Sustainable Biomass Feasibility on the Isle of Man

Prepared for the Isle of Man Government

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NNFCC is a leading international consultancy with expertise on the conversion of biomass to bioenergy, biofuels and biobased products.

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Contents

Definitions

ABE	Acetone, Butene and Ethanol production
AD	Anaerobic digestion
BAT	Best Available Technology
BECCS	Biomass Energy Carbon Capture and Storage
CCS	Carbon Capture and Storage
CO_2e	Carbon Dioxide Equivalent
FAME	Fatty Acid Methyl Ester
FOG	Fats, Oils and Greases
FT	Fischer-Tropsch
HEFA	Hydroprocessed Esters and Fatty Acids
HVO	Hydrotreated Vegetable Oil
IPCC	Intergovernmental Panel for Climate Change
ktpa	Kilotonnes per annum (1000 tonnes per annum)
LCA	Lifecycle Assessment
LCF	Low Carbon Fuels
MEA	Monoethanolamine
MIE	Minimum Ignition Energy
Mlpa	million litres per annum
MSW	Municipal Solid Waste
mt	million tonnes
mtpa	million tonnes per annum
PM	Particulate matter
rDME	Renewable Dimethyl Ether
RED	Renewable Energy Directive
RCF	Recycled Carbon Fuels
RFNBO	Renewable fuel of non-biological origin
SRC	Short Rotation Coppice (willow)
SRF	Solid Recovered Fuel
Tpa	tonnes per annum
TPO	Tyre pyrolysis oil

Executive Summary

Decarbonisation of an economy requires a system of integrated supply options to displace current fossil-based processes. There are many renewable options for decarbonising the power sector; however, most of these technologies will only supply power intermittently. In the periods of reduced generation from such technologies, fast start-up systems are required to cover the variable power demand. Systems running on biofuels offer the best versatility for such occasions. Likewise, the heating sector has access to a range of low carbon technologies, but not all are suitable for off-grid properties and businesses, where reliable and controllable supply is required. Therefore, biomass in solid, or more typically liquid form, offers a viable solution for decarbonisation in such situations.

The Isle of Man is committed to producing or procuring 100% of its electricity from carbon neutral sources by 2030. It is evident from the Future Energy Scenarios developed in 2020, that dispatchable renewable biomass generation will be required, regardless of whether the Island deviates from using natural gas to generate electricity. Significant investment will be required to achieve this commitment, with existing stations requiring replacement in the next 10-15 years.

Production of low carbon biomass fuels is an established industry that encompasses a wide range of conversion processes and renewable feedstocks. To decide on the best technologies a comprehensive feedstock assessment is essential, to understand availability, sustainability, infrastructure requirements and the timeline for implementation and delivery. A transitionary phase is likely, with established, mature technologies being deployed first, before larger-scale, less mature technologies are phased in, potentially accessing a broader range of feedstocks over time.

An assessment of availability, based on various production and use scenarios, identified a number of key feedstocks that the Isle of Man could potentially produce and use sustainably to serve an emerging biofuel industry, using commercial technologies. These were wood, miscanthus, sugar beet, oilseed rape, food waste, livestock waste and potentially also sea kelp. Analysis of the power and heat generation systems currently in use or intended for replacement then highlighted five fuels that could be implemented using these feedstocks, including:

- Biomethane, produced from manure and food waste
- Ethanol, produced from either sugar beet (*or miscanthus)*
- Hydrogenated Vegetable Oil (HVO), produced from rapeseed oil or UCO
- Methanol, produced from wood (*or miscanthus)*
- Renewable Dimethyl Ether (rDME), produced from wood (*or miscanthus)*

Conversion of miscanthus to one of these fuels was not considered in-depth in the analysis as currently there is no commercial interest in converting it to biofuels. However, it was still identified as a longer-term solution and key feedstock for use in solid fuel combustion applications, where it could potentially support on-island heat decarbonisation with necessary investment in the production chain.

Biomethane can be produced by upgrading biogas resulting from the anaerobic digestion (AD) of food waste and livestock waste, for injection into existing gas distribution infrastructure or for direct supply to gas users on the island. As a mature, scalable technology, AD could be deployed rapidly on the Island as a transitionary step to some of the other less commercially ready and less scalable technologies outlined below. Biomethane could deliver a partially decarbonised gas supply, but the favouring of waste as a feedstock means production is constrained and its contribution is limited.

Ethanol can be produced by fermentation of sugar juice and molasses from sugar beet and from the extractable sugars of sea kelp. Ethanol from sugar beet is a well-established commercial process that could yield significant fuel to power the gas turbines on the Isle of Man (max output 180,000 MWh per annum). However, farmed sea kelp can grow in much greater volumes and produce more fuel thus providing a greater energy output. It is understood from the analysis undertaken in this report however, that the energy output per hectare from the growth of sugar beet and its conversion to ethanol for combustion in a gas turbine is significantly higher than the production and combustion of ethanol from sea kelp indicating there are still many technical barriers to utilising sea kelp in such applications.

Rapeseed and used cooking oil (UCO) could be used to produce HVO, which could be used as a low carbon fuel in reciprocating engines, yielding up to 235,000 MWh of energy. The same process would also yield up to 7,000 tonnes of biopropane that could be blended into LPG for use in existing or replacement heating systems, offering a multi-advantage solution, whist avoiding the need to establish new crop production systems on the Island.

Methanol produced via gasification of wood residues arising on the Island could produce up to 65,000 MWh and rDME could contribute up to 50,000 MWh, both via combustion in gas turbines. Details of the production processes are described throughout the report and illustrated in simplified process flow diagrams; opportunities and challenges are also discussed, and costs considered where possible.

It is important that feedstocks are produced, gathered, and converted in a sustainable manner, and often policy intervention is required to define, dictate, and monitor sustainable production practices to ensure biomass and the resultant energy is making a valuable contribution to the low carbon economy. In some cases (wood, sugar beet and rapeseed) alignment with existing voluntary schemes could provide a simple and quick route to implementing sustainable supply chains. As the cost of biomass feedstocks, conversion technologies and associated infrastructure are typically higher than other fossil or low-carbon options, consideration should also be given to financial incentives that could be offered for sustainable management, removal, and use of such materials. Specific to SRC willow and miscanthus, there is existing guidance from the International Sustainability and Carbon Certification (ISCC) scheme, but new policy guidance could be produced that focuses on protection of soils and existing ecosystems, whilst at the same time establishment grants could be offered to assist with high initial upfront costs, since these crops have long lifetimes and could be hugely beneficial on the Island. For sea kelp specialist advisors and auditors would have to be used as this remains a developing sector and knowledge is not as widely available.

Overall, sustainable biomass can make a significant contribution to the decarbonisation efforts of the Isle of Man, with the priority feedstocks identified here able to contribute up to 30% of the Island’s energy needs from a single fuel source in some of the scenarios considered, and potentially up to 55% if multiple fuels are combined. In all scenarios, significant investment will be required from the government or firm commitments made, to give industry the confidence required to facilitate and make the necessary investments in the supply chains or technologies themselves.

1. Background

The Isle of Man is a self-governing British Crown dependency approximately 572 square kilometres in size located in the Irish Sea. The Island has sought to decarbonise and set out its ambition in its Climate Change Bill in 2020. This includes an ambition to be net zero by 2050 and a commitment to produce or procure 100% of their electricity from low carbon sources by 2030. The Isle of Man Government has previously commissioned two reports to highlight strategies to decarbonise the power sector (Future Energy Scenarios) and the heating sector (Renewable Heat Strategy). Within these documents various methods of decarbonisation have been recommended with a focus on electrification and using renewable technologies such as wind and solar to meet the grid demand. However, the strategy cannot be solely reliant on these technologies in case supply cannot meet demand because of poor meteorological conditions or, in the case of heating, for homes and buildings that are off-grid, cannot be electrified or require back-up energy supplies to prevent disruption (e.g. hospitals).

Utilisation of biomass is a necessary step to decarbonise economies, featuring in all scenarios and it is a critical part of the pathway to net zero as recommended by the Intergovernmental Panel on Climate Change (IPCC) in 2018. The attractiveness of biomass is in its versatility, simplicity, and familiarity (comparative to other more novel technologies). During down periods of generation from other sources, or during peak periods of usage, additional short-term dispatchable generators fired on biomass are required to ensure grid capacity is maintained. The Isle of Man has two systems in place currently to handle these scenarios. These are a set of reciprocating diesel engines and a gas turbine generator, set to retire in 2027 and 2031, respectively, currently running mainly on fossil-based diesel and natural gas. The Isle of Man Government has a commitment to produce or procure 100% of its electricity from low carbon sources by 2030, which means these systems need to be converted to run on bio-based alternative fuels, or replaced with more sustainable alternatives. In addition to the changes required in the power sector, the domestic heating sector is one of the biggest contributors to greenhouse gas (GHG) emissions on the Island (1). Although the Isle of Man Government is focused on first insulating homes and then electrifying heat sources, there will still be a requirement for biomass to be used to heat difficult to decarbonise homes and buildings.

Dispatchable generators operate throughout the year providing balance support to the gird. The generators could be used in a greater capacity to fulfil more of the Island’s energy demands; however, there should always be the flexibility to increase power output when needed for spikes in demand. If the renewable fuels produced, targeted at electricity production, could also be used in the heating sector this would be beneficial for the overall feasibility of a biomass supply chain. Potentially, surplus biofuels may also be used in the transport sector; however, this is out of scope of this report.

Production and use of liquid and gaseous biofuels is an established industry and offers a diverse landscape of production pathways, using a diverse range of feedstocks. However, new conversion routes are emerging, with improved conversion efficiencies, greater sustainability benefits, and flexibility to utilise a wider range of priority feedstocks; these may be suitable for commercial deployment in the near term.

To evaluate the most feasible options for liquid and gaseous biofuel production, an understanding of the raw materials and fuel processes that are either currently established, in development or likely to emerge in the near future, based on their likely technical and commercial viability, is required.

Additionally, the sustainability and feasibility of producing and using the desired feedstocks need to be considered, along with policy measures required to ensure their sustainability. This includes an understanding of the emissions from both production and combustion, as well as suggestions of abatement technology or best practices to minimise environmental impact.

In building this understanding, the Isle of Man Government require:

- An assessment of the available feedstocks on the Island, including the maximum yield, and forecasting changes in availability over time.
- Identification of the most viable feedstocks based on availability.
- An understanding of the drop-in fuels or likely replacements for current systems.
- An overview of the fuel production processes and the volumes of fuels that can be produced.
- The sustainability implications and environmental concerns of growing & harvesting the most viable feedstocks, the conversion processes to produce the key fuels of interest, and combustion of the fuels.
- An indication of costings, for feedstock and fuel production, and supply.
- Analysis of the relevant policies and sustainability measures applicable to the production processes being considered.

The output will be used to assist the Isle of Man Government in determining which feedstocks and technologies should be included in their future decarbonisation strategies.

While biofuels such as biogas, biodiesel (FAME) and bioethanol have developed at scale globally, more technically complex *advanced* biofuels based on the use of waste feedstocks, produced through thermochemical conversion or biotechnology routes, are at a much lower technology readiness level (TRL) and in many cases are yet to be deployed at scale. The stimulus for these more novel technologies typically comes from government incentives such as the UK renewable transport fuels obligation (RTFO). Additionally, incentives are driving the deployment of fuels from a non-biological origin, such as hydrogen and methanol; however, these processes are still in the early stages of development and challenges around transport, storage and distribution remain.

This assessment gives a holistic view of available feedstocks, potential conversion routes and their suitability for implementation on the Island. Although within this assessment recommendations are given for the most suitable feedstocks, based on the criteria mentioned, more detail may be required to fully understand the impacts of certain pathways, such as full lifecycle assessments (LCAs). The initial list of feedstocks, supplied by the Isle of Man Government, had been identified as of interest. Some additional recommendations have been suggested based on NNFCCs experience in the sector.

2. Approach

NNFCC led the analysis with some assistance from GemServ on stakeholder engagement, due to their prior involvement in related projects. It is important to highlight that some the production pathways considered are novel and in an early stage of development, so technical and economic data is not available, or remains commercially sensitive. Utilisation of certain feedstocks are currently limited to research- or pilot-scale facilities and some processes may still be at company-level R&D stage, so again technical, economic, and environmental information can be limited, and full pathway analysis is not yet possible. Using available data, the analysis was performed via a series of linked tasks.

Task 1 - Identification of relevant feedstocks and their availability

There are a diverse range of feedstocks that could be used for biofuel production. A list of feedstocks identified by the Isle of Man Government have been analysed for their availability, using up to three scenarios where necessary: considering low, medium, and maximum production potential (terms are defined in the following sections). Availability has been forecast to 2050, based on individual factors considered to have the greatest influence, using information in the public domain and through stakeholder interviews. Where appropriate, availability analysis accounts for competing uses in other sectors, where waste is seen as a by-product and of value elsewhere. As well quantifying availability, the potential contribution has been stated in energy terms, based on the gross calorific value of the feedstock.

Further information on each option has been collated and considered; including information on the challenges and sustainability of using specific feedstocks, how supply could affect the carbon balance, and the impacts on biodiversity from cultivation, harvesting, collection and removal or specific feedstocks.

Biomass imports have also been considered for those feedstocks that are currently being traded on a commercial scale, looking at availability in the UK and EU. Where information is available, the price of these feedstocks has been expressed and the factors that could influence prices in the future considered. Infrastructure implications of importing these feedstocks have also been accounted for.

The final consideration was the cost of producing the feedstocks of interest. In some cases, this is a farming activity whilst in others it is a collection and logistics process. In all cases the cost is indicative and considers the key supply chain activities, with consideration of sustainable production methods.

A Multicriteria Analysis (MCA) has been undertaken to determine the five most feasible feedstocks of interest. The factors used in the analysis include current and future availability (security of internal supply), competition from other markets, and the practicality of importing the material (including the infrastructure requirements), to deliver supply flexibility now and in the future.

Task 2 - Understanding of the current power generation systems, fuels for heat sources, and selection of the appropriate drop-in fuels

To determine the fuels that could be produced and used, the energy and heat generation systems utilising these feedstocks must be understood. This includes understanding the fuel requirements of the system, thus the potential drop-in replacements or fuels that could be part-blended into the mix. Based on the feedstocks of interest and current systems in place, the fuels of interest have been identified for further discussion. Only the most commercially ready processes have been considered and discussed at this stage.

The most promising feedstocks for use in decarbonising the dispatchable generators on the Isle of Man are discussed, based on availability and applicability in different conversion processes (fermentation, digestion, gasification, and pyrolysis), as identified in the initial two tasks.

Task 3 - Analysis of the conversion processes

An overview of the fuels that can be generated from various feedstocks is shown in Figure 1. The most commercially-ready production pathways were considered and a process flow diagram (PFD) presented for ease of illustration. Additionally, feedstock requirements and limitations, process constraints, and the volume of fuel that can be produced over the target timeframe have been considered, to determine the contribution each option could make to the Island's decarbonisation strategy.

Production costs have been considered where information is available. However, as some of the technologies are not yet deployed at commercial scale, cost information remains commercially sensitive and is not available. In such cases broad assumptions have been made or a comparative assessment has been made based on similar scales and types of technology. In some cases, fuel production costs (incl. feedstock cost) have been compared against the market price, providing an indication of the project feasibility or consumer impact.

The potential for bioenergy with carbon capture and storage (BECCS) has also been considered at a high level, with a focus on its potential connectivity with the UK's CCS network.

Task 4 - Assessment of the sustainability and environmental impacts from feedstock & fuel production and combustion

Based on the information and selections made in the previous sections, key sustainability and environmental considerations have been highlighted and discussed, including:

- Implications of growing and harvesting the selected biomass; soil carbon balance, requirements for pesticides and fertilisers, and the impacts this could have on land and water, the impact on biodiversity and land-use change.
- Emissions concerns from solid fuel combustion systems.

Task 5 - Policy recommendations

This task focusses on best practice guidance and current methods of production, conversion and use, to prevent negative impacts on the environment or local economy. Methods of implementing, monitoring and auditing this to maintain the necessary standards are also discussed.

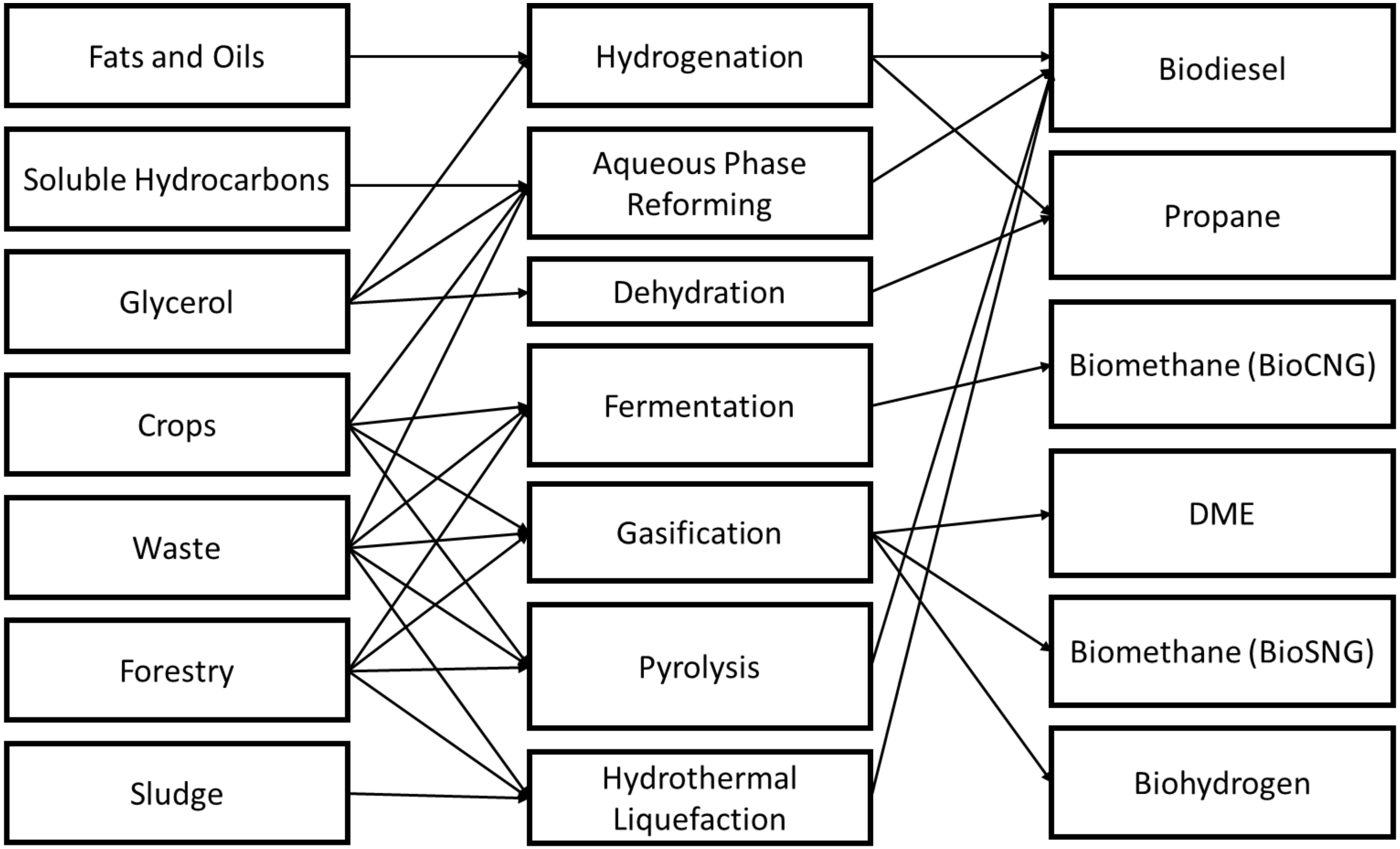

Figure 1: Fuel production pathways considered in the analysis

3. Feedstock Availability

The Isle of Man covers almost 60,000 hectares with land use varying from the undulating south, with rich soils supporting mixed farming, to the central uplands with thin soils supporting extensive beef and sheep production, and the flat northern plains used for arable and vegetable production. The Island is ideal for grass growing and livestock represents the mainstay of the agricultural economy. Traditional family farms, smaller fields and generally extensive production methods mean that farming continues to shape a landscape much valued by residents and visitors.

Livestock numbers on the Island have been relatively stable over recent decades, but have shown a slight decline in recent years, peaking at 208k in 2008, before slowly decreasing to 169k in 2018. Main livestock types include cattle, sheep, pigs and poultry (62). The Island has one abattoir, one creamery and one flour mill. All milling wheat grown on the Island goes to the mill which produces a range of flours sold on- and off-island. Most livestock are killed at the abattoir, although there are some live exports for slaughter or breeding.

According to the Future Energy Scenarios report, there has been little land use change on the Island since 2010 (up to 2018); this aligns with the Island's environmental policy, which is to avoid any permanent loss of high-grade agricultural land.

Woodland is estimated to cover approximately 5,388 hectares, equating to 9.4% of the Isle of Man. This includes 2,818 hectares of Government-owned conifer plantations, 400 hectares of Government-owned glens (mostly semi-natural broadleaved woodland), approximately 1,921 hectares of native broadleaved woodland, and around 200 hectares of privately owned conifer plantations.

In addition to the agricultural and forestry resources, biomass feedstocks could result from human activity in the form of food waste or processing residues, or from the marine sector, in the form of kelp. All such sources have been considered, with the key feedstocks discussed in this Chapter and additional opportunities discussed and quantified where possible in the Appendix.

This section analyses the potential available feedstock volumes based on up to three scenarios; low, medium, and maximum, defined as follows:

- The **low scenario** represents the amount of biomass that could be obtained from existing resources, without impacting land used for food production or other markets.
- The **medium scenario** represents the amount of biomass that could be obtained by addressing specific production constraints, such as collection infrastructure, competing markets or sustainable farm diversification.
- The **maximum scenario** represents the amount of biomass that could be produced if production was unconstrained; likely impacting on land-use, existing markets and wider ecosystem services. This scenario has not been modelled where it would lead to unrealistic, unsustainable and potentially damaging levels of activity.

All scenarios are based on current land availability and population, with forecasts out to 2050 based on expected market and demographic changes. The data used has been compiled from publicly available data sources and stakeholder interviews. These numbers are an estimation and should be used as such for context only.

The feedstocks considered in this Chapter include:

- Livestock Waste (manure)
- Agricultural Residue (straw)
- Agricultural Crops (miscanthus, sugar beet, rapeseed)
- Wood (forestry residue, wood processing residue and short rotation coppice willow)
- Fats and Oils (rapeseed oil, used cooking oil, and animal fat waste)
- Food Waste
- Sewage Sludge
- Seaweed (Sea Kelp)

Additional feedstocks that were considered in the preliminary analysis are shown in Appendix A, including: fruit and vegetable wastes; managed heathland, heather and bracken; the biogenic fraction of waste tyres; slaughterhouse and fish waste; brewery and distillery waste; and dairy processing waste. These feedstocks were discounted as priorities because of low availability, strong competition from other markets, or challenges collecting or using them. Volumes are summarised at the end of the chapter, in Table 3 for comparative purposes. For each feedstock competing uses have been listed, whether this would be considered a priority over fuel production and its implications for availability.

The final consideration for each feedstock was the availability of imports, with the primary question being is it feasible. For feedstocks that are already traded at commercial scale, availability in the UK and EU has been briefly discussed, as well as the current market price and the infrastructure requirements to be able to import them.

3.1 Livestock waste

Livestock waste, in the form of slurry and manure can come from a variety of animals including cattle, horses, sheep, pigs and poultry. Manure is rich in carbon but biologically active and therefore a good feedstock for anaerobic digestion (AD), with the AD process replicating ruminant digestion.

The majority of manure (>70%) is spread to agricultural land as fertiliser. Animal waste is typically collected as separate solid and liquid fractions, referred to as manure and slurry respectively. Manure is typically stacked on field edges or on hard standing for a minimum of 8 weeks before spreading (2); however, it can remain in storage for around 12 months without degrading significantly. Similarly, slurry can be stored for prolonged periods without degradation, but requires tanks or lagoons to contain the material in liquid form. Open storage of manure and slurry can have a significant greenhouse gas impact, resulting from methane release; however, good practice is to cover open storage to prevent the release of methane, and to spread manure and slurry using low-emissions equipment at times when run-off is low and uptake by the plants is high. The biggest constraint with using livestock waste more widely is its typically high moisture content, with slurry reaching over 80%, making transportation costly. Manure and slurry is best treated or used locally, within 10-15 miles of the source, to minimise transport costs and the associated environmental impact.

The AD market is expected to grow, as a greater number of typically larger AD facilities are established, producing biogas and subsequently biomethane to be injected into the grid. The resultant gas would be a potential resource available for energy generation on the Island; however, gas grid connections for such decentralised production facilities are not commonplace, so collection and distribution options need to be considered. The upgraded biogas, known as biomethane, can be injected into the national gas network, to decarbonise the contents, which will in-turn present a more sustainable fuel to the gas turbines on the island. Full decarbonisation via this route is unlikely, as there would be insufficient feedstock available to fully decarbonise the gas network on the Island. However, alternative options exist for direct supply to the existing gas turbines, including a virtual network (transporting biomethane by road), gas production and storage hubs collecting gas from multiple smaller production sites, or dedicated biomethane pipelines via direct connection.

3.1.1 Availability of livestock waste

Animal wastes considered in this report are those arising from sheep, poultry, cattle, pigs, and goats. Numbers of each animal were taken from the Agricultural Holding Census 2015-2021 (62). Sheep and goats are generally reared outside, making it unfeasible to collect the manure; therefore, production volumes are assumed to be zero from these animals in this analysis. The manure generated per day by each remaining animal was taken from previous work by NNFCC. The current volumes of manure arising from cattle, pigs and poultry on the Island are shown in Table 1.

Table 1: Estimation of the Island's livestock waste resource

Animal	Sheep	Poultry	Cattle	Pigs	Goats
Number (3)	123,090	15,342	26,740	1,628	174
Collection efficiency (%)	0	90	50	60	0
Total manure/day (t)	0	1.10	250.68	3.32	0
Total manure/year (t)	0	403	91,561	1,213	0
Total (manure t/y)	93,178				
Total on a dry basis (manure t/y)	15,000				

The main factor influencing availability is the number of cattle which is declining on the Isle of Man at a rate of 2% per annum; this rate is used to model the low scenario. The medium scenario is modelled on a decreasing rate of change. Forecast future availability is illustrated in Figure 1.

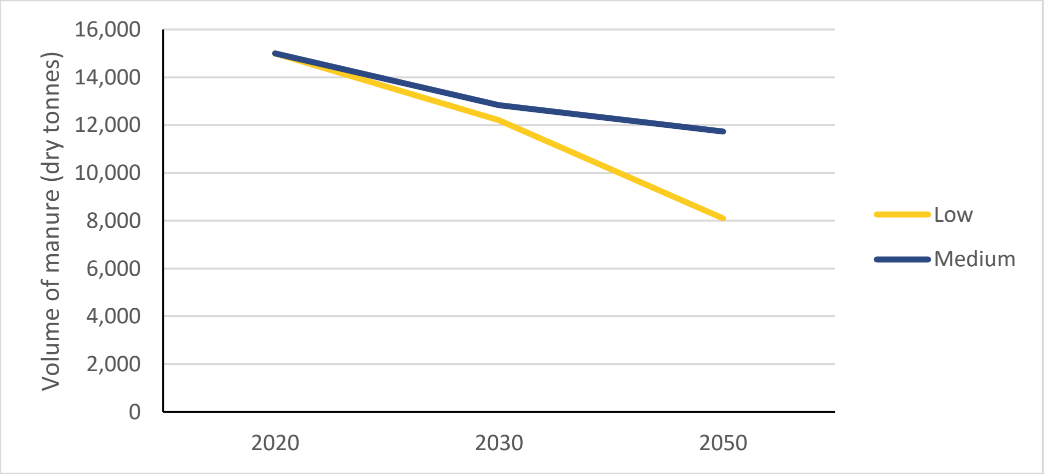

Figure 1: Livestock waste availability, actual and forecast, from 2020-2050

In the low scenario the decreasing number of cattle is expected to reduce the volume of manure available by almost 50% by 2050 (~8,000 (dry) tonnes per year). It is expected that with dietary changes, the population of cattle will continue to decrease; however, it is expected to eventually reach a steady state, as human population continues to rise. The medium scenario forecasts an early point when steady state is reached, thus estimated availability is slightly higher in 2050 at 11,700 (dry) tonnes (delivering 55,400 MWh).

Although not widely traded, as it is most commonly used on land adjacent to the point of production, typically under the same ownership as the source livestock, manure and slurry is generally valued based on its nutrient value. Currently, (solid) manure from cattle and pigs is valued at around £12-18 per tonne, whilst (liquid) slurry is valued lower, at around £3-5 per tonne, ex-farm. Manure and slurry should be processed or used locally (ideally within 10-15 miles of the source), given the low density and high moisture content, meaning transport and storage costs can be high.

3.1.2 Competing uses of livestock waste

Spreading of livestock waste to agricultural land is a critical process in ensuring soil health is maintained, through both soil organic matter levels and biodiversity. If all manure arising on the Island were diverted to energy production, it could have a negative impact on these two factors. However, if treated through AD the resultant digestate could be spread to land after the energy has been captured, returning the required nutrients and organic matter and capturing much of the methane contained within the slurry, thus delivering a more sustainable whole systems approach.

3.1.3 Importing livestock waste

Livestock waste is not a traded commodity. The high moisture content means it cannot be transported long distances and therefore it is not possible to increase availability beyond the levels produced and captured sustainably on the Island.

Due to feedstock limitations and logistical constraints, AD of solely livestock waste is not expected to make a significant contribution to the on-island energy requirements, but could be viewed as a useful transitionary step, available for immediate deployment before other technologies can be adopted.

3.2 Agricultural residues (straw)

Straw is a residue from the farming of food crops such as wheat, barley, oilseeds and pulses. In traditional farming methods this straw is either taken for animal bedding or left in the field to decompose and restore the soil carbon content. Straw is a seasonal feedstock, produced during summer, and when baled and collected it requires storage on field margins or hard-standing until it is required. Covering straw with temporary sheets or in buildings protects the quality of the straw and prevents decomposition prior to use.

Straw is a desirable feedstock because of its homogeneous chemical and physical properties. Straw is low in lignin but high in hemicellulose and cellulose meaning the sugars can be easily extracted, making it suitable for biological processing. It is also suitable for thermochemical processes, but can be high in chlorine and alkali metals which creates technical complexities (4). Straw has some commercial applications outside of the livestock sector, for bioethanol production and in AD, for example. The moisture content is variable depending on the weather conditions at harvest; however, it is typically left in the field for a few days to bring the moisture content below 15-18% before baling.

Currently it is recommended to incorporate 50-65% of straw into the soil post-harvest, which has a significant impact on availability when also considering demand from livestock (5). If only the fraction considered removable is taken, GHG emissions from field operations, nutrient recovery, and transporting the straw to a processor (within 30km) will be between 60-90 kg CO_2 eq. per tonne of straw (DM). However, if all the straw is removed this will increase to between 80-115 kg CO_2 eq. per tonne of straw (DM).

Counteracting the impacts of removal, if a cover crop such as mustard is used this can offset emissions and the overall carbon balance is net negative (between -13-67 kg CO_2 eq. per tonne of straw (DM)) (6). These values are dependent on the location and do not consider the end application; however, it does imply that the straw can be removed from the land without detrimental impact to environment.

3.2.1 Availability of Straw

The yield of straw was calculated using crop area data, yield per hectare, the ratio of straw to crop, and the percentage of straw recovery. The annual volumes of straw calculated to be produced on the Isle of Man are shown in Figure 2. In the medium scenario, the 2018 census data was used for the arable land (8,527 ha) and the crop split, assuming a greater proportion of wheat and slightly less barley, with similar areas of other cereal crops. When forecasting future availability, the land area, straw collection efficiency and crop split was varied based on current trends. More details of the forecast are shown in Appendix A.

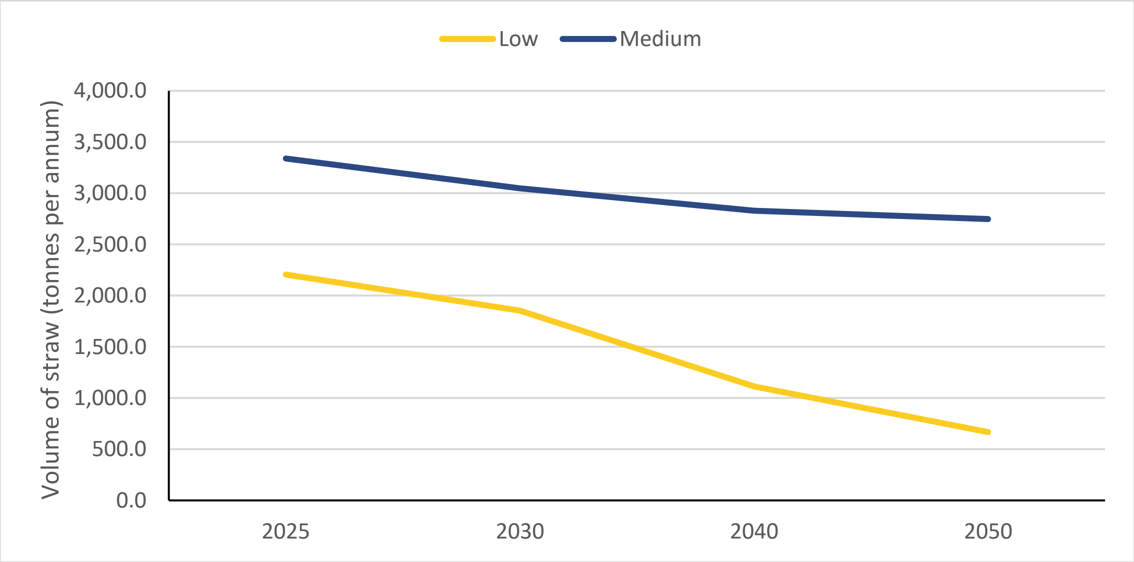

Figure 2: Straw availability, actual and forecast, from 2025-2050

In the low scenario, the annual yield is estimated to be 2,275 dry tonnes (delivering ~9,000 MWh), based on current availability. In the medium scenario because of the increase in land availability it is estimated that there will be 3,700 dry tonnes (delivering ~15,000 MWh). In both the low and medium scenarios, barley makes up most of the feedstock and it should be noted barley straw is also valuable as animal feed and bedding material, so competition is likely to be high.

The low scenario is forecast based on the current compound reduction in arable land, which results in only 660 dry tonnes of straw being available by 2050. In the medium scenario crop collection efficiency was increased, based on the assumption that harvesting technology will improve from 2040. This lowers the impact of the reduction in land use, thus by 2050 it is forecast there would be 2,700 dry tonnes of straw available.

No maximum scenario was modelled for this feedstock as removing higher volumes of straw from the land would be deemed unsustainable and would have damaging impacts on soils, the wider ecosystem and the environment, as well as impacting availability for livestock.

Across the UK, the current average ex-farm price for wheat straw is £44 per tonne – this represents a major reduction from mid-2021, where prices had reached a high of £105 per tonne due to production constraints and high demand because of a prolonged wet winter when livestock required housing. Barley straw traditionally commands a price premium over wheat straw due to its higher animal feed value.

Prices for the raw material on the Isle of Man, based on inherent nutrient value and in-field collection costs, are similar to those commanded in the UK, and equally volatile given production constraints and variable demand, depending on external factors such as rainfall and winter temperatures. However, in addition to the price of straw, costs will also be incurred for transport, storage, handling and insurance, for example. The addition of these associated infrastructure costs, adjusted for the standard mark-up experienced on the Isle of Man, bring the total price of straw to around £70-75 per tonne, delivered to the processing facility.

3.2.2 Competing uses of straw

Straw does have a value in other sectors such as animal bedding and feed, therefore if all the straw removed was used in energy production it could cause issues in other sectors. The main other use is for regulation of soil carbon and nutrients, which is becoming increasingly valuable given the recent rise in synthetic fertiliser prices and production constraints. If more straw is removed, this could have impacts on soil health and biodiversity. If the soil organic matter is not maintained this will impact on the population of worms and insects on the surface of the soil, which would have a compounding impact further down the food chain, for example on farm birds feeding on those worms (25).

There are many saprophytic microorganisms that are also dependent on straw as a substrate for growth (27). However, excess straw that does not degrade efficiently could lead to increases in cereal diseases which could impact future crop growth (26). Therefore, finding uses for excess straw could be beneficial to other sectors and the environment.

3.2.3 Importing straw

Straw has a relatively low energy density and thus is not typically traded or moved internationally because of the economic barriers. However, ongoing work and interest in straw as a feedstock is creating international supply chain scenarios which could be in commercial operation soon. Furthermore, densification of straw by pelleting or briquetting is also becoming more commonplace, so although it would be technically feasible to import straw pellets or briquettes, it would remain cost prohibitive due to the additional processing steps and energy demands for this activity.

3.3 Miscanthus

Miscanthus is a dedicated energy crop, grown as a raw material for bioenergy. Miscanthus grows well on lower grade land that is not highly accessible or productive for conventional cropping and therefore provides a diversification opportunity for farmers looking at alternative cropping options.

Miscanthus is a perennial rhizomatous grass originating from Asia. Stems emerge from the rhizome annually through March and April. In the first year of growth stems reach up to 1-2 metres in height by late August. The cooler temperatures in autumn trigger senescence and translocation of nutrients to below ground parts of the plant. By February only dry leafless canes remain; the fallen leaf material recycles nutrients and returns organic matter to the soil providing a mulch layer which helps to suppress weeds in spring. In the first year of growth the yield is limited, and the stems often remain uncut. Annual harvesting takes place from the second year, during which the crop can be expected to reach a maximum height of 3-3.5 metres. The crop has a useful life of 15-20 years (7).

Miscanthus uses more water than conventional crops during the spring season, capturing rainfall during prolonged wet periods and preventing runoff. Research has shown that miscanthus will dry out the ground more than other crops such as willow, corn and switchgrass (8); hence it can be grown on typically wetter pieces of land, which may be too wet for conventional crops. Miscanthus can grow without the need for fertilisers as so much organic matter falling from the plants is returned to the soil, which combined with its runoff protection ability delivers a sustainable crop option for less productive arable land, with low input demand post-planting. Miscanthus can remediate land from some impurities such as high levels of nitrogen or metals, thus cleaning up the land for subsequent crops. These are additional benefits that could help meet other environment and sustainability goals.

Growing miscanthus has been shown to improve soil organic carbon levels, sequestering between 0.42-3.8 mg per hectare per annum on arable land; however, where lands are well managed by effective crop rotation and organic loading, the impact is likely to be slightly lower (9). For grassland, the changes to soil organic carbon from growing miscanthus were insignificant, as a one-off cultivation on previously well-managed soils decreases the benefits. Therefore, it would not be sustainable to convert long-term grassland to miscanthus production (10).

Miscanthus is a dense canopy crop, so does not provide a good habitat for ground nesting birds and large mammals; however small mammals and other birds thrive in the crop during summer and winter months. Typically, well managed headlands remain around the crop to offer suitable space and habitats for such species to migrate into when the crop is cut and removed annually, in late winter through to early spring. It is also possible to improve the biodiversity benefits of the crop by mixing the growth of miscanthus with open areas of wild flowering or agricultural crops such as barley (11).

Miscanthus will grow on a wide range of soil types, however higher yields are achieved on moisture retentive soils which warm up quickly in spring to enable the longest possible growing season. It is typically planted as rhizomes from which the shoots propagate. In the UK, miscanthus is typically planted in March and April using specialist precision planters. Growing from rhizomes is expensive, costing approximately £2,500 per hectare to establish. It is recommended that a planting density of 15,000 plants per hectare is used. A typical yield is 15-18 fresh tonnes per hectare per annum (7).

3.3.1 Availability of Miscanthus

The area of agricultural land on the Isle of Man is just over 43,000 ha, with almost 30,000 ha dedicated to arable and temporary grassland, with the remainder being uncultivated rough grazing and unmanaged lands. Currently only 2.1% of arable land in the UK is used to cultivate energy crops and only 0.1% of land in England is used for miscanthus (12) (13).

There are no commercial producers of miscanthus on the Island, therefore it was assumed that a first harvest could be taken no earlier than 2024. To ensure the introduction of miscanthus was deemed sustainable, the ramp up of production area would have to be slow and well managed.

Yield data was taken from published sources (7) (14), assuming a modest yield for year two and a higher stable yield of 13.5 dry tonnes per hectare for twenty years thereafter, reducing to zero by 2050 if no new crops are planted. It may be possible to reduce this rapid decline by phasing planting and balancing a phase-out of old crop with new plantings as yields start to reduce from 2040 onwards. For the low scenario, 5% of managed agricultural land (arable and rotational grassland) is dedicated to miscanthus production, whilst in the medium scenario this increased to 20%. No maximum scenario was modelled, as increasing production above 20% would likely have a damaging impact on biodiversity, the ecosystem and the wider environment, as well as negatively impacting food production and existing market dynamics on the Island. The scenarios and availability forecasts are shown in Figure 3.

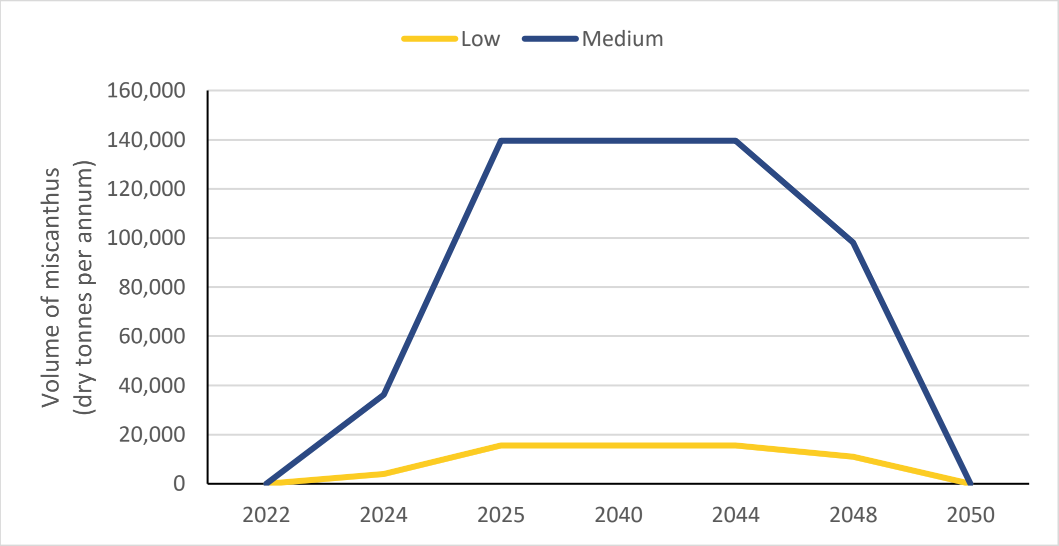

Figure 3: Miscanthus availability, actual and forecast, from 2022-2050

Under the low scenario, if 5% of the total managed agricultural land on the Isle of Man, equating to 1,500 ha, was used for miscanthus production this would produce approximately 15,500 dry tonnes per annum,. This volume has a net energy content of 70,000 MWh per annum from year three onwards (not considering the efficiency of conversion). By assuming all target land is converted in the first three years, the decline in feedstock availability is unavoidable unless old crops are removed and replaced on a cyclical 15-20 year basis. Effective plantation management could be established, to ensure a more consistent supply, but availability would be reduced given frequent replanting needs.

The medium scenario is a highly optimistic outlook, whereby around 6,000 ha would be dedicated to miscanthus, displacing some of the temporary rotational grassland and potentially a small amount of the 3,000-4,000 ha of arable land under active management at present (3). It is assumed that high proportions of the managed grassland on the Island is grown on a rotational basis with crops, not lasting for more than 3-5 years. This being the case, the grassland would be deemed 'temporary' and no land-use change issues would be foreseen. However, if areas of longer-standing grassland, deemed 'permanent' or recently unmanaged rough grazing, were considered for miscanthus production, sustainability questions around soil health, biodiversity and land use change would be posed. For biomass to be considered sustainable, historical data, and geological and environmental surveys would be required to demonstrate there has been no negative impact on the land. As this is a granular process, considered at individual field-level, it is not within the scope of this report. If longer-term grassland is to be considered for biomass growth, consultation with a sustainability certification body such as ISCC or SBTi (Science Based Targets) should be sought before any changes are made.

The price of miscanthus is largely dictated by the market and its energy value. In the UK, where the supply chain is relatively well established, prices of £50 – 70 per tonne are commanded, ex-farm. Haulage costs can be high, given the low bulk density of the material, so local use is preferable and in addition to the planting costs, additional costs will be incurred for transport, storage, distribution and insurance of the crop, increasing the price to the end-user. The total cost of supply into a processing facility would amount to around £110-120 per tonne (delivered) on the Isle of Man, based on typical UK costs for production and infrastructure, adjusted according to the standard mark-up on infrastructure costs for the Island.

3.3.2 Competing uses of Miscanthus

Miscanthus is mainly used for power generation and is either fired on its own or co-fired with coal into boilers. Alternatively, it can be used in smaller installations for combined heat and power. Because of its low density it can be expensive to move; even after drying, the transportation distance is limited because of the energy density (low relative to wood), therefore most miscanthus used in smaller-scale installations is pelleted to densify the material and to ease transport and storage challenges. Miscanthus can also be used as animal bedding (horses) and for geo-textile production, in composites and other material applications.

3.3.3 Importing Miscanthus

Currently miscanthus still presents economic and practical challenges and therefore is not traded as a commodity, so is unlikely to be imported onto the Island from the UK or elsewhere. However, densification of miscanthus by pelleting or briquetting is also becoming more commonplace and could ease logistical challenges for wider procurement by the Island. Although it may be technically feasible to import pellets or briquettes, it would remain cost prohibitive and unsustainable due to the additional processing steps and energy demands for this activity.

3.4 Sugar Beet

Sugar beet can be grown in a range of climates mainly in the northern hemisphere. The beet, the part that grows underground, contains sugars (~20%) that can be extracted and used to produce a range of products. Sugar beet is grown on arable land, and as a root crop it can have a significant impact on the soil, depleting it of carbon, nutrients, and moisture if not well managed. It is for this reason it should be grown in a rotation with other crops, to ensure soil structure and composition are retained.

Sugar beet is an annual crop, sown in spring and harvested from late-autumn through to late-winter, using specialised planting and harvesting equipment. Once harvested, sugar beet can be stored on hard-standing or the edges of fields until required for processing, with sheeting being used to protect the harvest from inclement weather conditions and frosts over the winter period.

Variable costs for sugar beet production are comparatively high, due to the need for specialist equipment and its bulky nature, for handling and storage. Variable costs (for seed, chemicals, fertiliser and fuel), range between £1,300 and £1,500 per hectare.

Advanced agricultural machinery has allowed the automation of beet harvesting, using multiple-row self-propelled harvesters, which has reduced the labour requirement and the time taken for harvesting. However, the purchase of harvesting machinery can be a significant capital investment for farmers. A six-row trailed harvester is estimated to cost between £140,000 and £200,000, and a six-row precision drill up to £40,000 with twelve row drills costing up to twice that amount [16].

There are several machinery ownership models that can help to reduce the cost burden on individual farmers. A contracting service can be set up by the sugar beet processing plant or intermediaries to spread the machinery cost over a larger production area. Under this model, farmers do not have to invest in their own machinery and can avoid certain financial risks.

Machinery Rings can also deliver substantial savings on machinery, labour and commodities (machines can be made available with skilled operators). A shortage of machinery and labour capacity on one farm is matched with a surplus on another and they can also benefit from the collective buying power of their members to source both machinery and other farm inputs at better prices than individuals. In this model, the farmers act as shareholders of the machinery, while an management team would remain responsible for the distribution, financing and maintenance of the equipment.

A machinery ring can also take the form of a co-operative of farmers and agricultural businesses who have the mutual aim of reducing machinery and labour costs. The supplier benefits by spreading machinery costs over a larger area and the member is able to reduce his capital investment in labour and machinery while at the same time having access to up to date equipment. In this model, the investment will be made by individual contractors or farmers, who will rent the equipment to members of the ring. Again, there is a need for an administration team who remain responsible for the machinery rental payments and the organisation of the ring.

Loading is a labour-intensive aspect of sugar beet production, often requiring manual loading of several HGVs per day using a front-loader, and the requirement to clean the beet prior to delivery is becoming increasingly common. This slows the loading process as all beet must be loaded via a cleaner, to remove soil and stones, thus reducing overall transport volumes, minimising waste derived on the processing site, and lowering the overall environmental impact. This activity intensifies labour demands in the autumn months, as often beet is delivered to processors at or shortly after harvest, due to the inability to store beet for long periods. A breakdown of the growing costs for a sugar beet crop is presented in Figure 4 and with the addition of storage, transport, loading and distribution costs, the price of sugar beet delivered to an end-user is likely to exceed £50-70 per tonne on the Isle of Man, given the standard mark-up on UK infrastructure costs encountered on the Island.

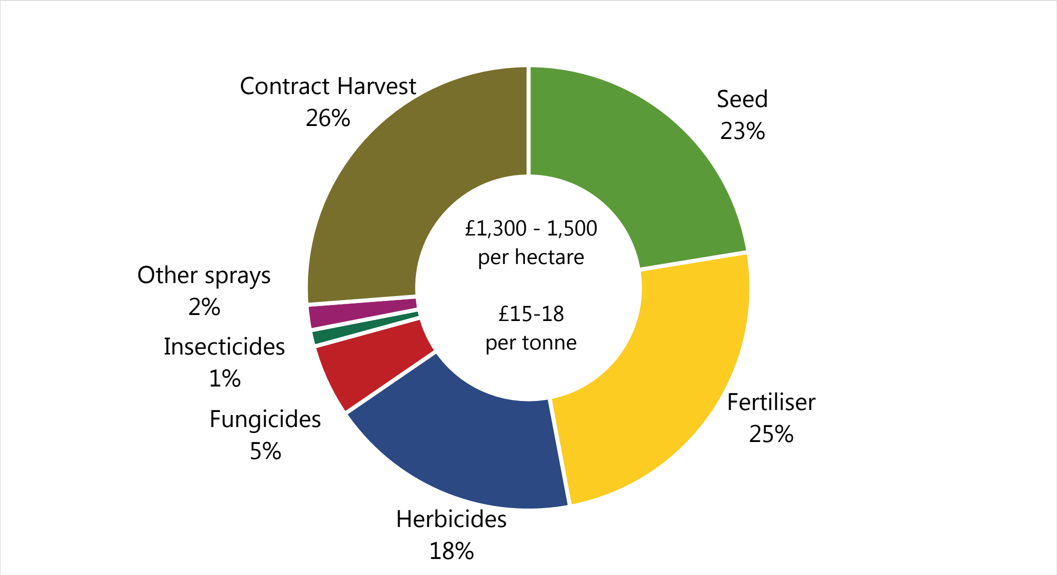

Figure 4. Growing and harvesting costs for sugar beet crops (2019). Data source: [16]

Transport costs for sugar beet can be significant and can hinder the economic performance of processing facilities. Beet is a heavy, bulky crop with a high moisture content which can lead to high haulage costs; however, due to the distribution of suitable land on the Isle of Man, transport costs are not expected to be prohibitive. Based on likely distances, the average cost of haulage is expected to be around £5-6 per tonne, but prices will vary according to distance and fuel costs (16).

To produce fuels from sugar beet, the beets are broken down into thin strips (cossettes) that are washed to leach out the sugars. The by-products of this process have a high value for use in animal feed, pharmaceuticals, and/or additives. This means the whole value chain has properties desirable to different sectors. Furthermore, sugar beet (typically, high energy yielding varieties) can also be used in AD facilities, producing good biogas yields.

3.4.1 Availability of Sugar Beet

The average yield of sugar beet in the UK is around 80 tonnes per hectare (15).

In the UK, ~0.5% of arable land was used to grow sugar beet in 2017/18 (16), although all production is grown under contract to one of four sugar processing plants and growers are typically located within a 90 mile radius of the processor to ease the transport burden. Based on the UK position, under a low scenario, if 0.5% of managed agricultural land in the Isle of Man was used to grow sugar beet, it would deliver 9,200 fresh tonnes per annum. However, as the Isle of Man is unlikely to be constrained in terms of production radius, the establishment of a central sugar processing facility could result in an increase in production area to around 5% of managed agricultural land. This area has been modelled as the medium scenario, resulting in production of 92,400 fresh tonnes per annum (450,000 MWh).

It would not be sustainable to convert more than 5% of arable land to sugar beet, due to the rotational requirements of the crop meaning it cannot be cropped on the same land more frequently than 1 in 5 years, topographical constraints and risks around site access at optimum times, to avoid causing damage to soils during wet harvest periods, for example. A maximum scenario for sugar beet has therefore not been modelled.

The price of sugar beet is dictated by the end market and quality. For 2023 harvest, in the UK British Sugar are paying £40 per tonne to growers, delivering a gross margin of around £750 per hectare, which exceed that achieved by cereals, oilseeds and grassland by around 30-40%.

3.4.2 Competing uses of Sugar Beet

The main use of sugar beet is for sugar production, with alternative uses in the energy sector, for bioethanol or biogas production depending on the process adopted. The by-products of sugar production, such as pulp and molasses, can also be used for animal feed.

3.4.3 Importing of Sugar Beet

Although most sugar beet is processed domestically and sugar products traded, sugar beet remains a traded commodity that could be imported. The global exporting rate is increasing (17.2% CAGR) and the main exporters are Germany at present, where most of the supply is moved by lorry.

Degradation of sugar beet means it can be challenging to transport it long distances (17); therefore it would be more likely extracted sugar could be imported to the Isle of Man, as opposed to raw beet.

3.5 Oilseed rape

Rapeseed oil is produced from oilseed rape, a winter- or spring-sown annual crop, widely grown across the UK and Europe. Oilseed rape is a good break crop, providing a valuable break to soils and the wider ecosystem, from otherwise continuous cereal production. Once harvested, using a conventional combine the seeds can be stored on-farm and/or transported to a crushing facility. Crushing of the rapeseed leaves a residue known as rapeseed cake that can be chemically treated to extract more oil.

Oilseed rape is planted and harvested using conventional cereal production machinery, so investment in specialised equipment is not necessary. Yields of 2-3.5 tonnes per hectare can be achieved on good soils, with the higher end of the scale typically being achieved by winter-sown varieties, and the lower end being achieved by spring-sown varieties. Variable costs (for seed, chemical, fertiliser and fuel) are not dissimilar to those incurred for cereal production, amounting to around £770 per hectare for winter-sown crops, and £454 per hectare for spring-sown crops.

Rapeseed is mostly grown for cooking oil production, as part of a crop rotation where intermediate crops, other combinable crops and cover crops are used to ensure the soil carbon is not depleted. This will also maintain the biodiversity of the soil. Intense farming of rapeseed can include high use of nitrogen fertilisers which directly impact the local ecosystem as well as indirect consequences such as water run-off and eutrophication. Rapeseed is prone to pest and disease attack in mild, dry weather conditions so often requires the use of insecticides and pesticides. Over-use of such chemicals can negatively impact biodiversity, especially on pollinating species (70); however, non-chemical control methods can also be adopted, to minimise risk of attack and to improve the sustainability and biodiversity benefits of the crop.

3.5.1 Availability of Oilseed Rape

The amount of managed agricultural land on the Isle of Man is around 30,000 ha. For the low scenario, 10% of this land was assumed to be used to grow rapeseed, whilst in the medium scenario, 30% of this land was assumed to be used. Beyond 30%, production would be deemed unsustainable due to the rotational requirements of the crop, meaning it cannot be grown more frequently than 1 year in 3. Future production forecasts were based on expected market growth and price (see Figure 5), which is discussed in more detail in the next section.

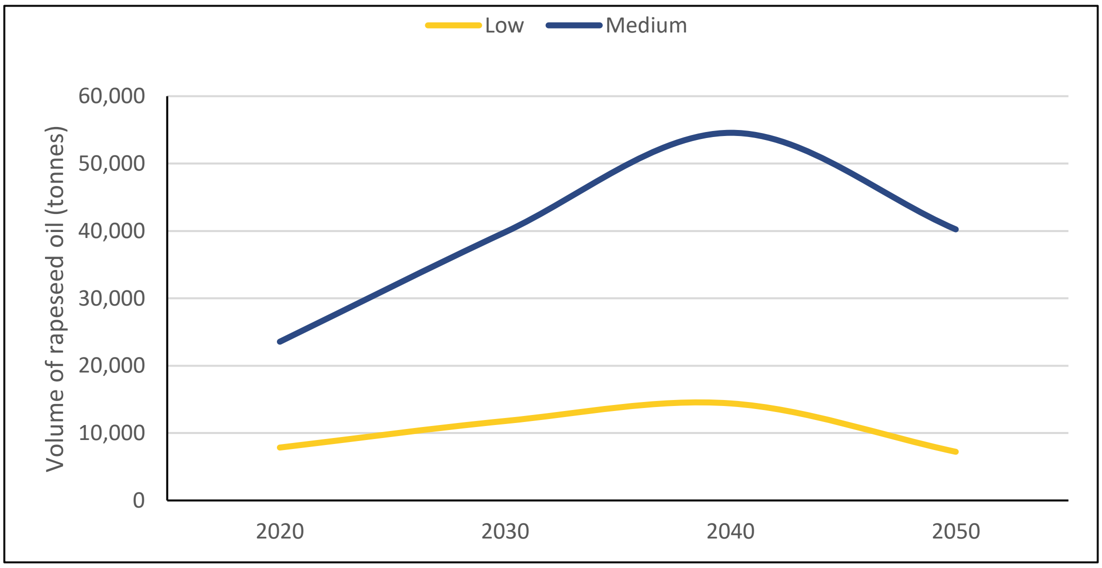

Figure 5: Oilseed rape availability, actual and forecast, from 2020-2050

Figure 5 shows the estimated available rapeseed oil volumes based on the scenarios described in the proceeding section. The maximum volume of rapeseed available is around 55,000 tonnes per annum under the medium scenario (based on a yield of 3.4 tonnes per hectare (18)), delivering ~400,000 MWh of energy. In the low scenario, availability is expected to peak around 2038. This growth will be from increased market demand from the aviation and marine fuel sectors. The decline post-2038 results from emerging technologies such as power to liquids that will reduce demand for such feedstocks in the other biofuel sectors. It is assumed that rapeseed for production of biodiesel for use in road transport has already started to decline (19).

By 2050 it is expected that the volume of rapeseed available would be lower than current volumes. In the medium scenario, the rate of growth is accelerated based on the large increase in demand from the aviation sector and current mandates announced in the UK and EU (20). In the medium scenario the largest volume of rapeseed available is around 2040 (54,000 tonnes). This is expected to decrease sharply by 2050 (~40,000 tonnes), resulting from growth of biofuels from emerging technologies.

The price for oilseed rape varies as it is a globally traded commodity; at present, prices of £450 - 500 per tonne (ex-farm) are being offered, delivering a gross margin of around £900 per hectare for winter-sown crops, and £735 per hectare for spring-sown crops. In addition to the cost of production, costs for transport and storage would also be incurred, amounting to around £20-30 per tonne for oilseed rape, resulting in a delivered price of around £470 - 530 per tonne to the end-user. However, price volatility is common, and in recent years lows of £190 and highs of £990 have been experienced, so sensitivity modelling to consider the impact of such variances would be prudent.

3.5.2 Competing uses of Rapeseed Oil

The main use of rapeseed oil is for cooking oil, spreads and ingredients in other product formulations. Rapeseed is an attractive oil for such uses due to its provenance and composition. Rapeseed prices are highly volatile, based on supply and demand for rapeseed oil and competing sources.

3.5.3 Importing of Rapeseed Oil

International trade of rapeseed oil is well established. The current market price is approximately 1,740 US dollars per tonne however earlier in 2022 the market price was between 2,000-2,300 US dollars per tonne which shows the heavy market fluctuation (21). This price spike was mainly driven by geopolitical factors, also impacting on fuel and energy costs, and the wider economy.

Importing of rapeseed is unlikely to the Isle of Man due to the demands on infrastructure and the requirement for primary processing (crushing) facilities which only become economically viable at scale. It is more likely that oil would be imported onto the Island, for further conversion into the desired biofuel should suitable facilities be developed to also process domestically produced oils.

3.6 Used Cooking Oil (UCO)

The use of fats and oils from waste have become increasingly popular and they are currently a key feedstock targeted for sustainable fuel production. There are however concerns over the sustainability of these feedstocks, and the availability of waste feedstock supply. Used cooking oil (UCO) is an attractive feedstock because it is relatively cheap compared to virgin oils.

Used cooking oil can be sourced from factories producing fried food such as crisps and chips or smaller volumes can be collected from local restaurants and takeaways for example. Almost the entirety of this feedstock is used for biodiesel production (typically FAME); however, many smaller producers still dispose of their UCO because of the infrastructure requirements for collection and storage, and the cost of transportation.

3.6.1 Availability of UCO

UCO availability on the Isle of Man was determined mainly through stakeholder engagement. After talking to stakeholders, the majority of UCO from commercial food ventures is passed on to a third party based around Laxey, who appear to convert it into biofuel. The volume of UCO arising and remaining on-island or being exported is unknown (22).

If UCO collections were made from local restaurants, takeaways, cafes, and bars it is estimated that approximately 55 tonnes per annum would be available. There are potentially an extra 15-20 tonnes per year available from fast food restaurants. Additionally, in the domestic sector, if households were able to dispose of UCO in local waste oil collection banks, an estimated 12-24 tonnes of UCO may be available per annum. This could deliver a total resource of around 100 tonnes per annum of UCO.

3.6.2 Competing uses of UCO

The main use of UCO is for biofuel production. It can also be used to produce biobased products.

3.6.3 Importing of UCO

UCO is an internationally traded product. Europe is the main market for the conversion of UCO with the majority being imported from south-east Asia. The current market price for UCO is approximately 1,200 US dollars per tonne (23).

Although the Isle of Man is well positioned to import UCO for conversion to biofuel on the Island, it may be challenging to compete on the global market with larger players, where other demands are non-existent domestically. However, there is an opportunity to procure and utilise UCO, in isolation or alongside other feedstocks in a number of production pathways, therefore import remains interesting.

3.7 Food Waste

Food waste is material generated by restaurants, catering outlets (including office and school canteens), and households which is deemed no longer suitable for consumption, as it is either out-of-date, spoiled or surplus to customer requirements. Food waste is a growing problem and in a recent report by UNEP, 17% of the total food available to consumers in 2019 was disposed of; globally this represents 931 million tonnes of food waste (24). There is little competition for this feedstock as it must be treated and processed according to regulations; therefore, it has little value in other markets. This is different to other forms of commercial or industrial food waste that could be used in animal feed production. Unless the Local Authority has established separate food waste collections, it is typically mixed into general waste, and therefore not highly accessible.

Across the UK, separate food waste collections are being more widely rolled out, to enable this resource to be valorised. When presented as a source-separated, relatively ‘clean’ waste stream, it is suitable for biological or occasionally thermal conversion. However, the moisture content is typically high (50-70%) which also makes it difficult to handle, transport and store. This can be overcome by drying and ensiling but is expensive. The other problem with food waste is its heterogeneity, therefore it is difficult to regulate its chemical composition. This composition will vary depending on the season.

In order to access food waste on the Island, separate food waste collections would need to be established, which poses challenges for householders, businesses, collection and disposal authorities. For the waste producer, the biggest challenge remains education around and practicality of separation, as separate food waste caddies or bins would be required, and the producer must adopt new habits to use these dedicated vessels. Based on UK knowledge, at best 60% of food waste can be removed from the mixed waste-stream, due to producer education, packaging contamination, and infrastructure constraints meaning not every household and business would have space for separate vessels to participate in such schemes. Furthermore, the cost of roll-out is high and would most likely be borne by existing collection and disposal authorities, or waste management companies working with end-users, to establish and operate the required infrastructure such as dedicated vehicles, personnel and disposal vessels. However, to counter these additional costs, savings would be made from the reduced volume of residual waste being collected and disposed of.

Whilst food waste has until recently attracted gate fees, with the disposal authority paying the end-user £5-15 per tonne to receive the material, its value for processing through AD or other routes is now well recognised and good quality, secure and consistent supplies of suitable waste can now be presented as a net cost to the end-user of £5-15 per tonne. Lower value wastes or those contaminated with packaging or other materials, would however still command a gate fee.

3.7.1 Availability of Food Waste

Currently, it is thought most of the food waste arising on the Island remains in the general waste stream, where it gets sent to the SUEZ energy from waste (EfW) facility. The facility has a design capacity of 60,000 tonnes per annum of wastes, and processes 50,000 tonnes of the IoM's domestic and commercial waste each year, generating up to 10% of the Island's electricity (25). As it is not separately quantified, food waste volumes are estimated for commercial food units (pubs, cafes, and restaurants), schools and the domestic sector where collection is typically most feasible and where consumer education is possible, to encourage appropriate disposal.

For the commercial units, an appropriate factor based on the waste produced per unit per year, by business type, is used to quantify availability. For schools, a typical figure representing waste generated per capita is used; however, figures are adjusted in the scenarios to account for not all school children having school meals. The low, medium, and maximum scenarios differentiate based on the percentage of children having school meals (low-40%, medium-70%, and max-100%). For domestic food waste, a waste generated per capita factor is used again and the collection rate is varied (low-0%, medium-30%, and max-100%). In the new Economic Strategy, the population has been modelled to increase to 100,000 by 2037. In this waste modelling exercise, it has been assumed population growth remains consistent out to 2050 – both scenarios are modelled in Figure 6.

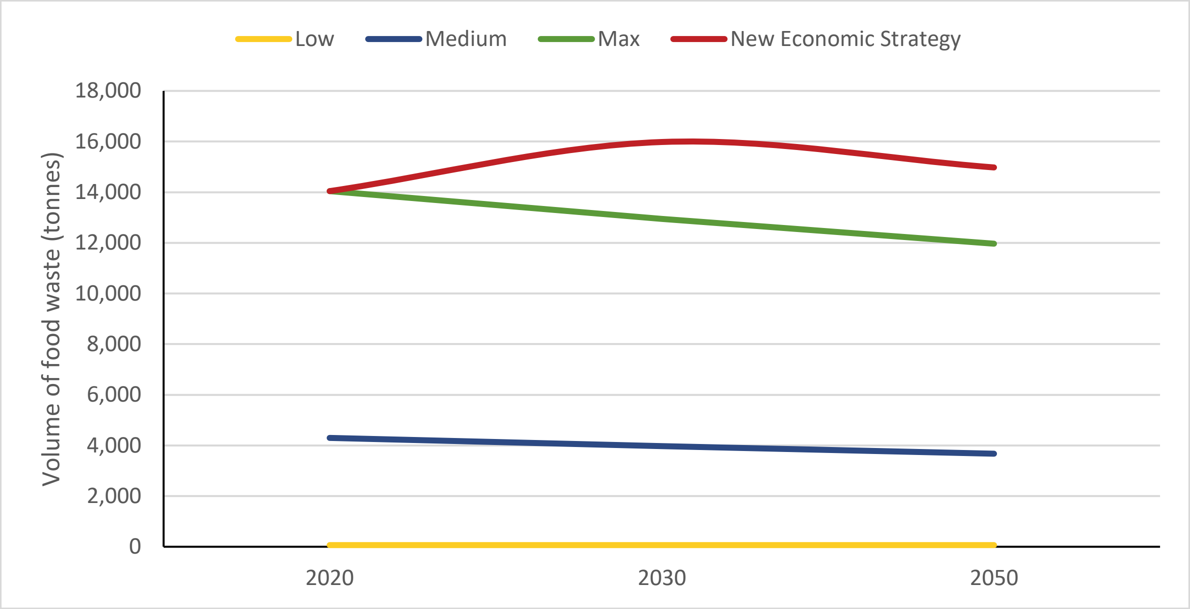

Figure 6: Food waste availability, actual and forecast, from 2020-2050

From Figure 6, the maximum availability of food waste is estimated to be around 14,000 tonnes per annum (assuming all domestic food waste is separated at source and collected). This would yield a maximum gross energy content of ~ 66,000 MWh. If the energy required to dry the feedstock is factored in, the net energy content of the maximum scenario is ~ 55,000MWh.

The main factor that will influence availability is the collection rate. The domestic sector makes up 99% of the availability, therefore this feedstock would be acquired by household collections. In the medium scenario a 30% collection rate is a modest target; however, international examples of where mandated domestic food waste collection have been implemented have shown a 30% participation rate is typical (26). One of the greatest challenges with food waste is collection, due to the often-small volumes produced at source, meaning the logistics of collecting the material is less economically favourable.

The forecasts for food waste availability show a decline. Most targets focus on reducing the amount of food waste produced and thus it is expected that by 2030 there will be a 10% reduction in the amount produced per capita and this reduction is expected to grow to 20% by 2050 (based on 2020 figures). Although the population will grow (27) this is outweighed by the reduction in food waste. This is less noticeable in the medium scenario than the maximum scenario where there is estimated to be a 2,000 tonne reduction in food waste by 2050.

The large increase in population in the New Economic Strategy has changed the trend in food waste availability. The volumes available will increase to 2034 (using 100% collection rate, the same as the max scenario). However, it is expected that food waste reduction measures will have an impact after this date and the volumes available will reduce.

3.7.2 Competing uses of Food Waste

Most separately collected food waste is currently sent to anaerobic digestion (AD) in the UK and Europe. Some food waste can be sent for composting; however, domestic and commercial food waste is unlikely to be used for this because of the high volumes of animal by-products contained within the sample, that could present a risk to soil health and the wider ecosystem when composted.

Currently most of the food waste presented in Figure 6 will go to incineration because it remains mixed with other domestic waste. Therefore, separation of this food waste from MSW would reduce feedstock supply to the energy from waste facility on the Island. Because this fraction makes up most of the biogenic fraction of the MSW it will also increase the CO_2eq. emissions per unit energy generated at the EfW facility.

3.7.3 Importing food waste

As previously mentioned, food waste is high in moisture and has a low energy density, this means it is not cost effective to transport long distances and it is difficult to store. It is likely it will have started decomposing before it reaches the processes facility if transported for more than a few hours, and therefore the conversion efficiency is reduced. Therefore, importing food waste is not a viable solution.

3.8 Forest Products

Although widespread harvesting of virgin forestry for bioenergy production is not widely supported by international sustainability standards (28), effective management and clear-felling of trees to maintain active growth is deemed appropriate, and in the absence of other stable, secure markets for timber should be considered. Using timber for construction locks the carbon in the product for a significant period and offers a higher value outlet for the forest products than bioenergy. However, in the absence of any commercial forestry operations on the Isle of Man, there may be opportunities to effectively harvest forestry on a long management cycle to increase biomass availability. Alongside such materials, residues arising in forests or during processing, and by-products of the timber industry can also be used for energy generation.

Actively managed forests are more sustainable than unmanaged forests, and therefore where trees are felled for management purposes, to remove old, damaged or diseased trees for example, or to re-establish more actively growing forests, this biomass could be diverted to the energy sector.

Forestry residue is well suited to bioenergy production, referring to the material left after wood harvesting. It can also include some material from forest management such as felling of young trees, to create clearing areas, or trimming branches to thin out the canopy and increase light exposure to the forest floor. For harvest residues, it is expected that 12% of the harvested mass is left as residue in the forest (24). Of the remaining, 61% is economically feasible to collect, this factor considers the feasibility of collecting and moving the residue considering weathering, terrain, and soil conditions, using anthropogenic collection techniques to maximise collection and vehicle mobility (25). Around 30% of all residue should therefore be left to maintain soil quality and other forest biodiversity (26).

Natural forest management is an essential part of ensuring carbon sequestration and biodiversity are optimised. Additionally, clearing the forest floor of some deadwood is an important step to prevent the spread of forest fires and to maintain the forest ecosystem; although not an adopted practice on the Island at present, this should be considered if forests were to be brough under more active management in the future. This form of management also prevents methane emissions, which have a worse global warming potential than carbon dioxide, to the atmosphere from the decomposing of the wood in the short term.

As there are no commercial operations in place at scale on the Island already, additional forestry equipment would need to be procured; additional skills and infrastructure would also be required, to ensure effective management, removal, transport, storage and treatment of the material. Establishment costs for a commercial plantation range from £5,000 - £10,000 per hectare, with higher costs being incurred for broadleaved plantations on lowland, whilst lower costs are typically incurred for planting conifers, especially in upland areas where pest and weed presence is less damaging. Once established the plantation will require careful management and maintenance, with costs amounting to around £600-900 per hectare per annum.

At maturity, a suite of specialised harvesting, grab-loading and haulage machinery will be required, costing around £1-1.5 million overall (incl. all equipment required to harvest, remove and haul timber), whilst haulage costs to the point of use will be around £15-20 per tonne, and the price of the product collected at roadside will be around £75 – 125 per tonne, depending on cut, quality and location.

3.8.1 Availability of Forestry Residue

Based on the current area of forestry on the Isle of Man, if 5% was actively managed and harvested each year, this would yield 18,000 tonnes of wood per annum, delivering 90,100 MWh of energy. Furthermore, assuming active management across the wider area, the amount of forestry residue has been calculated based on the land area currently covered in forest, amounting to 2,800 hectares (50). In the medium scenario, the forest area on the Isle of Man was expanded to 10% of total land area, at a consistent rate over a 20-year period (approximately 145 hectares per year of new forest).

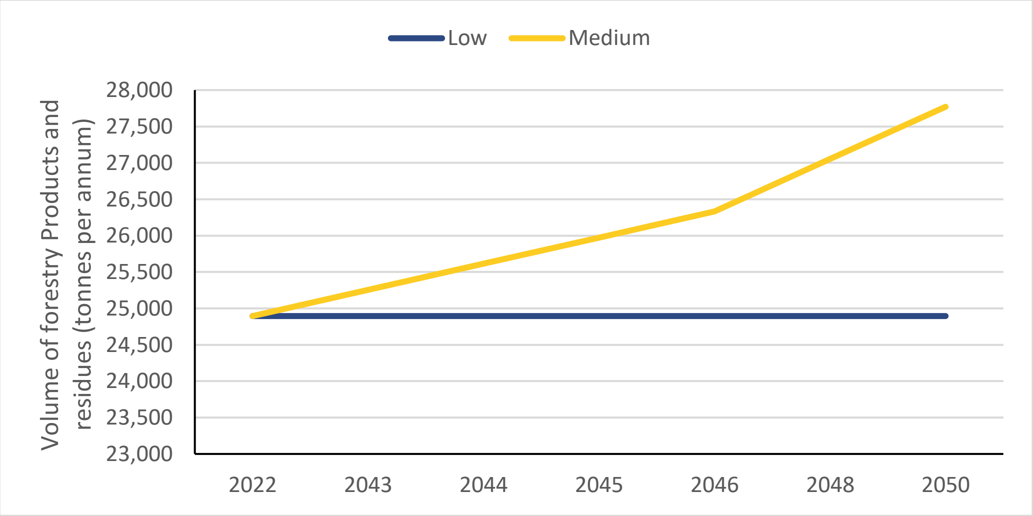

Figure 7: Availability of forestry products and residues, forecast from 2025-2050

Figure 7 shows the availability of forestry products and residues to 2050. In the medium scenario the highest volume available is 27,000 tonnes, delivering an energy content of approximately 150,000 MWh. In the low scenario the volume available does not change, delivering an energy content of

130,000 MWh. The medium scenario is a stretch; however, it would promote carbon sequestration from increased carbon locked in the trees and allow for active management of the extensive woodland area on the Island.

3.8.2 Competing uses of Forest Products and Residues

Currently alternative uses of forest products and residues are limited so there would be little competition for this resource on the Island.

3.8.3 Importing of Forest Products and Residues

Forest residues are pelleted in North America and Canada, for example, and imported to the UK for use in large-scale power stations such as Drax. Once pelleted, forest residues can be transported significant distances without impacting negatively on the carbon savings or hampering the economic case for its use. It may therefore be feasible to import wood pellets onto the Isle of Man, from the UK or elsewhere in Europe; however, consignment size may be a limiting factor, given shipping benefits from economies of scale, and transporting small consignments is not particularly efficient.

Forestry products are not traded for bioenergy, so importing of non-residual biomass would not be an option for the Island.

3.9 Short Rotation Coppice Willow

SRC coppice is a woody biomass that is sometimes considered an energy crop. It can be grown on a range of soils, but it does prefer well-aerated and moisture retentive soils that are slightly acidic (pH 5.0-5.7). Based on soil maps for the Island, (29) approximately a third to half of the Isle of Man is suitable for SRC growth.

SRC is typically planted in late spring on less productive arable lands or those less well suited to intensive cereal production, for example, using specialist equipment, placing rods in the ground at even spaces. The cost of planting material, equipment, fuel and labour is high, amounting to around £2,500 per hectare.

A first cut back takes place in winter to encourage the plant to coppice. The first harvest does not occur until at least two years after the first cut back, typically over the winter period from mid-October to March, after the leaves have fallen but before buds appear. Material can only be harvested every 2-3 years so planting is staggered over 3-years to ensure an annual yield is achieved, sufficient for any facility requiring biomass (20); however, the plantation can remain viable for 20-30 years, before yields start to reduce.

Yields of up to 30 dry tonnes per hectare can be achieved on productive soils, which when annualised over a 3 year harvest cycle equates to around 10 tonnes of dry biomass per hectare, per annum.

The price of SRC is largely dictated by the market and its energy value. In the UK, where the supply chain is relatively well established, prices of £70 - 100 per tonne are commanded, ex-farm. Haulage costs can be high, given the low bulk density of the material, so local use is preferable and in addition to the planting costs, additional costs will be incurred for transport, storage, distribution and insurance of the crop, increasing the price to the end-user. The total cost of supply into a processing facility would amount to around £130 - 180 per tonne (delivered) on the Isle of Man, based on typical UK costs for production and infrastructure, adjusted according to the standard mark-up on infrastructure costs for the Island.

3.9.1 Availability of SRC Willow

In the low scenario, it was assumed 3% of managed agricultural land was planted with SRC willow (700 ha), whilst in the medium scenario, 10% of land was converted (2,350 ha). It was assumed that the land used was planted up gradually, over a 3-year period.

The yield of SRC willow after the first harvest (one year) is 7 oven dried tonnes per hectare, increasing to 18 oven dried tonnes per hectare at the second harvest (after a 3-year cycle), reaching a maximum yield at the third harvest (6-years since planted). The volumes of biomass that are harvested are shown in Figure 8.

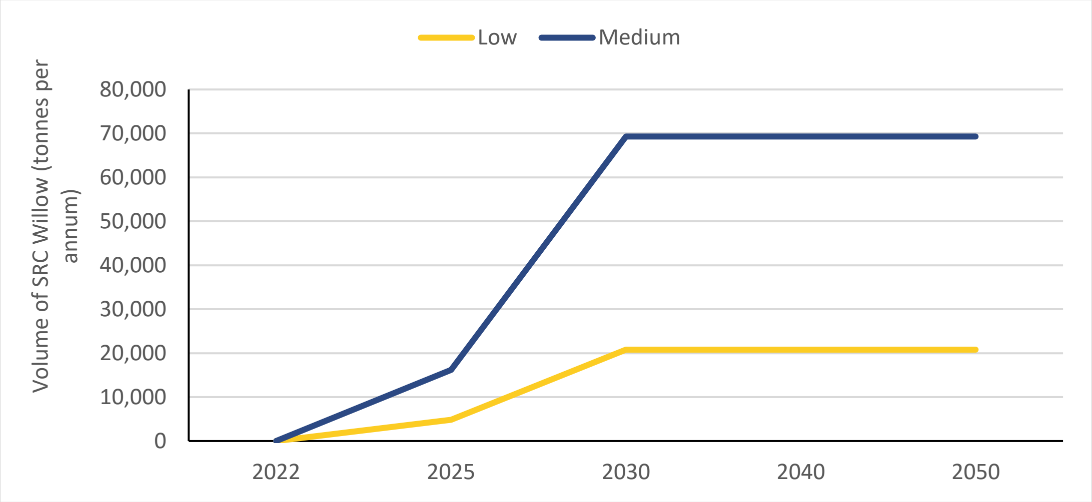

Figure 8: Availability of SRC willow, forecast from 2025-2050

The highest yield in the medium scenario would deliver 23,000 tonnes per annum, considering the 1 in 3 year harvest cycle (or a third of the available land area being harvested each year), and for the low scenario ~7,000 tonnes per annum. Each scenario assumes planting starts in 2022, therefore the earliest these harvest levels could be obtained is by 2028. The energy content of this yield of SRC willow is approximately 325,000 MWh per annum.

3.9.2 Competing uses of SRC Willow

SRC willow is grown solely for energy generation. There are some applications to remediate land or to protect land from flooding; however, the wood yielded is notably used for energy production.

3.9.3 Importing of SRC Willow

SRC willow is not currently traded in its harvested form internationally; however, trading of wood pellets is a common practice. Most of this material will come from wood processing residues; however, SRC willow can be milled down and added into the sawdust mix for pelleting (30). It is not envisaged the Isle of Man would import willow in its raw form or as pellets, due to the economic and environmental factors relating to the additional processing and distribution steps.

3.10 Wood Processing Residue

Wood processing residue refers to any waste material produced at a wood processing plant. This includes the production of sheet timber and timber beams as well as furniture. The initial process typically removes the bark. Bark is mainly carbon but is usually higher in inorganics such as calcium, phosphorus, and heavy metals and these can be problematic in fuel production processes such as gasification because they contaminate the catalysts (38).

Sawdust is generated from cutting and shaping the timber. Sawdust is carbonaceous and an energy dense (on a mass basis) source of material. Although on a volume basis the energy density is low this can be easily optimised by compressing the material to produce pellets or briquettes. Sawdust is frequently used to produce chipboard and, in the heat and power sector for energy.

3.10.1 Availability of Wood Processing Residue

The majority of wood processing residue generated on the Island comes from the sawmill; however, commercial activity is limited and availability of residues will be low. Ordinarily, wood processing residue includes split wood, bark, sawdust, wood trimmings, planer shavings and sander dust.

It is estimated that a few thousand tonnes of processing residues may be generated on-island at present, but no forecasting is provided as there are many dependent factors driven by other sectors that influence availability and it is therefore difficult to estimate future potential.

3.10.2 Competing uses of Wood Processing Residue

Wood processing residue can be used in alternative timber products such as machined boards and chipboards. It can also be used for animal bedding or in soil amendment, with values varying depending on scale and locality of market demand. However, as production is limited on the Isle of Man, these alternative markets do not widely exist.

3.10.3 Importing of Wood Processing Residue

Wood pellets made from processing residue are a commercially traded commodity. Companies such as Ensyn and Drax ship wood pellets globally. Data from LesProm analytics recorded wood pellet prices at $203 per tonne in April 2022 (31). Because of geopolitical issues the prices are expected to increase over the winter period before falling back again in 2023.

It is not envisaged the Island would import wood pellets due to the dedicated infrastructure required for storage, transport and distribution.

3.11 Sewage Sludge

Sewage is a carbon rich source of material but is a very wet feedstock. The sewage is separated from the liquid phase and a sludge is produced. The carbon from this sludge can be extracted by combustion, biological and thermochemical conversion routes. The sludge is biologically active and will contain live pathogens, so it must be treated correctly and is subject to various regulations and restrictions to prevent a public health issue. It is also high in polycyclic aromatic hydrocarbons (PAHs) which means there is higher probability of soot forming and more organic pollutants during combustion (32). Since sewage sludge is a biologically active waste product it must be disposed of in a specific way, therefore impacts to carbon balance and biodiversity are negligible based on current practice (incineration).

3.11.1 Availability of Sewage Sludge

The only figures available on sludge generated on the Island could be taken from Manx Utilities. The company say they produce 1,000 tonnes per year (33) of sludge pellets. This means per capita 11.7 kg of sewage sludge is formed. Based on the expected population growth this could yield 1,100 tonnes per year by 2050.

3.11.2 Competing uses of Sewage Sludge

Sewage sludge is typically disposed of at waste incineration facilities because of biological hazards to public health. If thermally treated it could be used in soil amendment or in AD.

3.11.3 Importing of Sewage Sludge

Sewage sludge is not traded across borders.

3.12 Seaweed (Sea kelp)

Sea kelp is a type of seaweed found in the Irish Sea. Sea kelp consists of a stipe (a stem) and blades (leaves) which make up most of the harvestable biomass. Kelp grows in dense patches termed forests and due to kelps rapid growth rate this creates a large carbon sink. If kelp were to be harvested, a review of how much could be removed over a specified period to promote carbon storage should be determined to maintain sustainable practices. Sea kelp is also very important for the local biodiversity. Many species use sea kelp to seek refuge and it is fundamental to supporting the ecosystem (34).

Using kelp as a feedstock has many challenges. The feedstock is very wet and makes transportation expensive. Additionally, kelp is very high in sodium which has a negative impact on most processing pathways. The kelp could be washed, however, that would incur more cost making it less feasible to use. One of the greatest challenges, when considering the short timeline for implementation, is the lack of skills and knowledge of using this feedstock and the low technology readiness level and commercial readiness level of the conversion processes.

3.12.1 Availability of Sea Kelp

It was assumed the sea kelp was grown on lines which are connected to form grids. Each farm is made up of multiple grids which span the area of the farm. The area used for sea kelp farming was varied based on the depth of the seabed, areas used for fishing, shipping channels and potential new energy infrastructure such as offshore wind farms or natural gas drilling sites.

The depth of the seabed was taken from Manx Marine Environment Assessments (Figures A.1 & A.2). The lines on which the kelp grows need to be submerged under the water, therefore the depth must be greater than 10m; this is also recommended to protect the sea kelp from erosion of breaking waves. It is also recommended that the seabed is no deeper than 60m as the mooring lines can be susceptible to increased drag forces which can drag the lines. In both the low and medium scenarios, the seabed depth was kept within the recommended limit.

The fishing areas were analysed by using Figures A.3-A.4 (35). No evidence was found to support the co-production of fishing and sea kelp in the same areas. Therefore, it was assumed that only one activity could take place in each area. In the low scenario the fishing areas identified were not used for the farming of sea kelp. In the medium scenario the areas on the east of the Isle of Man were still prioritised for fishing as this is the main hotspot. The fishing areas to the north and south of the Island were also retained because the depth makes this unsuitable for kelp farming. Any deviation from this and reprioritisation of other areas such as the west, would require a change to fishing practices and would likely negatively impact other markets, and has therefore not been considered here.

There are a few studies assessing the potential for an offshore wind farm or a natural gas platform to the east of the Island. The area in question is up to 20m in depth and is currently not used for fishing based on the maps in A.1-4. Therefore, in the medium scenario this site was also considered eligible for kelp farming. 2 summarises the considerations for each scenario.

Table 2: Assumptions for each scenario for sea kelp farming

	Low Scenario	Medium Scenario
Sea depth	Maintained between 10-50m	Maintained between 10-50m
Fishing areas	All fishing areas reserved; not used for kelp farming. Kelp predominantly produced in NE and SW.	Fishing areas to the west of the Island were used for kelp farming, as well as other areas in to NE and SW, also included in low-scenario.
Other infrastructure	Area reserved for offshore wind farm and gas platform were not considered. Shipping lanes avoided.	Area prioritised for kelp farming; no offshore wind or gas platforms considered. Shipping lanes avoided.

The yields of kelp reported previously vary depending on the density of the kelp growth. More productive farms in China yield up to 20 tonnes per hectare of dry kelp however the spacing between the lines is much narrower and this is having environmental impacts on the local waters (36). A smaller enterprise in Spain has measured yields of 4.7 dry tonnes of sea kelp per hectare, this was achieved with a 4m spacing between the lines. This level of spacing is to minimise shade on underlying habitats and protect phytoplankton communities which are essential to maintain a healthy ecosystem (37).

Plans for sea kelp cultivation off the Pembrokeshire coastline are estimating yields of 7.5 dry tonnes per hectare with a line spacing of 10m (38). The yields in Pembrokeshire are higher than in Spain because of the difference in line length. All three yields have been modelled for the low and medium scenarios shown in Figure 9, with indicative production scenarios considered given current sea territories, shipping routes and fishing grounds. The exact location of the priority production areas has not been determined, as a more strategic review of all related activities would be required to develop a future production strategy, should this be deemed a viable option in the future.

It is important to remember that only one harvest happens per year. This means the kelp would have to be stored throughout the year whilst conversion took place. Additionally, the sustainable practice of hand harvesting the kelp would take a considerable amount of time and resource. This could have good economic prospects for job creation but could also make the financial feasibility of sea kelp farming less profitable.

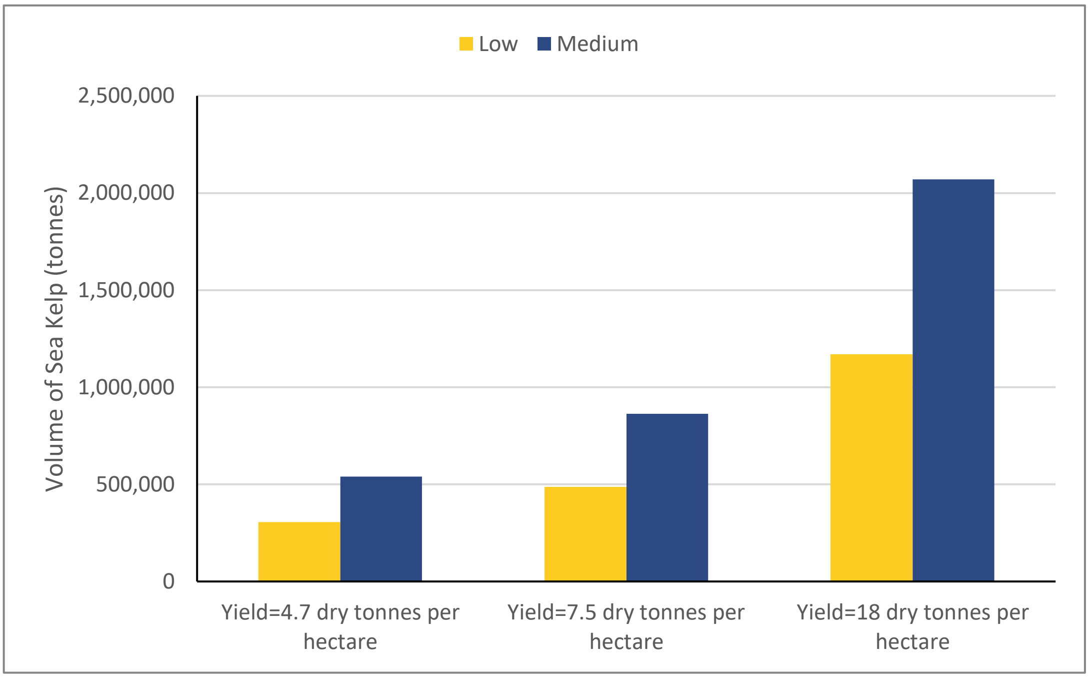

Figure 9: Availability of sea kelp, based on different yields.

As illustrated in Figure 9, the low scenario is estimated to deliver approximately 300,000 fresh tonnes per annum. It is reasonable to assume that a yield of 7.5 tonnes per hectare could be achieved without compromising the local aquaculture. This would increase the yield in the low scenario to 487,500 tonnes per annum. However, in the medium scenario an extra 300 km^2 of farming area is gained by converting the area from fishing to sea kelp farming and a further 200 km^2 from using the shallow shelf to the east of Ramsey for farming.

3.12.2 Competing Uses of Sea Kelp

Sea kelp can be converted into a wide range of chemicals and materials including food additives, therapeutics, fermentation media, and animal feed. Extraction of high value chemical components in sea kelp are making it more attractive to investors. The fuels market does not have the same financial capacity and thus it is less desirable to farm sea kelp for fuel production. It is possible in a biorefinery concept to extract the value components and then use the residue for fuel/energy production (39).

3.12.3 Importing of Sea Kelp

Currently there is no evidence to suggest sea kelp is traded internationally.

3.13 Summary

This section has analysed the availability of a variety of different biomass that are either currently available or could be available on or to the Island; findings are summarised in Table 3. The scenarios devised in this section are independent of each other. The values presented are estimates based on individual factors such as yields and collection efficiencies; they are indicative of what could be available in those scenarios. This information has fed into the MCA in the following section.

Table 3: Summary of feedstock availability

Feedstock		**Availability**	
		Minimum (Dry tonnes per annum)	**Maximum (Dry tonnes per annum)**
Food Waste		100	14,000
Dedicated Energy Crops	**Miscanthus**	4,000	15,500
Agricultural Residues	**Straw**	2,275	3,700
Agricultural Waste	**Fruit & Vegetable waste**	0	
Managed Feedstocks	**Heather**	1,373	6,864
	Bracken	600	
	Reeds	1.94	
Wood Products and Residues	**SRC**	5,775	23,000
	Forestry products and residues	25,000	28,000
Waste Tyres		759	
Sewage Sludge Pellets		1,000	1,100
Animal waste	**Manure**	8,100	15,000
	Slaughterhouse Waste	536	
	Fish waste	1,712	
Fats and oils	**Rapeseed oil**	7,226	55,000
	Used cooking oil	65	100
Sugar Beet		9,200	92,400
Marine feedstocks	**Kelp**	300,000	487,500
Industrial wastes	**Brewery and distillery waste**	N/A	
	Dairy processing waste	15,464	

4. Multicriteria Analysis

A multicriteria analysis (MCA) has been used to select the feedstocks of interest for further analysis. The MCA factors are based on the information discussed in Chapter 3. The maximum score is 30. The lower the score the more barriers there will be and thus it is not recommended for further analysis.

4.1 MCA Criterion

The feedstocks selected for further analysis have been assessed on their availability and suitability for fuel production; including the volumes available, the security of the supply chain and any risks that could impact on availability, as well as costs incurred for production, preparation and use. A number of key criterion have been selected for the analysis and these are discussed in more detail in the following sections. The weighting for each has been varied to highlight the importance of availability over cost and supply security, as this was deemed more important.

4.1.1 Availability

Availability was weighted as the most important factor, given the focus on utilising on-island resources to deliver low carbon energy solutions over the coming decades. This was used as an indicator of the maximum volumes of fuel that could be produced, giving the Isle of Man greater energy independence and thus security. The scoring criteria are shown in Table 4.

4.1.2 Seasonality

Biofuel production and energy demand will be stable and continuous throughout the year, meaning feedstocks that are only produced or sourced in a narrow period of the year could create supply chain issues if they cannot be stored effectively. This would increase the reliance on imports or feedstock switching, which could be expensive or pose further risk to the security of the production process; therefore where supply is seasonal or likely to be constrained at certain times of the year, scoring is lower than where a consistent supply, in terms of both quality and quantity, can be guaranteed.

4.1.3 Potential for imports

Biofuel production facilities require a continuous and consistent supply of feedstock. Imports may be necessary if there is a regular or sporadic supply shortage or production capacity needs to be increased, or the ability to switch to other feedstocks will also be important. The ability to import biomass improves supply chain security, but adds cost and logistical complexity, as well as adding emissions during storage and transport steps, delivering less carbon advantageous final fuels.

4.1.4 Competing uses

Other uses for the same feedstock may be a priority and therefore reduce the volumes available for biofuel and energy production. This includes the extraction of higher value products that would have a more profitable outlook for the feedstock. For products and non-wastes, often the highest value market takes priority, with lower value outlets providing a stable offtake in terms of volume but being less favourable in economic terms. Furthermore, for wastes, the waste hierarchy must be followed, so if an option exists for material to be reduced or reused, before being converted to energy, then that option should be pursued. The value and status of alternative uses has been considered.

4.1.5 Infrastructure requirements

Some of the feedstocks will require new knowledge, systems, and technology to be efficiently obtained, and this will require both finance and time investments. This can be assessed based on the originality of the feedstock in current commercial processes. Consideration has been given to the infrastructure requirements and existing provision on the Isle of Man, to determine likely development needs beyond the direct supply chain should such options be pursued in the future.

4.1.6 Transportation and Storage

A simple assessment can be made based on the characteristics of the feedstocks, such as moisture content and how this will impact transportation and storage. Lower value (energy) feedstocks can only be transported over short distances before it is no longer economically viable. Feedstock storage can also be problematic if the feedstock starts to decompose making it less valuable or in some cases unusable. Some feedstocks can be treated prior to storage, to prolong their lifetime before they decompose; however, this is usually at additional cost. The means of transport and storage have also been considered, to determine the level of investment and development required on the Island.

4.1.7 Feedstock Risks

Feedstocks can be susceptible to supply issues because of external factors such as meteorological issues or changes in human behaviour. In some cases, the activities requirement to obtain or farm the feedstock may present challenges and could have environmental impacts that will impact on future harvests. This will create risks in the supply chain which can reduce confidence for investors and process operators. These factors have been highlighted on an individual basis as they are often unique to a specific feedstock.

4.1.8 Cost and investment

The cost of producing new feedstocks, and the investment required elsewhere in the supply chain, to effectively produce, procure, access, store, transport and use the materials to deliver energy on the Isle of Man have been considered. In some cases, without understanding more about the specific production and conversion circumstances, it is not possible to quantify costs and investment requirements, so where commercial data is unavailable a qualitative assessment has been applied to this analysis, to provide a comparative evaluation.

4.2 MCA Results

The results of the MCA are shown in Table 4. From this analysis, wood is the most suitable feedstock for conversion to bioenergy on the Island, followed by manure, food waste, miscanthus, oils and sugar beet. These feedstocks have therefore been taken forward for further analysis. Sea kelp and straw are less favourable, due to costs, infrastructure requirements, competing uses or availability constraints.

Table 4: MCA assessment criteria and scoring

Availability	#	Seasonality	#	Imports	#	Competing Uses	#	Infrastructure	#	Transportation and Storage	#	Feedstock Risks	#	Cost & investment	#
Over 500,000 tonnes	5	Available all year	3	Readily traded commodity	3	No alternative uses	4	Existing infrastructure can be used	3	Transportation and storage have few barriers	3	Only a few factors that could affect the supply.	3	Low level supply chain investment required (<£1 million)	3
100,000–500,000 tonnes	4	Supply occurs once during the year	2	Low levels of trade	2	Some other uses but they are not at commercial scale or unlikely to be affected	3	Some new technology and/or knowledge is required	2	Transportation or storage could be problematic	2	A moderate number of factors that could affect supply	2	Moderate investment required in supply chain (<£5 million)	2
50,000–100,000 tonnes	3	Supply is erratic	1	Not traded	1	Priority is given to other uses but typically some is used in fuel production	2	Completely new sector requiring large investments	1	Transportation and storage would be difficult	1	Many factors could impact supply	1	Significant investment required in supply chain (>£5 million)	1
10,000–50,000 tonnes	2					Other uses are the priority and there is no availability	1								
less than 10,000 tonnes	1														

Table 5: MCA Results

Feedstock	Availability	#	Seasonality	#	Imports	#	Competing Uses	#	Infrastructure	#	Transportation and Storage	#	Feedstock Risks	#	Cost & investment	#	Total
Food Waste	Availability is dependent on collection efficiency.	2	Available throughout the year.	3	Imports not possible.	1	No commercial alternative uses (excl. Biogas)	4	New domestic collection system with source separation required.	2	Low value and typically wet so hard to move and degrades rapidly; local treatment required.	2	Reduction of food waste is expected to outweigh population growth.	2	Investment in collection infrastructure required; but no production costs.	3	19
Miscanthus	High volumes of availability depending on the land available. Will take a few years to reach high yields.	4	One harvesting period each year.	2	Material could be imported if it is pelleted.	2	Grown for use in energy	4	New machinery may be required for harvesting and planting.	2	Material can be transported but may require drying before storage.	2	Requires high volumes of water and could cause water shortages from reduced runoff.	2	High upfront investment cost for planting & establishment, specialised equipment required.	1	19
Straw	Dependent on the production of cereals.	2	Multiple harvests throughout the year which depend on the crop.	3	Material not imported.	1	Used for animal bedding and soil remediation.	2	Existing infrastructure in place.	3	Transportation will be for short distances due to low value.	1	Shortage of cereal crops and impacted by meteorological conditions and soil conditions.	1	Little investment required; improved collection infrastructure, no production costs.	3	18
Wood	High volumes available from a variety of sources.	2	Available throughout the year.	3	Wood pellets are a globally traded commodity.	3	Mainly used for timber products but SRC willow and processing residue is used commercially	3	New wood processing facility and collection system.	2	Material can be transported, and it can be stored for suitable time lengths.	3	Few factors with significant impact.	3	Investment in commercial forestry equipment required; skills & training.	2	21

Feedstock	Availability	#	Seasonality	#	Imports	#	Competing Uses	#	Infrastructure	#	Transportation and Storage	#	Feedstock Risks	#	Cost & investment	#	Total
Manure	Moderate volumes but would require a substantial increase in the number of cows.	3	Available throughout the year.	3	Not available for imports.	1	Used for soil remediation; but would be replaced by digestate, so unlikely to impact use.	3	Existing infrastructure is suitable.	3	Transportation would only be feasible for short distances.	1	Needs to be prioritised for soil remediation; but can be replaced by digestate.	3	No additional production cost; added value. Some additional infrastructure needs.	3	20
Oils	Mostly from oilseed rape; would require high levels of cropping on arable and some grassland.	3	Rapeseed will be harvested in a particular season but UCO available all year.	2	Readily traded commodity.	3	Rapeseed oil is mainly used for cooking oil and in other food products. UCO is available for fuels.	2	Existing infrastructure would need expanding but would be suitable.	2	Transportation and storage should not have any major barriers.	3	Over farming of rapeseed will damage soil and the ecosystem. Could impact productivity.	2	Low production costs, similar to counterfactual. Little investment required in supply chain.	2	19
Sugar Beet	Would require the increased farming of sugar beet on arable & some grassland.	5	Harvested in Autumn-winter.	2	Readily traded commodity.	3	Used for sugar production.	2	Existing infrastructure may need some adapting.	2	Transportation should not have many barriers, but sugar beet should be processed quickly.	2	Over farming could reduce soil health and decrease productivity.	2	Initial investment required for specialised equipment and infrastructure, then standard costs.	1	19
Sea Kelp	Will require large areas of sea coverage.	5	Harvested in late spring-early summer.	2	Not traded as a feedstock.	1	Contains high value chemicals that could be extracted for use in other industries.	3	New infrastructure would be required.	1	High volume ships may be required to carry material, storage should have no major barriers.	3	Bad weather can destroy annual harvest. Over farming will damage, the aquaculture, and the carbon/nitrogen levels in the water.	1	Initial high investment required for establishing lines and securing infrastructure, then lower operational costs.	1	17

5. Combustion Systems for Power Generation

The strategies for decarbonising the Isle of Man require the production of biofuels for a range of combustion systems to produce energy and heat. The power systems being decarbonised with biofuels include a combined cycle gas turbine and a series of reciprocating engines. The fuels that can be used in these systems must be understood first to identify the conversion processes of interest from the feedstocks considered in the earlier analysis. Later in this chapter technologies for the combustion of solid fuels have also been considered.

5.1 Combined-Cycle Gas Turbines

Turbine generators use the thermal expansion of gases to drive a turbine which in turn rotates a shaft that generates an electric current. In gas turbines, air is sucked in by a series of rotating blades that compress and warm the incoming air. In the middle of the turbine, fuel is continuously injected into the air stream which auto ignites when the fuel and air mix. The continuous injection of fuel sustains the combustion reaction and thus continuously propels the turbine. In a combined-cycle gas turbine the hot flue gases are used to produce steam which is also used to drive the turbine, increasing the efficiency and power output.

To achieve efficient combustion that maximises power output and reduces the amount of unburnt fuel, controlling the ignition timing of the fuel is critical. If the ignition delay is too short the air and fuel are given insignificant time to mix which results in a lower combustion efficiency. Conversely if the ignition delay is too long then the stoichiometry (ratio of fuel to air) may have surpassed the flammability limit and thus is no longer combustible, reducing the power output of the turbine. The properties of the fuel are critical in controlling this ignition timing.

Gas turbines can run on a wide range of gaseous and liquid fuels that vary in hydrocarbon chain length, as well as a combination, being duel-fuel compatible as is the case at Pulrose.

5.2 Reciprocating Engines

Reciprocating engines again use thermal expansion to convert chemical energy into mechanical energy (work) however, unlike a turbine, this is as linear motion, not rotation. The linear motion turns a crank shaft that produces the rotation to drive the generator shaft. The process happens in a cycle and the fuel dictates how the cycle operates. The most common fuels in these engines are diesel and gasoline. For a diesel engine (compression/auto-ignition), similar to those used at Pulrose, in the first stage air is drawn into the combustion cylinder by the lowering of the piston head, and the piston head then raises, compressing the air and heating it. As the piston head approaches the top of the cylinder, the fuel is injected which mixes with the warm air and combusts causing the gases to rapidly expand and drive the piston head to the bottom of the cylinder. The piston head raises again to eject the flue gases from the cylinder and the cycle repeats.

Like the gas turbine, ignition delay is the main property controlling combustion performance. Factors that can influence ignition delay include fuel viscosity (thickness), fuel reactivity, fuel energy density, droplet size, thermal conductivity, and fuel compressibility. If these properties vary, other factors can be modified to maintain optimised performance. Without modification it is essential the fuel is chemically alike, to be a drop-in fuel. Alternatively, a blend can be used to prevent modification.

5.3 Fuel Selection

Based on the systems described in the proceeding sections, the fuels of importance highlighted in the Future Heating Scenarios report and the feedstocks identified the previous section, five fuels have been identified as the most promising for production and utilisation on the Isle of Man. These include:

1. Biomethane, produced from manure and food waste
2. Ethanol, produced from either sugar beet (*or miscanthus)*
3. Hydrogenated Vegetable Oil (HVO), produced from rapeseed oil or UCO
4. Methanol, produced from wood (*or miscanthus)*
5. Renewable Dimethyl Ether (rDME), produced from wood (*or miscanthus)*

Although miscanthus has been identified as a suitable feedstock for three of the fuel pathways listed above, there is currently little or no interest in using it in these processes and therefore no evidence of its application in a commercial process. There has been interest in using miscanthus for commercial ethanol production; however, this requires the feedstock to be pre-treated to break down the lignin and release sugars that can be fermented (40). As a result, miscanthus is potentially a longer term feedstock option and has not been discussed in as a viable future fuel on the Island in subsequent sections. Other alternative fuels or production pathways that could also be considered appropriate to the Isle of Man feedstocks are explained in Appendix B.

5.4 Solid Fuel Combustion Systems

Solid fuel combustion systems come in a range of sizes from large scale power generation to domestic stoves. Large scale biomass power stations typically run on a specific feedstock such as wood, miscanthus or straw. Biomass power stations operate similarly to coal-fired power stations; the fuel is usually pulverised and then fired into the furnace in a jet stream with air. This causes the rapid combustion of the fuel particles and the residue ash falls to the bottom of the boiler. The heat released is used to superheat steam which drives the generator turbine. Other types of boilers are in operation such as a fluidised bed which uses a ceramic medium to create turbulence and encourage mixing of the fuel particles with air and heat, or a fixed bed with an updraft or downdraft. The main operational difference in each of these combustion systems in the fuel particle size (41).

Medium sized installations such as for district heating can also be fired with solid biomass. These systems often do not have the infrastructure to support biomass processing at the site. Thus, biomass pellets are typically fired into the system and the boiler has a fixed bed, with ash removed from the bottom (42). On the smallest scale are domestic biomass boilers and stoves. These systems are fixed bed systems that can be loaded manually or by automation (at higher capital cost). Wood logs, briquettes and pellets are the usual fuels for these systems. There can be a lot of variation between the fuel units and these systems do not burn at as a high temperature (maximum flame temperature of 800°C) which can create emission issues, which are discussed in Chapter 7 (32).

6. Conversion Routes

This section discusses the methods for converting the priority feedstocks to the respective fuels discussed the previous section. The systems that form part of the power and heat decarbonisation strategies can use the following fuels:

- Gas Turbines – Biomethane, ethanol, HVO, methanol, and rDME
- Reciprocating Engines (Compression Ignition) - HVO, rDME and ethanol
- Gas Boilers- Biomethane, rDME, and Propane*
- Oil Boilers- HVO

**Propane is a by-product of HVO production thus some fossil-based LPG could be displaced by this.*

6.1 Biomethane

Biomethane is a gaseous fuel produced through upgrading biogas from anaerobic digestion (AD) or by converting syngas from gasification. The CH_4 in the biogas is separated from the other components to increase the concentration of CH_4 to above 96%. This increases the energy density to ~40 MJ m^{-3} the same as conventional natural gas. Therefore, because of the similarities between biomethane and natural gas no modifications will be required, and the two fuels could be used interchangeably or as a blend. Biomethane can be blended in existing natural gas pipelines, to decarbonise gas supplies to end users, or can be used as a dedicated gaseous product, offering full decarbonisation of gas systems when derived from wastes, such as manure, slurry and food waste.

6.1.1 Biomethane production via AD

Biomethane is produced using AD, a biological process that generates a methane-rich biogas from bioresources such as manure and food waste. A process overview is shown in Figure 10.

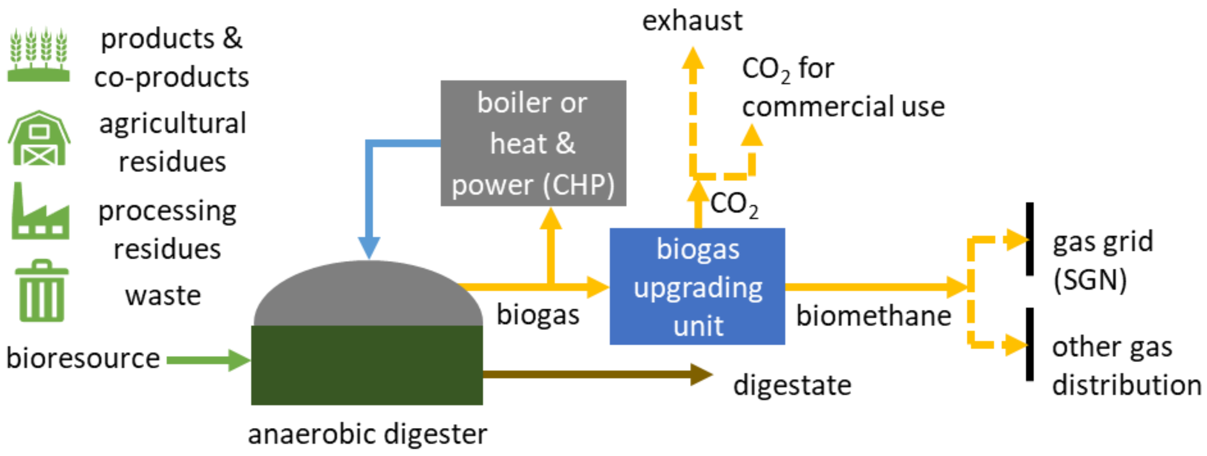

Figure 10: Overview of the production of biomethane, showing a typical commercial AD plant.

In Figure 10 feedstocks flowing into the digester are shown with a green arrow, while digestate flowing out is shown with a brown arrow. Gases are shown in yellow. Biogas leaves the digester and is upgraded to biomethane and/or used to generate process heat (or heat and power). Heat returning to the digester is shown with a blue arrow. Biomethane from the biogas upgrader is sent to the gas grid or to an alternative gas distribution system (e.g. virtual pipeline). Carbon dioxide rejected from the biogas upgrader can be vented into the environment or captured for commercial use or storage.

Biogas and biomethane production has been heavily subsidised in the UK and elsewhere in Europe in recent years, because of the high cost of building and operating such facilities. AD and biogas upgrading is subject to economies of scale, and currently small-scale biomethane production facilities, processing less than 20,000 tonnes of waste feedstock per annum are not commercially viable without support. Although AD can use a wide range of feedstocks, in practice there are several types of AD plant: commercial or merchant AD plants utilising packaged or unpackaged food waste, industrial AD plants processing food and drinks processing wastes and residues and agricultural AD plants processing livestock wastes and crops or crop residues. Hybrid systems are also technically and commercially feasible; the key to a successful AD plant is having a secure, stable and consistent feedstock supply. On the Isle of Man, a series of small livestock-waste fed systems, and/or a medium hybrid food waste and livestock waste fed system would be the most technically feasible, located close to the source of feedstock and existing gas infrastructure. Where food waste is included, a dedicated reception hall, de-packaging equipment and dedicated pre-treatment facilities may be required, adding cost and complexity to the site.

6.1.2 Cost of biomethane production

As the economics of AD are highly sensitive to a number of factors, including site selection, existing infrastructure, location, size, feedstock, output and structure, three scenarios are used here to illustrate the cost range.

Table 2: Capital and operational costs for AD, based on three 'typical' scenarios.

	AD size	**Small**	**Medium**	**Large**
	Approx. Biomethane Capacity - nm3/hr	**100**	**700**	**1200**
CAPEX	Pre-development £'000	1,150	3,200	5,500
	Construction £'000	1,900	6,600	9,500
	Additional/Other CAPEX £'000	950	3,000	6,000
	TOTAL CAPEX £ million	*3.5*	*12.8*	*21.0*
	Total CAPEX (with inflation) £ million	**4.0**	**14.7**	**24.2**
OPEX	Maintenance and Labour £'000/year	370	1,500	2,600
	Insurance, rates & fees £'000/year	350	550	800
	Digestate Management £'000/year	0	400	800
	Other £'000/year	20	260	320
	Feedstock costs (residues only) £'000/year	0	270	500
	Total OPEX £ million/year	**0.81**	**3.18**	**5.12**

In Table 2, each site is assumed to use biogas for biomethane upgrading. For the smallest site, all waste is manure, but for the medium and large sites a mix of livestock wastes and food waste is assumed, as small-scale food waste digestion is not feasible given additional front-end reception and processing infrastructure requirements. It should be noted that at the smallest size, biogas upgrading to biomethane is not available at this scale, so costs are based on a virtual pipeline connecting multiple (four) satellite sites to a central upgrading facility. On the Isle of Man, to process the food and livestock waste through AD, total capital investment required would be around £10-15 million.

6.2 Ethanol

Ethanol is a simple alcohol that is currently produced at a large commercial scale from sugar cane, sugar beet, wheat, and maize. Ethanol is a liquid fuel at room temperature and is commonly blended with petrol for use in spark-ignition systems. The gross calorific value of ethanol (29.7 MJ/kg) is lower than other conventional liquid fuels such as gasoline (46.4 MJ/kg). Ethanol could be used in gas turbines or the reciprocating engines (with modification) currently in operation on the Island.

When substituting natural gas it should be noted, on a volume basis, the energy density of methane (39.8 MJ/m^3) is much lower than ethanol (23,400 MJ/m^3) at atmospheric pressure. However, on a mass basis the calorific value of methane (55.5 MJ/kg) is much higher than ethanol (29.7 MJ/kg). This is important because the fuel injection pressure will have to be lower (lower flow rate) for ethanol to achieve the same thermal output; however, fuel consumption, on a mass basis, will be higher for ethanol which could be more expensive and require increased fuel supply. The other barrier to ethanol displacement of natural gas is the difference in volatility, which is much lower for ethanol. This would increase the ignition delay time and could reduce combustion efficiency if the air-fuel stoichiometry and droplet size are not controlled.

The main route to ethanol production is by fermentation and this is a well-established commercial process. Fermentation sites are usually large facilities that either start with the raw feedstock or a sugar solution that can be dropped directly into the reactor. Feedstocks for ethanol can be mixed; however, this is only once the sugars have been extracted as the feedstocks will require different pre-treatment steps to achieve sugar extraction. The process discussed in this report is not to be confused with ABE (acetone, butene and ethanol) fermentation which is growing in commercial interest.

6.2.1 Ethanol production by fermentation

The process starts with sugar beet which is shredded and ground to form cossettes. Using a press or extruder the juice is extracted from the cossettes, the pulp by-product has a value to the animal feed industry. The juice is rich in sugars but must be cooked and sterilised to remove any bacteria that could impact on the fermentation microbes. During cooking a thick syrup can form called molasses which is typically extracted and sold to other markets such as animal feed, the food industry, or the pharmaceutical industry. After cooking the juice is fed into the fermenter, mixed with yeast and nutrients and left in the reactor for 1-2 days.

After fermentation the liquid phase, termed “wine”, is distilled twice to form a 94-95 wt.% ethanol solution. The process flow diagram (PFD) is shown in Figure 11.

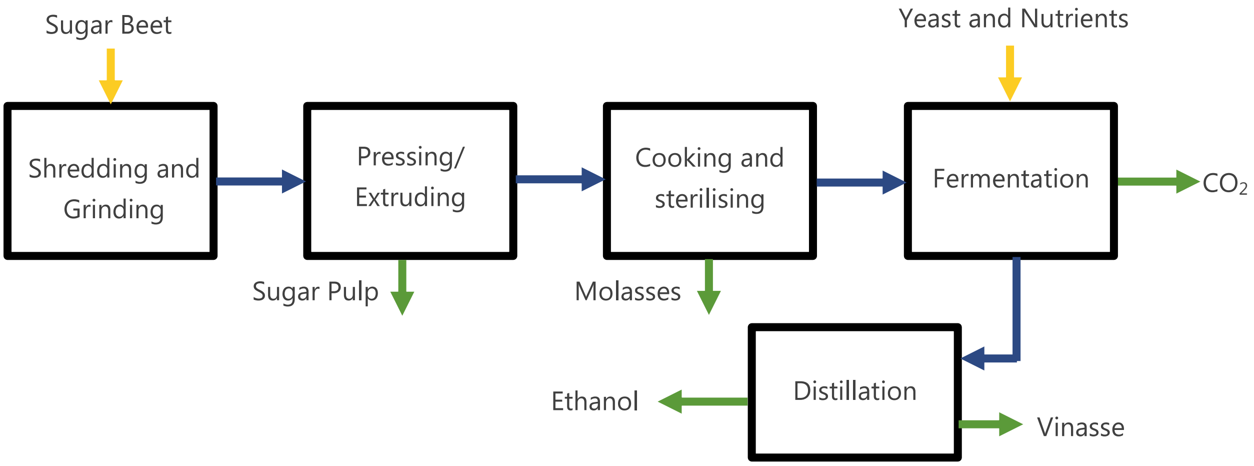

Figure 11: Process Flow Diagram for ethanol production from sugar beet

Yields of ethanol from sugar beet are 86.9 kg/tonne, using the process described in Figure 11 (43). Therefore, the potential yield of ethanol from sugar beet grown on the Island is between 800 tonnes per annum (low scenario) to 55,000 tonnes per annum (maximum scenario).

Fermentation of the molasses produced can yield 248.5 kg per tonne of ethanol (43). Therefore, if the ethanol from the molasses and sugar beet were combined, between 900 tonnes and 62,000 tonnes of ethanol could be produced on the Island, contributing between 7,500 to 510,000 MWh per annum to the Islands energy system. If this ethanol was fired into the gas turbines, assuming a conversion efficiency of 35%, this would yield between 2,500-180,000 MWh per annum.

6.2.2 Cost of ethanol production from sugar beet

The average cost of producing bioethanol from sugar beet in Europe has been reported at £403-520 per m^3 ethanol capacity (2019), significantly more expensive than the cost to produce bioethanol from Brazilian sugar cane, which is estimated to be £112 per m^3 (figures from (85), adjusted for currency and inflation). The cost difference is primarily down to the feedstock being used.

Although costs of commercial-scale ethanol production facilities are not widely disclosed and the scale required to process beet arising on the Island would be smaller than most other commercial ethanol production facilities, it is possible to provide indicative costs based on data available for similar-scale and type facilities.

The table below includes indicative costs for a plant appropriate to sugar beet availability on the Isle of Man, based on the *high* production scenario. In addition to the required ethanol output, a significant number of co-products would also be produced which could be utilised on the Island, and if resultant wastes and residues are processed through AD on-site, this could deliver additional biogas, which in-turn could be upgraded to biomethane for injection into the gas grid or presented directly to the end-users, from co-located facilities or via a virtual pipeline system.

Table 3: Indicative costs of sugar to ethanol facility, at scale appropriate on the Isle of Man based on the *high* sugar beet production scenario

***High* Sugar Beet Production Scenario**		
Key metrics		
Beet production	101,200	fresh tonnes
Land area	1,219	hectares
Ethanol production	10,474,200	litres
Capital Costs	**£ 19.84**	**million**
Lifetime	20	years
Co-products		
Pulp	7,084	tonnes
Topsoil	5,060	tonnes
Stones	172	tonnes
Spent lime	4,048	tonnes
CO_2	10,815	tonnes
Vinasse	58,237	tonnes
Biogas	6,359,431	cubic metres
Digestate	52,413	tonnes
Input (energy) requirements		
Electricity	1,872,000	kWh
Process heat	9,248,556	kWh
Process natural gas	15,414,259	kWh

6.2.3 Sea kelp as an alternative feedstock

Sea kelp could be used as an alternative feedstock for this process. Sea kelp is not high in lignin so does not have the same problems as other lignocellulosic feedstocks where the lignin inhibits decomposition of cellulose and hemicellulose. However, sea kelp does not contain many polysaccharides composed of glucose and therefore requires other carbohydrate components to be broken down to provide sugars. Therefore, a hydrolysis step is required using either acid or enzymes. This process would produce more free sugars for fermentation; however, research has shown they also produce inhibitor components. Large seaweed to ethanol production facilities have been proposed in Denmark and Japan, however, to date there is no large-scale facility producing ethanol from macroalgae so this option would be a longer-term option, with the potential to transition a facility from sugar beet to sea kelp over time.

Sea kelp to ethanol conversion efficiencies are all based on small scale processes or models. In this work a yield of 40 kg of ethanol per dry tonne of sea kelp was used (44). This would yield between 12,000-288,000 tonnes of ethanol per annum, which could be converted to 34,500-830,000 MWh of energy for the Island per annum. Compared to sugar beet, based on the scenarios described, sea kelp has the potential to produce more energy. However, when you consider the output per hectare of land/sea used to farm the sugar beet/sea kelp respectively, sugar beet produces 15.74 MWh per hectare (rising to 17.5 MWh per hectare when using the molasses as well) compared to 1.2 MWh per hectare for sea kelp. The efficiency from sugar beet is therefore much higher than sea kelp.

6.3 Hydrogenated Vegetable Oil

HVO is a direct replacement fuel for diesel. Diesel fuels are made from a range of chemical molecules (carbon chain lengths of 12-20). Conventional FAME biodiesel is a lower quality fuel compared to HVO because of the oxygen in the fuel and the presence of impurities, and the unsaturated nature of the molecules can result in blockages from crystallisation, flow problems from viscosity and reduced power output from premature autoignition.

HVO is made from oil-based feedstocks and uses hydrogen to form paraffinic molecules. During this process the oxygen, nitrogen and sulphur impurities are removed from the fuel which improves the emissions from combustion and the fuel can be stored at low temperatures without crystallising. All of this means that HVO can be used as a drop-in replacement for conventional diesel without any modifications and could be blended with conventional diesel without a blend limit.

6.3.1 HVO Production

Hydrogenation has been used commercially in the oil and gas industry for many years and is now being used for processing of virgin and waste bio-oils. The main objective of hydroprocessing is to convert a variety of lipid and hydrocarbon feedstocks into a range of products. This is achieved using hydrogen at various pressures and specific catalysts to deliver saturated molecules, to remove unwanted molecules and functional groups, and to break longer chain molecules into smaller ones suited to typical fuel ranges.

The process flow diagram is shown in Figure 12. The first step is to pre-treat the feedstock to remove any problematic species that could affect any of the processing operations. The feedstock must be a vegetable oil, this can either be extracted from oil crops such as rapeseed, soya, or sunflower, or alternatively, an increasingly popular choice is to use used cooking oil (UCO). Using UCO requires any food residue be filtered out and the UCO is then degummed and bleached. Once the feedstocks have been treated, they are mixed before being fed to the hydrogenator.

Hydrogenation is used first to saturate the triglyceride molecules (removing any double bonds), then the large triglyceride is broken into 4 molecules (3 free fatty acid molecules and a glycerol molecule). High pressure hydrogen reacts with oil droplets over a catalyst. There are a variety of catalysts that can be used but the most common are metal sulphides on an alumina support. The choice of catalyst is a critical step as it greatly influences the conversion efficiency.

The final stages convert the free fatty acid molecules into alkanes of desired lengths. The first step is to remove the acid functional group. This is done by either decarboxylation or hydrodeoxygenation. In decarboxylation the carbon is released as well as oxygen in the form of CO_2 and CO, whereas in hydrodeoxygenation the carbon remains in the hydrocarbon molecule. During decarboxylation low pressure hydrogen is injected into the process and removes the entire carboxylic acid (COOH) group. In hydrodeoxygenation high pressure hydrogen is required, and only the hydrogen and oxygen are removed from the acid group (OOH). It is for this reason that the hydrodeoxygenation method produces longer hydrocarbons. The alkanes produced are typically too long for use in most conventional transport engines.

Finally, alkanes undergo hydrocracking and/or hydroisomerization to produce the desired branched hydrocarbons. These have lower pour and cloud points which is valuable for jet fuel and winter-diesel. This reaction is typically catalysed by solid acids supported on zeolites. The liquid molecules are separated into specific fuels by conventional fractional distillation. The molecules produced are virtually all paraffinic with less than 1% aromatics. The cetane number of HVO is between 75 and 90 versus 48 to 52 for petroleum diesel, meaning HVO burns more completely, resulting in lower CO and NOx emissions.

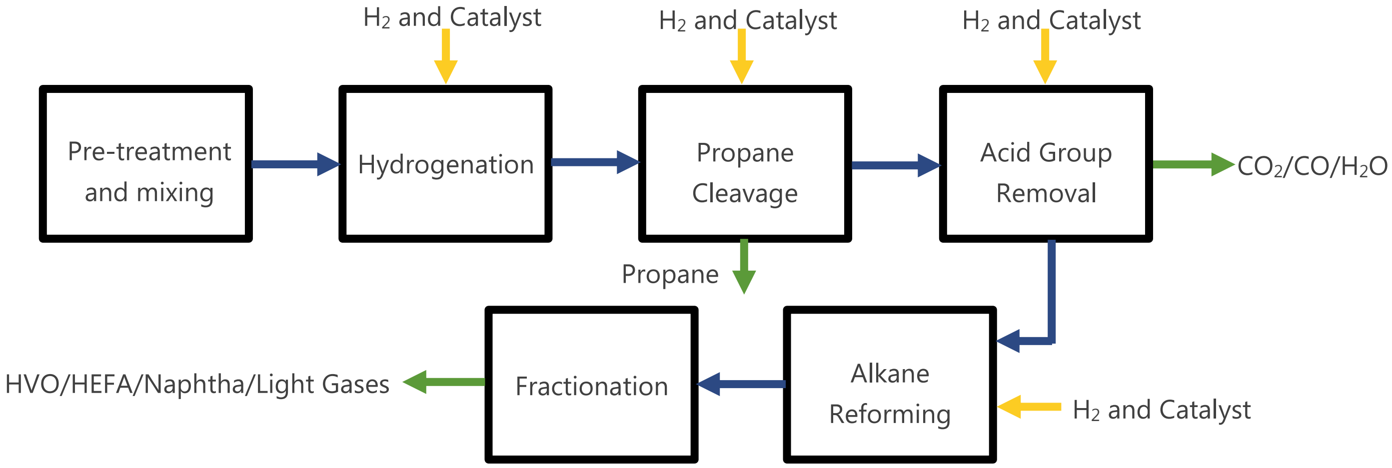

Figure 12: Hydrogenation process flow diagram

Yields of HVO from UCO are 1.1 MJ of product per MJ of feedstock which is higher than from virgin rapeseed, soya, or palm oil (0.98 MJ of product per MJ of feedstock). The maximum feasible production of HVO from rapeseed on the Island, based on the scenarios assessed in the feedstock analysis, is 70,000 tonnes of HVO and the lowest production volume is 6,500 tonnes. Using an efficiency of 40% for use in the reciprocating engines, this could yield between 30,000-320,000 MWh of power per annum.

Due to the limited number of commercial HVO production facilities operating globally, no data is available on the capital cost of HVO production plant; however the cost of production is estimated at around 1800-2000 USD per tonne (£1500-1650 per tonne).

6.3.2 Propane *(by-product)*

Propane is produced as a by-product of the HVO process (approximately 10% output by volume). The propane is produced in a secondary step of the main hydrogenation process, termed propane cleavage. During the propane cleavage step the hydrogen pressure is reduced and the temperature is increased. The catalyst is changed to a sulphated zirconia zeolite catalyst which is common in the petrochemical industry. This propane could be liquefied and added to LPG in domestic, commercial or industrial applications, or used as a gas and mixed with biomethane to increase the energy density (50 MJ/kg). Using the production volumes of HVO stated above, it is estimated that between 650-7,000 tonnes of propane could be produced on the Island.

6.4 Methanol Production from Gasification

Methanol is a liquid fuel that is rich in hydrogen. It has a gross calorific value of 23 MJ/kg which is relatively low compared to other fuels, meaning greater volumes will be required to achieve the same energy outputs.

6.4.1 Methanol Production

Figure 13 shows the process flow diagram for gasification with syngas cleaning. The feedstock is either solid biomass such as wood, or waste. The moisture content should be below 30% (air dried) and the particle size should be below 30mm. The cleaned syngas is then upgraded to methanol.

The objective of gasification is to breakdown solid fuels into gases and vapours which can be upgraded into fuel. The solid biomass materials are converted into syngas by exposure to high temperatures in an oxygen-starved atmosphere. The most common atmosphere is steam with a small amount of oxygen - this combination maximises the release of carbon and the production of hydrogen whilst preventing the gases from combusting. The syngas produced is a mixture of mostly carbon monoxide (CO) and hydrogen (H_2) and is thoroughly cleaned to remove impurities before the gas can be upgraded. Gasification can be paired with reforming and cracking processes before gas clean up to optimise fuel yields, this is dependent on the type of gasifier used.

Syngas cleaning is critical to the overall process yields. Typically, the clean-up process goes in the following order: particulate and tars, acid gas removal (S and Cl), ammonia stripping, metal absorption and syngas drying. The syngas exiting the gasifier is cooled and the condensable materials (tars and particulates) are filtered out. The gas can also be wet scrubbed with water to remove tars and acid gases. This produces copious volumes of wastewater.

The next stage removes the sulphur by using a solvent. The most common processes either use selexol or MEA. The selexol process will produce small volumes of acid gas that have to be purged from the system whereas the MEA process requires the solvent to be regenerated periodically in a sulphur recovery unit (SRU). An alternative method for desulphurisation is to use a ZnO bed - these are effective for low sulphur concentrations.

The removal of chlorine, which is present as HCl in the syngas, is important as it is highly corrosive. There are various methods to remove HCl typically using alkali solvents. Using $Ca(OH)_2$ with a sodium aluminate/carbonate catalyst produces $CaCl_2$ which is dissolved in water (also produced in the process). $CaCl_2$ is highly soluble in water and therefore disposal is usually through dilution and drainage - precipitation would be very expensive at the detriment of the process - use of this step is also dependent on the Cl content of the feedstock. Ammonia is stripped from the syngas by reacting with dilute sulphuric acid (H_2SO_4) to form ammonium sulphate ($(NH_4)_2SO_4$) which is then removed.

Volatile heavy metals in the feedstock must be removed from the process before the upgrading steps to prevent catalyst damage. Common volatile metals include Hg, Zn, Ar, Cd, Cr and Pb. The most common method is to pass the syngas through a bed of porous material. The high surface area causes the metals to be condensed on the particle surfaces. The most common beds are activated carbon. Sometimes ZnO can be used in conjunction to remove any remaining sulphur or sulphide compounds.

Methanol is produced by the reaction of the CO with H_2. To make this reaction feasible the concentration of hydrogen must be increased, and this can either be achieved by injecting more hydrogen produced externally into the reactor or by a water-gas-shift reaction (this increases the concentration of H_2 and reduces the concentration of CO).

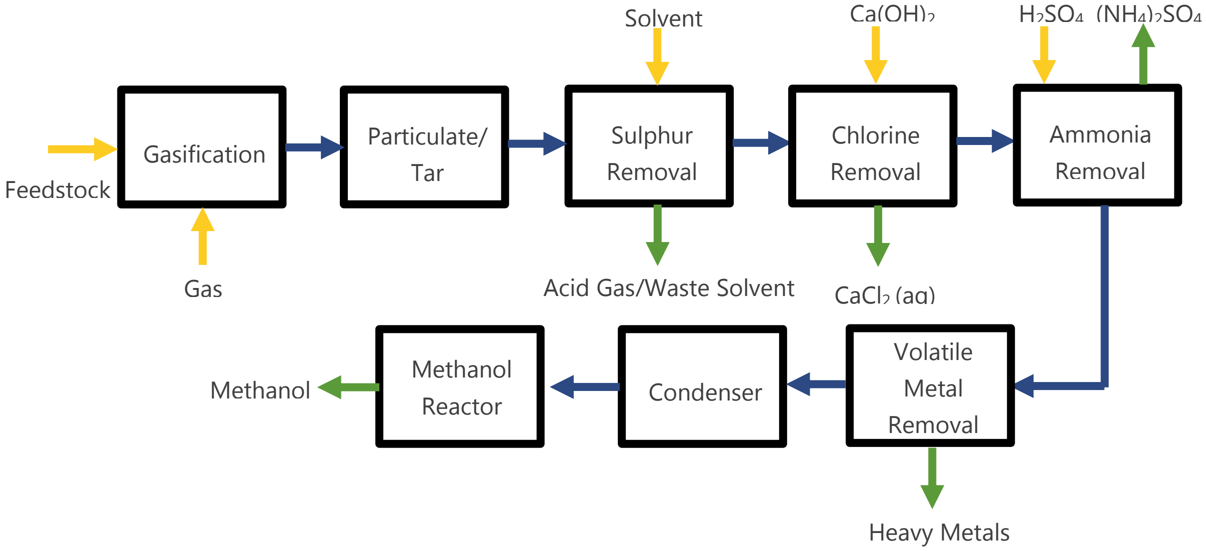

Figure 13: Process schematic for gasification to produce a clean and dry syngas

The yields of methanol from feedstocks available on the Island, based on a low wood harvest of 2,000 tonnes by 2050, is 900 tonnes. If this was combusted in the gas turbines, with an efficiency of 35%, this would contribute 2,000 MWh to the Island energy system (45).

Plant of such scale is not commercially available and as a result no data is available on the capital cost of establishing such a facility on the Island. The resultant fuel is known to have a production cost of around £2500 per tonne.

6.5 Renewable Dimethyl Ether (rDME) from Wood

rDME is a fuel that is gaining increasing commercial attention, that can be used in diesel engines with some modifications. A DME molecule consists of two carbon atoms, each with three hydrogen atoms, connected by an oxygen atom. rDME is a very clean combusting fuel with emissions of NOx, SO_2, unburnt hydrocarbons, and particulate matter relatively low compared to other fuels including HVO and synthetic diesel. DME has a gross calorific value of 31.7 MJ/kg which is significantly lower than diesel. This also limits the amount of DME that can be blended into LPG for the heating sector. However, the main drawback is, although the internal components of the engine do not have to be modified, the fuel injection system and timing must be modified as well as the temperature control in the engine and this can be very expensive (46).

6.5.1 rDME Production

rDME can be produced in a single step process via methanol. The reaction mechanism proceeds with the reaction of CO with H_2 both produced directly from the gasifier to form methanol. The methanol molecules then react with each other by dehydration to form rDME and water as a by-product. The syngas from gasification is deficient in H_2, therefore in addition to the water by-product from methanol dehydration steam is injected to convert some of the CO to H_2 (water-gas-shift reaction). The single step process uses a more expensive bifunctional catalyst to support the various reactions. The process can be performed in two stages, the first producing the methanol and the second dehydrating the methanol, using specific catalysts.

The lowest production volumes of rDME from feedstocks available on the Island is 620 tonnes. This could contribute 1,600 MWh of power to the Island, via the reciprocating engines (45). However, commercial production facilities have not yet been established at such scale and no commercial deployment has been seen in the UK, so no capital cost data is available.

7. Environmental Impact and Sustainability Assessment

In this section the environmental impacts and the sustainability of the identified non-waste feedstocks, fuels and combustion processes suitable for deployment on the Island are discussed. This provides an overview of the key risks and challenges; however, a more detailed analysis should be conducted before pursuing opportunities, considering locational details, scale and type of operation.

7.1 Feedstock sustainability

Five feedstocks (wood, miscanthus, sugar beet, rapeseed oil and sea kelp) were identified as being the most feasible for fuel and energy production on the Isle of Man. The scenarios presented in the earlier chapter provided an indication of the available volumes and potential energy contribution that could be expected. For some feedstocks, a high scenario was not considered due to environmental and sustainability impacts, so all scenarios presented are deemed sustainable, with good management and best practice being followed. In this section, the focus is more on sustainability of production, harvest and conversion methods, as opposed to the scale of opportunity.

Direct and indirect conversion of natural landscapes and ecosystems for biofuel cultivation can have a negative impact. This can be from the conversion of agricultural land for energy or oil crop production displacing food production, which could be pushed into using natural ecosystems. Second generation biofuels avoid this problem since they are typically wood or waste derived, meaning they do not compete with food and feed production and utilise resources that are otherwise not valorised. Second generation feedstocks can also include energy crops, such as miscanthus and SRC willow, that are can be grown on less productive agricultural land, so again do not impact on food production.

7.1.1 Wood

Wood produced on the Isle of Man and considered in this report could come from three sources: SRC, forestry residue, and processing residue. Tree felling is very complex in sustainability terms and must be approached with caution. Felling of ancient trees (100 years plus) for use in energy cannot be considered sustainable, unless the carbon released has a natural sink elsewhere. It would not be sustainable to fell one mature tree and to replace it with a young tree; the size of the tree and the amount of carbon stored in the wood needs to be accounted for and the planting and growth of new trees needs to match that carbon no longer being stored. Additionally, the value of a tree to the ecosystem must be considered. Ancient trees provide regular nesting, feeding and hibernation spots for birds and forest animals. Tree removal will influence the activities of those animals and this should be a consideration before trees are felled. Without considering the implications of these activities and implementing a detailed, effective, management plan the impact of tree felling for biomass is typically negative and can be the subject of a lot of criticism.

Tree thinning is a preferred practice as it can provide a regular source of biomass without creating a large carbon sink or impacting the ecosystem. Tree thinning increases the light that passes to the forest floor and increases tree growth as well as forest floor shrub growth. When balanced it creates a carbon natural scenario that can also be beneficial for the ecosystem. Again, this has to be planned and implemented as part of forestry management plan and regular assessments on biodiversity and the carbon balance should be undertaken to ensure the forest remains in a steady state.

Actively managed forests offer a strong and diverse ecosystem for a vast range of flora and fauna species. Planting new trees is an effective way of building up future resource, but careful management must be adopted to optimise the environmental, economic and social benefits of such activities.

Forestry Products and Residues

The natural environment benefits from leaving residue from forestry thinning and management activities on the floor of the forest to decompose. This process creates habitats for insects and wildlife and returns carbon and nutrients back to the soil. However, overloading of forest floors with residual material, or leaving predominantly woody materials in situ can also cause issues. It is therefore essential to effectively manage forests, to remove all elements that offer value added, whilst leaving leafy and brashy material in situ to breakdown over time, and to return essential nutrients and organic matter to the soil. Typically, 30% of residue is left on the forest floor to maintain good soil carbon levels and biodiversity.

Wood Processing Residue

Wood processing residue can be put back into the soil; however, as it arises after the material has been removed from the forest, this would require transporting back into to forestry areas for distribution, eliminating natural benefits. Residues arising during processing has minimal impact on the soil quality or biodiversity (47) (48), so it is best used direct from the process in other markets.

SRC Willow Farming

SRC willow is a high yielding crop that can supply biomass over a long period of time. One of the biggest issues with SRC willow growth is it requires larger volumes of water than standard arable crops. This means that soils can become dry and compacted by growing willow; however, frequency of cultivation, harvest and other machinery operations is much reduced, so land and soil quality is protected as a result. Before the SRC willow is planted and during the establishment phase, herbicides are typically used to clear the land and to prevent competition with weeds in the early stage of growth; however, after this initial treatment, no other chemicals will be required for the duration of the plantation.

The carbon balance from growing SRC willow is highly positive, indicating that SRC willow produces 30 times the amount of energy than is needed in its production; even the lowest results record this as being 14 times (49) which indicates high productivity.

Due to its perennial woody nature, conversion of arable land to SRC willow can be considered long-term land use change, and its placement needs to be carefully considered. SRC willow grows on lower quality arable land and wet parcels where annual cultivation and harvest may be challenging, and frequent machinery operations may damage soil structure and quality. Although there are some impacts already discussed regarding the biodiversity and water retentiveness of the soil; growth of SRC willow will act as a substantial carbon sink on arable land (50).

SRC willow could be used to remediate low-grade land such as that used for historical industrial activities or land that has become depleted in carbon or saturated in unwanted chemicals over time. The biomass produced would have to be analysed to ensure it did not contain high levels of heavy metals as these could create air quality issues if combusted, or prevent efficient fuel conversion.

SRC Willow as with some other biomass and energy crops could be grown on a range of land types. However, it is important to consider the carbon state before plantation and the impacts of cultivation on this land type. For example, peatland is great for natural CO_2 sequestration. Although well-suited to production of energy crops, it would be difficult to justify using it for biomass production, since this would reduce the impact the land is having as a sequestration mechanism (51).

7.1.2 Miscanthus

In the short-term miscanthus has been seen to increase the biodiversity of arable land, especially bird populations. However, these effects will diminish with time as miscanthus provides a dense canopy when mature, and less insect food than traditional crops such as cereals and oilseeds (52). Harvesting of miscanthus in the UK is typically in late winter to early spring (late February to late March). Typically, other field activities are low during this period and the ecosystem is typically in a sedated state. However, the soil is usually wet in this period and harvesting with heavy machinery can lead to soil compaction and water drainage problems; therefore, timely harvesting is essential and good practice guidance should be followed to reduce minimise longer-term impacts. Additionally, any birds or mammals that may be nesting or hibernating in the miscanthus crop would be disturbed and this could put their survival at risk; to mitigate the risk and reduce the impact of late harvests, biodiverse field margins should be established and effectively managed, providing a refuge for disturbed species.

Once established, miscanthus does not require much fertiliser as leave fall and replenish nutrients in the soil naturally, creating strong natural ecosystems for insects, invertebrates, ground nesting birds and mammals. Miscanthus can often be grown without any chemical treatments. In the early stages herbicides are required to clear the land and prevent competition from weeds; however, there is little or no requirement for pesticides once established (53).The carbon balance for miscanthus is net negative, meaning up to 2.35 tonnes of CO_2e is stored in the ground (54) during the growth and management of a plantation.

7.1.3 Sugar Beet

Sugar beet can be demanding on soil and thus have an impact on the biodiversity. Sugar beet is sown from seed in mid-March to mid-April, after the last frost. When the seeds are sown the soil is usually aerated causing soil carbon losses, and this is also the case when the sugar beet is harvested in late September to October, often through the winter when storage or access to equipment is limited. Soil can be wet at harvest, and although harvest can be done following a ground frost to prevent damage, the overall impact on the soil health is negative. Soil is also removed from the field when the beet is harvested, and soil compaction from heavy machinery can lead to drainage issues if operations are carried out at sub-optimal times.

The production cycle of sugar beet is different to other crops, which can impact negatively on small invertebrates in the soil and can have a cascading effect on the food chain. Sugar beet also requires significant chemical inputs, in terms of herbicides, fungicides and fertilisers.

Common farming practices such as spreading manure to replenish organic matter content and lost nutrients after the sugar beet has been harvested will help to restore the soil carbon concentration and improve quality. Furthermore, beet tops are often incorporated back into the soil after harvest, to replenish nutrients and soil carbon stocks, so depletion is minimised. However, it is recommended that sugar beet is only grown once in every 5 years, in a crop rotation, to reduce pest and disease persistence, and to minimise soil health impacts. The diversity of using the sugar beet can be beneficial in balancing out impacts from growing other crops.

7.1.4 Oilseed Rape

Although oilseed rape can be winter- or spring-sown from seed, with a relatively short growing season as harvest is typically carried out in July or early August, fertilisers containing nitrogen, phosphorus and sulphur are required to achieve good yields. Fertilisers are typically applied in autumn and spring which are higher rainfall seasons, presenting a moderate risk of run-off.

Rapeseed is harvested in the late summer from mid-July to August when the soil is dry, posing little risk of damage from harvesting activities. Rapeseed can be sown in September as a winter oilseed, providing the soil with a water retention mechanism and a source of food and energy for the ecosystem over the winter months. The overall impacts to biodiversity are considered negligible compared to other annual crops. However, placing oilseed rape in a crop rotation will balance out the impacts from growing other crops and will keep the soil and ecosystem in a healthy steady state.

The main threat comes from the over production of oilseed rape, such as from continuous growth cycles or frequent repetition of the crop in the rotation.

7.1.5 Sea Kelp

There are a variety of issues from sea kelp farming that could result in negative environmental impact, including:

- Light absorption
- Nutrient absorption
- Carbon absorption
- Kinetic energy absorption
- Addition of artificial material
- Habitats for disease and parasites

Cultivation of seaweeds in surface waters will lead to shading of underlying habitats if spacing between the lines is insufficient. This will also be dependent on the clarity and turbidity of the water. Creating shade will kill the underlying vegetation and destroy habitats for aquatic life. If shade affects phytoplankton this could be detrimental to the entire aquatic ecosystem (55). There is limited information on the impacts of growing sea kelp on lines above bare seabed which could provide a solution to preventing ecosystem damage. However, the shade produced from the surface will still cause issues with phytoplankton in the water, which is fundamental to aquatic life (55). If extensive farms covering large areas are used this will exacerbate the problem, regardless of the topography.

Sea kelp requires large amounts of nitrogen to grow. This can have a positive effect by reducing nitrogen levels in water. However, if the sea kelp depletes the local environment of nitrogen this will influence both the growth of other local aquatic plant life and the sea kelp itself. Anthropogenic sources of nitrogen can be used to maintain the nitrogen levels in the water, however, if the carrying capacity of the local environment is not exceeded this should not be required as the tide will naturally cycle nitrogen into the area (56).

Sea kelp farms could damage water flows through local environments if the growth density is too high. Poor circulating water becomes depleted in minerals which are vital for sustaining plant life. This can also affect the pH and temperature of the water (55). Artificial materials required for the growth of sea kelp that can cause problems such as entrapment and entanglement of sea animals. If the current is too strong and there is erosion and breakages of lines this can introduce more plastic pollutants to seas (55).

The cultivation of sea kelp will reduce the diversity of wild seaweed species which will make crops susceptible to abiotic stressors, disease, and parasites. This is a growing global concern which will be intensified by increased production of sea kelp (55). However, carbon storage in seaweed is highly efficient. It is estimated that up to 2.48 million tonnes of CO_2 is captured per year by seaweed. This is one of the biggest natural carbon sinks. The rapid growth of seaweed means carbon is quickly trapped in the plant structure and when effectively managed many of the environmental risks highlighted above can be mitigated. If particulates from erosion or larger pieces of plant material break off these can settle on the seabed creating long term carbon storage (57).

7.2 Combustion Emissions

Emissions from the combustion of solid fuels are variable depending on the chemical composition of the fuel and the moisture content. Flue gas emission controls on larger scale systems are more practical and economic to implement but as the scale reduces in size this becomes less feasible and the best emission control measures are on the fuel itself. In this section emissions of unburnt hydrocarbons, soot, particulate matter (PM) and NOx are discussed in a general context and some control techniques and abatement technologies highlighted.

7.2.1 Unburnt Hydrocarbons

Unburnt hydrocarbons are created when the fuel particles devolatilise, and the volatile products leave the boiler/combustion chamber without reacting with oxygen. The environmental impact is the release of tars and carcinogenic compounds to the air. The tars will often condense at this point and depending on wind conditions, they can move into public spaces reducing the air quality.

On large-scale systems these compounds are usually burnt out because of the hotter temperatures. If they are released from the boiler usually in the flue gas cleaning, they will condense into PM and be removed before emission to the air. In medium-sized systems this is also usually the case, sometimes excess air can be fired into the system, but this can also create more issues with NOx. Although medium-sized systems do not have the same level of flue gas cleaning as large-scale systems, there is usually an electrostatic precipitator (ESP) that will remove PM along with the condensed tars. At the small scale, in domestic boilers and stoves, no abatement technology is available. So, the fuel properties must be controlled.

Dry fuel (below 20% moisture) will help reduce the concentration of unburnt hydrocarbons; excess moisture cools the stove and prevents efficient combustion. Briquettes and pellets will typically burn more completely as the fuel breaks down into a fine powder after a period of being exposed to the heat. Ensuring there is enough fuel and trying to minimise cooling effects will also reduce the concentration of unburnt hydrocarbons, for example on a domestic stove not opening the door, to prevent an influx of cold air, or ensuring the air flow is right, to prevent fuel rich combustion (32).

7.2.2 Soot

Soot is formed by the growth of carbon structures from carbon radicals. These structures grow like building blocks where carbon atoms add to the structure. The result is a black powder that can be very fine or much larger in size. Soot is often the first step in PM formation. When released to the air fine soot can have devastating impacts on public health. Fine soot particles can become embedded in lung tissue that can lead to lung disease or cancer. Larger soot particles can be filtered out by the body but can also cause irritation to mucus tissue in the mouth and nose or to skin.

Soot is often removed before emission in large and medium-sized systems using an electrostatic precipitator (ESP). In small systems the control techniques are the same as unburnt hydrocarbons. There is a lot of evidence that moisture content has a large impact on soot formation especially for logs. Solid stove or boiler users should be properly informed on the correct ways to store and use fuels to prevent soot formation (32).

7.2.3 Particulate Matter

Particulate matter (PM) encompasses soot but also includes condensed inorganic material that can form particles of its own that grow and combine with soot or they can condense on the surface of soot particles. The most common inorganic elements in particulate matter are K, Na, Cl, S, Zn, Pb, and other heavy metals. These have the same issues as soot with the addition of toxic components that could be breathed in or worse deposited in water bodies or soils and taken in by nature, and they will bioaccumulate. Again, for large and medium-sized systems ESP will prevent the emission; however, operational problems for scaling of boilers known as slagging and fouling is a major issue from inorganic material. Slagging and fouling reduces' the efficiency of the boiler and can lead to shut down. Additives and fuel blending are often used to control this issue. For smaller systems, there is less that can be achieved by controlling the combustion process; instead controls are at the fuel level. Fuels that are contaminated with metals should not be used in these systems and the concentration of these contaminants in the wood should be monitored by the wood supplier (32).

7.2.4 NOx

Oxides of nitrogen known as NOx are formed by the reaction of nitrogen with oxygen. The source of the nitrogen can either be from the fuel (most common) or nitrogen in the combustion air. NOx can cause acid rain, reduced visibility from haze, nitrification of coastal waters and is an irritant to the respiratory system. It can also cause the formation of low-level ozone, known to accelerate global warming.

The nitrogen content of biomass is in a similar range to coal (0.5-2 wt.%) (58). However, animal wastes and sewage sludge tend to be higher >6 wt.%. The heterogeneous nature of biomass makes it difficult to predict the NOx emissions from combustion of biomass. As mentioned in the previous paragraph it is dependent on the scale of combustion and the factors that can be controlled. In large scale utility systems, combustion of natural gas is very clean as the air to fuel ratio can be optimised and they are in the same state of matter. Oils and solid fuels must be tailored through multiple properties to achieve optimised combustion (particle size, air-to-fuel ratio and the heat and mass transfer). The main advantage of large-scale power generation is that a series of measures can be used to mitigate NOx emissions. Controlling the combustion mechanism is more important that the fuel itself at this scale which means it is not possible to compare the impacts of using biomass to the current fuels used on the Isle of Man.

On large-scale systems, mechanisms that can be implemented to mitigate NOx emissions are catalytic reduction and flue gas scrubbing using a variety of solvents, low NOx burners, flue gas recirculation, reduced air combustion (fuel rich combustion), and fuel & air staging. Solvents should be recycled to reduce the volumes of hazardous waste produced.

On medium and small-scale systems this abatement is not always feasible; however, there is only likely to be one source of NOx and that is from nitrogen in the fuel. Low NOx burners are a mechanism that can be implemented as well as air staging. However, avoiding high nitrogen biomass is the main method of control and this should be based on a limit set for the fuel suppliers (32). Without this abatement technology or controlling the nitrogen in the fuel the emissions from biomass combustion could be higher than natural gas or oil (depending on the biomass).

In reciprocating engines, internal combustion, the NOx emissions can be controlled efficiently and have been reported to be as low as 1 ppm (59). Mechanisms can in include air staging, steam/water injection, catalytic combustion, or catalytic reduction of the flue gas.

7.3 Emission Limits

Globally there are many national and international directives and legislation that aim to measure and control emissions from power generation and general air quality emissions that protect public health. The Industrial Emission Directive (IED) applies in the EU and gives emission control limits to power generators. The emissions limits are specific to the generation type and Table 6 quotes some of the values in the IED, more emission limits can be found in the IED annex (60). These values could be used to form a new emissions control regulation on the Isle of Man for power generation systems. Emission limits are at 0°C, atmospheric pressure, dry and 6% O_2 concentration.

Table 6: Emission limits for power generators from the IED (mg/Nm^3) (60)

	NOx	CO	SO_2	Dust
Power station firing natural gas (not including gas turbines and engines)	100	100	-	-
Gas Turbines (including CCGT) using natural gas	50	100	-	-
Gas Engines	100	100	-	-
Coal and lignite power station (>300MW)	150 (200 in the case of pulverised lignite combustion)	-	150 (200 for circulating or fluidised bed combustion)	20
Biomass power station (>300MW)	150	-	150	20
Liquid fuel power station (>300MW)	150	-	150	20

An air quality act targets concentration of pollutants in air. Table 7 summarises some of the different legislation internationally for air quality. The highest air quality standards are from the World Health Organisation (WHO) and these are based the concentration limits for the benefits of human health. The monitoring is over a period and the average over that period should not exceed the stated value. As can be seen in Table 7, pollutant limits are very variable and there is no harmony between nation air quality objectives. The emission and pollutant limits in Tables 6 & 7 give an indication of the limits that could be put into practice on the Isle of Man however further research into the IED would be advised for specific limits for the technologies and fuels that are implemented.

Table 7: Comparison of air quality pollutant limits internationally (32)

Pollutant	**UK**		**US**		**China**		**WHO**	
(µg.m^{-3})	Limit	Time Period	Limit	Time Period	Limit	Time Period	Limit	Time Period
CO	10	8 hours	10.35	8 hours	4	Daily	n/a	
Pb	0.25	Annual	0.15	Quarterly Average	n/a			
NO_2	30	Annual	99.64	Annual	40	Annual	40	Annual
PM_{10}	40	Annual	150	24 hours	40	Annual	50	24 hours
$PM_{2.5}$	25	Annual	35	24 hours	40	Annual	25	24 hours
O_3	100	8 Hours	137	8 hours	n/a		100	8 hours
SO_2	350	1 Hour	196.5	1 hour	20	annual	20	24 hours

7.4 Carbon Sequestration

Carbon sequestration is the term given to processes that take carbon from the air and store it permanently in structures. This can be achieved through natural mechanisms such as plant roots and soil carbon, or anthropogenic mechanisms such as storing in geological structures underground.

Carbon sequestration can result in emissions from a process or a system being net negative. However, it is very complex to account for and if the ambition is to claim a sustainability certification or to publicise net negative activities are in place, then thorough reporting is required, and consultation would be required with an appropriate certification body.

Under an approved sustainability criteria methodology, such as ISCC which follows the EU RED II directive, fuel or energy can only be seen as net negative if it fulfils the following criteria:

- The CO_2 captured and stored is greater than the CO_2 emitted in the entire value chain (includes emissions from cultivation, processing, and transportation).
- Emissions from combustion or processing are captured and permanently sequestered (discussed in section 9.4.1), or the carbon stock of the land the crop is cultivated on is increased from improved management practices.

This type of analysis is very specific and under RED II can only be claimed if the carbon savings are directly related to the production of the fuel/energy. On a systematic level, looking at the whole Island's annual carbon accounting, it may be possible to say that the Island is achieving net negative emissions if the amount of carbon sequestered from new biomass growth is higher than that being emitted from energy processes. This could be done by growing more biomass if it fulfils the previous criteria. The carbon accounted for would be the total carbon sequestered in both the biomass stock and the soil. The carbon that was sequestered in the biomass would have to be permanently sequestered and could not be harvested in the future for other applications. Again, accurate numbers would have to be acquired to verify that the overall process is net negative.

Growing new biomass such as forestry on marginal land or growing sea grass (in areas that would maintain or improve the ecosystem) would create a natural carbon sink and is a practice that should be encouraged. It could be said that this is an offset to the CO_2 released from production of a fuel and its combustion. However, this only applies to the carbon that has been accumulated when the new forest is established; after this point, the carbon sequestered in its growth is considered part of the natural cycle. Again, this forestry could not be harvested, otherwise the carbon has not been permanently sequestered. This also means the longevity of offsetting carbon through this mechanism is limited since more land or sea would be required annually to offset this carbon and this is not infinite. This is a very contentious area and has been subject to a lot of criticism; careful planning is required and a plan for how this can be measured, monitored, and reported established at the outset.

7.4.1 Feasibility of Carbon Capture and Geological Storage

Combustion processes will produce CO_2 as the main waste product. Biomass Energy with Carbon Capture and Storage (BECCS) is a mechanism to achieve net negative emissions by preventing the CO_2 emitted from entering the atmosphere. To prevent the emission of this CO_2 to the atmosphere, it must first be absorbed in a solvent. The solvent is typically an amine, with the most common being monoethanolamine (MEA). The solvent must selectively absorb the CO_2 to prevent premature saturation. The CO_2 is bubbled through the solvent solution, absorbs the CO_2, and is then taken to be regenerated releasing the CO_2 and producing a pure CO_2 gas. The regenerated solvent is recycled back into the process. The CO_2 extracted could be pressurised and utilised in various industries, such as the fizzy drinks market or in the production of methanol, by reacting it with hydrogen. It could also be stored in an underground well.

Without a depleted well, the Isle of Man will have to work with a third party to make this feasible. The nearest CCS network in development is the HyNet Northwest project in England which intends to store CO_2 produced in the Merseyside industrial cluster in the Liverpool Bay, and in later developments this will expand to Morecambe Bay. More detail of the plans for the cluster are shown in Figure 14. For the Isle of Man to utilise the system, the CO_2 will have to be moved. This could be done by a pipeline along the bed of the Irish Sea which would incur high capital costs but once it was running there would only be the maintenance costs; or alternatively, the CO_2 could be shipped over and injected at the injection point in Cheshire.

If a pipeline were to be installed, considerations would have to be given as to the injection pressure. This is because the gas may have further to travel (higher pressure drop) and to prevent a significant pressure drop for mixing turbulence when the pipelines meet. This could be an expensive operation. One of the most important considerations to factor into this decision is how much CO_2 is going to be produced and will it be a continuous supply or an intermittent supply. For the dispatchable energy systems, the financial implications of BECCS would not be feasible for such a small supply.

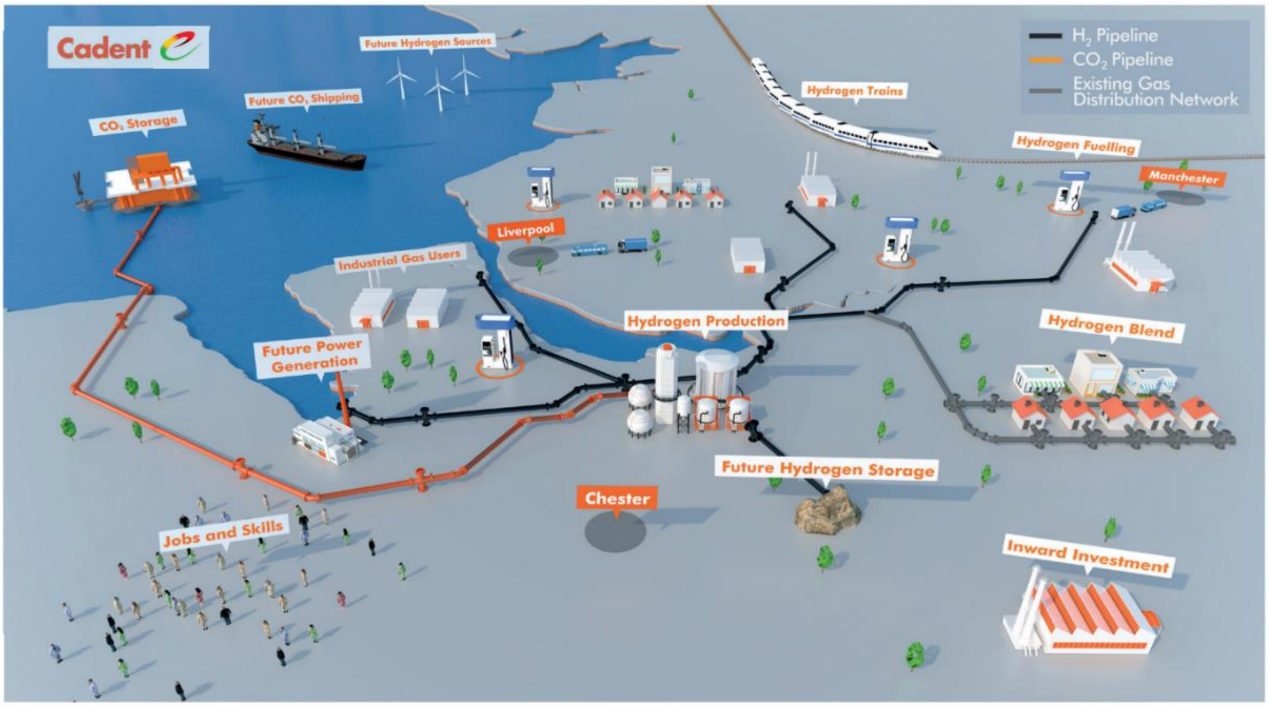

Figure 14: HyNet Network in the northwest of England (61)

8. Policy Recommendations for Using Biomass

The work in this report highlights key feedstocks and conversion pathways for producing fuels and energy that will contribute to the decarbonisation of the Isle of Man. There will need to be support from the Isle of Man Government to encourage the production and/or use of the priority feedstocks identified in this report, for new processes and markets.

Transitioning land to produce woody biomass, energy crops and alternative arable crops will require action from the Government or strong market pull from producers, to give development and offtake security for feedstock suppliers and other supply chain stakeholders, to justify investment in infrastructure, resource and equipment required for production and conversion. Similarly, for sea kelp, the entire infrastructure would have to be developed and it will require the adoption of new skills, not just for the farming but also to protect the aquaculture.

Policies should be consistent across all business models, regardless of production method, ownership, conversion route, or end use, to ensure a robust and fair market is established, delivering consistently high standards, and quantifiable benefits. An overarching policy objective should be focussed on carbon reduction as well as economic and environmental sustainability, with oversight from an independent panel or advisory board.

8.1 Policy Guidance for Waste

In terms of waste policy, the Waste Framework Directive (WFD) would need to be followed, to ensure wastes are used in the most appropriate way, first considering waste reduction strategies, before looking at reuse and recycling.

Food waste reduction strategies should be established, before separate collections are introduced for unavoidable waste which cannot be diverted to animal feed or other uses. Many examples of separate food waste collections exist across the UK and Europe, so existing guidance could be followed, and support would likely be required to assist with the collection and infrastructure costs.

For livestock wastes, although the material would be diverted from land-spreading to AD for biomethane production, the nutrients are retained in the digestate and that material would be returned to the land, resulting in minimal change to the existing system. Support or incentives for more effective nutrient management might encourage greater uptake of AD as a treatment option for such waste, to cover some of the additional costs incurred to establish the processing facilities.

8.2 Policy Guidance for Woody Biomass

Wood grown, collected or supplied for energy from any source should be produced to standards consistent with other markets. The guidance for production and procurement of woody biomass has been divided into two sections: wood from forestry and SRC willow.

8.2.1 Policy guidance for forestry

There are many examples of guidance on policy for effective forestry management, regardless of end market. It is important to note, wood grown, collected our sourced for energy production should be obtained under the same standards as wood grown for timber production, therefore sustainable forest management practices should be adopted across all sectors.

Guidance is usually aligned with voluntary schemes such as ISCC, FSC, PEFC, and SBP, meaning that wood suppliers already aligning with one of these schemes do not incur additional charges for extra administration, compliance requirements and repeat auditing, and auditors can accelerate the process of certification. This gives the forest managers the choice of which scheme they use, whilst giving fuel producers and National Governing Organisations confidence that management practices are being held to good standards.

Within these schemes, criteria usually includes ensuring: material has been legally harvested; material is not harvested from protected land; harvested areas are being regenerated in the correct way; monitoring and protection of soil biodiversity and carbon stocks is in place; native species in forest regeneration are being protected; mechanisms are in place to mitigate disease, pests and invasive species; and to ensure the long-term operation of the forest is permitted. Most of the schemes also include protection of workers and indigenous people, who have a right to the land, as well as criteria for the interaction with landowners and users.

There must also be a method for reporting land use changes that are creating carbon emissions. Auditors usually assess the criteria in a variety of methods including interviews, review of documents and visual inspections.

8.2.2 Policy guidance for SRC willow

Growers guidance for SRC willow has been produced in the UK previously, but as agronomic practices have advanced, guidance would need to be updated in line with best practice before being adopted.

ISCC also provides some guidance on sustainable production of SRC willow that could be used, especially when reporting emissions from production. The main considerations should be: the control of the amount of land used to grow SRC willow; the protection of soil health; ensuring biodiversity is maintained; measures to prevent the emissions of herbicides, pesticides, and fertilisers; and the reporting of mechanical activities on soil. This should include testing and monitoring of soil carbon and nutrient levels as well as biological tracers and also promoting the best use of SRC willow for the protection of other land, for example, using it as a wind breaker around coastal regions or to reduce flooding risk. An auditing process should be implemented so that farms observing best practices can receive appropriate financial reward.

Furthermore, due to the high cost of establishing SRC willow and the investment required in specialist planting and harvesting equipment, policy intervention may be necessary at this stage, to support the purchase of equipment, formation of grower groups, or the physical establishment of plantations. In Great Britain, planting and establishment grants were available in the past; however, uptake levels were low as market confidence remained low and growers felt they were taking too much risk, establishing a long-term crop with little or no market security. Further policy intervention may be necessary at this stage, to support the market and to provide security of offtake to potential growers, before committing to establish a new crop.

8.3 Policy Guidance for Miscanthus

Miscanthus will require the same policy guidance and intervention as SRC willow; however, the policy should be modified for the difference in growth characteristics. Again, in Great Britain, establishment grants have been available for miscanthus in the past but uptake has been low for the reasons discussed above for SRC.

Intervention in the market and establishment stages would be valuable, to give confidence and security to growers. Furthermore, the formation of grower groups or production co-operatives would be beneficial, to enable sharing of machinery and pooling of knowledge and skills, to maximise production whilst minimising costs. Policy intervention to encourage and support the formation of such vehicles should be considered, to provide certainty and risk mitigation support, to stimulate and accelerate uptake.

8.4 Policy Guidance for Sugar Beet and Oilseed Rape

Established voluntary schemes such as the Red Tractor Scheme can be aligned with government policy to ensure sustainability of annual arable crops.

The main policy consideration in regard to the target crops relates to soil health and protection. Any policy intervention should include: monitoring of soil carbon and nutrient levels, as well as biological tracers; having a management plan for enhancing the soil carbon levels such as crop rotations; using cover crops; using grass leys; preventing access in wet months; and application of manures.

Other criteria should protect against soil compaction and erosion, for example auditing logs of farming activities, preventing soil loss by taking heavy machinery over wet soil, using winter crops, planting trees, and using fences on field perimeters.

Good practice guidance is available in the UK for the production of sugar beet and oilseed rape, so additional grower guidance would not be required.

8.5 Policy Guidance for Sea Kelp

This is still an area under development so policy should be reviewed frequently to ensure best practices are maintained. There is legislation in Europe to set common farm management practices (EC Directive 2000/60/EC). These practices include siting the farm to minimise damage to sensitive environments (some environments such as Mearl beds and seagrass communities are protected and must be avoided); seed sources that maintain the genetic diversity of wild stocks; biosecurity management plans and training to prevent the spread of diseases and parasites; no fertilisation and control of anthropogenic sources of nitrogen; no cultivation of non-native species; and ensuring the infrastructure is well maintained, and foreign bodies such as rope and nets are not being released into the water (55).

Ensuring sea kelp farms meet these standards will require expert knowledge, and auditors should be appointed based on both their auditing experience as well as their scientific understanding of aquaculture. Auditing should be by a variety of methods including visual inspection, review of management records and monitoring records.

9. Conclusion

The Isle of Man Government intends to have a net zero power sector by 2030. To do this a combination of renewable technology and dispatchable generators are to be used to maintain grid power levels, whilst delivering low carbon solutions. The focus of this report is to give an understanding of the biomass feedstocks available for renewable power (and heat) production, and the fuels, processes, environmental considerations, and policy interventions that could be used to achieve the Islands decarbonisation targets to 2030 and beyond.

In the first step, the volume of biomass available for production or procurement in the Isle of Man was quantified. An initial assessment was used to highlight the feedstocks that could be available to produce suitable fuels, to decarbonise the energy system between now and 2030. To assess their availability a range of scenarios were considered, based on the key parameters affecting production or procurement, such as land availability, population, market price and competing demand. In some cases, forecasts were made to assess the security of feedstock supply to 2050.

For some of the feedstocks identified, cross-border trade is an established practice and imports could therefore be considered, to supplement on-island production, especially in the event of a time lag on production ramp-up, or when lower than expected yields are achieved. Such activities were considered in the availability analysis, and factored into the high-level cost analysis in subsequent stages.

A multi-criteria analysis (MCA) was used to evaluate critical parameters relating to the availability, suitability, sustainability and cost of production or procurement of potential feedstocks, to identify the priorities for further consideration. The results of the analysis can be summarised as follows:

Wood - high volume available on the Island; good infrastructure is already in place for harvesting and collection, and could be expanded easily with modest investment; storage and processing infrastructure is proven and scalable, so could easily be adopted and established on the Island, if required; and, international trading of wood pellets is common, so imports are available to supplement domestic production during the transitionary ramp-up phase, and overall supply risk is low. Economic and social benefits are notable, whilst the environmental impact of increased woody biomass collection would need monitoring.

Miscanthus – although establishment costs are relatively high, and productivity takes time to scale-up, high yields are possible on lower quality agricultural land; as miscanthus is harvested annually, at a time other crops are not demanding labour, there is good alignment with existing practices and a high likelihood of adoption by domestic growers. New equipment will be required for planting and harvest, but costs could be kept down by establishing grower groups or cooperatives, to share skills, equipment and labour, delivering economic, environmental and social benefits to the Island.

Sugar Beet – although not currently grown on the Isle of Man, sugar beet is widely grown in the UK and Europe, so production practices are well known and equipment widely available. Crop establishment costs are low, but equipment is specialised and costs can be high at the outset, so grower groups or cooperatives would be recommended to minimise investment requirements and to minimise risks. Additional sugar or sugar products could be imported, if required, to achieve the desired economies of scale.

Oilseed Rape - farming of oilseed rape is common across the UK and Europe, and the infrastructure is already in place on the Island to handle oil-based fuels, such as oil tankers and liquid import points. Establishment costs are low, and planting and harvesting is done using conventional equipment also used for cereal crops, so little additional investment would be required to enable production of such feedstock. Economic benefits would be notable, but social impact in terms of skills, employment and quality of life would be minimal, and the environmental impact is varied, benefitting both soil and ecosystem health when effectively managed.

Food Waste – food waste is highly suitable for biogas and biomethane production, through AD. The volume of food waste arising on the Island suitable for collection and conversion through AD is modest. However, it is available almost immediately, with very little investment required to establish suitable collection and transport infrastructure, with no production costs and a potential gate fee for its disposal, so this pathway could be implemented rapidly. There is also the potential for co-digestion of food waste with other wastes, from agriculture and industry, so capacity could increase and supply the impact on the energy systems, the environment and the economy would all be positive.

Livestock Waste – manure and slurry is arising from livestock enterprises across the Island, with the majority currently being spread to land close to the point of production. This resource would be immediately available for AD, when appropriate processing facilities could be established, and the existing land-spreading activity would not be effected, as the digestate resulting from the process could be returned to land as a more stable and environmentally favourable fertiliser. As AD can be deployed across all scales, there are opportunities to establish a number of smaller-scale decentralised facilities, producing biogas for central upgrading to biomethane, or for a larger-scale centralised plant to be developed, to aggregate and treat feedstock from across the Island, converting it to biomethane for injection or use immediately from the site. As livestock waste can be co-digested with other wastes, a larger-scale centralised facility would be preferable, benefitting from economies of scale, with minimal investment in collection and transport infrastructure being necessary.

Sea kelp - very high yields achievable, although significant infrastructure investment would be required to set up farms and to facilitate the annual harvest of the kelp; additional work is required on the sustainability impacts of sea kelp harvesting, and to optimise production and collection methods, to minimise disruption to the existing ecosystem. Social benefits, in terms of skills development and human resource requirements would be high throughout the supply chain, and economic advantages notable in the longer term, once the original investment had been covered.

Following this assessment, the priority fuels most suited to further decarbonise the Isle of Man energy system were identified by the combustion systems in place on the Island and those proposed in the future strategies. The fuels chosen were biomethane, ethanol, HVO, methanol and rDME. Miscanthus was not considered for conversion to a biofuel within the desired timeframe, as it is typically used as a solid fuel and there is little commercial interest in turning it into a biofuel. However, this could have application in solid fuel heating systems, in pelleted form, alongside SRC and other woody biomass. The yields of fuels and the energy output in the combustion systems considered demonstrated there is significant capacity for all the key feedstocks to help decarbonise the Island, but significant investment will be required to establish the necessary facilities and associated infrastructure, to deliver the desired energy contribution by 2030 and beyond.

Solid fuel combustion systems at a large, medium, and small-scale have been considered and discussed. Using biomass feedstocks such as those mentioned above in such systems, combined with appropriate technologies or abatement systems in place, can deliver clean, sustainable fuel across the Island. Analysis on how BECCS could be implemented was discussed; however, because the combustion systems are not achieving maximum output for prolonged periods, it would not make economic sense to inject low volumes of output into the planned UK BECCS system.

The environmental impact from increased production of these feedstocks was considered and sustainable management practices and mitigation strategies proposed, to ensure supply is environmentally, economically and socially sustainable and acceptable. Where available, the carbon balance, impacts on biodiversity, impacts from land use change, and policy intervention that could lead to effective management for all the key feedstocks has been stated and discussed.

It is important that feedstocks are produced, gathered and converted in a sustainable manner, and often policy intervention is required to define, dictate and monitor sustainable production practices to ensure biomass and the resultant energy is making a valuable contribution to the low carbon economy. In some cases (wood, sugar beet and rapeseed) alignment with existing voluntary schemes could provide a simple and quick route to implementing sustainable supply chains. Consideration should also be given to financial incentives that could be offered for sustainable management, removal and use of such feedstocks, either by rewarding sustainable feedstock production or use, or to support planting and establishment of new plantations to yield greater sustainable biomass volumes in the future. Specific to SRC willow and miscanthus, there is some existing guidance from ISCC, but new policy guidance could be made that focuses on protection of soils and existing ecosystems, since these crops have long lifetimes and could be hugely beneficial resources on the Island. For sea kelp specialist advisors and auditors would have to be used as this remains a developing sector and knowledge is not as widely available.

Overall, sustainable biomass can make a significant contribution to the decarbonisation efforts of the Isle of Man, with the feedstocks identified here as priorities and discussed above, able to contribute up to 30% of the Island’s energy needs from a single fuel source in the medium scenarios considered, and potentially up to 55% if multiple fuels are combined. In all scenarios significant investment will be required from the government or firm commitments made, to give industry the confidence required to facilitate and make the necessary investments themselves.

The output from this report gives an insight into the potential for a variety of feedstocks and fuels that could decarbonise the Isle of Man energy system between now and 2030, with a longer-term view also provided out to 2050, for less mature, larger-scale processes and production pathways. The more mature and established pathways, such as biomethane from AD of food- and livestock-waste, could be implemented immediately with production commencing within as little as 18-24 months. This would provide an important transitionary solution before some of the larger investments, such as ethanol from sugar-beet, are considered, developed and commissioned, within the next 5-10 years.

Quantification, in terms of available feedstocks, suitable conversion technologies and established management practices, should give confidence and security to renewable investments being considered, and will help to decarbonise the difficult to electrify areas of the bioeconomy. The work in this report could also be transferred across, to consider the potential for decarbonisation of the transport sector on the Island, or feedstocks considered for production of biobased products.

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Appendix A - Alternative Feedstocks and Feedstock Data

A.1 Determination of Straw Availability

Table A.1: Land availability for straw production in 2025

Land Use (ha)				
	Wheat	Barley	Oats	Total (ha)
Low Scenario	423.5	1,656.7	468.0	2,586.2
Medium Scenario	615	2665	615	4100

Table A.2: Land availability for straw production in 2030

Land Use (ha)				
	Wheat	Barley	Oats	Total (ha)
Low Scenario	337.3	1355.9	381.6	2108.7
Medium Scenario	484.7	2139.8	534.8	3343.0

Table A.3: Land availability for straw production in 2040

Land Use (ha)				
	Wheat	Barley	Oats	Total (ha)
Low Scenario	200.7	811.8	227.2	1262.5
Medium Scenario	385.1	1756.3	426.1	2731.4

Table A.4: Land availability for straw production in 2050

Land Use (ha)				
	Wheat	Barley	Oats	Total (ha)
Low Scenario	119.4	486.1	135.3	755.9
Medium Scenario	340.9	1593.3	390.3	2470.3

Table A.5: Low scenario straw production in 2025

Low Scenario	Wheat	Barley	Oats	Total (ha)
Yield (t/ha)	6	4	4	-
Mass of Crop (tonnes)	2540.9	6626.7	18721	11306.1
Straw % of grain	44	41	52	-
Collection efficiency	56	58	57	-
Mass of Straw collected (tonnes)	626.1	1575.8	554.8	2844.8

A.2 Fruit and Vegetable Waste

Fruit and vegetables that are unable to be sold at markets due to being either misshapen or rotten have also been considered. Through stakeholder interaction, it was deemed that there is very little of this waste generated on the Isle of Man and therefore none is available (0 t/annum). This is because the wastes are either fed to the animals or worked back into the soils to aid soil health (22).

A.3 Managed Heathland, Heather and Bracken

Heathlands are wide open areas of land dominated by shrubs and grasses. These areas have a value to wildlife and are used by birds for nesting and burrowing animals for hibernation. Heathland soil is low in nutrients and typically acidic in nature. This means it is only suitable for the growth of certain plant species. Heathland is defined as either upland or lowland based on its height above sea levels (if its above 300m it is classed as upland heathland) (62). There is a difference between the soils, upland soil is more clay like whilst lowland soil is more silty and free draining. The land is sometimes used for the grazing of cattle or to encourage wild game. Heathland requires human management otherwise it can develop into woodland which would be damaging to the biodiversity created in that ecosystem (62). Two plants commonly found on heathland are heather and bracken.

A.3.1 Heather

Heather is a low spreading shrub (bush) that has purple flowers and is the most common shrub to be found on heathland. As it is a shrub it has woody stems and small leaves, it flowers between late summer and early autumn. They are suited to heathland as they prefer acidic soils. The lifetime of heather plants is about 30 years. For 25 years of this there is continual steady growth. If the heather is just left to grow it can form a blanket which can impact on the insect diversity and the potential of the land for grazing. Under management of heather can be prone to cause wildfires if the density becomes too high in dry months. One of the management techniques for heather is controlled burning to break up mature stands, however this has implications of GHG emissions for open burning practices (63).

Currently there are no commercial uses for managed heather. Some research suggests it could be used effectively as solid biomass for heat or power generation. For heather grown on peatland a single study measured the carbon budget over a period of three years demonstrating that vegetation management is required to maintain soil carbon levels, unmanaged heathland can cause reduced water retention and increased carbon flux from the soil (64). A ten-year burning management cycle can reduce carbon emissions to the environment by at least 25% (64).

As mentioned previously, heathlands are unique areas with high biodiversity interest. To maintain a broad diversity of fauna, areas of the heathland should be cleared to prevent the heather from dominating in colder parts of the year when annual and perennial plants are unable to grow (65). Heathland is especially important for reptiles, migratory birds, and over 5,000 species of insect. Effective management should maintain a mosaic effect with bare ground patches, areas of wildflowers, and mixtures of younger and more mature heather and other shrubs/grasses. Maintaining this is critical to ensuring the continued biodiversity of the landscape (66).

The greatest challenge with maintaining heather is in the infrastructure and logistics of the management practices. Removing heather from upland heathland in wet seasons can cause damage to the soil if machinery is used either for transportation or harvesting. During the spring and summer, management is not advised as this could impact on nestling birds and reptiles. On lowland heath there are similar problems however because the soil drainage is better vehicles should cause less damage.

According to the Isle of Man's Heath Burning Code (67), 12% of the Island is covered in heather. This equates to 6864 hectares. Assuming a heather growth density of 2 tonnes per hectare (68), and between 10-50% of the resource being able to be acquired, there is a potential 1373-6864 tonnes per year that could be valorised.

A.3.2 Bracken

Bracken is not a unique crop to heathland as it highly opportunistic therefore it can be found in woodlands, on grass verges, in urban areas and in a variety of soils. Bracken has a rhizome that is up to a meter depth from the soil surface. Fronds sprout from the rhizome and can be up to 1.5m in height. The fronds grow in dense patches which cover large areas of land and can provide shelter for a variety of nestling birds, reptiles, and amphibians. Bracken has a perennial growth cycle meaning in summer it is green and leafy but through autumn it turns orange/brown and becomes more straw like, this is because of natural senescence which is vital for its regrowth in the spring (32). During the senescence period the fronds lay down and prevent the growth of other fauna hence it becomes the most dominating plant species. Additionally, dense areas of bracken are breeding grounds for tics which cause Lyme disease (32).

The study of bracken for bioenergy applications has some been studied in a variety of scenarios. The energy content of bracken is like wheat and barley straw (19-20 MJ kg^{-1} dry basis) meaning it has potential for use as an energy crop. For a plant biomass specie, it is relatively high in nitrogen and sulphur however these concentrations are small comparative to waste feedstocks containing meat. The main issue with bracken is its high moisture content during the summer months this is as high as 70wt.% however this does reduce to approximately 50 wt.% in late autumn. This would make it expensive to transport (32).

Based on previous work, it is estimated that 2,000 tonnes of fresh weight bracken can be feasibly harvested per year from heathland, only harvesting the stipe (32). On a dry basis this is 600 tonnes of bracken which is not a significant mass of feedstock. Harvesting the bracken with the heather could make this a more attractive option.

A.4 Managed Reeds

Reedbeds grow in wetland areas such as floodplains and in coastal areas. Traditional reeds are perennial species of grass that can grow up to 2m in height. Like bracken it grows from a rhizome however this rhizome can be below 2m from the soil surface. Reeds prefer a shallow water environment such as lightly flooded areas and wet soil. They can grow in a variety of soil conditions and in fresh & brackish waters. Reeds are very dominant and can easily take over large wetland areas as the only species of plant. If the water body is particularly shallow the reedbed can expand covering the whole surface of the water (69).

Reeds can have important roles in managing local hydrological conditions such as buffer zones between farming land and water bodies (preventing runoff), phytoremediation of heavy metals from soil and water bodies, slowing the water flow rate, and controlling erosion/sedimentation on coasts & in water basins. They also have an important role for wildlife providing food and habitats for birds, fish, insects, mammals, and amphibians. In some cases when the reed bed breaks forming a floating island this becomes a protected habitat. However, without management the reeds become too big creating large amounts of coverage, this can lead to the growth of woodland species such as willow, alder, and poplar trees. If these trees grow it changes the ecosystem and can lead to the water body drying up (69).

Reeds are important methods for carbon sequestration as they can form peat from the accumulation of leaves and stem material that does not completely decompose. Peat formation is a stable method of carbon sequestration. Therefore, if reeds were harvested for bioenergy purposes this should be done in the winter once the leaves have dropped. To optimise carbon sequestration a management plan should be in place to maintain the reed beds in the optimal growth stage (69).

There are a few sites on the Island where managed reeds may be acquired: Ballalough Reedbeds, Manx Utilities' Croit e Caley site, Manx Wildlife Trust's Barnell Reservoir and (in the future) Manx BirdLife's Point of Ayres Reserve. However, figures could only be estimated from Ballalough Reedbeds which cover 1.4 hectares (70). With a reed growth density of 6.46 tonnes per hectare per year (71), and approximately 30% of the reeds being removed through management each year, 1.94 tonnes per year of reeds could be acquired.

A.5 Biogenic Fraction of Waste Tyres

A tyre is a mixture of materials including natural rubber, synthetic polymers, steel, textiles, and fillers. Each tyre (including heavy duty tyres and aviation tyres) contains on average 25% natural rubber (19). Most of the feedstock is used for repurposing (retreading, building material and outdoor resurfacing) or for energy recovery (cement kilns and incineration). Possibly further material could be diverted from other energy recovery facilities to biofuel production however in the case of cement kilns that fuel would have to be replaced and this would most likely lead to increased coal usage (21).

To efficiently extract the organic component, the tyre material must be made into a crumb. This requires some energy to break the tyre down into small particles. Often some of the inorganic components are removed to either recover the material or limit the number of inorganics going to the fuel production process. It is very difficult to separate the fossil polymers from the natural polymers which means around half of the processed tyre crumb feedstock will be from a fossil source and will produce a fossil carbon fuel.

The potential tonnage of waste tyres on the Island was taken by extrapolating the data from the SUEZ Energy from Waste facility annual public report 2021 (25). This assumes that the EfW facility processes all the waste tyres on the Island, yielding 759 tonnes per year of waste tyres.

A.6 Slaughterhouse Waste/Fish Waste

Slaughterhouse waste and fish waste consists of blood, fat, and organs. Blood is mostly water (up to 80%) which means it is expensive to transport. Besides water, protein is the next major component (up to 17%) and carbohydrates makes up a maximum of 0.01% of blood composition (72). Animal fat consists of fatty acid chains between C12–C20 depending on the animal species. For example, cow and pig fat is mainly made up of stearic acid (C18) and palmitic acid (C16) (73) (74). Animal fat grading impacts on the price and sustainability credentials: grade 3 is higher quality and used for animal feed, grade 1 is used for biofuel production. Organs are often used as delicacies in various countries however this market demand is massively outstripped by the supply. Organs are mainly made up of gastrointestinal and renal tract organs and these are collected and disposed of together. A large amount of this waste goes to incineration due to strict rules and regulation of the sector. Feedstock supply from these sources is seasonal based on when different animals are reared. As these feedstocks are from animals, they can be high in nitrogen, from the amino acids that make up the protein, that can make them less desirable for certain applications.

As the Isle of Man only has one abattoir, it was assumed that all the slaughterhouse waste goes to the SUEZ EfW facility. The yearly tonnage was estimated by forecasting the meat and bone meal data from the SUEZ Energy from Waste facility annual public report 2021 (25). The calculated yield was 536 t/annum of slaughterhouse waste. There may be some additional meat and bone meal from deceased livestock that did not arrive at the abattoir that is not included in SUEZ's statistics, however this material is unlikely to be of any value to biofuel production.

For quantifying the fish waste available on the Isle of Man each year, tonnages of commercial fishery species in Manx waters were taken from the 2018 Manx Marine Environmental Assessment: Commercial Fisheries and Sea Angling (75). From this, the species with considerable tonnages (>50 tonnes per year) were explored further. These species were king scallops (2137 tonnes), queen scallops (1365 tonnes), common whelk (810 tonnes) and brown crab (456 tonnes). Despite having the fourth largest tonnage, the brown crab waste was not quantified. This is because crabs are generally cooked and served to consumers whole, so the waste generated (and able to be collected) would be difficult to estimate.

For king and queen scallops, their composition was separated into muscle (61.3 wt.%), shell (26.7 wt.%) (76) and gonads (12 wt.%) (77). The fish waste fraction was taken to be the shell and gonads, leading to 38.7 wt.% of waste. This came out as 827 tonnes and 528 tonnes of king and queen scallop wastes, respectively.

The composition of common whelks was divided into meat, gonads, and shell. The total masses of individual common whelks, their meat and gonads were taken from Emmerson (2016) (78). The shell mass was estimated by differences. From these absolute values, the weight percentages were collated and averaged. The waste components of common whelk were only taken to be the shell, estimated to be 40.9 wt.% of the whelk. This was used to estimate common whelk waste as 356 tonnes per year.

A.7 Brewery and Distillery Waste

Brewery and distillery waste is typically high in sugars and therefore a good source of glucose for fermentation processes. There are a variety of wastes produced and they vary in moisture content and composition. These wastes come from residues from pressing material, broths from fermentation processes, and sludges & wastewaters from processing operations. Most of this waste is typically used for animal feed with some being used for anaerobic digestion, and other yeast products (such as food preserves and flavourings). Diverting this material from animal feed could have a negative impact on the carbon balance as the deficit would be recovered from other sources. To recover this deficit, it could result in more intensive farming methods which would impact on the local biodiversity.

Most distilleries on the Isle of Man source their feedstocks from wastes, and so there appears to be very little valuable waste or residue that could be valorised. According to the ex-Managing Director of Kella Distillers (22), Outlier Distillery Company are the only Island-based distillery that use virgin feedstocks.

Outlier Distillery Company produces rum from Caribbean sugar cane-derived molasses. As of now, the generated waste from this process is split between being fed to their livestock and being disposed of. Outlier Distillery Company also produces vodka from bread waste, with most of the waste being fed to livestock again. Methanol is one of the by-products of vodka production, which they retain for cleaning their facilities (79).

Okell’s Brewery is said to generate 0.13 m^3/day of beer discharge (80). However, there is said to be limited value in this discharge, so this is disposed of.

Kella Distillers’ key feedstock is sourced from a Tate and Lyle’s facility in London. Tate and Lyle send an alcohol-rich residue to the Isle of Man. Detailed information regarding the exact composition of this residue could not be found. Kella fractionally distils and condenses the residue to produce their own feedstock. Therefore, the residue has some lignin, is very dilute, and has a very low value.

As not all brewers and distillers were able to be contacted, the figures for the waste are not representative of the Island. They can, however, be used as an indication of the types and proportions of waste being generated.

A.8 Dairy Waste

The dairy industry produces waste from a variety of products. The main wastes from the dairy industry include whey protein, dairy sludge, rotten milk, and butter residue. Whey is a by-product of milk and cheese processing. After the milk has been curdled it is strained and the liquid residue remaining is whey protein. Whey has a value in the nutrition market however it must be sterilised and treated to make it into a consumable product. Whey can also be used for animal feed. Most of the whey ends up being disposed of through wastewater treatment or, in plants producing enough waste, anaerobic digestion is used (17).

The dairy industry is considered the main industrial generator of wastewaters and the majority of this is in the form of dairy sludge. Dairy sludge decomposes easily as it is high in fat, oil, and grease as well as suspended solids and therefore cannot be stored for long periods. Additionally, its high moisture content makes it expensive to transport. Dairy sludge can be used in anaerobic digestors or turned into fertiliser as it contains a high concentration of phosphorus. Besides these applications the remaining goes to waste (18).

Rotten milk is milk that has become spoilt by the development of bacteria within the milk. The bacteria give the milk an off taste. The rotten milk is typically disposed of with the dairy sludge and sent to AD or wastewater treatment. Mixing the rotten milk with the dairy sludge can accelerate bacteria growth and therefore create further issues with storage and transportation. A small proportion of rotten milk is used to make soured products however the majority is sent for disposal (19).

During butter production milk solids are clarified to ensure the butter has a smooth consistency. The clarified residue is high in fat and protein. This residue is termed butter residue, some of this residue can be turned into a product known as ghee. Ghee is used in cooking and animal feed however there is still a large amount of waste that cannot be used which goes to landfill or AD (20).

To determine the dairy waste produced on the Isle of Man, the Isle of Man Creamery was interviewed. The Creamery has two main waste streams from their cheese production process: a whey waste stream (15 million litres per year), and factory wastewater (48.6 million litres per year).

The factory wastewater stream is not a valuable feedstock as it is mostly water. The whey waste stream is composed of:

- Water: 94 wt%
- Lactose: 5 wt%
- Protein: 0.9 wt%
- Minerals: 0.1 wt%

The whey waste stream was calculated to generate 15,464 tonnes of waste per year (81) (82) (83). In discussion with the Manufacturing Manager of the Creamery, the facility has previously investigated treatment methods on the non-water components of the whey waste so that they could be valorised. However, the costs associated to valorise 6% of the waste renders the stream unfeasible.

A.9 Sea Kelp

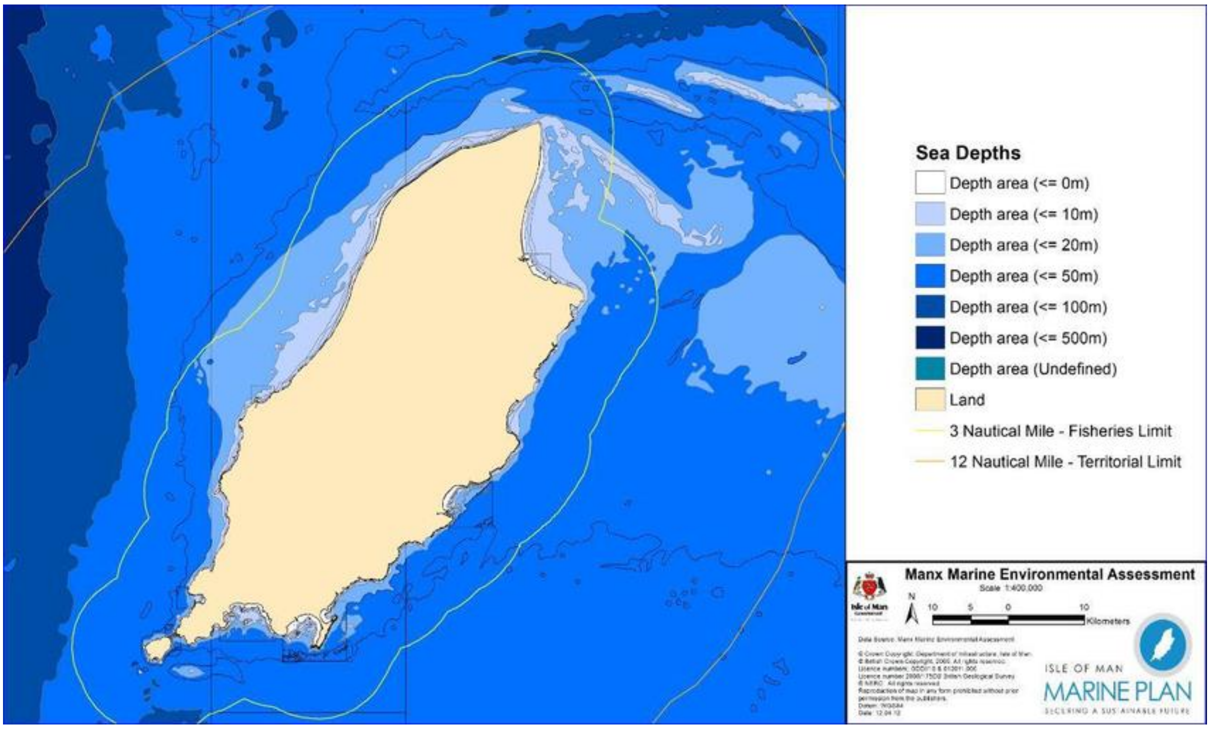

Figure A.1: Depth of the Isle of Man Seabed

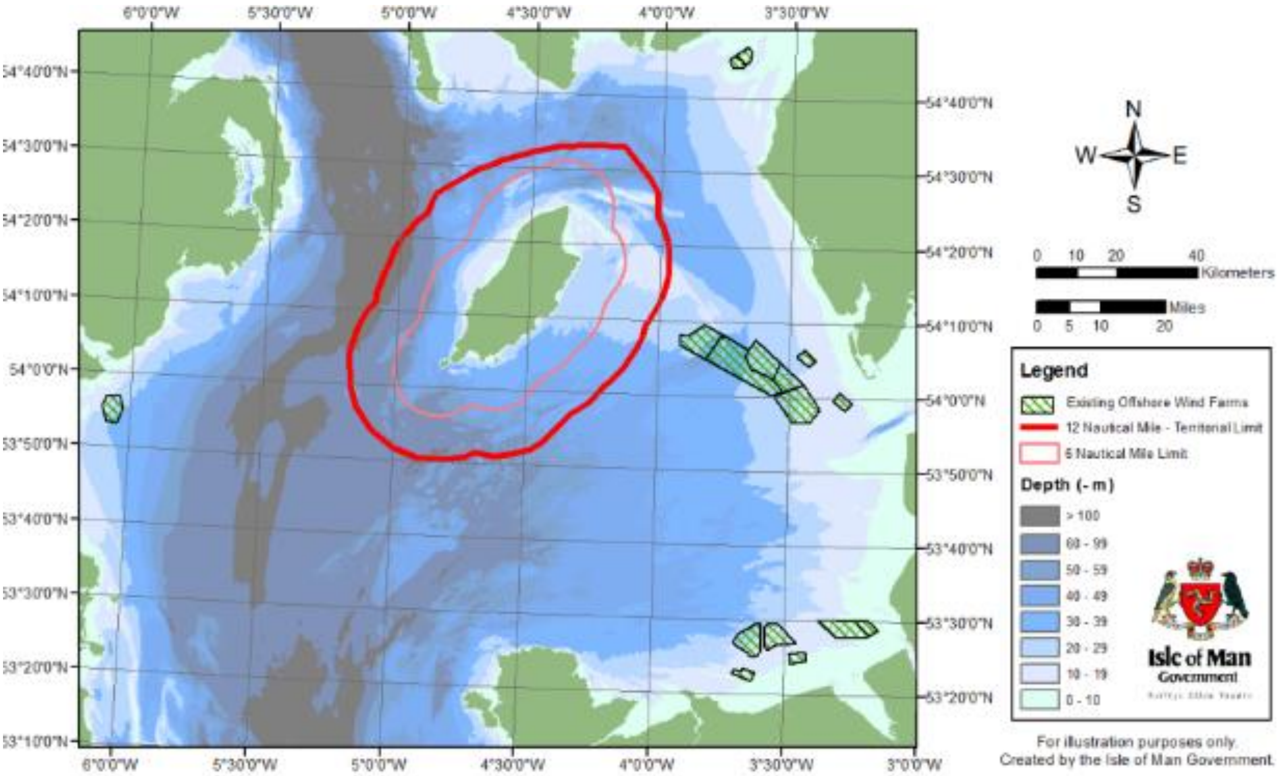

Figure A.2: Depth of the Isle of Man Seabed (84)

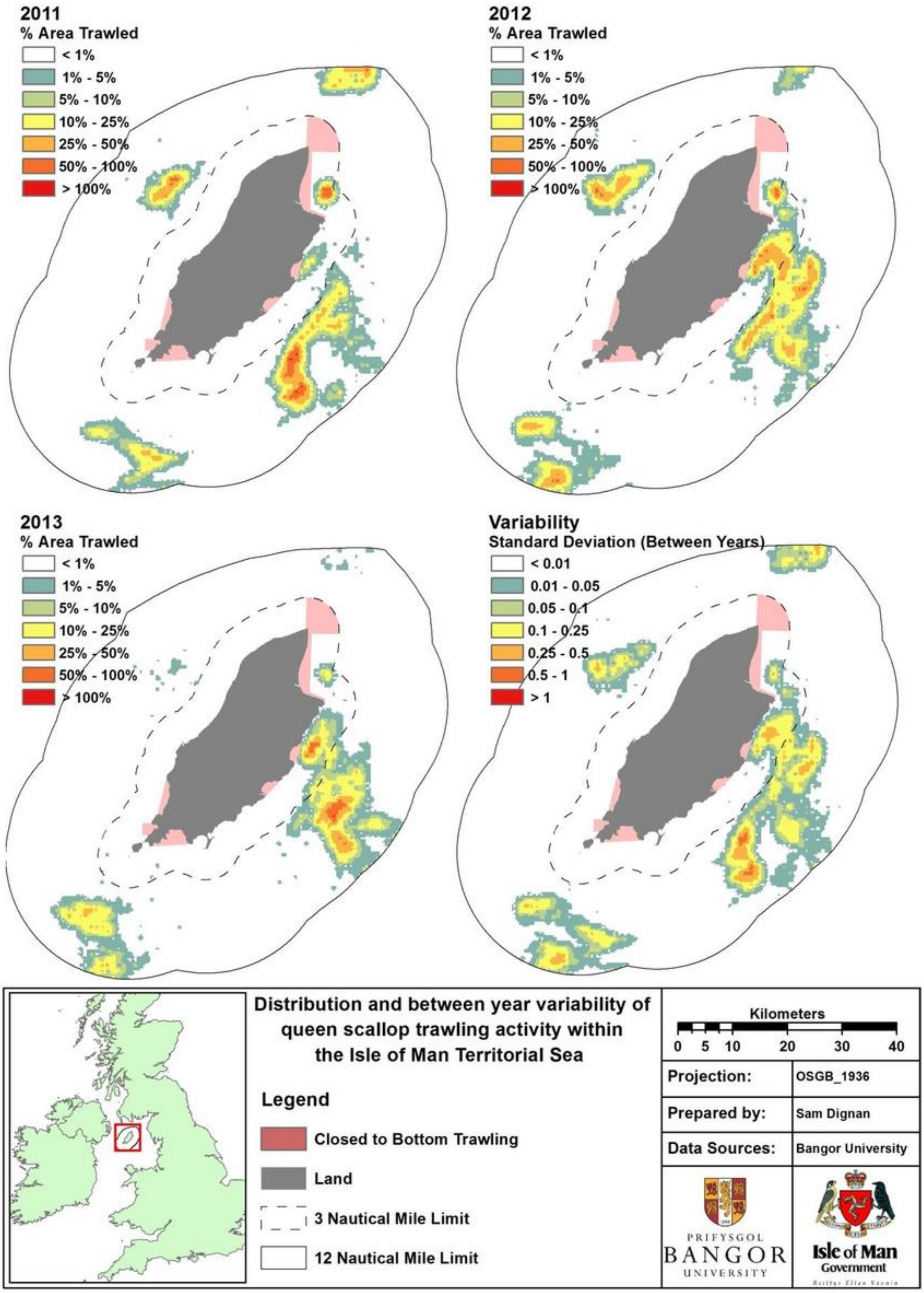

Figure A.3: Hotspot areas for fishing (35)

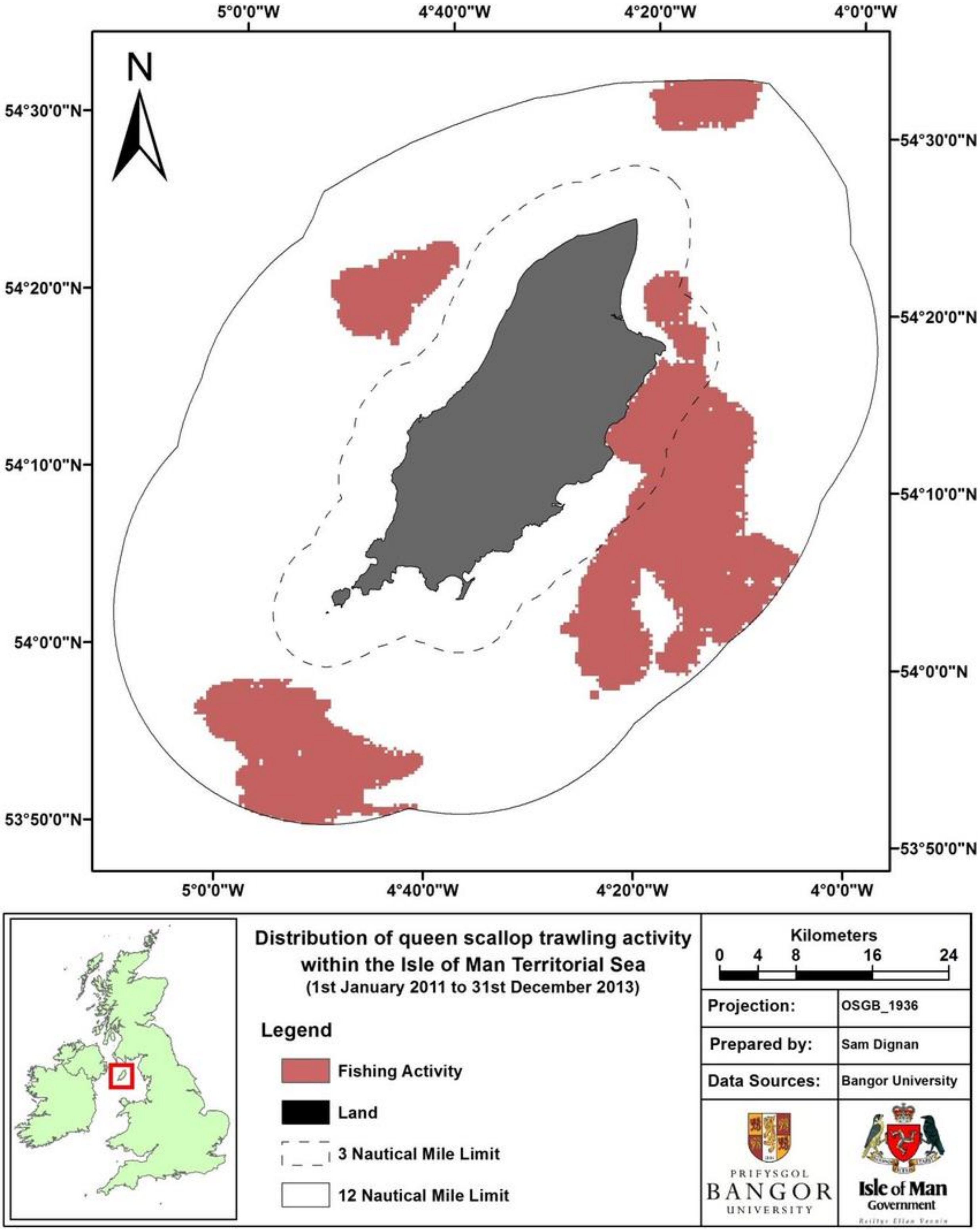

Figure A.4: Fishing area hotspots (35)

Appendix B - Alternative Fuels

B.1 Natural Gas Replacement Fuels

The conversion pathways discussed here are included in Figure 1. For drop-in replacements of natural gas, the fuels must be chemically alike ensuring the system can run with limited modifications.

B.1.1 Biogas

Biogas is the raw gas that is released from anaerobic digestion that consists mainly of methane, $CH_{4,}$ (50-75%), but also contains carbon dioxide, CO_2, (25-50%), nitrogen (<8%), and trace impurities such as hydrogen sulphide and ammonia. Because of the presence of impurities, the gas is lower quality than conventional natural gas and this is reflected in the energy density, 20-26 MJ m^{-3} for biogas compared to ~40 MJ m^{-3} of conventional natural gas. This difference in energy content as well as the presence of impurities in the gas would have implications on the combustion performance and emissions. The main impacts would include increased fuel feed in rate and usage to compensate for the energy difference, increased probability of corrosion or internal deposit damage from the impurities (this will also make storage more problematic) and increased emissions of sulphur and nitrogen emissions (SO_2 and NOx respectively). Some modifications will also be required to account for the reduced combustion reactivity of biogas from the presence of CO_{2}, this will influence the ignition timing.

B.1.2 Syngas

Syngas is the primary product of gasification. It is a wet low-quality gas mainly made up of carbon monoxide, CO, (30-60%) and hydrogen (25-35%). There are also smaller amounts of CO_2 (<18%), nitrogen, and CH_4 (<5%). The syngas composition is influenced by the feedstock material and the gas used in the process. This influences the energy density of the syngas which is typically between 2-8 MJ m^{-3}. Using syngas in a natural gas system is not without many challenges the main one being the lower energy density. This would require an increased flow rate (approximately 7 times higher than natural gas) to maintain the temperature in the combustion chamber, this would in theory increase the power output but would also require much higher volumes of syngas (85). The emissions could also be more problematic as there will be more nitrogen, sulphides and halides produced. On a final note, if waste such as MSW is used the fuel cannot be considered fully renewable, this is because the feedstock will contain plastic from fossil fuels which means some of the fuel will be fossil based.

B.1.4 Biohydrogen

Biohydrogen can be produced from either steam reforming of biomethane or by upgrading syngas (water-gas-shift). There is a method of producing hydrogen by electrolysis powered by a gasification plant however this has not been considered. Although on a mass basis the energy density of hydrogen is very attractive (120.2 MJ kg^{-1}), the low density of hydrogen (0.09 kg m^{-3}) means that the energy density on a volume basis is relatively low (10-12 MJ m^{-3}). Therefore, the hydrogen must be pressurised to achieve the same combustion temperatures. Hydrogen is very reactive and therefore increasing the pressure would increase the probability of the system becoming explosive. The advantage of combusting hydrogen is the emissions are mostly water however because of the assimilation of nitrogen in the air, emissions of NOx would still be present.

B.2 Alternative Diesel Replacements

B.2.1 Synthetic Diesel

Synthetic diesel is produced from non-vegetable oil-based biomass feedstocks such as waste. In these processes the carbon is extracted from the feedstock and upgraded into diesel molecules. The main processes to extract the carbon are gasification (produces syngas) and pyrolysis (produces a bio-oil, can be high in oxygen). Hydrothermal liquefaction is a more novel process of growing interest that can also breakdown carbon rich feedstocks into a bio-oil. Once the syngas or bio-oil are upgraded the molecules are like HVO molecules, mainly isoparaffins without the presence of inorganic molecules.

B.2.2 Diesel from Hydroprocessed Fermented Sugars (direct sugars to hydrocarbons)

These fuels are made by using genetically modified microorganisms to convert sugars into hydrocarbons or lipid fats. The main example of this is a molecule called farnesene which is a long-chained alkene. There are other examples of this process that produce lipids and isobutene. The products are converted to diesel by hydroprocessing or isomerisation/oligomerisation. The diesel produced is mainly formed of isoparaffins so performs similarly to conventional diesel.

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