the inclusion of CNG sales. The cost benefit analysis and sensitivity analysis were based on scenario four, as this provided the community with the most benefits based on the feedstock inputs and economic performance. It should be noted that there are numerous alternative output methods for the biogas created, from the use of biogas for community heating, to the conversion into hydrogen for storage and distribution. Beyond using digestate by direct application to land as a fertiliser, future scenarios could be based on further valorisation including resource recovery producing mineral fertilizers such as struvite, feedstocks for microalgal biomass to produce bioplastic and production of multi-functional biochar following thermal pyrolysis [43]. However, such valorisation would require huge investment in separation technology at the very least and require extensive expertise which would be a huge challenge for an island community where they can readily use the digestate as is.

5.2. Cost-benefit analysis results

The cost benefit analysis was conducted on the basis of a digester capacity of 1.29 MW, this size was chosen due to the research showing that electrical efficiency tends to be higher for larger CHP systems that have the ability to include energy efficiency systems within the process [20].

Based on the economic analysis, scenario four provides the greatest benefits for the community. The digester has the capacity to produce 5,319,699 m^3 of biogas annually and 60,944 tonnes of digestate for use as a bio-fertiliser. With digestate being sold by the biogas plant at $3.40/t, this provides a saving for the agricultural industry of $4.7 million on the basis that all fertilisers used in Orkney are brought and not supplied by onsite farm production. The inclusion of abattoir waste in the AD production process will also provide a saving of at least $136 per animal for the farming industry. Based on the previous abattoirs' pre-closure figure of 3500 tonnes of abattoir waste, this would provide a total saving of $667,590 with the removal of transport costs and a less expensive gate fee. However, the inclusion of this waste source does create an additional cost for the biogas plant with the inclusion of licensing fees at $15,000 upfront and $10,244 annually [21]. Licencing fees are also required with the inclusion of food waste. The inclusion of

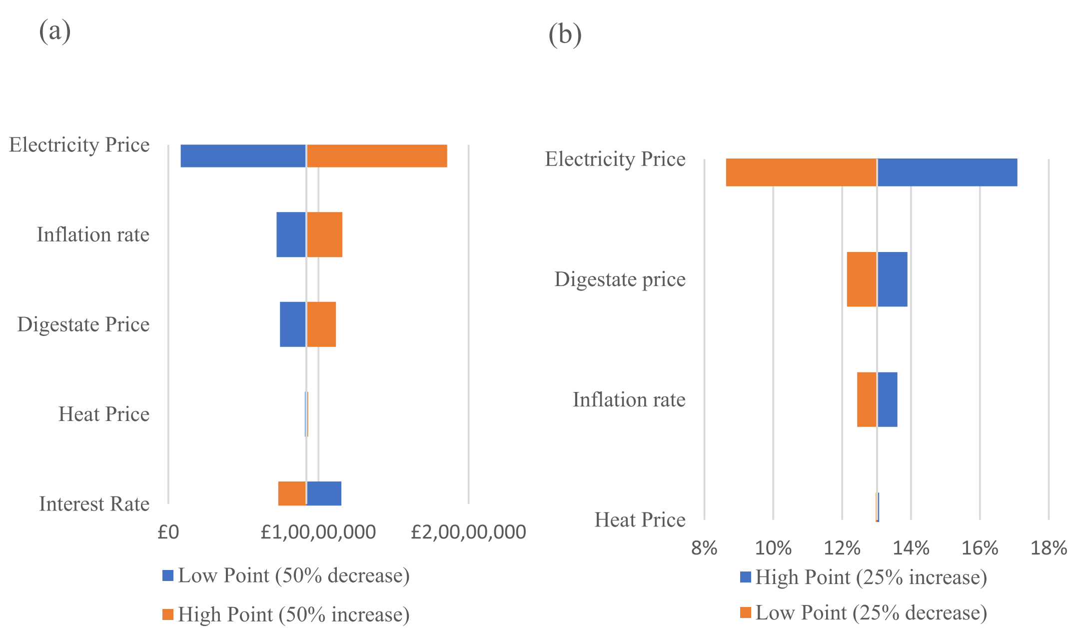

Fig. 3. Sensitivity Analysis of Scenario Four A Feedstock (a) with the sale of heat and power only (NPV) and (b) with the sale of heat and power only (IRR).

food waste will provide OIC with a saving of $104,907 a year with a gate fee of $14/t at the AD plant. However, this does create an additional cost of $15,000 upfront and $5465 annually from licensing fees.

The inclusion of a waste specific gate fee differs from many other economic AD studies; it is common to assume a flat rate of $14–27/t. This tipping fee is received by the AD facility for each ton of material received and processed [23,24]. However, in the case of Orkney, the gate fee is determined by the energy potential of the waste source to provide an incentive to the locals who already have waste management systems in place to use the AD plant as an alternative method to dispose waste with high biopotential.

The inclusion of the selected waste provides great benefits to the community of Orkney. Waste chosen is based on the local community, for example in Sacramento [23], a 1.8 MW capacity AD plant is run solely on garden and food waste due to the high amounts available. Despite the difference in biogas potential from these sources, they were selected based on the individual needs of the local area. It is extremely common for feedstock supply to be affected by the seasonality of the waste produced. In the case of many university/college cities and towns it is common for food waste to be a significant feedstock supply. However, these are subject to seasonal variability due to the large proportion of the population being college and university students that leave during the summer months [50]. This means that AD facilities in these settings require the inclusion of feedstock storage areas to hold significant amounts to allow for buffering. Fortunately, in the case of Orkney Islands, there is not a large fluctuation in population throughout the year. The seasonality of other feedstocks has been considered. The agricultural waste is subject to seasonal variability, as the cattle on the island are only housed for 6 months of the year. Therefore, a feedstock storage facility was included in the economic calculations. The inclusion of abattoir waste provides a local destination for animal by-products and retracts the need to transport animals to mainland Scotland for slaughter. This addition to Orkney will provide a key part of the move to become an independent island system and a potential industrial symbiosis system, whilst helping to close the loop and create an island circular economy.

Unfortunately, unlike Samsø, Orkney does not have the grid capacity for the energy to be directly connected, despite this the similar community spirit and environmental mindset on sustainability provide a similar setting [25]. However, the grid capacity allows for a much larger contribution in Denmark than the islands of Scotland. Providing an end-user for the energy generated is not the simplest output method. Contractual issues may arise in the procurement phase of planning however this avoids potential excess energy being released into the atmosphere [24].

In the case of an industrial symbiosis business model in Orkney, the energy produced could be used further on-site or connecting producers. This is the case in the Outer Hebrides Local Energy Hub [52], the inclusion of a wind turbine in the energy hub produces energy used in the AD plant due to the curtailment of the grid connections for the turbine. The similar island settings set the premise for familiar circular economy practices in Orkney, with similar issues of grid connection curtailment [26]. A proportion of the electricity generated in the OHLEH is sent to a hydrogen system to produce hydrogen and oxygen whilst a small amount is sent back to the fishery that provides waste for the AD plant. This hydrogen system has a capacity of 30 kW, storing hydrogen at 350 bar. There is significant potential for a similar process to be implemented in Orkney. The inclusion of agricultural greenhouses in the AD development will provide a fruitful output option. Alternative options include the use of the energy created being supplied back to the distilleries that provide significant amounts of waste for the digester. As demonstrated in this report, the suggested AD plant has the potential to provide 97% of the energy needs for the largest distillery in Orkney.

Other operational observations can be noted at this stage. The locations available do not provide significant restrictions to the space available for installations. As this is not an issue in Orkney, the consideration of micro-scale anaerobic digestion is not needed. This is the case in other parts of the UK. In large cities like London, space is very limited, and this has provided problems in the installation and maintenance of AD plants. Due to the urban area of the plant installation, noise and odour were other operational observations that needed significant consideration that Orkney does not [27].

The community benefits are difficult to cover in a cost-benefit analysis as many aspects are hard to quantify. Like many other AD plants, the community benefits are significantly recognised in the agricultural community with the use of bio-fertiliser over other types. This study suggests that the digestate (fertiliser) should be sold at a rate of $3.40/t relevant to the nitrogen content. However, alternative methods include calculating the costs by identifying the potential nutrients provided compared to organic fertiliser. In Idaho, the digestate provides 72% of nutrients, which is sold at 72% of the cost of organic fertiliser at a rate of $0.42 per ft3 [50]. If this method was used in the economic analysis above, the digestate in Orkney would be sold at a different rate. Other community benefits can be seen in the potential to produce CNG for biofueled trucks on the island. The inclusion of an acre greenhouse system will provide sustainable produce for the community and set an example for other island communities to upgrade their society towards a more circular economy lifestyle.

The methods used in this study provided a surface layer of waste data, however a deeper and more informative data set would have been preferable to gain more of an insight into the specific nutrient breakdown of the waste steams available. COVID-19 also has a significant effect on the data collection process as all data collection methods were required to take place online. Further research is required to gain a more detailed picture of the waste available in the case study location on a wider scale. The barriers to the commercialization of the project findings can be found in the financial aspect of installation and operation. An anaerobic digestion plant of this size will require significant funding and requires a local member of the community to champion the process and follow through with the commercialization.

5.3. Barriers

Despite the many benefits of AD to farmers, distilleries, businesses, and communities, regulatory and financial/operational challenges barriers limit the commercialization of AD technologies in the UK. The key barrier to the commercialization of AD, especially in the UK, is the increased regulatory requirements that farmers and AD operators should meet when planning and installing AD plants in their facilities. With the number of regulations and requirements to ensure that AD plants operate with minimal or no negative environmental and health consequences, an AD plant's operating and capital costs, especially with CHP, are too expensive for operators and AD suppliers. The issue is more pronounced in Orkney due to the island's sensitivity and pristine environmental conditions.

Besides the regulatory barriers, this research indicates that capital and operational costs, including maintenance, are another barrier facing AD farmers and operators in the UK. With the capital costs of about $4million and the running cost of around $425,000 per annum, AD technologies, especially in Orkney, may not be attractive for investors considering the payback period of 9–18 years depending on the Scenario choice. The potential lack of consistent supply of feedstock due to seasonality and waste management strategies encouraging waste prevention can prevent biogas production at scale, limiting the attractiveness of AD technologies to investors.

However, the Scottish government incentives and the opportunities to generate revenue from biogas production and its by-products could provide economies of scale for farmers and operators. While the UK government replaced Feed-in-Tariff (FIT) with Smart Export Guarantee (SEG) to empower small-scale generators, the selling cost per kilowatt of electricity generation is too low for any reasonable income/revenue. This issue makes AD less cost-effective and generally unattractive to

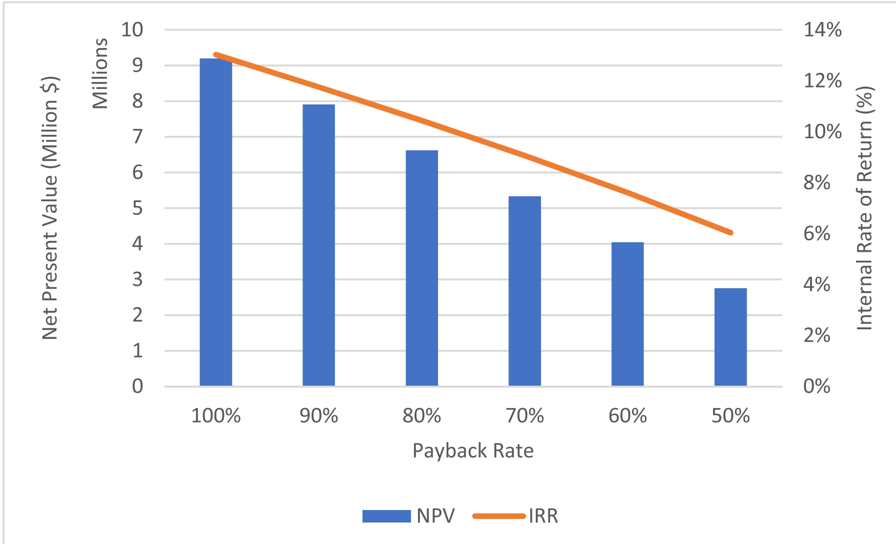

Fig. 4. NPV and IRR depending on payback rate (50–100%).

investors and generators compared to solar photovoltaic. The UK government can reduce/eliminate the impacts of these challenges and barriers by reducing regulatory requirements and policy burdens while providing grants rather than loans from banks to support AD operators and suppliers.

Although this research focuses on the Orkney Islands as a unit of analysis, the findings are relevant and applicable to other locations, especially rural areas and islands sharing the same attributes as the case study. Islands' vulnerability due to their relative isolation, a sensitive environment, high dependency on seasonal activities and external inputs, demographic imbalances, insufficient public structures, and the limited number of available resources suggest the importance of this case study to rural communities and islands. However, other rural areas and islands may not share the same sustainability and innovation culture, community spirits, social norms, and positive attitudes towards waste as Orkney islands, limiting the transferability of the findings of this research.

5.4. Sensitivity analysis

In the current economic position of the UK, many factors influenced the economic profitability of this project. The sensitivity analysis was performed to investigate the sensitivity of the biogas plants economic parameters to the varying factors over the expected range of variations. As a result, these changes could affect the financial indicators. The typical parameters investigated were outlined in the previous section. This data was presented in tornado diagrams (Fig. 3) which are a highly effective tool when analysing sensitivity and risk management of a project. The analysis showed that the most effective varying factor was the selling price of the produced electricity. Due to the high price compared to the sale of heat, the electricity provides more of a drastic change when modified. The second biggest risk of the project is the selling price of digestate. However, market research showed that the biogas plant could increase the cost as it is currently low compared to alternative fertilisers.

Based on the model (Four A) with a gross profit of $572,200, the table below shows the estimated IRR and NPV at suggested payback rates with 10% intervals. A positive IRR and NPV can be found at a minimum payback rate of 63%, as this provides an IRR of over 8%, ideal for investors. Fig. 4 shows the drop in NPV, and IRR based on the payback rate.

The sensitivity analysis provides a lot of what ifs. There are numerous external factors that could affect the inputs and the outputs of the suggested AD plant operations. Through strategic analysis, it was concluded that the industry competitors in Orkney are not a big threat. However, in a small community like Orkney, it could be possible for a much larger organisation outside of the community to infiltrate the island and distort the current settings of the suggested plant.

Due to the number of external factors the AD project is sensitive to, it is difficult to compare potential production scales with other CHP plants. External factors, such as the economic landscape of the country, can play a big part in the projected outcomes of an AD plant. For example, within the UK, the inclusion of governmental incentives in the production of renewable energy has been an option for a significant period of time. Before the development of the RTFO's, the renewable energy sector has been supported by Feed-in-Tariffs, RHI, and ROC's. The UK government has been a big supporter of the uptake of renewable energy [27]; however, there has been very limited uptake in the technology at the micro-scale [28]. As well as the development of financial incentives the UK government has attempted to further encourage the expansion of AD technology by addressing non-monetary barriers. The introduction of the Quality protocol for AD digestate, ensures that the bio-fertiliser meets the needs of the Publicly Available Specifications (PAS)110 standard [29]. It is fair to suggest that in economies below the blurred line of lower income countries, the uptake of renewable energy is hindered by some governmental practices. This is an example of how not all governments are as supportive of this type of renewable energy development.

In countries such as Mexico, the production of renewable energy has many barriers in place, such as instability in governmental policies put in place [24]. However, within the energy island in Samsø, there is significant support to aid the adoption of renewable energy sources through government legislation [25]. The inclusion of feed-in-tariffs act as an incentive for the first 10 years of operations, encouraging the uptake of biogas production. Studies suggest that with the inclusion of governmental subsidies and feed-in-tariffs that the 2million m3 biogas/year Samsø AD plant within the energy island will hold a payback period of 8.4 years. The suggested Orkney AD plant will provide a similar payback period without the use of feed-in tariffs, but the inclusion of RFTO's. In most AD plant financing solutions, it is suggested that borrowing is paid back over 5 years, with the target being met through the use of gate fees and energy sales. In many situations, the sales of the by-product in the form of digestate offers sustainable income of the AD plant.

Table 8
Study scenarios.

		Scenario 1A/B:		
Type of waste	Total t/a	Biogas yield m3/t		Energy generation (kWh/a)
Brewing and distilling waste	45,364	4,820,958		10,316,851
Slurry	3811	70,732		151,366
Animal manure	1100	76,560		163,838
TOTAL	**50,275**	**4,968,250**		**10,632,057**
Digestate	**45,248**			1.21 MW
Project Income and Expenses				
Scenario	**A**		**B**	
Total Annual Income	$1,262,250		$930,847	
Total Annual Costs	-$712,116		-$712,116	
Total Profit	$392,115		$60,712	
Project Outcome				
Profit (after tax)	$313,692		$48,569	
Payback Period	12.89		60.85	
IRR	8.99%		−1.16%	
NPV	$5,862,229		-$1,782,612	
		Scenario 2A/B:		
Type of waste	**Total t/a**	**Biogas yield m3/t**		**Energy generation (kWh/a)**
Brewing and distilling waste	45,364	4,820,958		10,316,851
Slurry	3811	70,732		151,366
Animal manure	1100	76,560		163,838
Abattoir Waste	3500	186,912		399,992
TOTAL	**53,776**	**5,155,163**		**11,032,049**
Digestate	**48,400**			1.26 MW
Project Income and Expenses				
Scenario	**A**		**B**	
Total Annual Income	$988,886		$1,233,606	
Total Annual Costs	-$288,367		-$288,367	
Total Profit	$516,884		$761,604	
Project Outcome				
Profit (after tax)	$413,507		$609,283	
Payback Period	11.88		8.22	
IRR	9.81%		14.17%	
NPV	$8,045,827		$13,691,061	
		Scenario 3A/B:		
Type of waste	**Total t/a**	**Biogas yield m3/t**		**Energy generation (kWh/a)**
Fish Waste	10,790	3803		8139
Food Waste	2200	139,392		298,298
Sludge	9,50	21,340		45,669
Brewing and distilling waste	45,364	4,820,958		10,316,851
Slurry	3811	70,732		151,366
Animal manure	1100	76,560		163,838
TOTAL	**64,215**	**5,132,787**		**10,984,165**
Digestate	57,794			1.25 MW
Project Income and Expenses				
Scenario	**A**		**B**	
Total Annual Income	$1,162,099		$1,261,403	
Total Annual Costs	-$731,509		-$731,509	
Total Profit	$247,513		$346,816	
Project Outcome				
Profit (after tax)	$198,011		$277,452	
Payback Period	23.21		17.14	
IRR	4.15%		6.43%	
NPV	$1,847,169		$4,137,882	
		Scenario 4A/B:		
Type of waste	**Total t/a**	**Biogas yield m3/t**		**Energy generation (kWh/a)**
Fish Waste	10,790	3803		8139
Food Waste	2200	139,392		298,299
Sludge	950	21,341		45,669
Brewing and distilling waste	45,365	4,820,959		10,316,852
Slurry	3811	70,732		151,367
Animal manure	1100	76,560		163,838
Abattoir Waste	3500	186,912		399,992
TOTAL	**67,716**	**5,319,699**		**11,384,157**
Digestate	60,944			1.29 MW
Project Income and Expenses				
Scenario	**A**		**B**	
Total Annual Income	$1,203,979		$901,583	
Total Annual Costs	-$303,041		$303,041	
Total Profit	$716,740		$410,344	
Project Outcome				
Profit (after tax)	$573,939		$328,276	
Payback Period	8.97		15.16	
IRR	13.02%		7.48%	
NPV	$12,532,172		$5,464,228	

Table 9
Summary of cost benefit analysis.

Summary of cost benefit analysis of the 1.29 MW biogas plant (Scenario 4 A)		
Components	AD plant generation	Alternative methods
Cost		
Investment costs	$4,100,000 initial costs	
Total operating costs	$680,000/a	$1360–6800/a (per organisation)
Total Costs		
Benefits		
Annual costs saving from the use of fertiliser	$3.40/t	$82/t (at lowest point in the past 12 months) [22]
Annual costs saving from fuel production	$49,047 based on the assumption of $1.9/l of diesel	
Annual costs saving from abattoir waste use in AD	$476,849 income from feedstock sales Minus licensing fees of $15,000/annum [21]	$327/animal (including transport costs) $1,144,437/annum
Annual saving gate fee of food waste	$29,973 at $14/t	$134,880 at $61/t gate fee at Shetland EfW facility [9]
Annual costs saving from energy production	$55/MWh heat $200/MWh power	$0.04/kWh heat $0.35/kWh power
Annual earnings from governmental incentives	$183,927 at $0.40/kg	–
Total benefits		
NPV	$12,532,172	
IRR	13.02%	
Discount Rate	2%	
Payback period	8.97 years	
Biogas plant use period	30 years	

Table 10
Calculated Payback rate.

Payback Rate (%)	IRR (%)	NPV	Payback Period (years)
100%	13.02	$12,532,172	8.97
90%	11.75	$10,775,242	9.94
80%	10.43	$9,018,312	11.15
70%	9.06	$7,261,381	12.71
60%	7.60	$5,504,451	14.79
50%	6.03	$3,747,521	17.70

5.5. Management of fermentation residues and membrane technology

The potential biorefinery products would be dependent on final AD feedstocks, operational parameters and require a good understanding of digestate composition. Depending on local/national needs some possible options are outlined in Table 11. Given that phosphorus is a critical raw material, approximately 400 y supply remaining, essential to life and only mined in a few countries with extensive societal and environmental impact, before even considering transportation costs re fuel carbon footprint etc, it is a prime resource for local recovery and reuse. Phosphate is successfully recovered from wastewater treatment plants by a range of processes including chemical and filtration processes. Chemical precipitation of phosphorus to produce struvite (magnesium-ammonium-phosphate (MAP) $MgNH_4PO_4$), a slow-release fertiliser is popular and efficient and ultimately more sustainable than application of digestate direct to land where significant phosphate can enter the watershed contributing to eutrophication, supporting an increase in toxic algal blooms [37]. Clearly the benefit of this process is additional recovery of N & K. Fertiliser can also be obtained by ammonia stripping, however, given the composition of the digestate and the need to maximise recovery of resources this would not be the preferred future option.

Pyrolysis, thermal decomposition in the absence of oxygen, of the dried solid fraction can be used to produce biochar, a designer charcoal which is an excellent soil modifier, adsorbent for pollutant removal and additive for biogas enhancement. In addition, this process can also produce syngas (CO_2, CH_4, CO and H_2) and bio-oil (hydrocarbons and platform chemicals such as furans and phenols) which have many potential applications. Combined application of biochar for carbon sequestration and nutrient rich digestate to land has been shown to offer improved net productivity and the combined AD-pyrolysis of biomass has the potential improve waste management of organic biomass and lower greenhouse gas emissions. It should be noted that the management of fermentation residues will become more complicated if "sludge" is used as a feedstock, levels of organic pollutants, nutrients (which significantly affect the process), heavy metals, etc. And therefore will need to be closely monitored.

Volatile fatty acids (VFAs) such as acetic, butyric and propionic acids are important platform chemicals traditionally produced from fossil fuels for use in a wide range of applications such as production of polymers, dyes, adhesives, food additives and pharmaceuticals. As there is a progression from a sustainable, linear economy decoupled from fossil fuels new sources of essential materials and chemicals are needed. Digestate from AD often contains high concentrations >5 g/L VFAs which may be recovered efficiently by a range of traditional and new methods (Table 8). Further, there is growing interest to use AD to produce these higher value chemicals in preference to biogas and biomethane or even use them as a feed stock for growing oleaginous microbes for production of high value polyunsaturated fatty acids such as docosahexaenoic acid (DHA) [38].

Nutritious digestate can serve as a feedstock for biomass production (microalgae, fungi, bacteria) to produce useful biomass for a wide range of products contributing to sustainability and removal from fossil fuels. Microalgae, in particular have the focus of much attention and grown successfully in heterotrophic and autotrophic systems, producing high, quality protein which can replace imported sources such as soya. Although the digestate typically needs some pre-treatment ranging from sand to membrane filtration, the advantages of using microalgae are vast as they can produce a huge array of compounds (lipids, proteins,

Table 11
Current and future options of valorisation of digestate.

PRODUCT	PROCESS	SCALE	APPLICATION	REF
STRUVITE ($MgNH_4PO_4$ or $MgKPO_4.6H_2O$)	Chemical Recovery	Commercial	High quality fertiliser	[54,55]
Ammonia	Ammonia stripping	Commercial	Fertiliser	[30]
Biochar	Pyrolysis	Commercial	Soil improver Pollutant removal Biomethane enhancement	[31] [56]
Volatile Fatty acids	Membrane technology, Liquid liquid extraction, Ion exchange electrodialysis	Pre-commercial	Platform chemicals	[32]. [33]
Microalgal biomass	Autotrophic or heterotrophic bioreactors	Pre-commercial	Feed for agriculture and aquaculture Biofuels	[34] [35]
Bioplastics	Autotrophic or heterotrophic bioreactors	Pre-commercial	Replacement of petrochemical based plastics	[57]
Nanomaterials	Thermochemical	Research	Pollution remediation Energy storage & conversion	[36]

pigments, polymers) and may exploit surplus heat and energy from AD plant along with waste CO_2.

The liquid fraction of digestate is a suitable feedstock for production of polyhydroxyalkanoates (PHA), a group of polyesters produced by bacteria and cyanobacteria (blue-green algae) triggered by nutrient limitation and stress. These biopolymers have been used to make high quality plastic with properties very similar to polypropylene, with the added advantage of it being completely biodegradable. In most cases, other co-products such as pigments may also be recovered whilst waste biomass may be returned to the AD plant completing the circle.

Production of functional nanoparticles with potential applications in many areas from AD digestate is also receiving increasing attention highlighting that this waste/co-product has great potential for valorisation.

Consideration to the recovery of metabolites throughout the different stages of fermentation is an important aspect of the anaerobic digestion process. However, this can require additional steps as the separation and recovery are very challenging, as an alternative to the traditional methods through the use of membrane-based technologies such as microfiltration, ultrafiltration, and nanofiltration [39]. The success of the process is determined by the characteristics of the compounds and operating parameters, and the type of membrane material, noting that appropriate to assess the quality of the organic matter which changes with storage time and conditions. The performance of the membrane is affected by the porosity and the morphological structure; however, improvement can be made by varying the pH, immobilising enzymes and incorporating specific functional compound groups. The performance of the membrane is gradually affected by the contamination of organic or non-organic matter in the pores or membranes surfaces as they build up and restrict or reduce the transport through the membrane. The membrane technology however offers a realistic opportunity for the recovery and capture of such renewable energy (molecules, gas, metabolites, chemicals) especially while considering the developments in membrane gas separation and pervaporation. The pressure driven membrane technologies facilitate the recovery of metabolites from fermentation broths, high-added value compounds from waste and biomass, algae harvesting among other applications.

6. Conclusions

Overall, this paper confirms the hypothesis of the implementation of an anaerobic digestion plant for an isolated island community providing a profitable outcome for all scenarios. The benefits within the community will not only be of economic value but also in a social context. This demonstrates that there is still value to gain from waste products such as brewery, distillery and farming waste, that are currently being disregarded, whilst suggesting the best possible mixture of waste streams. This paper also outlines the importance of providing a local community with the infrastructure required. The implementation of an anaerobic digestion plant, an abattoir, and a waste management structure will support the community to become an independent island system and potentially home to an industrial symbiosis system whilst helping to close the loop and create an island circular economy. It has been proved that there are many challenges with this technology, such as the gas upgrading requirements, fermentation residue management and grid connectivity, however a collaborative effort for the entire community will be vital in the success of the circular economy in an isolated environment.

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Conceptualization- Jemma Reynolds, Robert Kennedy, Mariah Ichapka, Abhishek Agarwal, Adekunle Oke, Elsa Cox, Christine Edwards and James Njuguna. Data curation - Jemma Reynolds, Robert Kennedy, Mariah Ichapka, Abhishek Agarwal, Adekunle Oke, Elsa Cox, Christine Edwards and James Njuguna.Formal analysis, Jemma Reynolds, Robert Kennedy, Christine Edwards and James Njuguna.Funding acquisition - Robert Kennedy, Christine Edwards and James Njuguna.Methodology, Jemma Reynolds, Robert Kennedy, Adekunle Oke, Christine Edwards and James Njuguna.Project administration - James Njuguna. Resources - Jemma Reynolds, Robert Kennedy, Mariah Ichapka, Abhishek Agarwal, Adekunle Oke, Elsa Cox, Christine Edwards and James Njuguna. Supervision, Abhishek Agarwal, Christine Edwards and James Njuguna. Validation - Jemma Reynolds, Robert Kennedy, Mariah Ichapka, Abhishek Agarwal, Adekunle Oke, Elsa Cox, Christine Edwards and James Njuguna.Writing – original draft- Jemma Reynolds and James Njuguna. Writing – review & editing, Jemma Reynolds, Robert Kennedy, Mariah Ichapka, Abhishek Agarwal, Adekunle Oke, Elsa Cox, Christine Edwards and James Njuguna.

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.

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