A SUSTAINABLE ENERGY MODEL FOR A CIRCULAR ECONOMY

A case study of
CREED Integrated Waste Management Facility,
Stornoway, Western Isles

FINAL REPORT

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The Report has been prepared by:

- Abalo Irene Jerry Fabiano
- Asutosh Nayak
- Bewin Tom
- Binita Shrestha
- Blessing Nwaokete
- Diana Carolina Yule
- Edrees Nori
- Evandro de Santana Garcia
- Hamed Shahinkhoo
- Ivando Lossio Jr
- Kambez Ahmad
- Maisarah Kadir
- Natalia Pachon
- Niraj Shrestha
- Rafaella Dourado
- Sandhya Naik
- Syed Ahsan Abbas Bokharee

Under the supervision of
- Prof. Dr. Bernd Möller
- Dipl.-Ing. Wulf Christian Boie
- Dipl.-Soz. Dorsi Doi Germann
- Dr. Miria Agunyo

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"The strength of the team is each individual member. The strength of each member is the team." – Phil Jackson

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List of Abbreviations

AD	Anaerobic Digester
CES	Community Energy Scotland
CHP	Combined Heat and Power
CnES	Comhairle nan Eilean Siar
HH	Household Waste
IWMF	Integrated Waste Management Facility
OHLEH	Outer Hebrides Local Energy Hub
SSC	Scottish Salmon Company

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1. Introduction

1.1 Project Description

Islands around the world face numerous challenges to become self-sufficient in terms of energy and economy. These challenges can be mainly due to their isolation from mainland, which can cause limited grid connectivity, high import costs of fossil fuels, and lack of business opportunities. Such constraints and challenges can lead to new opportunities by focusing on the maximal utilization of local resources, connecting the waste streams to the resource streams and bringing business opportunities and thus benefiting the whole island. This leads to the concept of local energy economies and circular supply chains in the island.

The International Class within the Energy and Environmental Management (EEM) programme from Europa-Universität Flensburg, Germany aims to prepare students for future careers as sustainable energy professionals by means of a real-life project within a given time frame, applying research and scientific methods and knowledge to solve a complex energy problem. For the year 2018, the international class is focused on creating an integrated model for a circular energy economy for the CREED Integrated Waste Management Facility (IWMF), Stornoway on the Isles of Lewis and Harris, Western Isles, Scotland.

The Outer Hebrides Local Energy Hub (OHLEH) project, with Community Energy Scotland (CES) as a technical consultant, is envisaged as a successful model of local energy economies and circular supply chains which integrates the different renewable technologies available locally on the island. This project intends to benefit the community through proper waste management, the conversion of waste into energy, minimisation of the negative effects on the environment by reducing landfill, decreasing fossil fuel consumption and carbon dioxide emissions, using clean technology, and by utilizing local resources available in the island.

The OHLEH project is an amalgamation of different projects owned by various project partners. Comhairle nan Eilean Siar (CnES), the project lead and local council of the Western Isles, aims to shape the Outer Hebrides into a confident and self-reliant community and make it an attractive place to live, work and perform business. CnES owns CREED IWMF, an integrated waste management facility which runs a combined heat and power (CHP) generator, a wind turbine, and an electrolyser system located in Stornoway.

One of the main income-generating activities in the Western Isles is the fishindustry comprising of fish hatcheries and a fish processing facility owned by the Scottish Salmon Company (SSC). From the OHLEH project, waste from fish industry is introduced as a feedstock for the anaerobic digester in IMWF. The digester produces biogas for the CHP generator, producing heat and electricity to be utilised by the facility and for export. Additionally, electricity from the wind turbine can be supplied to the electrolyser for producing hydrogen and oxygen. The hydrogen produced is planned to be used in a hydrogen-powered refuse collection vehicle and oxygen produced is planned to meet part of the oxygen demand of the fish hatchery. The project is also supported by the Pure Energy Centre which provides the electrolyser and other technologies.

With close collaboration of the project partners associated with OHLEH, a five-week field research was carried out by the students of EEM from Europa-Universität Flensburg. The study was focused on developing a sustainable energy model for a circular economy taking the case study of Creed IWMF at Stornoway, Western Isles.

1.2 Problem Description

From early consultation and interviews with the project partners, it is found out that Lewis and Harris presently faces the issues of a weak electricity grid, underutilization of local resources. In terms of the fish waste from the fishing hatcheries, current regulations prevent them from being disposed into landfill due to the methane emissions. Thus, there is a need to find alternative disposal methods for the waste, one of them being for the anaerobic digester. The fish hatcheries also currently import oxygen bottles, which is cost intensive.

For IWMF, an extensive analysis was carried out to recognize the current problems associated with each of the present technologies and equipment in place at the facility. The electricity generation from current wind turbine installed at the IWM Facility is being curtailed due to grid constraints and hence the wind resources are not used optimally. It was found that IWMF does not receive sufficient organic waste to run the anaerobic digester at full capacity. This results in an inability to meet local heat and electricity demand from the CHP plant, increasing the usage of kerosene boilers, contributing to carbon emissions. It was also observed that the fish waste as local resources have not been used effectively to enhance the biogas production and quality. The current electrolyser is also not in operation and integrated with the whole system to meet the potential hydrogen and oxygen demand.

Consequently, the OHLEH project intends to rehabilitate the electrolyser and integrates it into the energy system of the IWMF. However, there are still opportunities and alternatives that can be explored to achieve optimal solutions for the issues mentioned above. This can be studied and simulated by utilizing local resources available and modelling the components into an integrated system, allowing flexibility of operation and scenarios.

1.3 Project Objective

As described in the background above, the OHLEH project is unique as it incorporates local resources to produce energy and meet the local demands of oxygen and hydrogen within a constrained environment to create a sustainable energy system. Thus, our overall objective for this case study undertaken at the CREED Integrated Waste Management Facility is to develop a sustainable energy model that integrates various renewable technologies that are sourced locally, and simulate various scenarios to explore the opportunities for solutions that are economically and environmentally attractive.

1.4 Methodology

In order to meet the objective, the methodology employed is briefly described as below. Meetings and interviews with project partners were conducted throughout the international class to understand the project partners' motivation behind the collaboration as well as to receive the required information to develop our model and scenarios such that each project partner can see the potential benefits and savings from a circular energy economy.

Primary data are obtained from the project partners, such as specific operations, historical production records, data logs, and configuration for the components and equipment. The OHLEH project outcomes by Community Energy Scotland are also used to further develop our project. In such cases where data was not readily available, this was complemented by literature study and research data available in the public domain.

From the anaerobic digester perspective, several scenarios to improve the quantity and quality of biogas are simulated. The simulation is done using the SIMBA® software, which models the different scenarios. These scenarios include incorporation of local resources such as household waste, fish waste and cow slurry, and conversion of the digester from a thermophilic to a mesophilic condition in the future. The study also includes the possibility of methanation to cut down flaring hours and enhances the methane content in the biogas.

The inclusion of fish waste for the anaerobic digester may have a positive outcome to the facility. Therefore, an assessment of the fish waste potential in the island is conducted. Furthermore, a study where fish ensiling can further provide additional fish waste input for the anaerobic digested is also assessed.

As the focal point of this case study is the IWMF facility, the various components and operation within it are also evaluated to be included into the model. This includes the wind turbine, the combined heat and power (CHP) generator, electric boiler, kerosene boiler and a thermal storage system, as well as an electrolyser system. For the wind turbine, three scenarios of low, high and average wind are incorporated into the model. This is done through simulation with WindPRO®, where long-term mesoscale modelled data is correlated with the local measurement data to produce estimated annual wind generation profiles of the three scenarios. For the electrolyser, the parameters and configuration of the currently installed electrolyser are assessed and inputted into the model. The hydrogen and oxygen output is also assessed against the demand available for the bin lorry and potentially for the fish hatcheries. A future impact of how a new electrolyser system can impact the overall model is also projected.

Finally, the inputs of various scenarios for each component at the facility as described above are integrated into a single system model, using Microsoft Excel®. The developed model is capable of simulating different combinations of scenarios and operational philosophies in an integrated energy system that comprises all processes and flows on an hourly basis, producing outputs which can be assessed from a financial and technical perspective. The model is a simulation tool that considers the supply and demand of resources such as waste, heat, electricity, hydrogen and oxygen for each corresponding component. Financial components such as tariffs, prices, and fees are also integrated into the model. The model also allows a flexibility to add or remove additional components, to indicate whether additional investments can further optimise the overall efficiency of the system. From here, several optimal solutions and their technical and financial impact can be presented to project partners.

2. Fish Waste Estimation and Storage

Fish waste can play a vital role in improving the operation of the biogas plant at IWMF. This has been reflected in the subsequent Chapter 3 about the anaerobic digester. Co-digestion of fish waste along with other biodegradable wastes such as cow slurry and household wastes, yielded high amount of biogas with increased methane content required for continuous operation of CHP. It is evident that there is a need for fish waste to be used in the co-digestion process.

This Chapter will therefore discuss how the fish waste can be made available for feeding into the anaerobic digester (AD). For uninterrupted production of biogas and subsequently continuous operation of the CHP, there is a need of regular and defined amounts of fish waste into the anaerobic digester. The continuous flow of fish waste needs to be ensured to enhance the performance of anaerobic digester. Safe-guarding the amount of fish waste required for anaerobic digestion for enhanced production of biogas is possible only with the introduction of fish waste storage options. As a storage option, ensiling could be one of the options to store fish mortalities. Such storage facility can ensure regular and defined amount of supply to the anaerobic digester.

The fish waste estimation and storage requirement for various anaerobic digester scenarios using fish waste for biogas production results in three scenarios for running the anaerobic digester Scenario 1 with annual demand of 1,103 tonnes fish waste, Scenario 2 with an annual demand of 1,591 tonnes fish waste and Scenario 3 with a demand of 1,499 tonnes fish waste. Among the three scenarios, Scenario 3 was identified as the best scenario. In Scenario 3, the anaerobic digester is fed with fish waste, cow slurry and household waste. Also, the centrate is diluted in Scenario 3. The result of Scenario 3 is an increased production of biogas with higher methane content. The fish waste estimation and requirement of storage size are based on these three anaerobic digester scenarios. The main objective of this chapter is to estimate and ensure required quantity of fish waste that can be made available for AD at the IWMF.

2.1 Benefits of Fish Waste

Scotland as a country is relishing growth in its fish farming industry. Scotland is the third largest exporter of Salmon in the world. (Zero Waste Scotland, 2016). In 2014, Scotland exported about 179,022 tonnes of Salmon (Zero Waste Scotland, 2016, p. 10). In a community where fish farms are one of the major sources of income, it is essential to study the aspects associated with fish farming. One of such aspects is the management of the fish waste.

Fish waste as by-product from fishery industry possesses utility if they are managed properly. Fish waste, when used in anaerobic digester as feedstock can produce biogas, biofuel as well as bio-fertilizer with high nitrogen, phosphorus and potassium content (NPK) (Kafle, Kim, & Sung, 2013). Fish waste can contribute in high biogas yields, increasing the efficiency and quantity of gas generation due its specific chemical composition, as show in Table 1 below. More details about how each chemical fraction can improve the biogas yield, is explained in the Chapter 2 of this report.

Source	Moisture	Protein	Lipid	Ash
Salmon (head)	71,40%	14,20%	3,90%	3,90%
Salmon (viscera)	78,30%	17,10%	1,80%	1,80%
Salmon (viscera)	59,40%		24,10%	
Whole salmon	62%	18%	17%	2%

Table 1: Fish waste fractions (Source: Creed Wind and CHP outputs (5/04/2016))

Similarly, fish waste can also be incinerated to generate heat following combustion of the fish waste. Additionally, fish waste can be used in In-Vessel Composting (IVC) to produce fertilizer (Zero Waste Scotland, 2016). Certain marketable products like fish meal and fish oil can also be produced by processing fish waste via process called Rendering. Rendering is the process of converting fish waste into purified fats such as fish oil and fish meal (Mack, et al., 2004, p. 24). Depending on waste management option, fish waste can be converted into products with market value such as electricity through integration of CHP with biogas plant, fish meal, etc. Rendering however, is the least preferred method of managing fish waste due to limited number of rendering facilities accepting category 2 fish waste (fish mortalities) for rendering in Scotland (Mack, et al., 2004, p. 9). Secondly, according to EU-regulation on animal by-products, rendering process cannot accept fish mortalities as raw material to produce fish meal.

Any initiatives other than land filling to manage fish waste can utilize fish waste to produce useful products. Such initiative would not only reduce the land filling of the waste and but also produce by-products that have market value. The anaerobic digester at IWMF had incorporated fish waste into anaerobic digester as a trail in June 2017. However, the introduction of fish waste into the anaerobic digester led to the problems discussed in the previous chapter. Nevertheless, the facility is still planning to cautiously continue to use fish waste as a feedstock for their anaerobic digester. Utilization of fish waste into anaerobic digester in IWMF will contribute in operation of CHP within the facility producing heat and electricity.

2.2 Fish Waste Potential of Western Isles

2.2.1 Fish Production of Western Isles

The Western Isles is an archipelago which comprises of islands including Lewis and Harris, Benbecula, North and South Uist and Barra (Netspace, 2010). As of 2016, the contribution of Western Isles on the total salmon production of Scotland was 32,662 tonnes. Salmon production from Western Isles accounts to around 20 percent of the overall Scottish salmon production (Munro & Wallace, 2017, p. 32). On an average Lewis & Harris collectively has the highest share of 13.2 percent, followed by South Uist with 6.1% of the total Scottish production (Scottish Salmon Producers Organisation, 2018, pp. 53,55,61). This is summarized in the Table 2 below.

Location	Percentage of Total Average Scotland Production (%)	Active Farms	Source
West Lewis	3.1%	7	(Scottish Salmon Producers Organisation, 2018, p. 53)
East Lewis	5.8%	8	(Scottish Salmon Producers Organisation, 2018, p. 55)
Harris	4.3%	8	(Scottish Salmon Producers Organisation, 2018, p. 57)
North Uist	2.2%	6	(Scottish Salmon Producers Organisation, 2018, p. 59)
South Uist	6.1%	11	(Scottish Salmon Producers Organisation, 2018, p. 61)
Scotland	100%	253	(Munro & Wallace, 2017, p. 32)

Table 2: Annual fish production of Western Isles

The production of salmon of Lewis & Harris is estimated from overall salmon production of Scotland. According to Murro & Wallace, the overall Scotland's salmon production was 129,930 tonnes in 2007 which increased by 32,887 tonnes in 2017 and reached to 177,202 tonnes. In last decade, there was general tendency of increase in salmon production, which is predicted to be around 222,000 tonnes for the year 2026. The details of salmon production number can be seen in Table 53 in Appendix A. To estimate the production of Scotland in the following years, linear increase of the production is assumed based upon the production from 2007 to 2017 with the 95% of the confidence interval and prediction interval until 2026, which is shown in Figure 1 and in Table 53 in Appendix A.

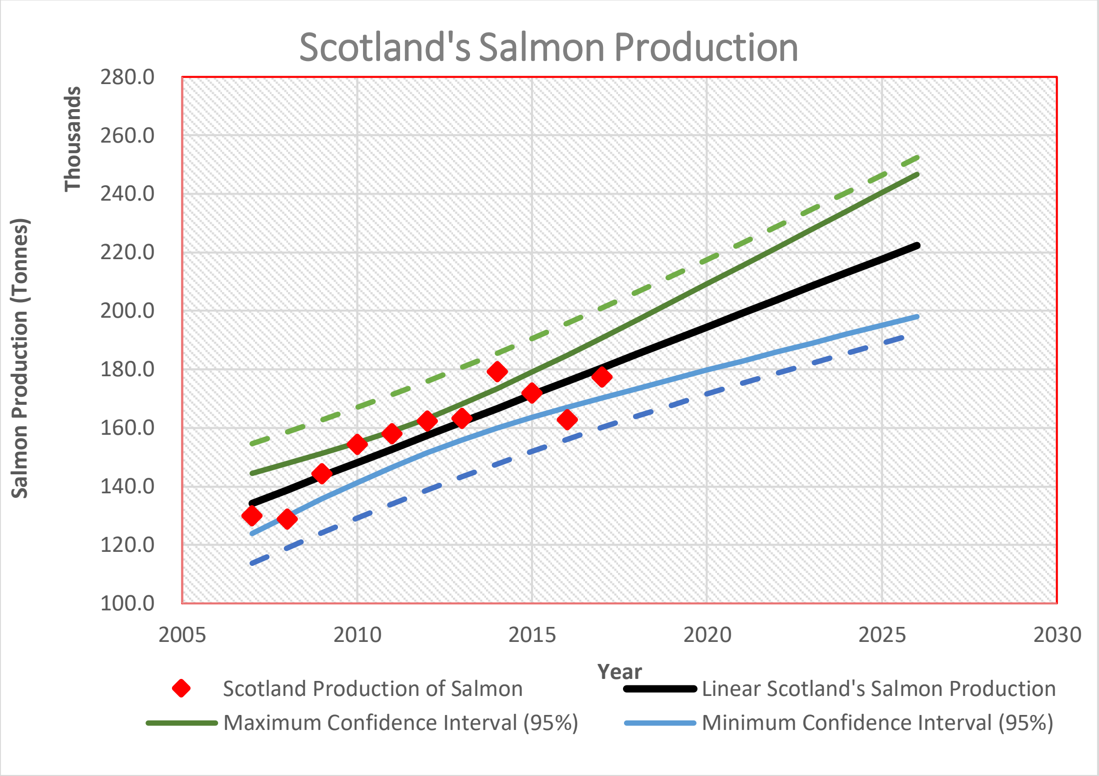

Figure 1: Predicted Scotland Salmon Production with 95% confidence and prediction interval (own based upon the annual salmon production from Munro & Wallace, 2017)

As shown in Figure 1, with 95% prediction level the annual salmon production of salmon was estimated to be 185,230 tonnes. The estimated number for salmon production can vary between 206,000 and 164,000 tonnes. Since Lewis and Harris accounts to 13.2% of the Scotland's salmon production, the share of salmon production for Lewis and Harris for 2018 was found to be 21,650 tonnes. This figure represents the worst case (95% minimum prediction interval value for 2018). The estimated annual production of the Western Isles along with share of Lewis and Harris is summarized in Table 3. The production of Lewis and Harris has been used to estimate the mortalities of Lewis and Harris.

Location	**Production (tonnes per annum)**	**Percentage (%) of Scotland's Production**
West Lewis	5,085	3.1%
East Lewis	9,500	5.8%
Harris	7,050	4.3%
North Uist	3,600	2.2%
South Uist	10,000	6.1%
Western Isles	35,300	19.9%
Scotland	164,000	

Table 3: Estimated annual production of the Western Isles for 2018 assuming worst case (own estimation based upon the Scottish Salmon Producers Organisation, 2018, Munro & Wallace, 2017)

2.3 Fish Waste Estimation of Lewis & Harris

2.3.1 Processing Waste

According to Munro & Wallace (2017) and Scottish Salmon Producers Organisation (2018), Lewis and Harris are located in close proximity sharing common landmass. Collectively, Lewis and Harris produce 21,491 tonnes of Salmon. Along with salmon fish farms, two salmon fish processing plants are also located with Lewis and Harris, one of which is The Scottish Salmon Company (SSC). The fish waste from these processing plants includes the skins, trimmings, head and frame of the fish. SSC owns one of the fish processing plant at Marybank Estate, Lewis. SSC is also one of the partners of the OHLEH project and can therefore supply 312 tonnes from the Marybank processing plant in a year (Browne, 2016). The amount of processing waste produced by the SSC processing plant is low, which suggest that relatively smaller amount of fish waste is processed in the plant and considerable amount of salmon produced on the island is exported unprocessed (whole salmon). The processing fish waste therefore accounts to a daily supply of 1 tonne, excluding the weekends (Browne, LECF Opportunity Assessment, 2016, p. 4; 5).

2.3.2 Fish Mortalities

Mortalities in fish farms vary over the year and could be due to several reasons. A study on the production cycle of around 60 million Atlantic salmon was conducted for four years (2000 to 2006) in the western coast of Scotland (Soares, Green, Turnbull, Crumlish, & Murray, 2010). According to the study, the causes of mortalities can be attributed to 52 causes, that were categorized into diseases, production (transfer of fish within fish farm), environment, predation and unknown causes. Therefore, given the number of factors mentioned above, the trend of mortalities is hard to predict and can differ from one year to another. However, to estimate the number of mortalities for each day of year, a polynomial regression analysis has been performed using the average monthly mortalities from one of salmon producer in Scotland for 2017 (Marine Scotland Directorate, 2018). The regression analysis can be seen in **Error! Reference source not found.** below.

The per month average mortalities data used for this study (as shown in Figure 2) has missing values for the third and fourth month. Missing values can be attributed to either low or no mortalities reported for these two months. Predicting mortalities are difficult since they are attributed to number of reasons. However, to develop trend of mortalities various literature was referred. As per RSPCA (2017) report on salmon and trout conservation in Scotland, higher mortalities of salmon were found to be occurring in the third or fourth quarter of the year. Based on this reference, the study has attempted to develop mortality profile resembling to the mortality trend illustrated in RSPCA (2017) report. Nevertheless, it should be noted that the mortality trend could vary from one year to the other and from one farm to another.

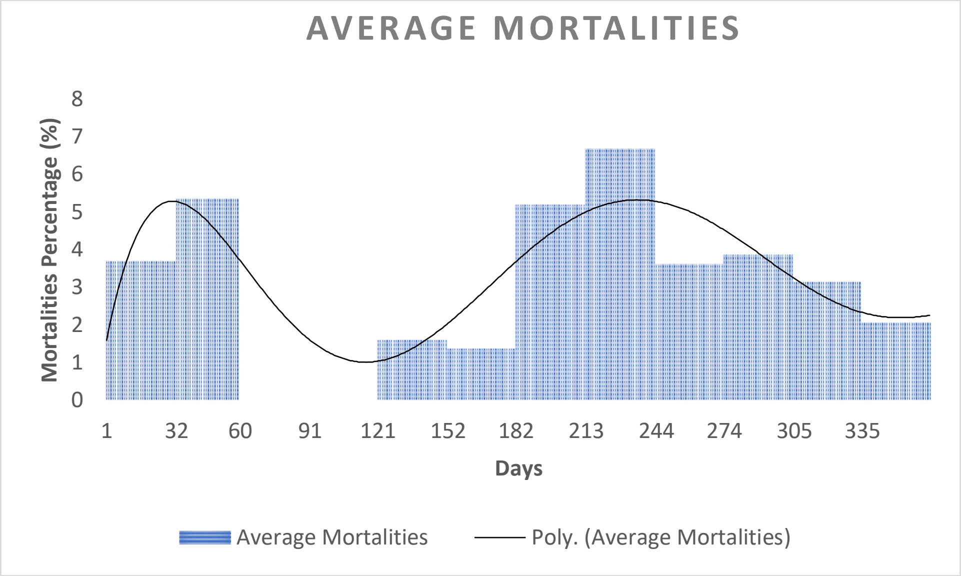

Figure 2: Average monthly mortality of SSC Farms with daily estimation profile for year 2017 (Based upon Marine Scotland Directorate, 2018)

With the help of salmon mortality data and mortality trend was identified to develop daily profile. The daily profile was developed using the polynomial regression analysis ($y = -5 * 10^{-13}x^6 + 6 * 10^{-10}x^5 - 3 * 10^{-7}x^4 + 8 * 10^{-5}x^3 + 0.3192\,x + 1.2597$; $R^2 = 0.634$) from the monthly average mortalities retrieved from aforementioned literatures. Typically, the average rate of mortality of salmon is 6.7% of the annual production (Zero

Waste Scotland, 2016). Based on a mortality rate of 6.7% and incorporating the trend of mortalities over the year mentioned earlier, the mortality profile for salmon was estimated on a daily basis for Lewis and Harris. The result of regression analysis has been tabulated in Table 4 and while annual mortality amounts can be seen in Table 4 below.

Region	**Production (tonnes/year)**	**Estimated Mortalities* (tonnes/year)**
Lewis	14,600	978
Harris	7,054	472
Lewis& Harris	21,653	1450

Table 4: Annual mortalities estimation for Lewis and Harris

Source: Author's calculation based on (Zero Waste Scotland, 2016), (Munro & Wallace, 2017)(Marine Scotland Directorate, 2018)

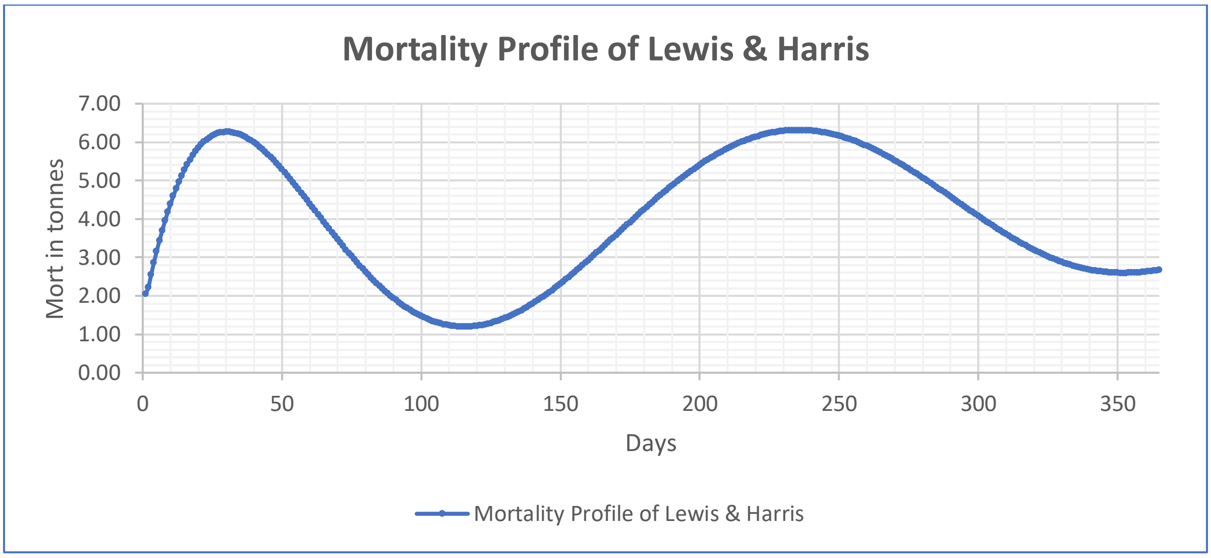

Figure 3: Estimated daily mortalities of Lewis and Harris

Source: Author's calculation based on (Zero Waste Scotland, 2016), (Munro & Wallace, 2017)(Marine Scotland Directorate, 2018)

2.4 Total Waste of Lewis & Harris

The overall fish waste of Lewis & Harris (including the estimated mortalities and the fish processing waste from SSC processing plant) is shown in Table 5 below. Considering the processing waste of 312 tonnes annually from SSC and estimated mortalities, Lewis would have total waste of around 1,290 tonnes per year, while the total waste from both Lewis and Harris would be 1,762 tonnes per year. The monthly estimated mortalities are also presented in Table 5. The mortalities shown in Table 5 were calculated based on estimation from regression analysis while the processing waste data has been referred from LECF Opportunity Assessment done by Browne (2016).

Processing Waste from SSC** (t)	Lewis		Lewis and Harris	
	Estimated Mortalities* (t)	Total (Processing Waste + Mortalities*) (t)	Estimated Mortalities * (t)	Total (Processing Waste + Mortalities*) (t)
312	978	1,290	1,450	1,762

Table 5: Total quantity of fish waste estimated for Lewis and Harris;

Source: Author's calculation based on (Zero Waste Scotland, 2016), (Munro & Wallace, 2017) and (Marine Scotland Directorate, 2018)

Month	Lewis	Lewis & Harris
Jan	102.9	153.1
Feb	104.3	155.1
Mar	64.1	95.4
Apr	28.0	41.7
May	35.0	52.1
Jun	67.5	100.5
Jul	108.4	161.3
Aug	129.3	192.4
Sep	118.9	176.9
Oct	96.3	143.3
Nov	65.4	97.3
Dec	54.9	81.7
Grand Total	**975**	**1,450.7**

Table 6: Estimated monthly mortalities of Lewis and Harris for the year 2018 with worst case scenario

Source: Author's calculation based on (Zero Waste Scotland, 2016), (Munro & Wallace, 2017) and (Marine Scotland Directorate, 2018)

Based on the estimation of the daily profile of mortalities and the inclusion of the accessible processing waste, Lewis and Harris could have a consistent amount of fish waste of around 1,100 tonnes per year. The amount of waste available through these calculations has been termed as amount of waste available in the reference scenario or per quarter based fish waste for this study. This amount of fish waste could be supplied to AD for their reference case and this amount of fish waste has been used in this study to analysis best case AD scenario with enhanced production of quality biogas. The estimation of availability of annual mortalities for the reference case (AD Scenario with fish waste demand of 1,100 tonnes) can be seen from Figure 4.

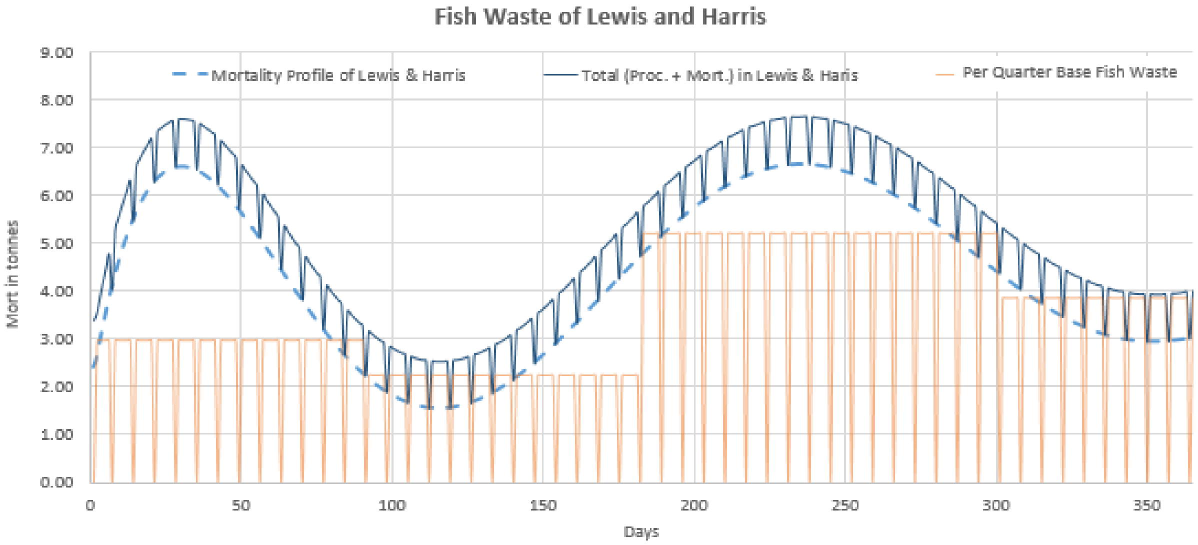

Figure 4: Estimation of total waste of Lewis and Harris, with base level mortalities

With quarterly base level of fish waste (1,100 tonnes), there would be a significant amount of excess (and un-predictable) amount of fish mortalities (from 600 tonnes to 1000 tonnes annually) would be available. This amount of fish waste from mortalities needs to be stored in order to provide consistent required fish waste to AD and hence a reduction in the annual amount of fish waste going to landfill. Moreover, since the mortality profile can be different from the one considered in this study, so there is a necessity of storage options to deal with the fluctuations in the mortalities.

2.5 Pasteurization of Fish Waste

Before fish waste can be sent to the anaerobic digester, it has to be pasteurized. However, before pumping fish waste into the anaerobic digester, fish waste is pre-treated into a mush before it is pumped into the biogas reactor. Pre-treatment aims at increasing the waste quality that goes to anaerobic digester by killing pathogens and breaking the wastes in to sizes that can be processed in the AD. This specific technique is called pasteurization.

2.5.1 Pasteurization Process

This type of pre-treatment is only applicable to the feedstock that contains pathogens or infectious microorganisms. Such waste needs hygienisation or sterilization, depending on the degree of contamination. At IWMF, the whole pasteurization process is performed as follows:

Homogenization

The purpose of this stage is to turn the fish waste into liquefied slurry. A fish reception/ensile tank of 10m³ size consists a special pump with shredder propeller and extended knife system which performs two duties; recirculation (homogenisation) and pumping of the waste out to the downstream.

Maceration

This is the process by which the wastes are shredded to a maximum particle size of only 12mm by a blade and grinder. This blade and grinder is located between the reception/ensiler tank and the pasteurizer tank, guaranteeing the waste entering the pasteurizer tank is as stipulated by the regulations.

Pasteurization

Pasteurization is defined as the process of heating the slurry at a temperature of 70°C and keeping it at this temperature for at least 1 hour. The pasteurization system is designed with an 8m³ vessel, a pump and a side entry propeller-based mixer, to ensure the tank contents are continually mixed for even heat distribution.

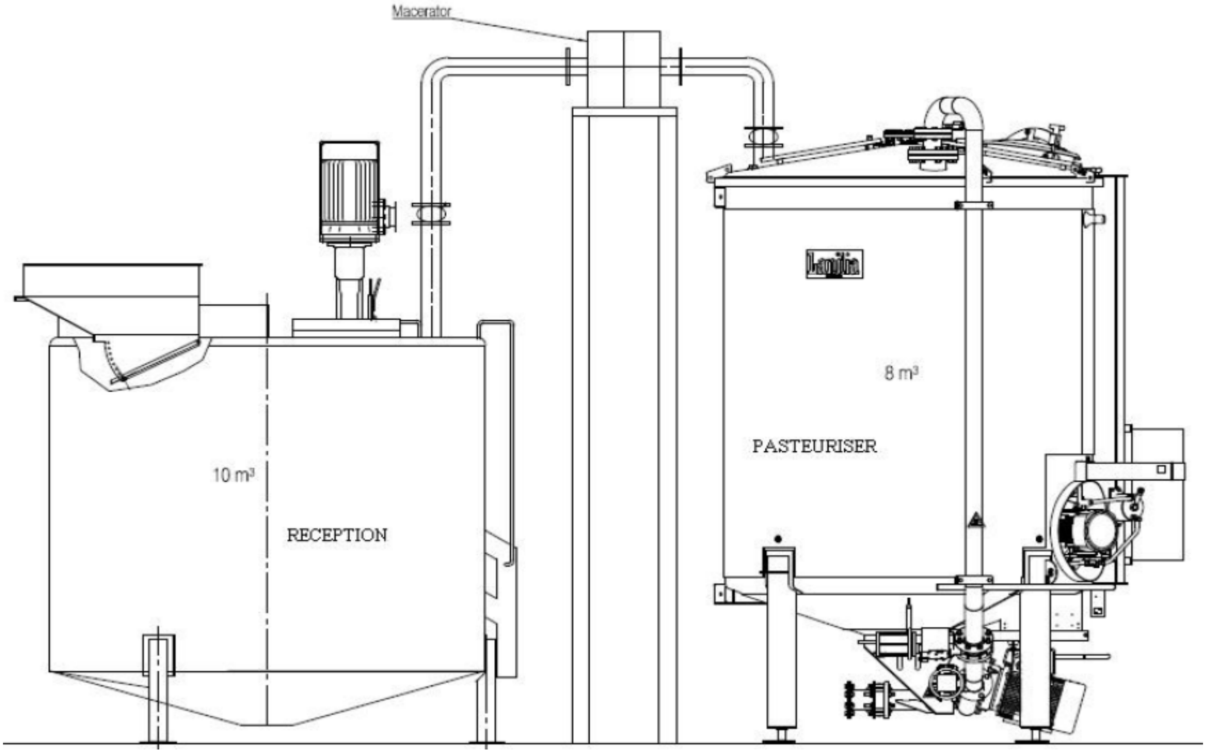

Figure 5: A diagram showing the pasteurization unit at IWMF (Source: Landia 2016, Description of Hygienisation plant)

2.5.2 Heating demand

Heat is supplied by hot water from CHP that is pumped into the pasteurizer tank designed with a simple plate heat exchanger on the inner wall and the base of the tank to ensure that the heat is evenly distributed throughout the tank content. The heat demand of the pasteurisation unit varies with batch size, based on a 3-hour duration for heating the fish waste from the ambient temperature to 70°C, plus 1 hour for maintaining this temperature.

Initially, the data registered by the SCADA system was analysed to observed the variation of heating demand for different amount of fish waste. Based on this, a regression analysis was performed to identify amount of heat necessary for heating specific amount of fish waste at given period of time. A graph showing the heating demand in kWh per tonne for amount of fish waste can be seen in the **Error! Reference source not found.** below

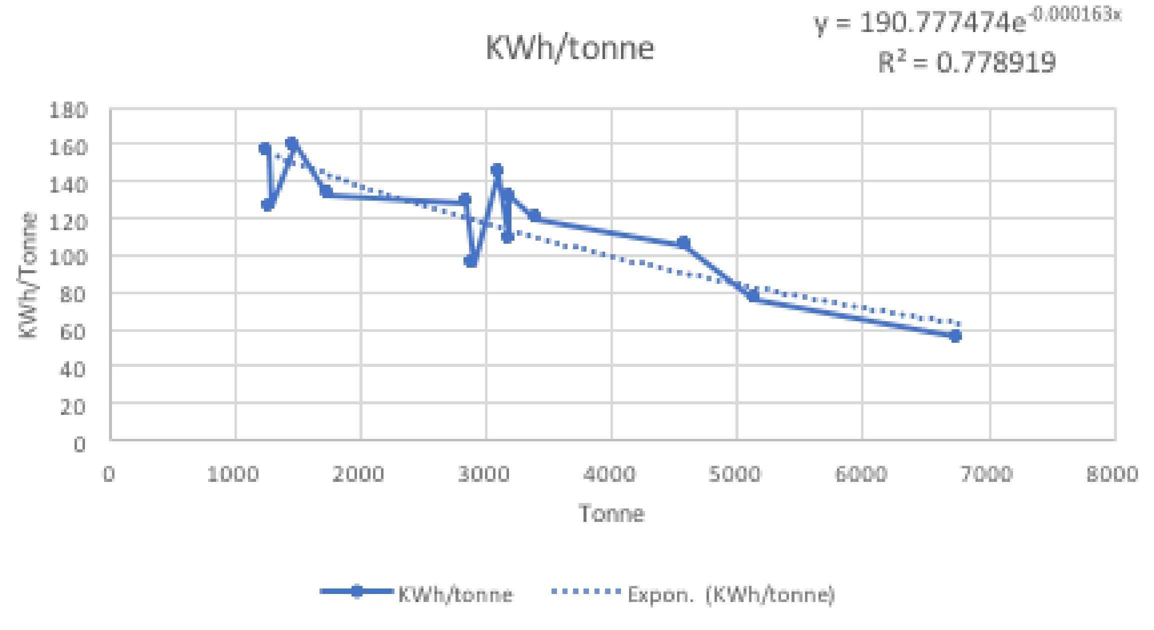

Figure 6: Pasteurizer Heating Demand

3. Anaerobic Digester

This section of the report puts emphasis on improving the quality as well as the quantity of the biogas that is being produced by the anaerobic digester located at the Integrated Waste Management Facility (IWMF), in Stornoway. The digester is a dry thermophilic plug flow digester. However, Total Solid content (TS) of 20% is maintained inside the digester itself (IWMF, 2006).

According to IMWF, the digester upon its installation in 2006, processed only household waste of Lewis and Harris Island. However, in mid 2017, fish waste from Salmon Scottish Company (SSC) was introduced as a co-substrate going in to the digester. Unfortunately, this led to severe technical problems due to ammonium accumulation in the digester. In the effort to implement mitigation actions, cow slurry was added as a buffer and as inoculums to revive the system. Another action also taken was the usage of portable water instead of centrate, which is the concentrated water that is filtered from the by-product (digestate) of the digester, to provide lubrication for easy feeding in of relatively dry substrate in to the digester. The main challenges and problems faced by the current anaerobic digester are described in detail in the sub-section 3.1.4of this report.

Therefore, this study aims at finding solutions to improve the quality and quantity of the biogas being produced by the anaerobic digester. This is to be done by modelling optimization conditions using a biogas simulation and modelling software ‘SIMBA#biogas®. This software adapts to the Anaerobic Digestion Model No. 1 (ADM1) of the International Water Association (Simba, 2018). The software will be used to optimise the operation of the biogas plant in order to produce more biogas of higher quality while minimizing ammonium build-up in the system.

The most recent operation will be modelled in the software using historic data from the years 2016 and 2017 in order to depict the status quo of the digester. In these years, the digester started to develop problems that are discussed in later parts of this report at Sub-Section3.1.4. Simulation of these base years will lead to development of diagnostic measures to solve these problems.

This section of report also highlights that the diagnostic measures in this study are modelled around three main operation parameters; composition of substrates such as household wastes, fish wastes and cow slurry, dilution of centrate, and a mesophilic condition. In the first diagnostic measure, the effect of changing the composition of feedstock is observed while finding an optimised composition of household, fish waste and cow slurry that will work best for the system. The second measure considers dilution as a measure of reducing the ammonium content in the digestate. Thus, dilution of centrate which is the liquid portion of digestate recycled into the digester is considered. The third measure looks into the conversion of the digester thermal conditions from thermophilic to mesophilic condition through a reduction in the operating temperatures of the digester.

Furthermore, this section of the report studies the possibility of methanation of carbon dioxide. This is because since one of the main challenges of the current anaerobic digester is the lack of high quality biogas, meaning that more carbon dioxide instead methane is being produced. Methanation process is considered a measure for boosting the quality of biogas by increasing the CH4 content.

Most of the input data required for simulation of the digester is acquired from IWMF so as to reflect on the real working parameters of the anaerobic digester with a few data assumed from literature studies.

3.1 Technology Overview

3.1.1 Plug Flow Digester

An anaerobic digester is a biochemical reactor in which organic matter is decomposed and converted into biogas by an anaerobic digestion process (Biarnes, 2018). Inside the digester, substrates and micro-organisms are contained for a certain period of time before the digested substrate is flown out of the digester as a digestate[1] after biogas is produced from it. A plug flow digester is a type of anaerobic digester in which substrate is fed from one end, and effluent is pushed out from the other end. Thus, inside the plug flow digester, physical processes and as well as biochemical processes do take place.

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[1] By-product (sludge) of anaerobic digestion process.

Process Flow Diagram of illustrating IWMF's Plug Flow Anaerobic Digester

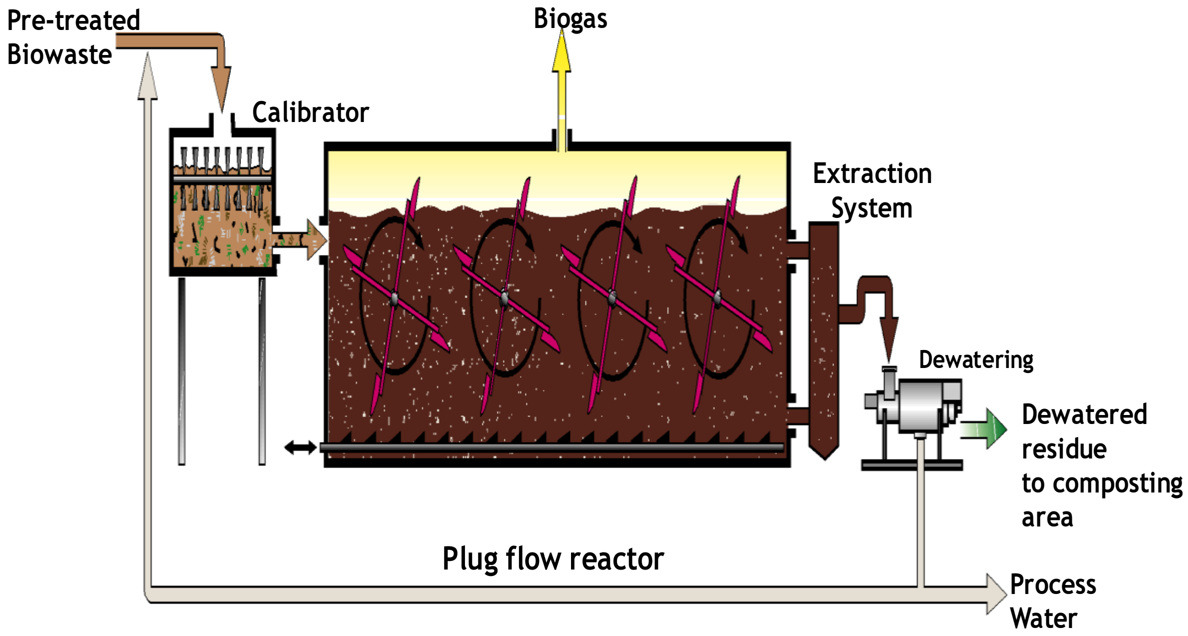


Figure 7: A process flow diagram showing the mass balance of the anaerobic digester in Stornoway Scotland. (IWMF, 2006)

The bacteria in the digester have the tendency to survive in a wide range of temperatures. However, for their optimal operations, the bacteria are classified by a specific range of temperature conditions known as thermophilic and mesophilic conditions. The type of digester in which the operating temperature is in the range of 25^0C to 40^0C is known as Mesophilic Digester (Arsova, 2010 a, p. 23). The microorganisms functioning in mesophilic digesters are more tolerant to changes in temperature conditions and can be maintained easily. The type of digester in which the operating temperature is in the range of 50^0C to 60^0C is known as Thermophilic Digester. When compared to Mesophilic Digesters, the amount of the methane produced is higher in Thermophilic Digesters.

3.1.2 Processes in Anaerobic Digestion

Early researchers have studied and categorized anaerobic digestion into two stage processes. These stages were mainly distinguished by the nature of bacterial response or observed bacterial actions that are either sequential acid forming or methane forming (Bajpai, 2017). However, recent researchers have shown that anaerobic digestion is a complex fermentation reaction that is due to a result of different types of bacteria that operate in different environmental conditions (Carreas, 2013).

Furthermore, the recent researches have also shown that inside an anaerobic digester, the process of anaerobic digestion takes place in four fundamental stages. These stages are: Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis. Each of these steps occur and are accelerated by the presence of microorganisms and at different process conditions.

3.1.3 Factors Influencing Anaerobic Digestion

Following are the factors that influence the anaerobic digestion process.

Loading Rate in Total Solids Content

The organic loading rate is a measure of biological conversion capacity of the anaerobic digestion system. If the organic loading rate is high in the system, the number of the acidogenic bacteria increases, which means that the pH level of the system falls (Arsova, 2010, p. 20). As the pH level of the system decreases, the methanogenic bacteria that play an important role in the breaking down of the organic materials die off which may ultimately lead to the shutdown of the anaerobic digestion system. Therefore, optimality or balance in the organic loading rate must be observed and maintained.

Temperature

Temperature is considered as one of the most important factors that determines the performance of the anaerobic digestion process. It is an important environmental condition inside the digester for the survival and thriving of the microorganisms. As the temperature is high in thermophilic digestion, it speeds the degradation of the organic materials in the reactor to produce more biogas.

Substrate and pH

The type of substrate being fed into the digester influences the quality of the biogas as well as the quality of the digestate produced. Furthermore, the pH of the biological processes influences the digestion process. A pH between 6.5 and 8 is considered suitable for the last stage of anaerobic digestion process (UNIDO, 2013). The pH value in the digestate is an indication of the types of compounds and possible reactions taking place in the digester.

3.1.4 Problems with the IWMF Digester

According to the IWMF, in the first ten years, the digester functioned without major problems, even though the digester’s capacity was oversized with regards to the expected feedstock. By the end of 2016, rising levels of ammonium (from 3347mg/l to 4470mg/l) were observed in the digestate by laboratory tests in IWMF.

Two main factors were cited as possible reasons for the build-up of the ammonium in the digester. After the dewatering of the digestate, the centrate obtained is used to provide lubrication for feeding in of relatively dry substrate in to the digester. As much as recycling of the centrate helps push substrates in to the digester, it affects the process by adding more ammonium in to the already high concentrations of ammonium and other contaminants.

Furthermore, the digester is fed with substrates such as fish wastes and household wastes, that are very rich in protein content. From the chemical structure of protein, Nitrogen is a dominant element of protein molecules (Li, 2009). Therefore, it could be that the household wastes being fed in to the digester might be having high protein content already, and the addition of fish; another substrate with high protein content (AE*, VV, MS, SM, & D, 2013), further increases the overall protein content in the feedstock going in to the digester. Therefore, instead of carbon and hydrogen bonding to form methane, nitrogen ions compete for the hydrogen atoms to form ammonium ions that inhibit Methanogenesis process.

By June 2017, the ammonium concentration in the digestate was as high as 4819 mg/l and the attempt of using fish wastes to boost biogas production contributed to an even higher concentration of the ammonium concentration to 6403mg/l as stated in the daily production report obtained from IWMF.

In the IWMF, the biogas should contain methane content higher than 47% for CHP generator to run. Biogas with lower methane content is flared. Regardless of mitigating the ammonium situation, the fish waste is still a good option for increasing the quality and quantity of biogas production. According to IWMF production data, a shoot up of the daily and hourly biogas production was observed in the first month of usage of fish waste (average of June: 61,7 m^3/h) when compared to the previous month (average of May: 37,5 m^3/h). Afterwards, due to the build-up in concentration of ammonium as observed in the digestate, the production of biogas decreased, reaching its lowest value in October (average: 4,58m^3/h).

As a mitigation to solve the problems previously explained, some immediate actions took place:

- the usage of fish waste was stopped to stabilize the system;
- the usage of potable water instead of recirculated centrate to reduce the ammonium content build up inside the digester was initiated; and,
- the usage of animal manure as a buffer to complement the protein content and boost the biogas production also commenced.

3.2 Procedures for Simba Software Simulations

In order to better understand and diffuse the already mentioned problems of the anaerobic digester at IWMF, there was need to try different simulations with different combinations of parameters. With this in mind, the simulations took in to consideration changes in composition of household waste, fish waste and cattle manure. It also considered the utilization of potable water for the dilution of the centrate to lower the ammonium concentration. Furthermore, another parameter considered was a change in temperature conditions from thermophilic to mesophilic conditions.

To give an illustration of the simulation process, the tool used for the simulations is as explained below. Thereafter, the inputs needed for the simulations are presented as well as the procedures to get to the best scenarios found.

3.2.1 Description of Simba Tool

This sub-section describes the main tool that has been used in modelling the scenarios. The diagram below shows the layout of the model used for the simulations. The layout is divided into 3 parts i.e. input, process and output. These are described in detail as follows:

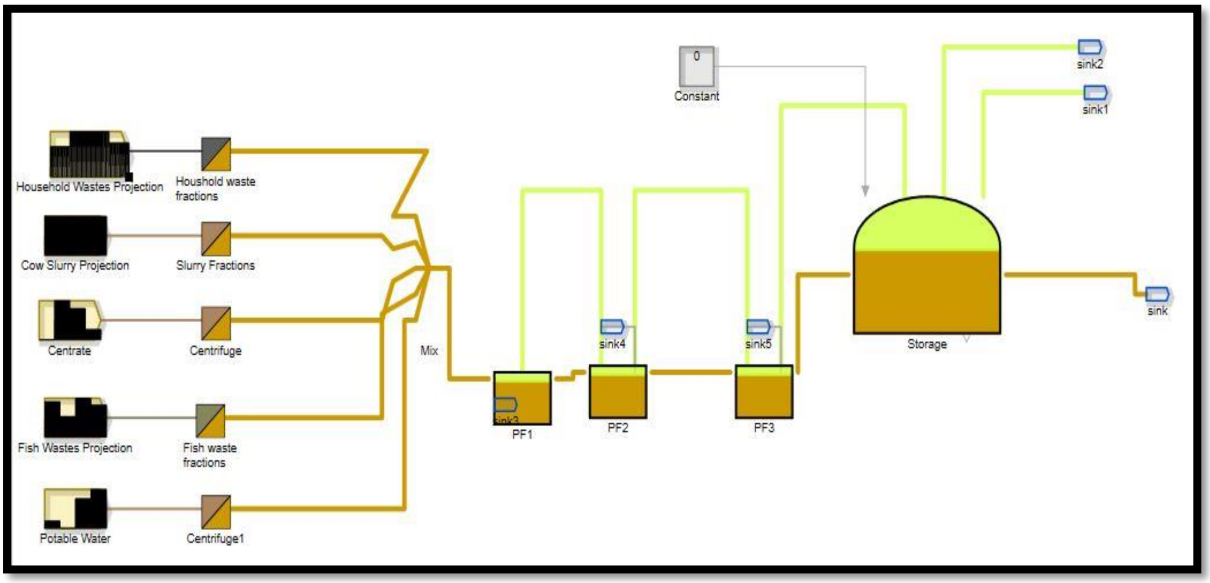


Figure 8: Layout of Anaerobic Digestion Model in SIMBA

3.2.2 Input Blocks

Import Block from Excel

Feedstock parameters and the values for the simulations such as Total Suspended Solids (TSS), Volatile Suspended Solids (VS), Fresh Matter (FM) and Ammonium (NH_4^+) are first tabulated in Excel and imported in SIMBA using the block shown in the Figure 9 below. The values of the parameters can be specified on hourly, daily or monthly basis depending on the availability of data.

Figure 9: Import Excel Block

Converter Blocks

A converter block in SIMBA is used for inputting the parameters of substrate that are going into the digester (Karlsson, 2017, p. 11). Characteristics of the substrate vary with the type of the feedstock that is being fed in to the digester such as silages, manure etc., as shown in the Table 7 below. The amount of the ammonium (NH_4) in kg/m^3 need to be specified for each substrate. The Figure 10 below shows a converter block.

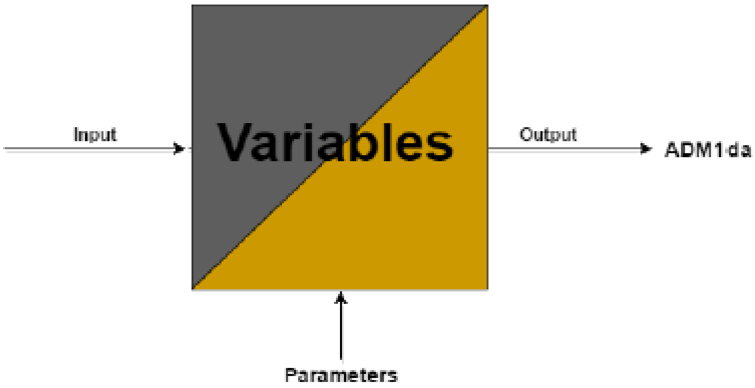
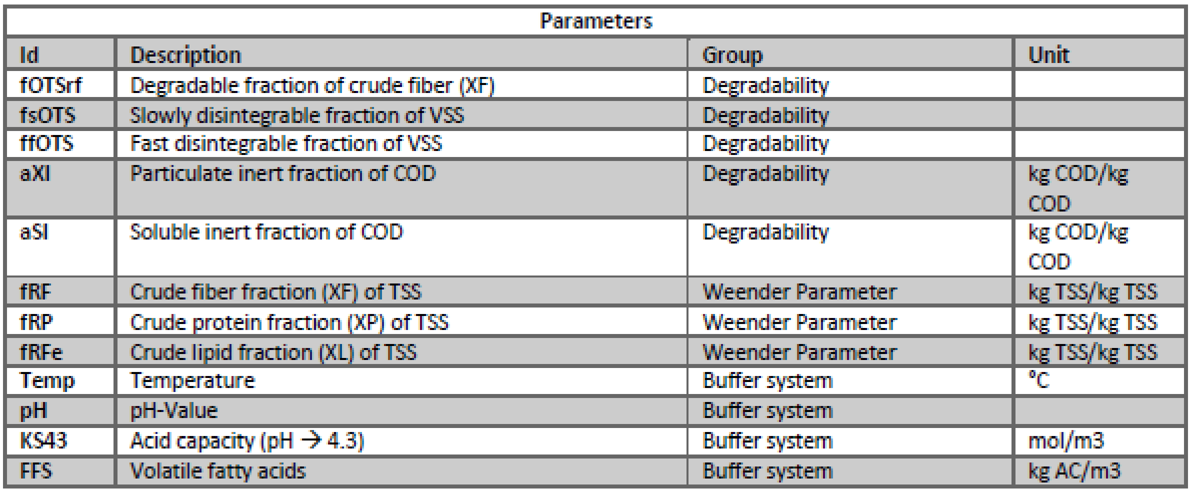


Figure 10: Converter block in SIMBA (Karlsson, 2017, p. 11)

In addition to the characteristics already mentioned above, other characteristics such as Chemical Oxygen Demand (COD), fraction of fibre, protein and lipid, based on the type of substrate, are calculated inside the converter block. The description of these additional but important characteristics with their specific units is shown in the Table 7 below.



Parameters			
Id	Description	Group	Unit
fOTSrf	Degradable fraction of crude fiber (XF)	Degradability	
fsOTS	Slowly disintegrable fraction of VSS	Degradability	
ffOTS	Fast disintegrable fraction of VSS	Degradability	
aXI	Particulate inert fraction of COD	Degradability	kg COD/kg COD
aSI	Soluble inert fraction of COD	Degradability	kg COD/kg COD
fRF	Crude fiber fraction (XF) of TSS	Weender Parameter	kg TSS/kg TSS
fRP	Crude protein fraction (XP) of TSS	Weender Parameter	kg TSS/kg TSS
fRFe	Crude lipid fraction (XL) of TSS	Weender Parameter	kg TSS/kg TSS
Temp	Temperature	Buffer system	°C
pH	pH-Value	Buffer system	
KS43	Acid capacity (pH → 4.3)	Buffer system	mol/m3
FFS	Volatile fatty acids	Buffer system	kg AC/m3

Table 7: Various Parameter inside the Block (Karlsson, 2017, p. 12)

The output of the converter block hence becomes the input for the anaerobic digestion process as represented by Anaerobic Digestion Model number 1 (ADM1da) in the software.

3.2.3 Process

The SIMBA software is normally used for modelling Continuous Flow Stirred Tank (CSTR) reactors. Hence, for the simulation of the IWMF's plug flow digester, 3 CSTR were used to represent the Plug Flow digester. The Table 8 below shows the parameters that are specified in the reactor.

Parameters		
Description	**Group**	**Units**
Maximum volume of reactor	General	m^3
Maximum volume liquid phase	General	m^3
Initial volume liquid phase	General	m^3
Maximum sludge height	General	m
Temperature	General	^0C

Table 8: Reactor Parameter

3.2.4 Output

The output tools used are Storage and Sinks. These blocks are described as below.

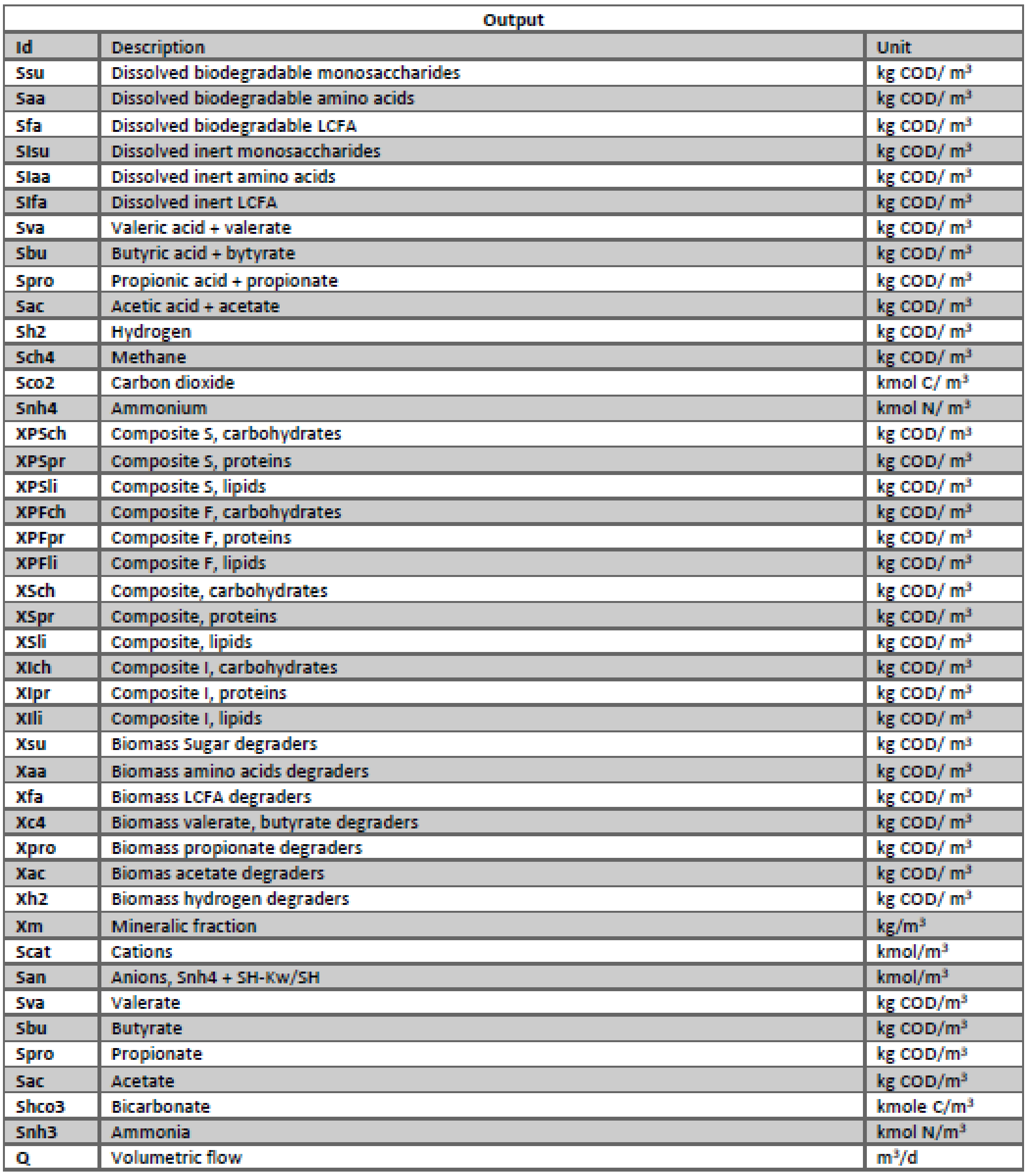
Storage Block

For the Storage of the gas, another reactor of similar specification as shown in the Table 8 above, is used.

Sink Block

A Sink block shows outlet routes of the outputs of the biogas plant. There are three Sink Blocks used in the model representing the outlet for digestate, methane gas that is to be flared and methane gas that is used to run the CHP engine.

The following table shows how results of the digestate sink after simulation are displayed.



Output		
Id	**Description**	**Unit**
Ssu	Dissolved biodegradable monosaccharides	kg COD/ m^3
Saa	Dissolved biodegradable amino acids	kg COD/ m^3
Sfa	Dissolved biodegradable LCFA	kg COD/ m^3
SIsu	Dissolved inert monosaccharides	kg COD/ m^3
SIaa	Dissolved inert amino acids	kg COD/ m^3
SIfa	Dissolved inert LCFA	kg COD/ m^3
Sva	Valeric acid + valerate	kg COD/ m^3
Sbu	Butyric acid + bytyrate	kg COD/ m^3
Spro	Propionic acid + propionate	kg COD/ m^3
Sac	Acetic acid + acetate	kg COD/ m^3
Sh2	Hydrogen	kg COD/ m^3
Sch4	Methane	kg COD/ m^3
Sco2	Carbon dioxide	kmol C/ m^3
Snh4	Ammonium	kmol N/ m^3
XPSch	Composite S, carbohydrates	kg COD/ m^3
XPSpr	Composite S, proteins	kg COD/ m^3
XPSli	Composite S, lipids	kg COD/ m^3
XPFch	Composite F, carbohydrates	kg COD/ m^3
XPFpr	Composite F, proteins	kg COD/ m^3
XPFli	Composite F, lipids	kg COD/ m^3
XSch	Composite, carbohydrates	kg COD/ m^3
XSpr	Composite, proteins	kg COD/ m^3
XSli	Composite, lipids	kg COD/ m^3
XIch	Composite I, carbohydrates	kg COD/ m^3
XIpr	Composite I, proteins	kg COD/ m^3
XIli	Composite I, lipids	kg COD/ m^3
Xsu	Biomass Sugar degraders	kg COD/ m^3
Xaa	Biomass amino acids degraders	kg COD/ m^3
Xfa	Biomass LCFA degraders	kg COD/ m^3
Xc4	Biomass valerate, butyrate degraders	kg COD/ m^3
Xpro	Biomass propionate degraders	kg COD/ m^3
Xac	Biomas acetate degraders	kg COD/ m^3
Xh2	Biomass hydrogen degraders	kg COD/ m^3
Xm	Mineralic fraction	kg/m^3
Scat	Cations	kmol/m^3
San	Anions, Snh4 + SH-Kw/SH	kmol/m^3
Sva	Valerate	kg COD/m^3
Sbu	Butyrate	kg COD/m^3
Spro	Propionate	kg COD/m^3
Sac	Acetate	kg COD/m^3
Shco3	Bicarbonate	kmole C/m^3
Snh3	Ammonia	kmol N/m^3
Q	Volumetric flow	m^3/d

Table 9: Output of the Block (Karlsson, 2017, p. 13)

3.2.5 Parameters Used for Simba Simulations

Actual parameters of the existing digester were inputted in the software to reflect the actual digester. The data below obtained from IWMF were used in all the simulations.

- Volume of digester: 1000 m^3
- Maximum Volume of liquid phase: 820m^3

- Volume of Storage: $400m^3$
- Pressure of Storage: 1.01325 bars (Pressure at atmospheric conditions)
- Height of digester: 7m
- Maximum sludge height: 5m
- Thermophilic conditions: 57°C in the digester and 45°C in the gas Storage.
- Mesophilic conditions: 40°C in the digester) and 35°C in the gas Storage.

Characteristics of the organic household waste described above are important because they influence the efficiency of the system. Table 55 in the appendix shows the characteristics of the waste used in the composition scenarios as well as the characteristics of the centrate and potable water, used for dilution in some scenarios, in addition to total solid contents (TSS), volatile solid contents (VSS) and Ammonium (NH4+) for each feedstock.

According to IWMF, physical nature as well as chemical characteristics and amount of household waste changes with season. It is said to be more in summer due to the availability of garden waste and increased touristic activities. Table 56 in Appendix A shows the monitored results of waste for 2016 and 2017 and their estimated average value for 2018 (projected year), which were also used in the simulations.

The characteristics offish waste were taken from the estimated values in Chapter 3 of this report.

Fish Waste			
Month	**TSS (kg/m^3)**	**VSS (kg/m^3)**	**NH_4^+ (kg/m^3)**
	2017/2018 (Projected Year)		
Jan to Dec	380	359	0,01

Table 10 Fish Waste Characteristics

According to IWMF, the volume of centrate recycled during the year varies between 0,2 to 4,0 m^3 per feed, depending on the size and dryness of the feedstock. The centrate characteristics were analysed in IWMF’s laboratory that monitors the ammonium content of the digestate. Therefore, values obtained and used for these simulations are presented in Table 11 below.

Centrate					
Month	**TSS (kg/m^3)**	**VSS (kg/m^3)**	**NH4+(kg/m^3)**		
	2016/2017/2018		**2016**	**2017**	**2018 (Projected year)**
Jan	25	17	3.925	4.713	4.000
Feb	25	17	3.925	4.863	4.000
Mar	25	17	4.025	4.682	4.000
Apr	25	17	3.755	4.190	4.000
May	25	17	3.695	4.307	4.000
Jun	25	17	3.923	4.540	4.000
Jul	25	17	3.780	5.100	4.000
Aug	25	17	3.927	5.277	4.000
Sep	25	17	4.195	5.910	4.000
Oct	25	17	4.207	6.140	4.000
Nov	25	17	4.283	5.566	4.000
Dec	25	17	4.315	5.600	4.000

Table 11: Centrate Characteristics

From studies done on the global acceptable quality of potable water by (Nazaroff & Alvarez-Cohen), (World Health Organization, 2003) and Scottish Water, the characteristics of potable water in Stornoway could be estimated as shown in Table 12 below:

Potable Water			
Month	**TSS (kg/m^3)**	**VSS(kg/m^3)**	**NH4+ kg/m^3** (Scottish Water, 2017)
	2018 (Projected Year)		
Jan to Dec	0,005	0	0,0005

Table 12 Potable Water Characteristics

The amount of wastes used for status quo scenarios were taken from the weighbridge data from IWMF. The data contained exact amount of organic waste comprising of garden waste, animal manure and organic household waste and 17% of rejected wastes for the respected years. These are as tabulated as shown in Table 57 and Table 58 in Appendix A of this report.

Although simulations were done for historic data from 2016 and 2017, in choosing a reference scenario for analysis, 2017 was not considered because it was a year in which the digester's failure occurred. Therefore, 2016 is much more representative because it was the latest year in which the digester worked alright, and thus for the analysis of all the scenarios, it was considered as the reference year.

The average quarterly values for the year 2016 used as a reference to project household waste for the simulations are as shown in the table below;

Quarters	**Reference Scenario 2016**	**Estimated Fish wastes, t/day** (From Chapter 1)	**Projected Cattle Manure (t/week)** (Moorpark Diary, 2018)
Q1	4,47	2.82	10
Q2	7,0	2.24	10
Q3	7,0	4.2	10
Q4	5,0	4.85	10

Table 13: *Averaged and Estimated Waste Values for Simulation*

For the diagnostic measures, a projected year (2018) was selected and quarterly projected values for household and estimated quarterly values of fish waste were used. Six days per week of digester feeding rate was considered for the simulations for each of the diagnostic measures. This was done for enabling a better analysis of the behaviour of the co-digestion simulation.

Due to ammonium related issues, the usage of fish wastes in large amounts will necessitate the need for buffering such as the addition of cow slurry. Cow slurry is usually used as an inoculums but it can also be used as a booster of methane content as well as a buffer for ammonium related issues (ADEBAYO, JEKAYINFA, & LINKE, 2013).

According to Moorpark Diary, the dairy farm located in Stornoway that supplies IWMF with cow slurry, with the current available number of cattle (34 cattle), a weekly supply of about 10 tons or more of cow slurry is possible on a regular basis. This can be used at once or divided twice a week (5t per time).

3.2.6 Limitations Encountered in the study

- Lack of exact household waste characteristics from a laboratory analysis.
- The ammonium concentration used in the simulations is not the exact ammonium concentration that built-up inside the digester. It was merely the ammonium concentration present in the centrate. The other portion of the ammonium concentrations from digester is lost in the digestate cake of which laboratory tests and records are not available.

3.3 Scenarios

3.3.1 Simulation of Historic Data for the Years 2016 and 2017: Reference Scenario 2016 and Status Quo 2017

For any optimization alternatives to be suggested or simulated, it was key to first replicate the anaerobic digester's current or historic operation in terms of efficiency and behaviour. This is to study, analyse and estimate the relations between the output (biogas & digestate) and the input (feedstock) of the digester.

The objective of this replication is to compare the results obtained from Simba simulation to the recorded data obtained from IWMF. The aim is to make sure that the two results are the same and/or very similar. Hence a validation that the model actually works. This therefore led to two replications (two scenarios) of the anaerobic digester. First scenario was based on 2016 input data and the second scenario was based on 2017 input data.

Inputs Used for the Simulations

Reference Scenario 2016

The inputs of this scenario are the daily feeds of household and garden wastes for the whole year 2016. They are tabulated in an excel file as shown in Table 57 in the Appendix A, but a quarterly summary of this is as shown in Table 13 above. Table 57 in the appendix A also contains the corresponding monthly Total Solid (TS) contents and the Volatile Solid (VS) contents for the feedstock.

Status Quo 2017

The inputs of this scenario are; the daily feeds of household and garden wastes for the whole year 2017, fish wastes fed from June 2017 to October 2017 and cow slurry fed in only one day of December 2017. They are tabulated in an excel file as shown in Table 58 in Appendix A. It also contains the corresponding monthly Total Solid (TS) contents and the Volatile Solid (VS) contents for the feedstock.

3.3.2 Development of Alternative Scenarios

Development of the scenarios revolved around three main conditions. These conditions are variation of substrates composition, dilution of centrate and mesophilic conditions. Upon a review of data obtained from IWMF**,** it was noted that along the year, there were a number of days with more hours of gas flaring than the hours of gas combustion in the CHP. As previously set by the operators of the plant, the gases are mostly flared if the methane content in the gas is less than 47%. This observation therefore gave rise to the development of methanation option as an alternative scenario that are described in the sub-section 0 of the report.

Variation of Substrates Composition

In the variation of substrates composition, co-digestion of biodegradable substrates like organic household waste, fish waste and cow slurry, is necessary. Co-digestion not only enhances production of biogas but also increases the methane content in the biogas. According to Kafle et al., (2013), co-digestion with fish waste and fruit/vegetable waste can increase the gas production by 8 percent. Similarly, the study made by Solli et al (2014) found that fish waste and cow manure can be mixed in ratio between 13-16 %and 84-87 % by volume for enhanced methane production as well as avoiding the accumulation of ammonium ions. This is adapted in the development of our scenarios, however, not in exact ratios.

Therefore, several scenarios were developed by mainly juggling between different compositions of feedstock into the digester. A total of **26** scenarios were developed in which each had different household wastes to fish wastes to cow slurry ratios.

Scenario 1: Maximum Household wastes + Estimated Fish waste

To start off the composition simulations, a scenario in which the maximum quarterly values of household waste and estimated values of fish wastes were to be simulated first. Based on the quarterly values mentioned in Table 14, daily feed into the digester for a whole year was computed in excel for both household wastes and fish wastes. Each day of a specific quarter had the same value as per that quarter in the year. And the values for household wastes used here are the maximum estimated quarterly values of the household wastes with reference to the household wastes in reference scenario.

The Total Solid (TS) contents and the Volatile Solid (VS) contents used for the household and fish wastes are as show in Table 56 and Table 58in Appendix A. Parameters such as temperature, protein content, fibre content, lipid content and pH are maintained as in Table 55 in Appendix A.

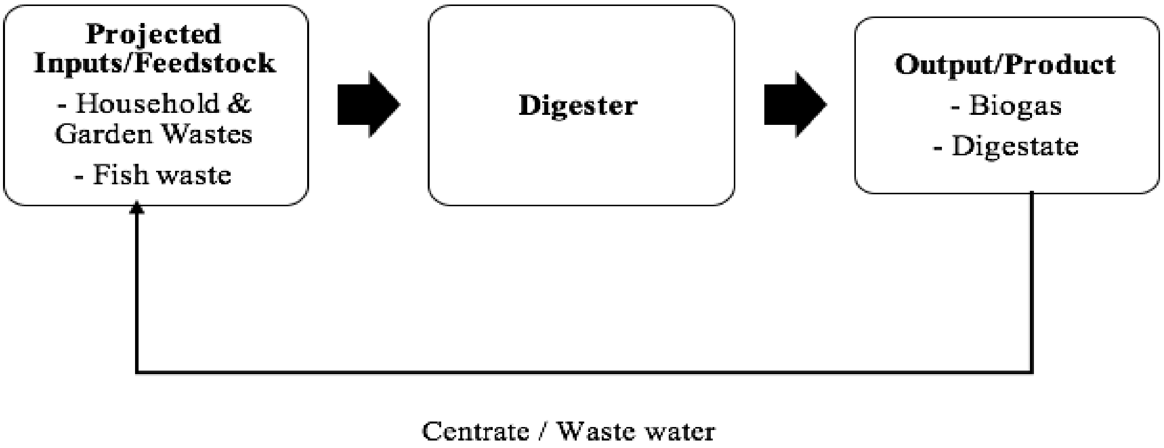


Figure 11: A figure showing the main feedstock used in the Base Scenario

Quarters	**Household wastes (t/day) (% increase/decrease to reference scenario inputs)**	**Fish wastes (t/day) (% increase/decrease to reference scenario inputs)**	**Volume of Centrate, m^3/feed**
Q1	5.1 (14% increase)	2.82	0.2
Q2	10.88 (55% increase)	2.24	4
Q3	10.88 (55% increase)	4.2	4
Q4	7.14 (43% increase)	4.85	2.1

Table 14 A table showing the percentage increase or decrease of Reference Scenario's feedstock values used in Scenario 1(Maximum Household + fish waste)

Scenarios with percentage increase or decrease in the quarterly amounts of feeds of Reference Scenarios

Due to the observed results obtained from scenario 1with maximum household wastes and estimated fish wastes above, there was need for further modification and optimization of the scenario in order to obtain better and improved response or results. This therefore meant several feedstock compositions and ratios between fish wastes and household wastes had to be played with to achieve a worthwhile result.

Therefore, a total of about ten (10) scenarios with different combinations of household wastes to fish wastes were simulated. The scenario of this classification that was considered for inclusion in the overall system's model was scenario 2.

In scenario 2, the household to fish wastes quarterly ratios were increased or decreased as shown in the table below.

Therefore, a total of about ten (10) scenarios with different combinations of household wastes to fish wastes were simulated. The scenario of this classification that was considered for inclusion in the overall system integration's model was scenario 2.

Scenario 2: Household + Fish waste

In scenario 2, the household to fish wastes quarterly ratios were increased or decreased as shown in the table below.

Quarters	**Household wastes (t/day) (% increase/decrease to reference scenario inputs)**	**Fish wastes (t/day) (% increase/decrease to reference scenario inputs)**	**Volume of Centrate, m^3/feed**
Q1	5.1(14% increase)	3.95 (40% increase)	0.2
Q2	7.62 (9% increase)	4.03 (80% increase)	4
Q3	7.62 (9% increase)	7.56 (80% increase)	4
Q4	7.14 (43% increase)	4.85 (maintained)	2.1

Table 15: A table showing the percentage increase or decrease of Reference Scenario's feedstock values used in Scenario 2 (Household +Fish Waste)

Scenarios with percentage increase or decrease in the quarterly amounts of feeds of Reference Scenario + Addition of Cow Slurry Regularly

Due to the readily available cow slurry, its addition to the overall feedstock going in to the anaerobic digester more frequently is advantageous to the system's performance. Addition of cow slurry in this case is to act as a buffer for ammonium accumulation, inoculums and as an agent to improve biogas quality.

Therefore about 15 scenarios considering daily feeding of cow slurry in to the digester were simulated. However, considering the cost for the transportation of the cow slurry, it was only logical to consider weekly or twice a week feeding of the cow slurry in the digester.

A total of 3 scenarios with weekly and once or twice a week feeding of cow slurry were simulated. For the inclusion in the overall modelling of the entire OHLEH project, only scenario 3 deemed fit and the best option of all the simulations in the category of composition of substrates.

Scenario 3: Household +Fish Waste + Cow Slurry

Quarters	**Household wastes, t/d (% increase/decrease to base scenario inputs)**	**Fish wastes t/d (% increase/decrease to base scenario inputs**	**Quantity of Cow Slurry added, tons/week**	**Volume of Centrate, m^3**
Q1	5.1 (14% increase)	5.36 (90% increase)	10	0.2
Q2	7.62 (9 % increase)	3.14 (40% increase)	10	4
Q3	7.62 (9 % increase)	5.88 (40% increase)	10	4
Q4	5.71 (14% increase)	4.85 (No change)	10	2.1

Table 16: A table showing the percentage increase or decrease in the Reference Scenario's initial feedstock values used in Scenario 3 (Household +Fish Waste + Cow Slurry)

Dilution of Centrate

The purpose of creating dilution scenarios was to reduce ammonium content in the digestate by diluting the centrate with potable water. As already mentioned, centrate is required for enabling ease in feeding in of solid substrates in to the digester. However, it is also already mentioned that recycling of the centrate adds on to ammonium accumulation in the system.

Depending on the quarterly amount of substrate, centrate requirement is a set value in the control system of the IWMF and it is of range of 0.2 to 4 m^3 volume per feed.

Therefore, a more diluted centrate with various centrate to portable water ratios were simulated. A total of 10 scenarios was simulated for dilution conditions, out of which, dilution of scenario 2 and dilution of scenario 3 gave the best result in terms of low ammonium content in the digestate and were selected for inclusion in the system integration model.

Scenario 2 (Household + Fish Waste) + Diluted Centrate

The quarterly ratios of centrate to potable water used for the two selected scenarios are as presented in the tables below:

Quarter	**Centrate, m^3/Feed**	**Potable Water, m^3/Feed**
Q1	0.2	0
Q2	2.8	1.2
Q3	2.8	1.2
Q4	2.1	0

Table 17: Scenario 2 (*Household + Fish Waste) + Diluted Centrate*

The above table shows that in scenario 2, the 30 %of potable water were added to the overall volume of liquid entering the digester in quarter 2 and 3 whereas in quarter 1 and 4, there was no dilution of the centrate.

Scenario 3 (*Household + Fish Waste + Cow Slurry) + Diluted Centrate*

Quarter	**Centrate, m^3/Feed**	**Potable Water, m^3/Feed**
Q1	0	0.2
Q2	4	0
Q3	3.2	0.8
Q4	1.05	1.05

Table 18: *Scenario 3* (*Household + Fish Waste + Cow Slurry) + Diluted Centrate*

The above table shows that in the dilution of centrate in scenario 3, 20% and 50% of potable water was added to the overall volume of the liquid going in to the digester in quarter 3 and quarter 4 respectively, whereas there was no addition of potable water in quarter 2 and only potable water was used in quarter 1.

Mesophilic Conditions

Under mesophilic conditions, the operating temperature of the digester is reduced to 40 ^{o} C, while monitoring the effect its effects on the digester's operation with the simulated scenarios mentioned above.

Currently the AD operates under thermophilic conditions which could be one of the reasons for the ammonium accumulation highlighted earlier. Thus, the behaviour of ammonium build up under mesophilic conditions of AD will be analysed.

The characteristics of substrates and other AD parameters (except the temperature) are maintained as in the variation of substrate composition and dilution of centrate scenarios.

In Simba software, the value of temperature inside the digester is changed to 40 ^{o} C and the simulations are then carried out.

A total of 5 scenarios were simulated, but for the purpose of inclusion to System integration's model, only scenario 1(Maximum Household wastes + Estimated Fish waste) and scenario 3 (Household+ Fish Waste + Cow Slurry) were selected from this category.

3.4 Results

3.4.1 Validation of the Model

Considering the fact that there were several limitations in acquisition of consistent data for certain parameters in several number of days, simulation results that exhibit similar patterns and values are to be considered in the validation of the model. However, even though the actual amounts weren't the same, they were close to the daily production as measured and recorded by the gas flow meter at IWMF. The two data also exhibited similar patterns of production along the year. Random selection days in different quarters of the year showed very similar and in some occasions same values of produced biogas in over 100 days. In

consideration of methane content, hourly or average values of the methane percentages were not a reflection of the profile of methane content to be considered for the comparison.
This is a satisfactory comparison in the attempt to validate the tool.

3.4.2 Reference Scenario 2016 Result

Quantity of Biogas

The amount of gas produced in Reference scenario 2016 is as shown in Table 19 below.

Quality of Biogas

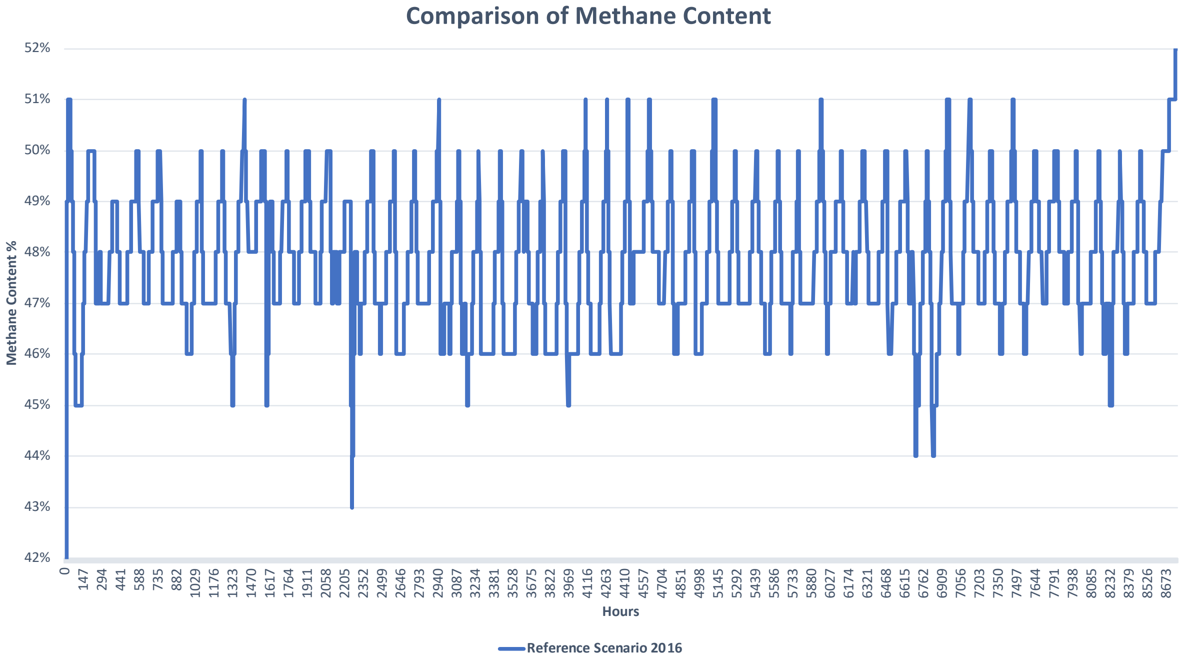


Figure 12: A figure showing the methane content of the produced biogas in Reference Scenario 2016

Ammonium Concentration

The average ammonium concentration in the reference scenario 2016 is 3476mg/l as shown in the Table 19 below. But the overall profile of this ammonium concentration is as shown in the figure below.

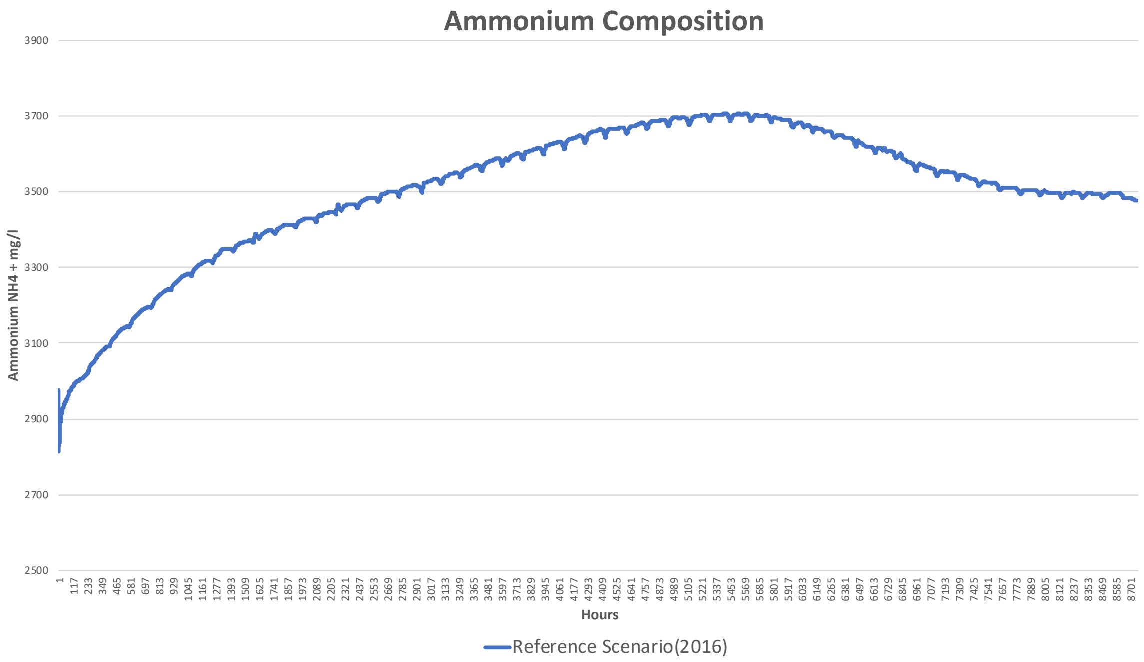


Figure 13: The ammonium profile of Reference Scenario

3.4.3 Scenarios Results

After several trials and simulations, a total sum of 41 scenarios (excluding Reference scenario 2016 and status quo 2017) of all the three categories of diagnostic measures were simulated. Based on the following parameters; ammonium profile (NH4+), methane content (CH4%), total biogas production (Q) and hydraulic retention time (HRT), 6 scenarios were deemed worthy alternatives. A summary of their averaged results is tabulated below.

	Reference Scenario 2016	**HH+ Fish (Scenario2)**	**HH+ Fish+ Cow Slurry (Scenario 3)**	**HH+ Fish (Scenario2) +Diluted Centrate**	**HH+ Fish+ Cow Slurry (Scenario3) + Diluted Centrate**	**HH+ Fish+ Cow Slurry (Scenario3) at Mesophilic Conditions**
NH_4^+ (kmol N/m^3)	3476	3399	3244	3177	2989	3318
CH4 (%)	51.72	49.4	49.52	49.4	49.14	52.38
HRT (days)	93	61	59	63	59	59

Quantity of Biogas (m^3/year)	564,000	918,000	894,000	915,000	892,000	825,000

Table 19: A table showing a summary of the results of the Scenarios as taken from SIMBA software

The hydraulic retention time (HRT) determines the duration of degradability of the substrate inside the digester. This becomes a concern mainly for wet-digesters with ODM < 12%. (Chesshire, 2011)As can be seen in the table about, the hydraulic retention time in scenario 3 at all conditions are the lowest at 59 days when compared to all the other scenarios. Graphic results of the above criteria for analysis of the scenarios selected are discussed in the analysis chapter of this report.

3.5 Analysis of Results

In the analysis section, each scenario has been compared with modifications made in the input parameters of that scenario, such as change in the various of substrate compositions, the dilution of centrate with potable water and changing the operating temperature of the digester to mesophilic temperature of 40°C. The analysis of the different results obtained will be on the basis of comparing the graphical profiles of the following output parameters:

- Quantity of biogas,
- Quality of methane in the biogas,
- Ammonium (NH_4^+) concentration,
- Organic Loading Rate (OLR)

The quantity of biogas indicates the daily amount of biogas produced by the digester. Along with quantity of biogas, the quality of the biogas is also an important output parameter to be monitored. As per the set minimum value condition at the IWMF's control system for the operation of the CHP engine, the acceptable value for the quality of biogas in this analysis is limited to anything ≥ 47% methane content.

Ammonium concentration inside the digester is another important parameter that can inhibit the anaerobic digestion process in the digester. As earlier mentioned in this report, it is considered as one of the major reasons for the digester's failure that led to a complete shutdown of the digester towards the end of 2017. Therefore, it is very necessary to study the trend of ammonium build-up throughout the year and enable making adjustments where necessary to prevent inhibition. As a requirement from IWMF, the cap set for $NH4^+$ level is to be maintained in between 3000 mg/l to 3300 mg/l.

Organic loading shows the amount of organic matter that can be fed into the AD. According to (Chesshire, 2011)the preferred range for OLR is from 3 to 6 kg ODM/m^3 per day. The OLR is a very important parameter which can affect the rate of digestion process. According to the literature, for a dry-digester with organic dry matter (ODM) of more than 12%, OLR becomes a rate-limiting factor (Chesshire, 2011).The analysis is carried out for a period of 1 year equivalent to 8760 hours' time slices.

3.5.1 Comparison of Scenario 1 (Maximum HH+ Fish) with Scenario 1(Maximum HH+ Fish)under Mesophilic conditions

In this analysis, Maximum HH+ Fish (Scenario 1) is compared with Maximum HH+ Fish (Scenario 1)at Mesophilic condition which operates the digester at a temperature of 40 ^{o} C but with same substrate composition as in Maximum HH+ Fish (Scenario 1).

Quantity of biogas

As seen in Table 19, higher production of biogas can be seen in Maximum HH+ Fish (Scenario 1) at thermophilic conditions compared to the amount of gas produced by Maximum HH+ Fish (Scenario 1) at mesophilic conditions. The daily production of biogas varied from 3417 m^3 to 920 m^3 in Maximum HH+ Fish (Scenario 1)at thermophilic conditions and 3123 m^3 to 250 m^3 in Maximum HH+ Fish (Scenario 1) at mesophilic conditions. The annual difference in biogas production obtained from simulation is 67455 m^3.

Quality of Biogas

Comparing the methane quality of biogas produced, it is found that Maximum HH+ Fish (Scenario 1) at mesophilic conditions produced more high quality methane compared to Maximum HH+ Fish (Scenario 1) at thermophilic conditions as shown in Figure 14 below. In Maximum HH+ Fish (Scenario 1) at mesophilic condition, the quality of biogas varied from 47.48% to 55% whereas in scenario 1 at thermophilic condition, it varies from 45.78% to 50%. Thus, showing that reducing the digester temperature to mesophilic temperature has a positive effect on the methane content of biogas.

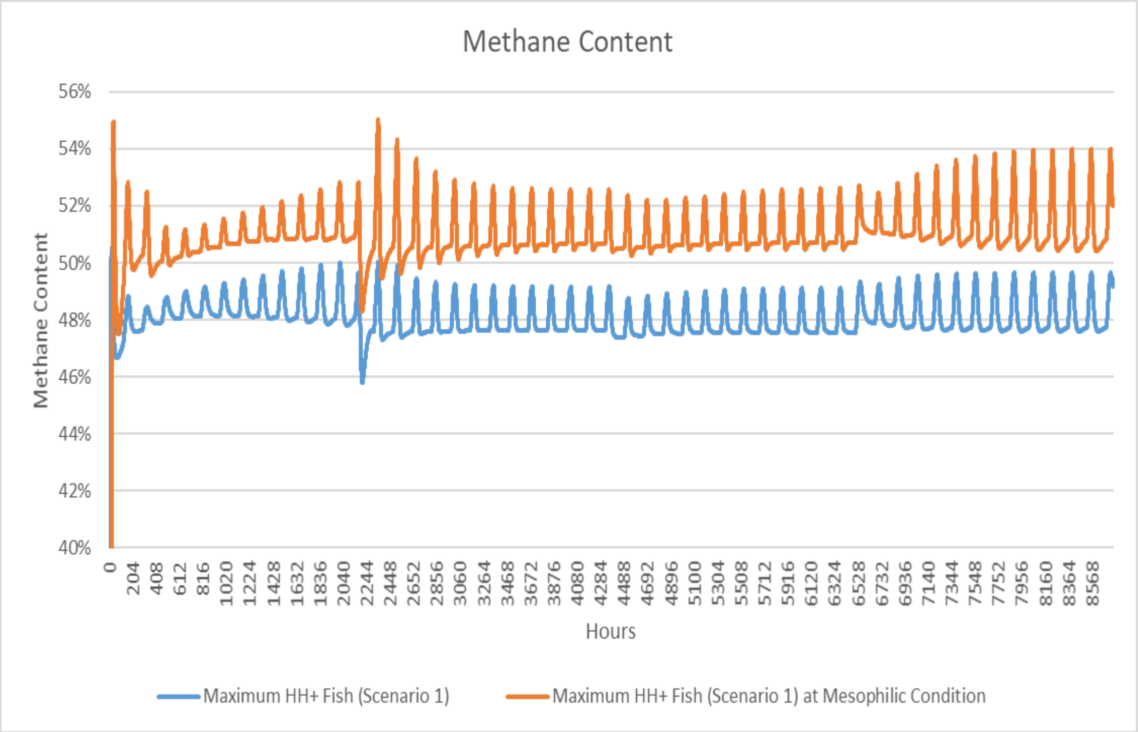


Figure 14: Quality of methane in the biogas for Maximum HH+ Fish (Scenario 1)and Maximum HH+ Fish (Scenario 1)at Mesophilic condition

Ammonium Concentration

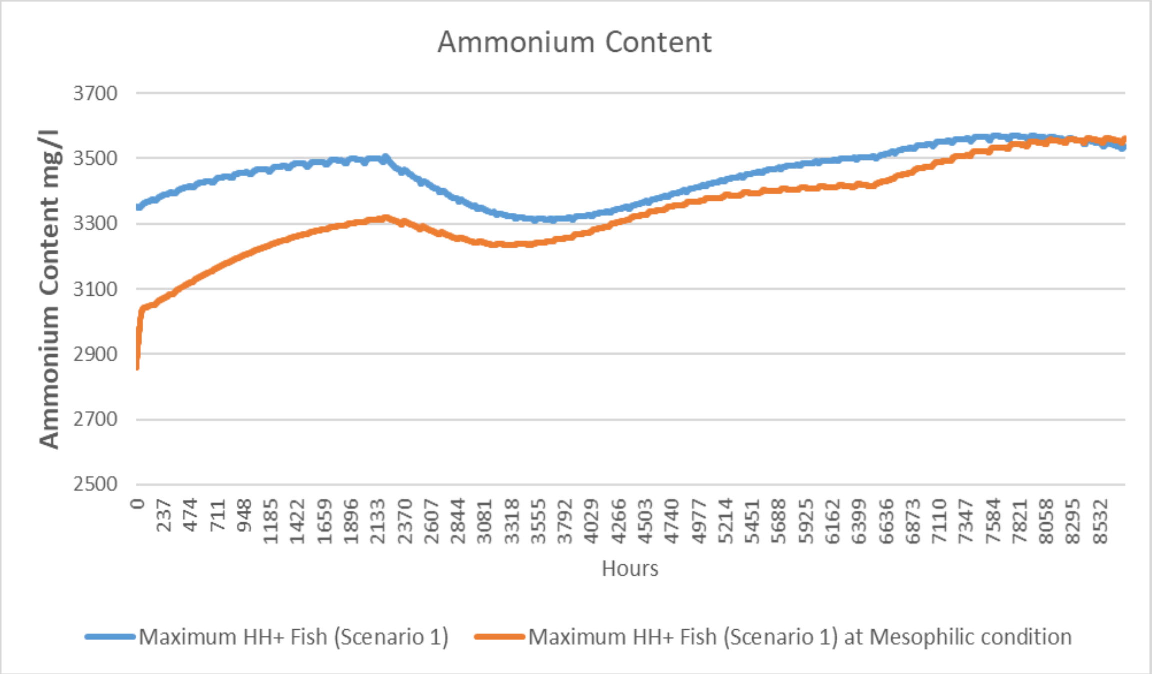


Figure 15 Ammonium Composition build up in Maximum HH+ Fish (Scenario 1)and Maximum HH+ Fish (Scenario 1) at Mesophilic Condition

In the figure above, the difference in ammonium build-up in Maximum HH+ Fish (Scenario 1) at thermophilic condition and Maximum HH+ Fish (Scenario 1) at mesophilic condition are shown. It can be seen that in Maximum HH+ Fish (Scenario 1) at thermophilic, the build-up of ammonium concentration is comparatively lower and thus reducing the possibility of ammonium ($NH4^+$) inhibition. In both simulations, the highest amount of $NH4^+$ is below 0.1974Kmol/m^3 which is equivalent to 3500 mg/l. These points towards the possibility of varying the composition and dilution parameters of substrates to further bring down the $NH4^+$ level.

Organic Loading Rate

Comparing the organic loading rate (OLR) for Maximum HH+ Fish (Scenario 1) at thermophilic condition and Maximum HH+ Fish (Scenario 1) at mesophilic condition, it is found that OLR is increased under mesophilic conditions with an increase of up to 0.17 kg.VSS/m^3/d in quarters 2,3 and 4.

3.5.2 Comparison of Reference Scenario 2016 with Scenario 2(*Household + Fish waste*+ Diluted Centrate)

Quantity of Biogas

According to the results in Table 19 above, the amount of gas produced in scenario 2 is a lot higher than the amount of gas produced in the base scenario. The total amount of gas in the reference scenario is 564,000m^3/a whereas the total produced biogas in scenario 2 is 915,000 m^3/annum , making it 351,000m^3 more gas in scenario 2 than in reference scenario.

Quality of Biogas

The range of methane content of biogas in scenario 2 (*Household + Fish waste* + Diluted Centrate) is slightly higher than the reference scenario as shown in figure below. This proves that higher quality of biogas is obtained when the centrate is diluted.

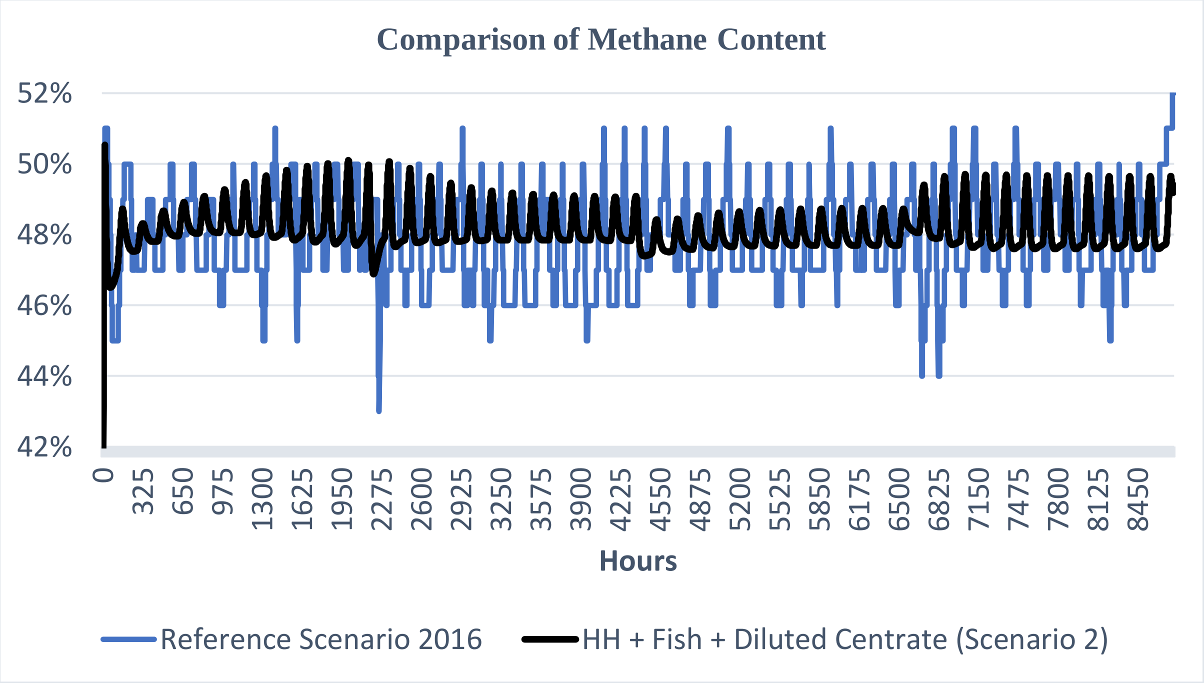


*Figure 16: Comparison of Methane Content between Scenario 2 (**Household + Fish waste** + Diluted Centrate) Dilution and Reference Scenario*

Ammonium Concentration

The comparison of ammonium concentration in the reference scenario with scenario 2 (Household + Fish waste + Diluted Centrate) is shown by the Figure 17 below. When compared, the graph shows that the amount of ammonium in the digestate is much lower in the scenario in which centrate was diluted than in reference scenario. The slight increase shown in the second quarter is due to the increase of the fish and household wastes in the feedstock in those quarters. The ammonium concentration decreases again in the third quarter and is stabilized until the end of the year. This is due to the usage of potable water in the second quarter for diluting centrate. When centrate is diluted, the average ammonium level decreased from 3476 mg/l to 3399 mg/l.

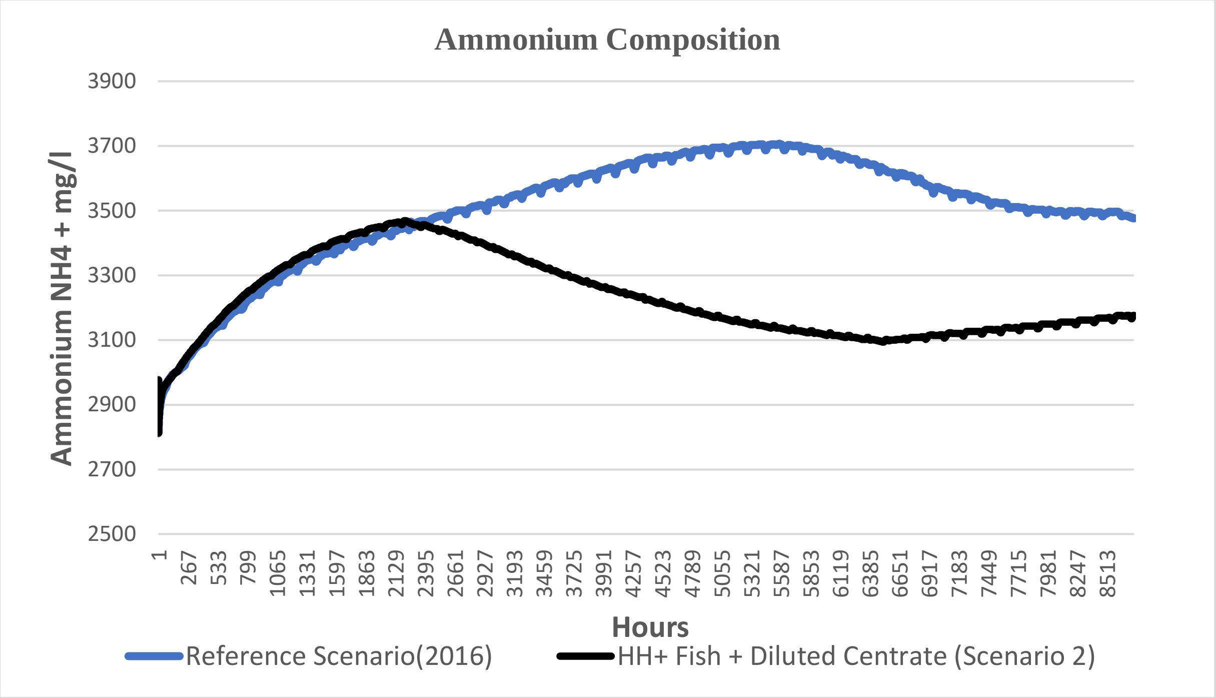


Figure 17: Comparison of Ammonium Concentration between Scenario 2 Dilution and Reference Scenario

Organic Loading Rate (OLR)

The OLR is slightly higher in Scenario 2 with diluted centrate as compared to the reference. This is because increase in the estimated amount of fish waste increased the OLR. With that explanation in mind, it is safe to conclude that scenario 2 with diluted centrate is the better option in this comparison.

3.5.3 Comparison of Scenario 3 (Household+ Fish waste + Cow Slurry) with Scenario 3 with Dilution of Centrate and Scenario 3 at Mesophilic conditions

Quantity of Biogas

In *Table 19*above, it is shown that in scenario 3 under thermophilic conditions, the annual biogas production (894000m^3) is higher than in scenario 3 at mesophilic conditions (825000.5m^3), showing a difference of 69000 m^3. It was noticed that because of dilution of centrate in scenario 3, with an annual biogas production was 892000m^3. This is slightly lower than the annual quantity of biogas produced in scenario 3(Household+ Fish waste + Cow Slurry) by 2000 m^3.Therefore, when analysing the biogas quantity, the scenario 3 (Household+ Fish waste + Cow Slurry) composition is considered better due to its higher biogas quantity.

Quality of Biogas

The Table 19 above also shows that it is possible to compare the methane content of biogas in the scenarios 3 (Household+ Fish waste + Cow Slurry), scenario 3 with dilution of centrate and scenario 3 under mesophilic conditions. The average methane content was 49.52% in scenario 3 (Household+ Fish waste + Cow Slurry) and slightly decreased when centrate was diluted at 49.14%. This means that the usage of potable water did affect the formation of methane in the process. However, there is an increase in the methane content of the biogas produced in the scenario 3 at mesophilic conditions to 52.38%. Hence showing that at mesophilic conditions, high biogas quality is produced when compared to the other two scenarios in thermophilic conditions.

Ammonium Concentration

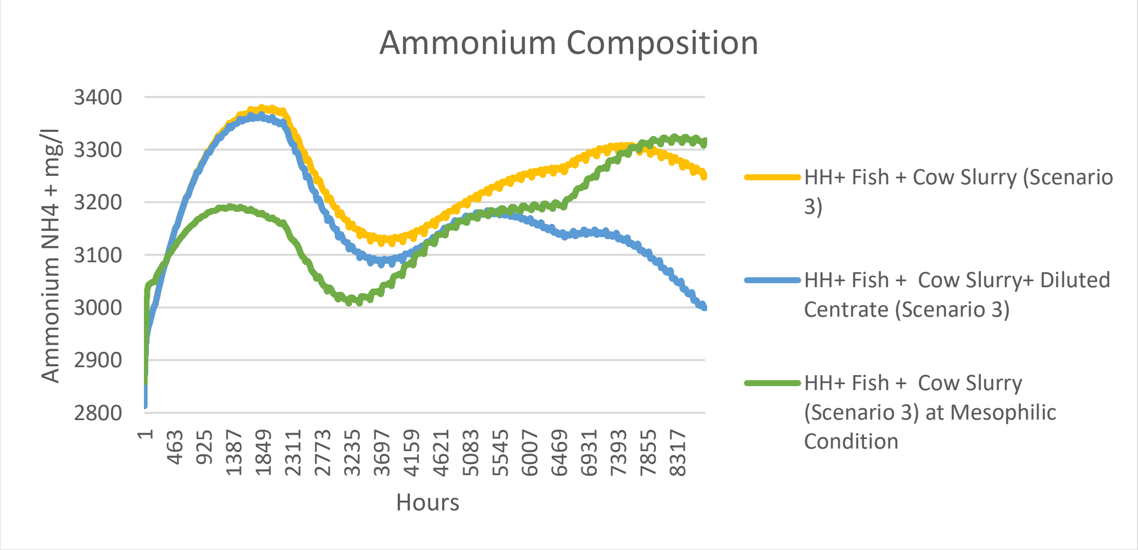


Figure 18 Comparison of Ammonium Composition Profile: Scenarios 3(HH+Fish+Cow Slurry) - Composition, Dilution and Mesophilic

From the graph above, of the three scenarios, scenario 3 (Household+ Fish waste + Cow Slurry) shows a rather higher ammonium profile at a high peak of 3360 mg/l when compared to scenario 3 with diluted centrate with highest peak at 3350 mg/l and scenario 3 at mesophilic conditions with highest peak at 3320mg/l.

It is visible that Scenario 3 (Household+ Fish waste + Cow Slurry) and scenario 3 with diluted centrate showed a rapid increase in the first quarter of the year due to the high waste feed and the faster formation of ammonium under thermophilic conditions. However, the ammonium concentration in the scenario with diluted centrate started to gradually reduce compared to scenario 3 compositions, due to the addition of potable water in quarters 3 and 4. Relatively, mesophilic scenario shows a much lower trend in the ammonium concentration in the first two quarters as compared to scenario 3 (Household+ Fish waste + Cow Slurry) and scenario 3 diluted. However, even though there was a lower trend or profile in the ammonium concentration in scenario 3 at mesophilic condition, it was gradually increasing with time. Towards the middle of the fourth quarter, the ammonium content in the mesophilic scenario increased to a point where it exceeded the concentration in scenario 3 Composition by 59 mg/l.

Therefore, to conclude, in this comparison, as much as under mesophilic conditions, scenario 3 exhibited attractive results in the beginning, with time, it can be concluded that scenario 3 (Household+ Fish waste + Cow Slurry) with diluted centrate is the better pick for a simple fact that the concentration of ammonium was gradually decreasing to a much lower value at 3000mg/l when compared to the other two scenarios.

Organic Loading Rate

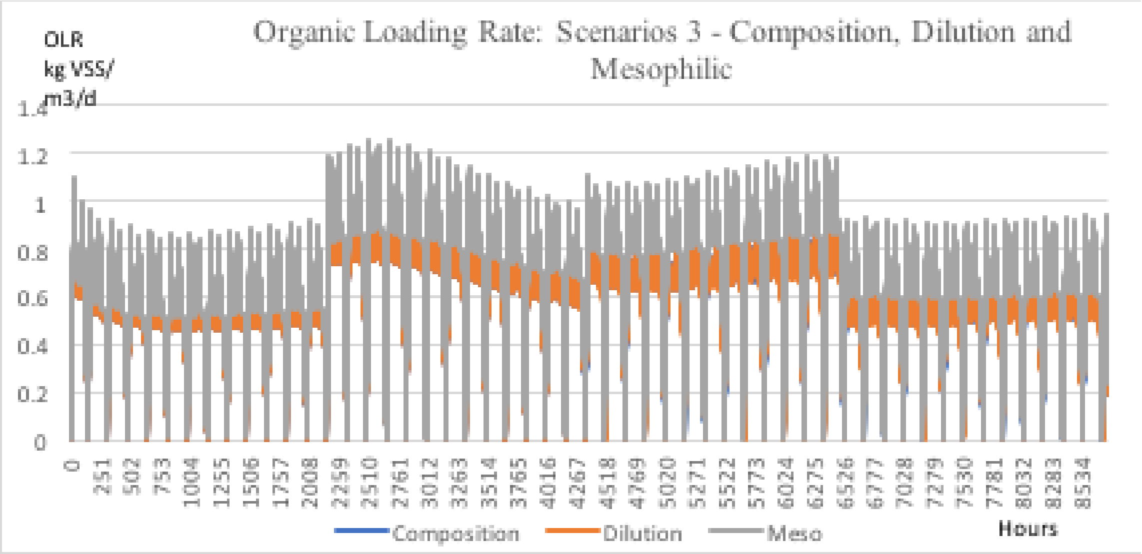


Figure 19 Comparison of OLR: Scenario 3 - Composition, Dilution and Mesophilic

The figure above shows that of the three scenarios, scenario 3 at mesophilic condition showed a much more balanced and slightly better organic loading rate compared to the scenario 3 (Household+ Fish waste + Cow Slurry) and Scenario 3 with diluted centrate. The organic loading rates for scenario 3 (Household+ Fish waste + Cow Slurry) and scenario 3 with diluted centrate had exactly the same OLR profiles. This is an indication that dilution of the centrate didn’t affect the OLR in the system.

Therefore, due to the fact that our scenarios should aim at increasing the OLR in the digester to optimal conditions, the scenario with a higher OLR is to be considered the better option in this category of OLR. Hence, it can be justified that the scenario 3 at mesophilic condition is the better choice as can be shown in the graph above.

3.5.4 Final Comparison of all scenarios

The tabulated and graphical assessment of the results discussed above showed positive differences between the scenarios of the diagnostics measures when compared to the status quo 2017 and base scenario.

When compared to the other scenarios the methane content in the produced biogas throughout the year is high in scenario 3 in all conditions at values of over 49% CH_4.

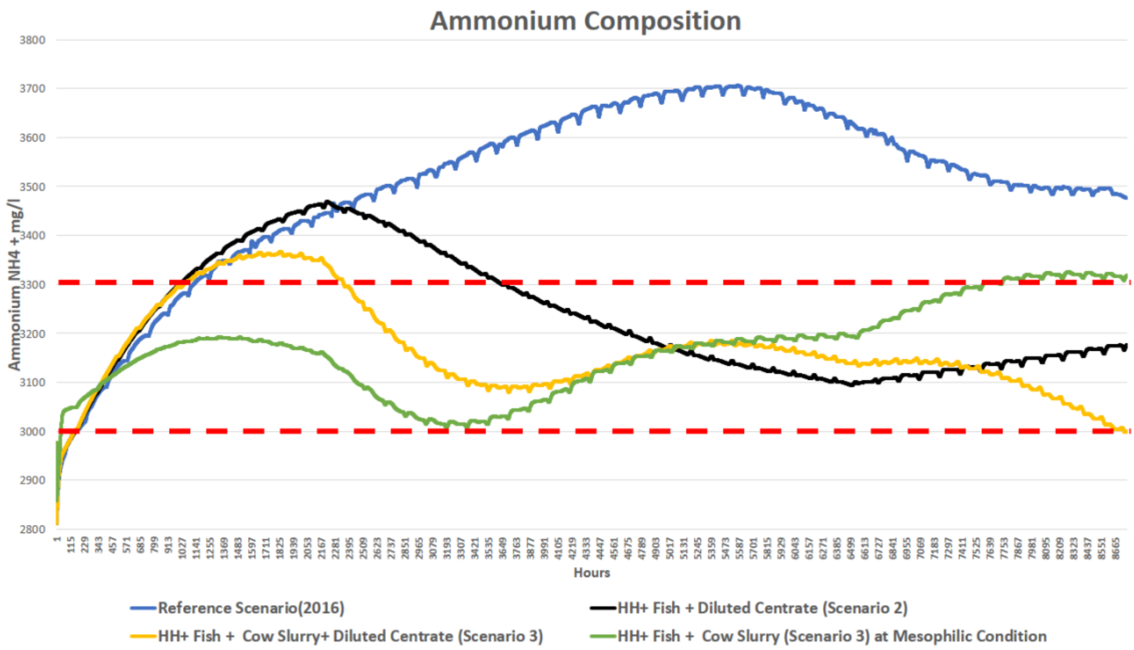


Figure 20: A figure showing the Ammonium profiles of all scenarios

Comparing the Ammonium concentration for all scenarios, it could be seen that HH+ Fish+ Cow Slurry + Diluted Centrate (Scenario 3) and HH+ Fish+ Cow Slurry (Scenario 3) are in limits of permissible ammonium concentration. But HH+ Fish+ Cow Slurry + Diluted Centrate (Scenario 3) is more sustainable since the profile of ammonium concentration shows a decreasing profile indicating more stable ammonium concentration than other scenarios.

The above summary of the results also entails that scenario 3 Dilution is the best scenario in comparison to all the other scenarios. Its ammonium content and the Hydraulic retention time are the lowest of all the scenarios in all conditions.

3.6 Cost Parameters and Environmental Savings

3.6.1 Cost of Potable Water

The cost of potable water depends on the meter size and volume used. The cost of water for 25mm and 100mm is Pound 0.7068 per m^3 for the first 100,000 m^3 used. This figure was used to calculate the total cost of potable water used for the whole year in ‘Scenario 2 Dilution’ and ‘Scenario 3 Dilution’. The cost per year for ‘Scenario 2 Dilution’ and ‘Scenario 3 Dilution’ was Pound 132.31 and Pound 113.61 respectively.

3.6.2 Cost of Transportation of Cow Slurry

As per information from IWMF, cow slurry is free, but the cost of hiring a tanker of 14 m^3 capacity for the transportation of the cow slurry is £400/hire. Since some of our scenario suggests either weekly or twice in a week requirement of cow slurry, the total cost of transportation of slurry per annum would be equivalent to £41,600 (twice of week delivery) and £20,800 (weekly delivery).

3.6.3 Greenhouse Emissions Saving from Fish Waste

The study also calculated the greenhouse gas emissions savings by using fish waste as co-substrate in the anaerobic digester rather than sending it to the landfill. This was done by simulating the scenario 1 with and without fish waste. The results of the calculation were as in Table 20 below. From the table, it was calculated that greenhouse emission savings due to methane released from degradation of 1 tonne fish waste in landfill would be equivalent to 2.3 tonnes CO_2 eq.

Quantity of biogas with household and fish waste, $Q_{HH+Fish}$	877000 m^3/year
Quantity of biogas with only house hold waste, Q_{HH}	556,000 m^3/year
Quantity of biogas production due to fish , Q_{Fish}	321,000 m^3/year
Quantity of methane in the biogas production due to fish, Q_{CH4} *(CH_4 % = 48%)*	154,000 m^3/year
Quantity of methane in the biogas production due to fish in kg, Q_{CH4}	101,000 kg

Using density of methane at 20 C as 0.667 kg/m^3 (Dutt, 2003)	
Total greenhouse emission savings from 1100 tonnes fish waste *As per fourth assessment report of IPCC, one kg of methane is equivalent to 25 kg CO_2-eq. (Susanne Woess-Gallasch, 2011)*	2530tonnes CO_2equivalent

Table 20: A table showing greenhouse gas emissions savings from Fish wastes

On simulating the 'System Model' for scenario 1 composition with fish and without fish, it was found that a total of 132 tonnes kg CO_2 eq. by replacing grid electricity, kerosene boiler and diesel. Thus, total CO_2 saving from using 1,100 tonnes fish waste in digester is 2,662 tonnes kg CO_2 eq. which is equivalent to 2.42 tonnes kg CO_2 eq. for 1 tonne of fish waste used in digester.

3.7 Fish Waste as Substrate to AD

The result of fish waste estimation from Lewis and Harris depicts that a significant amount of fish waste can be made available as feedstock to AD at IWMF. The amount of fish waste required in the scenarios developed and shown in the above part of this report is summarized in Table 21 below.

	AD's Status Quo 2017	**AD's Scenario 1: Base Scenarios**		**AD's Scenario 2**		**AD's Scenario 3**	
Quarter	(t/Q)	(t/d)	(t/Q)	(t/d)	(t/Q)	(t/d)	(t/Q)
Q1	0	2.82	217.14	3.948	303.996	5.358	412.566
Q2	17.26	2.24	174.72	4.032	314.496	3.136	244.608
Q3	43.4	4.2	327.6	7.56	589.68	5.88	458.64
Q4	7.96	4.85	383.15	4.85	383.15	4.85	383.15

Table 21: Quantity of fish waste fed into AD

3.7.1 Ensiling

Ensiling is a process in which harmful pathogens in the fish mortalities are inactivated to facilitate secured disposal or utilization of the waste. Ensiling is not a new process. It was first adopted in Sweden in the 1930s and has since been used by the fish industry in Denmark and Norway (Tatterson & Windsor, 2001) and Scotland (Zero Waste Scotland, 2016, p. 69). The fish industry in Norway undergoes through ensiling which has been regarded as a suitable option for the storage of fish mortalities at farm level (European Commission, 2003, p. 58). For ensiling, fish mortalities are macerated such that the particle size is about 4 mm (Forbes & Summer, n.d., p. 19). The macerated viscous waste is mixed with formic acid; an organic acid of a pH level less than or equal to 4. Acid ensiling is regarded an effective means to handle and store salmon mortalities (British Columbia, 1990, p. 5). For the ensiling process, 35 kg or 30 litres of formic acid are required for 1 tonne of fish mortalities (Tatterson & Windsor, 2001). Formic acid aids in autolysis whereby the fish waste is broken down into fragments by enzymes (Mack et al., 2004, p. 15). Presence of formic acid prevents the ensiled fish mortalities from putrefaction. Afterwards, the ensiled fish waste can be stored in tanks. The pH of each batch of ensiled mortalities should be tested before transferring to the storage. Also, during storage, the pH needs to be checked to ensure that silage pH is within 1.5-4.5 (British Columbia, 1990, p. 9).

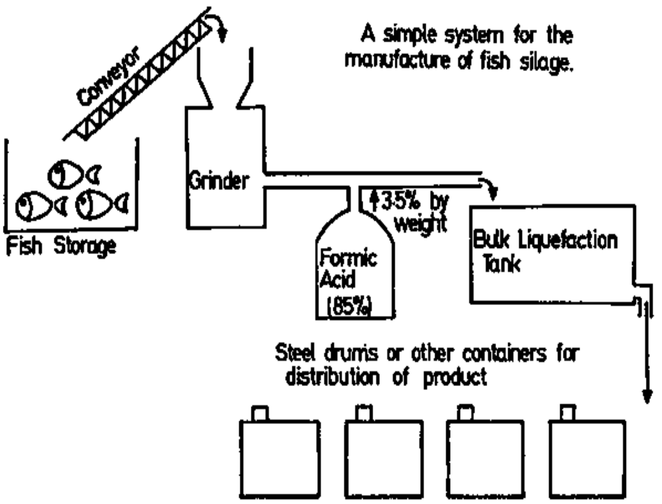


Figure 21: Process Diagram of Ensiling Fish Waste (Tatterson & Windsor, 2001)

Furthermore, the warmer the mixture of acid and mortalities, the faster is the process of ensiling. Fresh fish waste at 20°C takes about 2 days while at a lower temperature of 10°C the process takes much longer, around 5-10 days (Tatterson & Windsor, 2001a). Ensiling also helps to tackle the problem of foul odour from fish mortalities. The ensiled product exhibits lower nitrogen content which is desirable in an AD that utilizes fish waste as a feedstock. Lower nitrogen content in ensiled product, yields higher C: N ratio which reduces the rate of ammonium formation inside the AD and subsequently in the digestate (Zero Waste Scotland, 2016, p. 20). In case of anaerobic digester at IWMF, higher ammonium concentration was the main reason that was inhibiting production of biogas. Therefore, ensiled fish was as feedstock can be helpful to limit the ammonium formation inside the anaerobic digester. The ensiled fish mortality with the right amount of acid at room temperature can be stored up to 2 years.

But it is recommended to store the ensiled waste up to 6 months only (Tatterson & Windsor, 2001b).

In Scotland at present, the Orkney fish waste processing facility is involved in ensiling and storing fish waste in Intermediate Bulk Containers (IBC) (Zero Waste Scotland, 2016a, p. 16). Additionally, SEPA is responsible for the issuance of licences required for the installation of an ensiled waste storage facility. According to SEPA, there is a provision of having 10 such IBC on site that can be used for storage at the fish farms (Zero Waste Scotland, 2016b, p. 16). At processing plant facilities, the size of the storage can be more than 50m^3. There has been a record of the existence of 400m^3 bulk storage facility in Inverness Harbour Scotland (SEPA, 2007, p. 1) in the past.

3.7.2 Ensiling Sizing and Cost Estimation

The equipment required for ensiling is readily available in the market. Ensiling comes at certain costs. The cost analysis has been done on the basis of cost of ensiling equipment obtained from Norfab Products Ltd located in Inverness, Scotland. There are several sizes of ensilers that are available in the market. The cost of various equipment and operating cost can be found in Table 54 in the Appendix A.

The cost provided by the Norfab Products Ltd has been used to calculate cost of ensiling per tonne of fish mortalities. The unit cost of ensiling was calculated by annualizing the investment required to buy the equipment. The lifetime of ensiler was taken as 20 years. The ensilers are made up of stainless steel, therefore with regular maintenance should be able to last up to 20 years (University of Wisconsin, 2018). The storage tank that was considered in the cost analysis was polyethylene tank which is leakage resistant. The ensiled fish mortalities can be stored in such black polyethylene tanks (Tatterson & Windsor, 2001) and (Enduromaxx, 2015). Additionally, the cost of formic acid, the cost of repair and maintenance and labour has been considered as operating cost. The repair and maintenance cost has been taken as 10 percent of the investment cost and labour wage as £7.83 per hour (Minimum Wage, 2017). According to British Columbia (1990), it takes around 4.16 man hour to ensile 1 tonne of fish mortalities (p.7). The labour wage therefore has been calculated taking 4.16 hours of labour requirement and the total amount of waste that has been ensiled in respective scenarios. The interest rate of 5 percent has been assumed to be the discount rate to annualize the investment cost for the ensiling system. According to the Bank of Scotland, the interest rate varies from 0.25% to 5%, so for the cost analysis interest rate on higher side has been considered (Bank of Scotland, 2017).

Based on the cost of ensiling equipment and assumption of various cost components, the cost of ensiling fish mortalities for the best AD Scenario which is Scenario 3 are shown in Table 22 below.

Ensiler Capacity (Litre)	**No of ensiler**	**Selected Ensiler**	**Unmet Demand**	**Cost per Tonne (GBP/Tonne)**
2,000	1	2000 L	3.87%	96.30
2,820	3	940 L x 3	0.58%	98.36
2,940	2	2000 L and 940 L	1.72%	127.03
3,880	3	2000L and 940 L x 2	0.65%	100.14
5,000	1	5000 L	0.98%	126.92
5,880	4	2000 L x 2 and 940 L x 2	0.30%	111.82
5,940	2	5000 L and 940 L	0.32%	165.79
6,000	3	2000 L x 3	2.07%	116.76

Table 22: Unmet Demand and Cost of Ensiling for AD Scenario 3

The cost of ensiling was analysed with respect to various size of ensiler. The time required to ensile fish mortality in different size of ensiler has been assumed.300litres and 940 litres ensilers were assumed to take 2 days to ensile the waste, while higher capacities of 2,000 litres and 5,000 litres were assumed to take 5 days to ensile fish mortality. Based on the result of cost analysis, ensiler capacity of 2,820 appeared to be suitable as the per tonne cost of ensiling and unmet demand was the least among other ensiler capacities at £98.36 and 0.58 percent respectively. The cost of ensiling was calculated with respect to investment and operating cost. However, depreciation of the ensiling equipment has not be considered. The unmet demand is the total amount of fish waste that was not supplied to anaerobic digester by ensilers at the time of its requirement on specific days of the year. The difference between the annual demand of fish waste and total of fish waste supply to anaerobic digester plus fish mortalities sent to the storage after ensiling gives the unmet demand of fish waste.

The effect of cost on various ensiler capacities for AD Scenario 3 can be seen in Figure 22.As seen from the figure, the size of the ensiler does not have impact on cost of ensiling across different sizes as the cost of ensiling is fluctuating without definite trend. However, the number of ensiler to be chosen has an effect on cost of ensiling. The percentage of unmet demand is varying between 0.3% to 3.9%. The unmet demand in this particular scenario (with annual demand of 1,499 tonnes per year) does not exceed beyond 59 tonnes a year.

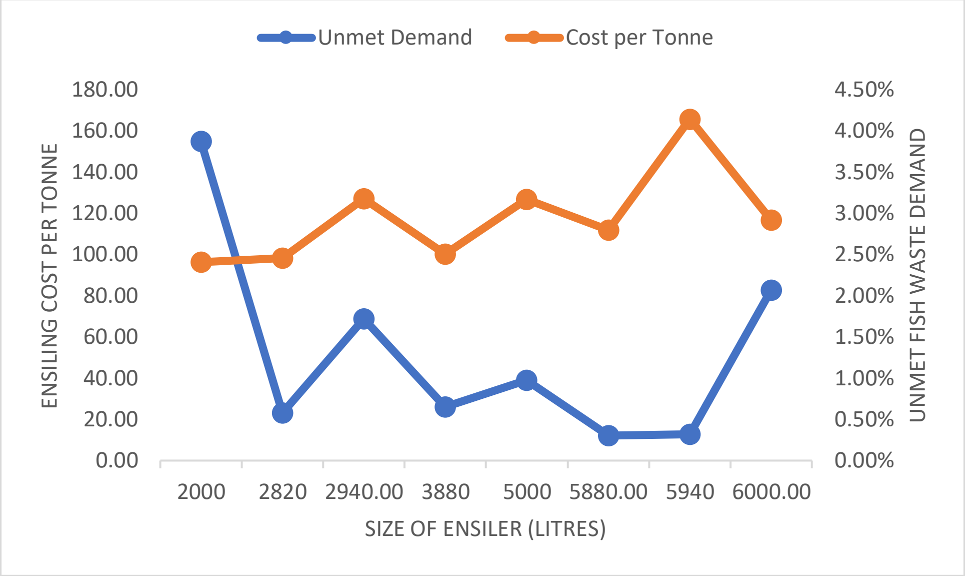


Figure 22: Unmet Demand to AD vs Cost of Ensiling Fish Mortality for AD Scenario 3

In general, the time required to ensile the fish mortality has an impact on unmet demand and cost of ensiling. Having single ensiler is less desirable as in a week the larger capacity ensiler can only be operated once a week. In contrast, if you have more ensilers that can be operated in every working day of the week, the cost of ensiling and unmet demand is on lower side compared to having only one ensiler of bigger size. In such circumstances, it was found that having three smaller ensilers of 940 litres would have comparatively a lower cost of around 100 GBP/tonne of ensiled fish mortality. Moreover, with such combination of ensilers, it is possible to have ensiled product every day of the week as 940 litre ensiler can process the fish mortalities within 2 days.

The ensiled fish waste from the ensiler has to be stored to supply the anaerobic digester with the feedstock whenever it is required. Regarding the appropriate storage size required to store the ensiled fish mortality, a storage size of 50 tonnes was identified. As shown in Figure 23 below, 50 tonnes of storage size was regarded as optimum for AD Scenario 3 with the maximum biogas output. In reference to the ensiler size (2,820 litre capacity with combination of three 940 litres ensiler) desirable for the AD Scenario 3 as beyond 50 tonnes of storage size, increasing the storage size did not have any effect on reducing the unmet demand of fish waste to the anaerobic digester. The storage size would be affected by an increase in the number of ensilers. In reference to AD Scenario 3, based on the availability of fish waste, additional or bigger storage size is not required as there is no scope of increasing the number of ensilers due to the limitation of available fish waste under AD Scenario 3.

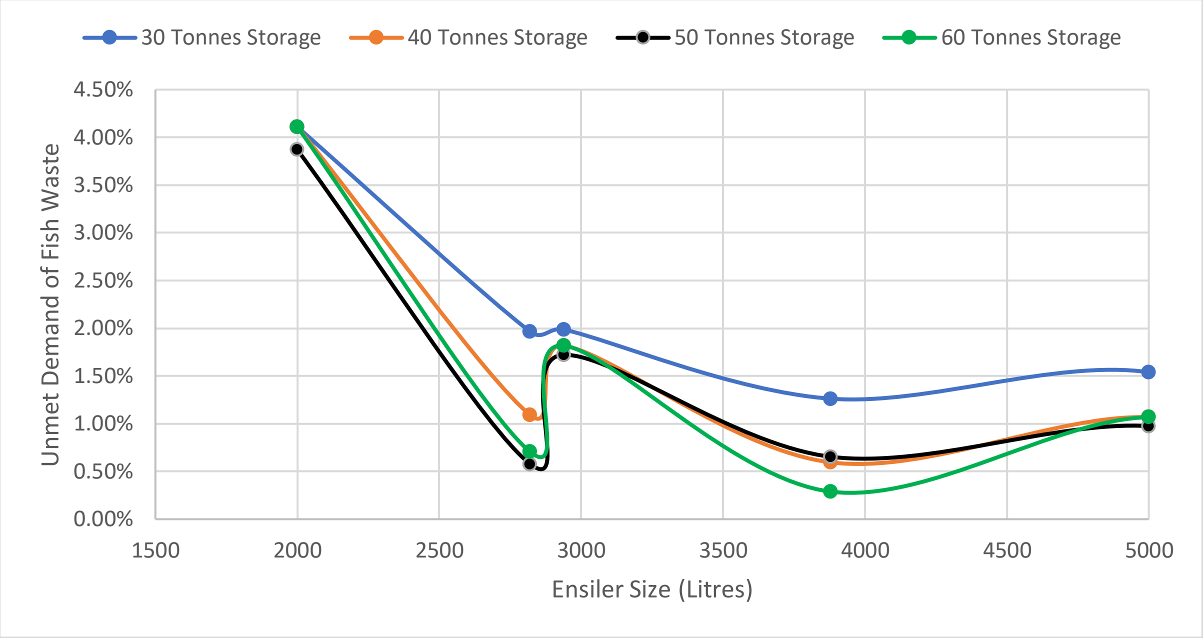


Figure 23: Selection of Storage Size Requirement

For the other AD scenarios using fish mortalities, Scenario 1 does not require any ensiler or storage to meet the fish waste demand for the AD. However, there will be mere 3 percent of unmet fish waste demand to AD of 1,102 tonnes. Similarly, for AD Scenario 2, although there was no variation in terms of biogas production in comparison to AD Scenario 3, the increased ammonium concentration became a major issue in AD Scenario 2 as analysed above. But if AD is to be operated under AD Scenario 2, provided the system introduces ammonium buffering protocols, the appropriate ensiler size and cost of ensiling can be seen in the Table 23 below.

Ensiler Capacity (Litre)	**No of Ensilers**	**Selected Ensiler (litres x no. of units)**	**Unmet Demand**	**Cost per Tonne (GBP/Tonne)**
2,000	1	2000 L	8.59%	94.06
2,820	3	940 L x 3	3.28%	85.48
2,940	2	2000 L and 940 L	0.05%	106.50
3,880	3	2000L and 940 L x 2	2.65%	82.05

5,000	1	5000 L	0.98%	126.92
5,880	4	2000 L x 2 and 940 L x 2	1.73%	90.13
5,940	2	5000 L and 940 L	1.48%	125.75
6,000	3	2000 L x 3	4.14%	92.86

Table 23: Unmet Demand and Cost of Ensiling for AD Scenario 2

As per the result of cost analysis, ensiler capacity of 3,880 appeared to be suitable as the cost per tonne of ensiling and unmet demand was the least among other ensiler capacities at £82.05 and 2.65 percent respectively. The effect of cost on various ensiler capacity for AD Scenario 2 can be seen in Figure 24.

Figure 24: Unmet Demand to AD vs Cost of Ensiling Fish Mortalities for AD Scenario 2

However, AD Scenario 2 does not appear to be an exciting prospect because this scenario has higher ammonium concentration which is not desirable for the stability of the digester. Overall, AD scenario 2 will not yield benefits for the concerned stakeholders in the long run due to accumulation of ammonium within the digester inhibiting desirable production of biogas for IWMF.

3.7.3 Ban on Fish Waste Disposal to Landfill

Scottish Government will be banning the disposal of biodegradable municipal waste from beginning 2021 but in the case of Western Isles in Scotland, the ban will be implemented from 2026 (The Scottish Government, 2012, p. 11). The fish waste generated from retail shops and food factories dealing with meat and meat-based products are allowed to dispose

20 kg/week animal waste coming from healthy animal bodies into the landfill (APHA, 2014, p. 30). Furthermore, the Scottish regulation also has provision of derogation which allows animal waste to be disposed in landfill. Article 16(d) from European Commission regulation 1069/2009, provides provision of derogation for disposal of animal waste (Fish Waste) for remote areas like parts of CNES. Areas located within CNES has been termed as remote areas in Scotland (The Scottish Government, 2013, p. 6). Furthermore, article 19(b) from same regulation states that in remote areas animal waste can be disposed by burning, burial or by other means such as landfill, but only under the supervision of competent authority (European Commission, 2009, p. 18)& (European Commission, 2009, p. 19). It is due to this provision that the fish waste producing facilities are still being disposed in landfill at Isle of Lewis. These provisions might continue until the government decides to make amendments in existing regulation.

Fortunately, the Isle of Lewis already has anaerobic digester which has been installed at IWMF since 2006. The cost of disposal also plays important role in deciding appropriate waste management option. With regards to fish waste, the cost of disposal also known as gate fee to IWMF and Landfill Tax (LFT) has been shown in the Table 24.

Fish Waste Type	IWMF		Bennadrove Landfill Site		
	LFT	Disposal Fee	Disposal Fee	LFT	Total
Fish Processing Waste and Ensiled Fish Mortalities	£0	£130	£49.82	£86.10	£135.92
Fish Farm Mortalities	£0	£180	£190	£86.10	£276.10

Table 24: Cost of Fish Waste Disposal under Supervision of IWMF

Apart from the option mentioned in Table 24, there is a provision of sending fish wastes to the mainland for incineration. The cost of exporting fish waste from island sites to mainland for incineration accounts to £300 per tonne which includes transportation fee, gate fee and landfill tax (Zero Waste Scotland, 2016, p. 18). As of now, the incinerator named SecAnim located at Widnes is accepting fish farm wastes from the sites in Western Isles (Zero Waste Scotland, 2016, p. 30). The cost of ensiling the fish mortalities was calculated and found to be £100 per tonne for the best AD scenarios (AD Scenario 3). As per the disposal cost set by IWMF, if the fish waste is ensiled and brought to IWMF, the cost of disposal would be around £230 (£130 as disposal cost for ensiled fish mortalities, plus cost of ensiling which is

£100). Ensiling the fish mortality and then sending to IWMF is more beneficial for fish farm to manage waste from fish mortalities by sending them to the anaerobic digester in IWMF. In disposing one tonne fish waste to AD in IWMF, there is saving worth £48 per tonne whereas for incineration at mainland, the saving worth £72 per tonne.

Cost saving can be assured if the fish mortalities are ensiled and stored for supply to AD at IWMF. But the amount of saving might not be attractive for the waste producer if they consider easier option to dispose their fish mortalities. The cost of disposal of ensiled fish mortalities might have to be revised to make the disposal to IWMF as feedstock for anaerobic digestion more attractive. For this purpose, in the later chapter, a detailed comparison of cost of available disposal options has been done to analyse appropriate disposal fees for the ensiled fish mortalities that would be beneficial for both parties in question.

3.8 Possibility of Methanation

Biogas flaring is a common practice in the biogas production industry. It is used as a safe biogas disposal method of the surplus biogas produced. In the industry, this could be due to concerns about the levels of Sulphur in the biogas which brings about a need to flare the biogas with excess Sulphur (Energ-G Natural Power Limited, 2014) Or it could also be used as a means of disposing biogas where the cost benefits of energy recovery are not achievable, for example, where the quality of biogas is too low (Caine, 2000). This case applies to the project at the in Stornoway. The gas is being flared if biogas output contains less than 47% of methane content. In addition to the low quality of the biogas, another reason for flaring is a limitation of storage for the biogas.

The type of biogas flare used in the facility at Stornoway is an open flare system which has the following features; a flame arrestor (safety measure to prevent explosions), failsafe valve, ignition system, flame detector and a gas blower (booster) to raise the pressure of the gas at the burner (Teodorita Al Seadi, 2008, p. 85).

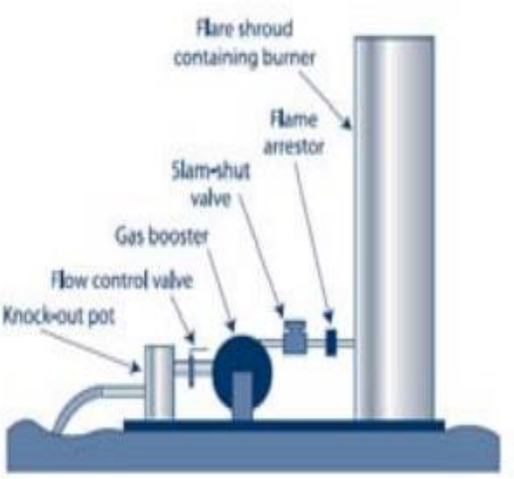


Figure 25 Schematic Illustration of the essential features of a flaring system (GHD Pty Ltd, 2008, p. 16)

Figure 26 : *Modern biogas flares (Teodorita Al Seadi, 2008)*

With the main aim of the project being to optimise the biogas plant at IWMF, there is an inherent disadvantage in burning the biogas which could have been otherwise used in CHP. Alternative methods of utilizing the biogas such as the proposed methanation process with excess hydrogen produced from the electrolyser could serve a possible solution.

To study the possibility of converting low quality biogas to high quality containing more CH_4 content a simulation was carried out in Aspen plus simulation software.[2]

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[2] "ASPEN is a process simulation software package widely used in industry today. Given a process design and an appropriate selection of thermodynamic models, ASPEN uses mathematical models to predict the performance of the process;ASPEN *does not* design the process. (Michigan State University ; College of Engineering, n.d.)

3.8.1 Methanation

An established method of achieving methanation of carbon dioxide is called the “Sabatier Process”. It is an exothermic reaction and is carried out in the presence of a catalyst (Schlereth, 2015)

$CO_2 + 4H_2 \longleftrightarrow CH_4 + 2H_2O \quad \Delta H^0_R = -165.12kJ/mol$………eqn(1)

Other methanation reactions include the following, but for the purpose of simulation in ASPEN plus only equation 1 will be considered as it most represents the state of IWMF facility process;

$CO + 3H2 \longleftrightarrow CH4 + H_2O \quad \Delta H^0_R = -206.28\ kJ/mol$…….eqn(2)

$CO + H_2O \longleftrightarrow CH_4 + 2H_2O \quad \Delta H^0_R = -41.16kJ/mol$………..eqn(3)

$C_2H_4 + 2H_2O \longleftrightarrow 2CO + 4H_2 \quad \Delta H^0_R = +210kJ/mol$…………..eqn(4)

Common catalyst used in this process include Ruthenium(Ru), Rhodium(Rh), Platinum(Pt), Iron(Fe), Nickel(Ni) and Cobalt(Co); Nickel catalysts is preferred due to its selectivity (product yield), cheaper price and activity (Hana^a Er-rbib, 2014).

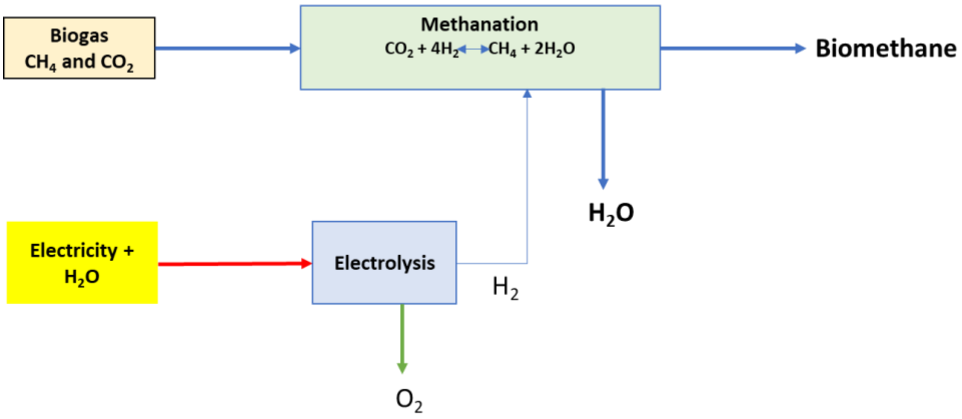


Figure 27: Process flow diagram for methanation

3.8.2 Reaction Kinetics

In order to simulate the methanation process in ASPEN plus, a few inputs must be known such as the reactor type to be used and the reaction kinetics. This also includes the thermodynamic model to be selected, the kinetic rate equations with their rate constants, activation energy heat of adsorption values, temperature and pressure.

Based on literature, the thermodynamic model RKSMHV2 based on Redlich-Kwong- Soave equation of state is applied, as it can be used for mixtures of non-polar (e.g. Hydrogen, Methane) and polar (Water) compounds in combination with light gases (Hana^a Er-rbib, 2014, p. 2).

The reactor type to be modelled is an ideal plug flow reactor based on a simple adiabatic reactor design, which is easy to construct and maintain. More complex reactor designs have been applied in commercial plants, where more than one reactor is used. Due to the high heat produced in the methanation reaction that could result in catalyst sintering (loss of catalyst activity), product gas recycling and steam addition to control the temperature rise is done at the first reactor (Hana^a Er-rbib, 2014). An example is a plant developed in the USA whose process is composed of an isothermal reactor and two adiabatic fixed bed reactors with recycling. (Hana^a Er-rbib, 2014, p. 3)

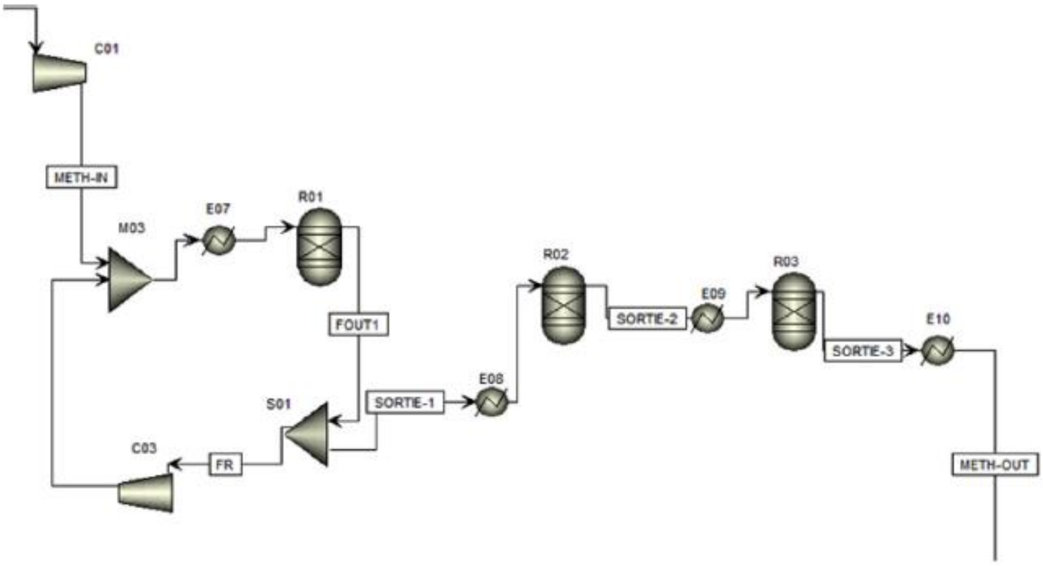
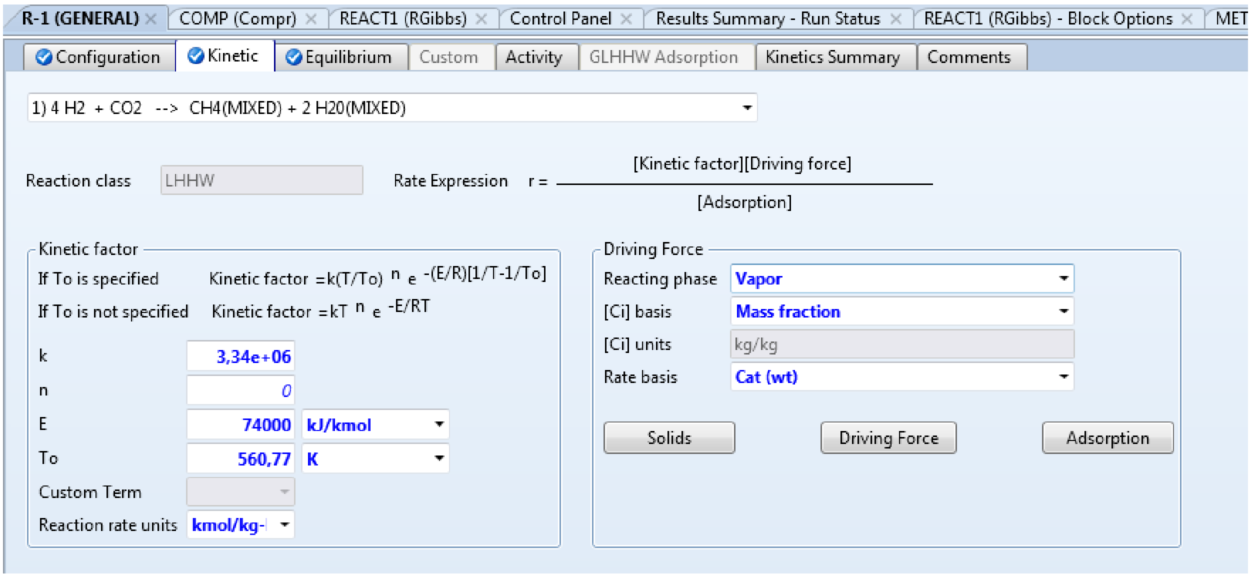


Figure 28: Methanation process with recycle loop and additional reactors(Hana^a Er-rbib, 2014)

Rate constant used in ASPEN plus (Hanaâ Er-rbib, 2013, p. 3)

$$k_1 = 3.34 \times 10^6 \exp\left(-\frac{74000}{RT}\right) \qquad (\mathrm{mol/kg_{cat}.s})$$



1) 4 H2 + CO2 --> CH4(MIXED) + 2 H20(MIXED)

Reaction class: LHHW

Rate Expression r = [Kinetic factor][Driving force] / [Adsorption]

Kinetic factor

If To is specified: Kinetic factor =k(T/To) ^{n} e $^{-(E/R)[1/T-1/To]}$

If To is not specified: Kinetic factor =kT ^{n} e $^{-E/RT}$

k: 3,34e+06

n: 0

E: 74000 kJ/kmol

To: 560,77 K

Custom Term:

Reaction rate units: kmol/kg-

Driving Force

Reacting phase: Vapor

[Ci] basis: Mass fraction

[Ci] units: kg/kg

Rate basis: Cat (wt)

Figure 29: Kinetic data and rate equation as inputted in ASPEN

The reaction kinetics equation to be used as input data in the simulation have been obtained from literature (Duyar, 2015, p. 89)

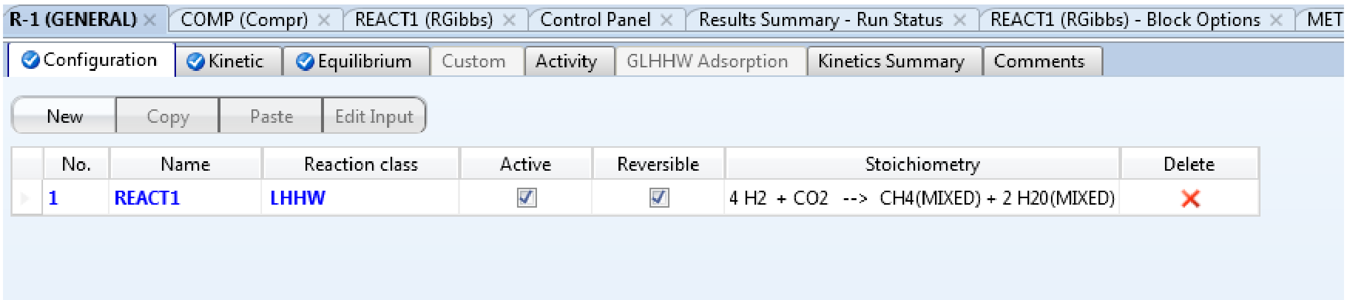
$$R_{CH_4,f} = \frac{k \times K_{eq} \times P_{CO_2} \times P_{H_2}}{1 + K_{eq} \times P_{CO_2}}$$

Where k = rate constant for the reaction,

Keq = equilibrium constant for CO_2 adsorption

P_{CO2}, P_{H2} = partial pressures of CO_2 and H_2

The Kinetic Model used is the Langmuir-Hinshelwood-Hougen-Watson(LHHW) Kinetic Model as it shows closeness in result to experimental data (Jürgensen, 2015, p. 66).



No.	Name	Reaction class	Active	Reversible	Stoichiometry	Delete
1	REACT1	LHHW	☑	☑	4 H2 + CO2 --> CH4(MIXED) + 2 H20(MIXED)	✗

Figure 30: Kinetic Model used in simulation

The following assumptions are also made with respect to the simulation;

- Inlet pressure is 1bar and temperature is 57°C
- Flow rate of the inlet biogas is assumed to be constant
- Volume flow rate and volume fractions are used as input for each component

- All Hydrogen is used up in the reactor
- There is some CO_2 in the end product
-

3.8.3 ASPEN Plus Simulation

To model the scenario, simulation has been done in ASPEN plus. The input components involved include CH_4, CO_2, H_2S, H_2 and O_2. The volume of hydrogen inputted is obtained as 5.33m^3/h from (Pure Energy Center, 2010, p. 33). Operating conditions such as pressure were derived from previous simulations in literature (Sharath Kumar Ankathi, 2014, p. 57).

The yearly average gas flow and average methane percentage is found to be 41.62 m^3/h and 44.31%. It is based on a spool of figures having long flaring hours more than 10 hours and methane percentage lower than 47%. The rationale is to select these figures in order to show that for biogas produced with methane concentrations less than 47%(for which flaring is being done) an alternative process can be applied by adding hydrogen to increase the methane content of the biogas.

Year Average Gas Flow	41.62 m^3/h
Methane percentage	44.31%
H_2S percentage	0.01%
CO_2 percentage	53.53%
O_2 percentage	2.16%
Temperature (Celcius)	57
Pressure (bar)	1

Table 25: Inlet biogas volume with volume fractions (2017 data)

The total flow of biogas and hydrogen is found to be 46.95%. It is just an addition of 41.62m^3/hour of biogas with 5.33m^3/hr of hydrogen (based on data obtained) and is the volume going into the reactor from the mixer. It is only used as an input parameter to specify in the software. The figures 20,20 and 60 are percentage volume fractions of methane, CO_2 and hydrogen. Based on the reaction equation that has 4 moles of hydrogen reacting with 1mole of CO_2 to give methane and water, the assumption is that a larger percentage of hydrogen will react with a lower percentage of CO_2. This arrangement is one way of input, and other volume fraction arrangements could be inputted into the software (as long as it amounts to 100%) and the results obtained can be compared.)

Total flow (Biogas and Hydrogen)	$46.95m^3$/hr
Temperature(C)	87
Pressure(bar)	10
Methane	20%
CO_2	20%
Hydrogen	60%

Table 26 Components and their reacting volume percentages

Temperature from the Biogas digester is at 57^{o}C, volume flowrate and respective percentage fractions are shown as provided by project partner. Table 26 shows how these figures have been inputted into the simulation software. The overall process includes the cleaning of the biogas from impurities such as H_2S, and other contaminants which could arise from the fermentation process. Furthermore, the process also includes the compression of the biogas and addition of already pressurised hydrogen at 12 bars, and temperature of 30^0C (Pure Energy Center, 2010, p. 33). In continuation, it goes to a mixer, then to a heat exchanger to preheat the gas before entering into the reactor and to another heat exchanger to cool the product gas as close as possible to ambient temperature (283K, 1atm/1bar) (Jürgensen, 2015, p. 78).

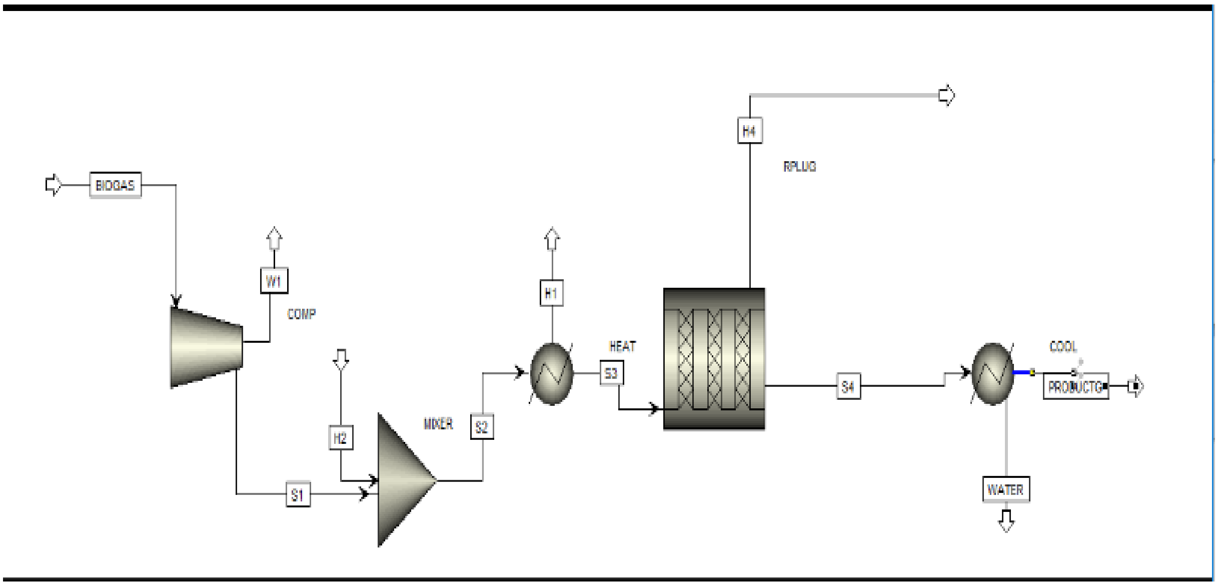


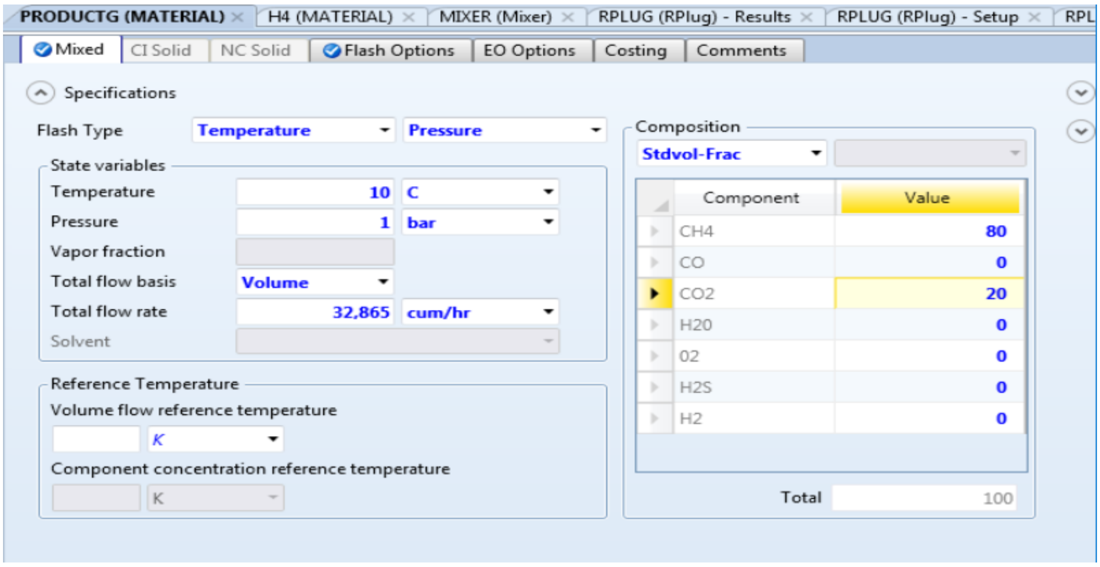
Figure 31 ASPEN plus flowsheet as simulated using single reactor configuration

The process simulated shows only a simple model, however modifications and upgrades (such as adding more reactors and a gas recycle loop as shown in (Hana^a Er-rbib, 2014, p.

7)) can be made to suit additional industry requirements based on the plant`s own daily processes.

3.8.4 Justification for the methodology of the scenario

The aim of the entire scenario is to come up with and simulate the possibility of using the excess hydrogen from the electrolyser and combining it with the poor quality of biogas to obtain a higher percentage quantity of methane. Plug flow reactor was modelled in order to simulate in closeness to the current method used in the Anaerobic Digester in Stornoway. Reactor dimensions, catalyst specification, and operating conditions have been adopted from literature (Hana^a Er-rbib, 2014, p. 5). Mass flows of components in and out of the reactor have been calculated by the ASPEN plus software as only the desired volume fractions have been specified as shown below.



Specifications

Flash Type: Temperature, Pressure

State variables

Temperature: 10 C

Pressure: 1 bar

Vapor fraction:

Total flow basis: Volume

Total flow rate: 32,865 cum/hr

Solvent:

Reference Temperature

Volume flow reference temperature: K

Component concentration reference temperature: K

Composition: Stdvol-Frac

Component	Value
CH4	80
CO	0
CO2	20
H20	0
02	0
H2S	0
H2	0
Total	100

Figure 32: Product gas volume and percentage volume fractions

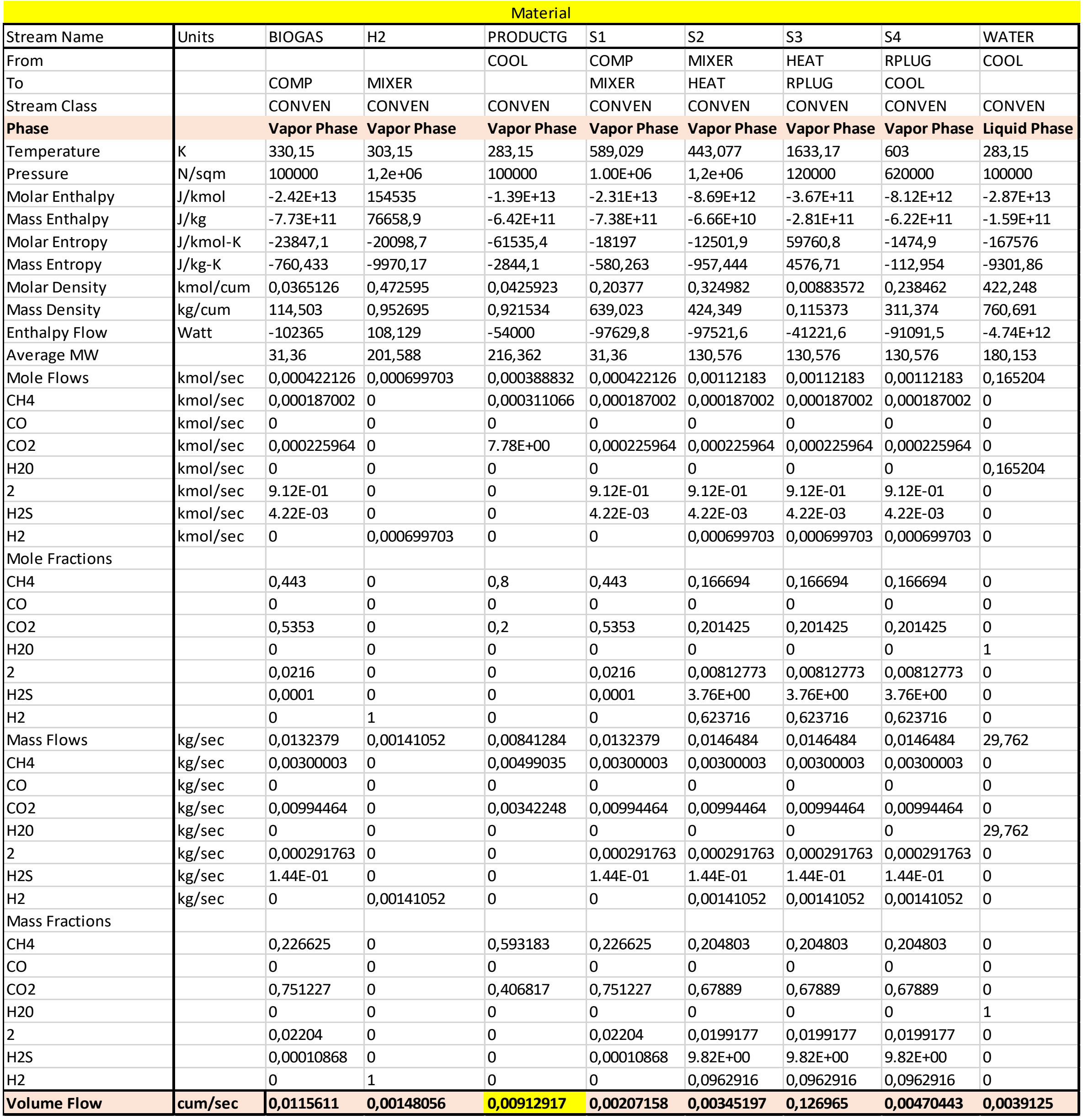
Simulation was done for 2017, and 2016 base years and the result is shown below for the 2017 base year. According to data obtained, average flaring hours for 2017 was obtained as 17.22 hours with the total being 155hours and total for 2016 was 118 hours with the average being 16.86 hours for the year. These input data were based on pool of biogas flaring hours longer than 10 hours and biogas volumes with percentage of methane below 47%. Average volumes of the biogas were obtained and likewise average percentages of all the biogas components and then inputted in the software as in

Table *25* and Table 26. According to simulation carried out by (Hana^a Er-rbib, 2014), the methanation reaction yielded 80.4% of Methane output from reactor 01 as shown in Figure

28 above therefore a product gas containing 80% of methane was simulated and results obtained as shown in Table 28 below.

Compounds / Conditions	**Simulation Results**	**Experimental Results**	**Reference**
Inlet H_2(volume %)	60%	67.5%	M. Specht, 2010, p. 22
Output CH_4	80%	90.5%	M. Specht, 2010, p. 22
CO_2	20%	6%	M. Specht, 2010, p. 22
H_2	0%	3.5%	M. Specht, 2010, p. 22
Temperature(C)	330	240-600	(Jekaterina Porubova, 2011)pg. 2
Pressure(bar)	6.2	6.5	M. Specht, 2010, p. 22

Table 27 Simulation results compared with experimental and simulation data)



Material									
Stream Name	Units	BIOGAS	H2	PRODUCTG	S1	S2	S3	S4	WATER
From				COOL	COMP	MIXER	HEAT	RPLUG	COOL
To		COMP	MIXER		MIXER	HEAT	RPLUG	COOL	
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Phase		**Vapor Phase**	**Vapor Phase**	**Vapor Phase**	**Vapor Phase**	**Vapor Phase**	**Vapor Phase**	**Vapor Phase**	**Liquid Phase**
Temperature	K	330,15	303,15	283,15	589,029	443,077	1633,17	603	283,15
Pressure	N/sqm	100000	1,2e+06	100000	1.00E+06	1,2e+06	120000	620000	100000
Molar Enthalpy	J/kmol	-2.42E+13	154535	-1.39E+13	-2.31E+13	-8.69E+12	-3.67E+11	-8.12E+12	-2.87E+13
Mass Enthalpy	J/kg	-7.73E+11	76658,9	-6.42E+11	-7.38E+11	-6.66E+10	-2.81E+11	-6.22E+11	-1.59E+11
Molar Entropy	J/kmol-K	-23847,1	-20098,7	-61535,4	-18197	-12501,9	59760,8	-1474,9	-167576
Mass Entropy	J/kg-K	-760,433	-9970,17	-2844,1	-580,263	-957,444	4576,71	-112,954	-9301,86
Molar Density	kmol/cum	0,0365126	0,472595	0,0425923	0,20377	0,324982	0,00883572	0,238462	422,248
Mass Density	kg/cum	114,503	0,952695	0,921534	639,023	424,349	0,115373	311,374	760,691
Enthalpy Flow	Watt	-102365	108,129	-54000	-97629,8	-97521,6	-41221,6	-91091,5	-4.74E+12
Average MW		31,36	201,588	216,362	31,36	130,576	130,576	130,576	180,153
Mole Flows	kmol/sec	0,000422126	0,000699703	0,000388832	0,000422126	0,00112183	0,00112183	0,00112183	0,165204
CH4	kmol/sec	0,000187002	0	0,000311066	0,000187002	0,000187002	0,000187002	0,000187002	0
CO	kmol/sec	0	0	0	0	0	0	0	0
CO2	kmol/sec	0,000225964	0	7.78E+00	0,000225964	0,000225964	0,000225964	0,000225964	0
H20	kmol/sec	0	0	0	0	0	0	0	0,165204
2	kmol/sec	9.12E-01	0	0	9.12E-01	9.12E-01	9.12E-01	9.12E-01	0
H2S	kmol/sec	4.22E-03	0	0	4.22E-03	4.22E-03	4.22E-03	4.22E-03	0
H2	kmol/sec	0	0,000699703	0	0	0,000699703	0,000699703	0,000699703	0
Mole Fractions									
CH4		0,443	0	0,8	0,443	0,166694	0,166694	0,166694	0
CO		0	0	0	0	0	0	0	0
CO2		0,5353	0	0,2	0,5353	0,201425	0,201425	0,201425	0
H20		0	0	0	0	0	0	0	1
2		0,0216	0	0	0,0216	0,00812773	0,00812773	0,00812773	0
H2S		0,0001	0	0	0,0001	3.76E+00	3.76E+00	3.76E+00	0
H2		0	1	0	0	0,623716	0,623716	0,623716	0
Mass Flows	kg/sec	0,0132379	0,00141052	0,00841284	0,0132379	0,0146484	0,0146484	0,0146484	29,762
CH4	kg/sec	0,00300003	0	0,00499035	0,00300003	0,00300003	0,00300003	0,00300003	0
CO	kg/sec	0	0	0	0	0	0	0	0
CO2	kg/sec	0,00994464	0	0,00342248	0,00994464	0,00994464	0,00994464	0,00994464	0
H20	kg/sec	0	0	0	0	0	0	0	29,762
2	kg/sec	0,000291763	0	0	0,000291763	0,000291763	0,000291763	0,000291763	0
H2S	kg/sec	1.44E-01	0	0	1.44E-01	1.44E-01	1.44E-01	1.44E-01	0
H2	kg/sec	0	0,00141052	0	0	0,00141052	0,00141052	0,00141052	0
Mass Fractions									
CH4		0,226625	0	0,593183	0,226625	0,204803	0,204803	0,204803	0
CO		0	0	0	0	0	0	0	0
CO2		0,751227	0	0,406817	0,751227	0,67889	0,67889	0,67889	0
H20		0	0	0	0	0	0	0	1
2		0,02204	0	0	0,02204	0,0199177	0,0199177	0,0199177	0
H2S		0,00010868	0	0	0,00010868	9.82E+00	9.82E+00	9.82E+00	0
H2		0	1	0	0	0,0962916	0,0962916	0,0962916	0
Volume Flow	**cum/sec**	**0,0115611**	**0,00148056**	**0,00912917**	**0,00207158**	**0,00345197**	**0,126965**	**0,00470443**	**0,0039125**

Table 28 Results extracted from ASPEN plus showing mass, mole and volume fractions

3.8.5 Cost Analysis

According to Lehneret. Al (2014, p. 66) for a methanation process, defining the investment costs is strongly influenced by the specific plant layout and its current operational conditions. Since the facility is involved in flaring the biogas, the amount lost due to flaring is calculated as part of defining the cost of investing in an alternative usage for the excess hydrogen.

Using the measured data provided by the facility for 2016 year;

- the total hours of flaring for the year 2016 is 867 hr.
- the maximum flow rate of the gas in the flare is 200 m^3/hr. (Klärgastechnik Deutschland GmbH, 2006, p. 4).

Thus, assuming that the flare runs always at maximum flow rate, the maximum amount of gas flared can be estimated as 1, 73,400 m^3 and this amounts to 43% of total gas produced in 2016. From the below Table 29, it can be seen that flared gas could have produced electricity of 247,000 kWh amounting to £ 12,350 if supplied to the grid and total carbon savings can amount to 91,500 Kg CO_2 (ENER-G Combined Power Limited, 2016). Thus, there is an economic advantage and environmental benefit in using methanation process to improve the quality of biogas rather than flaring.

Parameter	**Value**	**Reference**
Amount Flared	173400 m^3	
Calorific Value of Biogas	4.6 kWh/ Nm^3	Considering 46% methane content in biogas (Banks, n.d, p. 26)
Energy in Biogas	798,000 kWh	
Electricity Produced	247,000 kWh	Electrical conversion efficiency of IWMF CHP 31% (ENER-G Combined Power Limited, 2016)
Total carbon Savings	91,5 00 CO_2 Kg	Replacing Grid electricity emissions of 0.37 kg CO_2 equivalent/kWh. (Map, 2018)
Price per Kwh Electricity	13.5 pence	CES OHLEH Model
Amount lost due to flaring	**£12,350**	

Table 29: *Savings from flared biogas*

According to (Markus Lehner, 2014, p. 66) , the investment costs for chemical methanation plants less than 10MW ranges from 300-500 €/kW$_{CH4}$ (£265.25 - £442). According to (NNFCC Project, 2010, p. 42) the investment cost of large scale methanation plants are cheaper compared to small-scale plants. In case of IWMF, the size of plant could be in range 100 to 500 kW (rough estimate), therefore expected investment cost is higher than larger scale plant.

Therefore, even though, it is technically feasible to carry out methanation process for the current facility in IWMF but economically due to large investment cost it may not be feasible.

3.9 Conclusion

Under the current operating conditions of the anaerobic digester, it is obvious that there are challenges to produce enough high-quality biogas. Thus providing solutions to this issue was the main objective of this study. The modelling and the simulating of the IWMF`s anaerobic digester in Simba biogas software was a success in terms of the provision of several alternatives that can be used not just now, but also for the future.

The validation of Simba software was at first challenging but however, with several trials and runs and also several literature for household waste chemical components, the study achieved a rather acceptable results. Out of these 41 overall scenarios simulated, 6 best scenarios were chosen based on their optimum results in terms of quality and quantity of biogas production, ammonium concentration, OLR and HRT.

The various composition scenarios showed that introduction of fish waste into the digester was very important in maintaining high quantity and quality biogas. Dilution scenarios proved that dilution of the substrate using potable water had a significant effect in maintaining the NH_4^+ in low concentration.

To decide the overall best scenario from the selected 6 best scenarios, it would come down to a decision between long term stability in the digester with relatively high content of methane as exhibited by scenario 3 dilution; and a short term stability in the digester with a considerably very high content of methane as in scenario 3 at mesophilic conditions.

Therefore, due to its sustainability in terms of low and stable ammonium concentration, scenario 3 with dilution of centrate could be considered as the overall best option for this study.

The study also demonstrated that CO_2 savings from using fish waste in digester rather than dumping in landfill amounts to 2.42 tonnes kg CO_2eqfor 1 tonne fish waste. It also looked into the possibility of methanation to upgrade the quality of biogas utilizing the hydrogen produced from the electrolyser thus finding a demand for hydrogen. The results from the simulation showed that it was possible to upgrade the biogas up to 80% CH_4 but the investment cost is high. Thus, it would be worthwhile to look into possibility of replacing current CHP with a new CHP which could run at lower methane content also.

4. Wind Turbine Operation and Contribution

4.1 Objective and Scope

The objective of the present chapter of the report is to shed light on the contribution of the wind energy from the wind turbine currently operating at IWMF, analyse the data provided, and simulate variable wind scenarios within the wind simulation software WindPRO, developed by (EMD, 2018). The final outputs are three different wind generation profiles (Worst Case, Average and Best Case scenarios) which are fed into the system integration model. This outcome can be further analysed from a technical and economic perspective to observe how wind energy can contribute to electricity consuming processes within the facility against exporting it to the grid.

During the preparation phase of International Class, we have also studied the wind potential and wind development on Lewis and Harris, as well as considering the potential the installation of a small-scale wind turbine for the Barvas Hatchery. However, upon consultation with the Barvas Estate Trust, they are currently engaged with another consultant for this purpose, whose study is due to complete in March 2018. Hence, our only focus is the current wind turbine installed at IWMF.

4.2 Overview of Wind Turbine in IWMF

Within the vicinity of IWMF, there is a 300 kW Enercon E-33 wind turbine installed (Location -6.428179, 58.195207), shown in Figure 33 below. The wind turbine has a 33.4m rotor diameter and is installed at a 37m hub height. It was installed and commissioned in December 2013 and is owned by the area council, Comhairle nan Eilean Siar (CnES)(NRS, 2014). It was built to benefit from the Feed in Tariff (FIT) scheme, currently administered under Office of Gas and Electricity Markets(OFGEM, 2018). Under this scheme, the wind turbine benefits for both generation of electricity and export of electricity into grid, each carrying different tariffs.

Figure 33: CREED Park Wind Turbine(NRS, 2014)

However, there is a constraint that limits the total export of the electricity generated by the wind turbine into the grid. This is due to the weakness of the current grid, which is currently connected to the mainland through a sea cable of insufficient capacity, departing from the southern part of the Western Isles. Proposals for a new High Voltage Direct Current (HVDC) interconnector have been long been discussed, to connect more wind turbines in the Western Isles, whether in large scale or community-based. To date, the HVDC link is planned to be completed by December 2020 (The Scottish Government, 2017). However, this completion date could be further delayed as the project is under regular reviews and there are some uncertainties regarding policy support for wind developers(SSEN, 2017).

As a result of the grid constraint, there is a curtailment of wind turbine power export to the grid above 225 kW of the rated power at the facility, set by the Distribution Network Operator. Since the FIT scheme pays for electricity generation and electricity export into the grid, rather than solely exporting it into the grid, it can be utilised for the equipment in IWMF before exporting, where by the losses due to curtailment could be minimized. Overall, electricity purchase from the grid can be reduced, making the operation of the facility less cost intensive. Therefore, it is worthwhile to investigate how electricity generated from the wind turbine can be utilised for equipment in the facility before exporting it to the grid. Table 30 below shows the configuration of the wind turbine that is inputted into the system integration model.

Max Output of Wind Turbine	300 kW
Max Export to Grid Set by DNO	225 kW
Max Export Limit Set by IWMF (to ensure limit is not exceeded and more electricity can be used within IWMF)	200 kW
Min and Max Output Limit (before shutting off turbine)	Min: 3 kW Max :275 kW
Transmission Losses from Wind Turbine to IWMF	4%
Electricity Utilizations in Facility	1. Electric Boiler 2. Electrolyser

Table 30: Configuration of Wind Turbine into System Integration Model

4.3 Technological Review

Wind power is one of the renewable energy resources that can produce electricity. It is dependent on the air speed, and the air density, making it highly location dependent. The power contained in the wind is formulated by;

$$P = \frac{1}{2}\rho A V^3$$

where ρ is air density (kg/m^3), A is the area swept by the rotor (m^2), while V is wind speed (m/s). Therefore, the wind power extracted from is cubically related with the wind speed. However, the maximum wind power that can be extracted by a wind turbine is limited to the Betz limit, or a 59% efficiency(Kalmikov & Dykes).

A wind turbine's power output can be simply calculated using a power curve, which is dependent on the wind speed. A good indicator of how good a wind potential is at a certain location is by the Weibull distribution of wind, a graphical presentation of how frequent wind blows at a certain speed. The Enercon E-33 wind turbine power curve and the Weibull distribution at the site is shown in Figure 34 and Figure 35 below. The capacity factor, formulated by the equation below, is dependent on the capacity of the wind turbine generator and the turbine site characteristics.

$$Capacity\ Factor = \frac{Total\ Electricity\ Generation\ in\ period\ [kWh]}{installed\ capacity\ [kW] * hours\ in\ a\ period\ [h]}$$

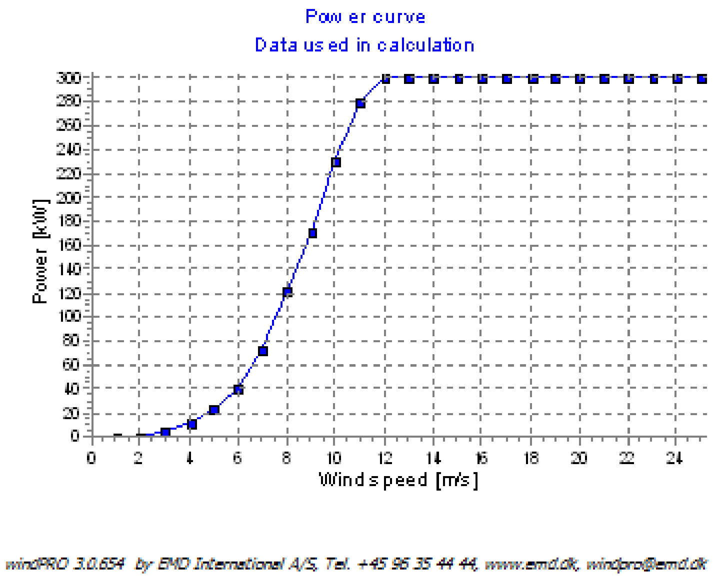


Figure 34: Power Curve of Enercon E-33 (Source: WindPRO)

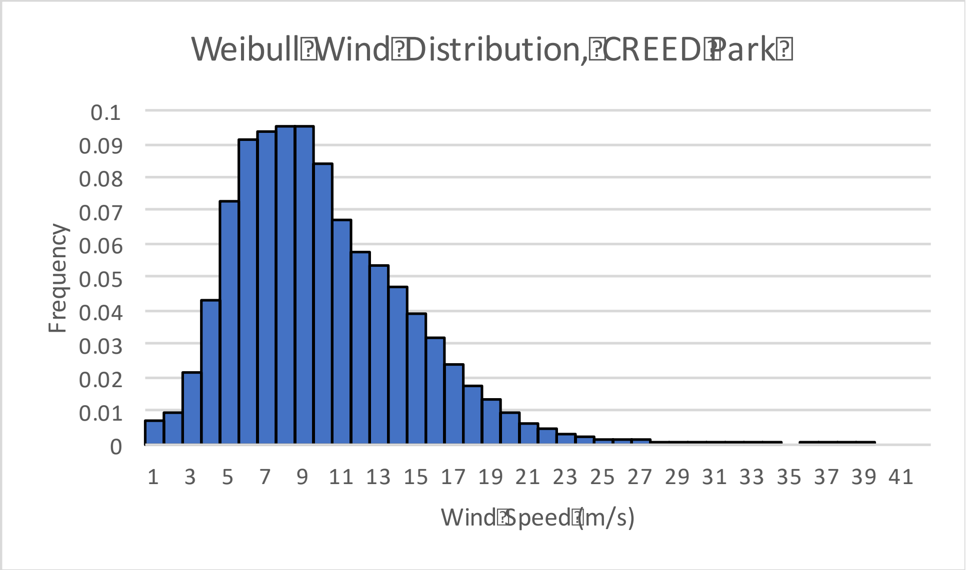


Figure 35: Weibull Distribution at CREED Park (source: IWMF)

Wind speed is considered an intermittent energy source as it is not continuously available and varies at any given point in time. Since there is always uncertainty and variability in wind speeds and corresponding electricity generated, it is useful to observe the wind speed patterns for longer periods. Since the system integration model is modelled for the whole year in hourly time series, wind speed profiles will also be analysed on a yearly basis. In our case, different annual wind generation profiles are chosen to represent the worst case, average case and best case scenario from 10 years of simulated wind generation data. This is based on total annual generation, considering monthly capacity factors.

4.4 Selection of Wind Profiles: Methodology and Process

To establish the different wind generation profiles that represent the worst case, average case and best case scenario, the following methodology shown in Figure 36is used.

Figure 36: Methodology for Wind Generation Profile Selection

The wind speed and corresponding power generation data of the existing wind turbine is provided for the year 2015 by the facility(IWMF, 2016) in a time series of 10-minutes interval (herein referred to as local site data). This is then averaged and converted into 8760-hour time series in Microsoft Excel. However, data provided has some missing data, resulting in only 8157 hourly data points for 2015. As only 1 year of data is available, it is decided to purchase mesoscale[3] data from WindPRO for longer periods of observation. To generate the mesoscale data, the wind turbine is first set up inside the WindPRO software according to the location, type and its characteristics such as roughness. The roughness map is as shown in Figure 37 below.

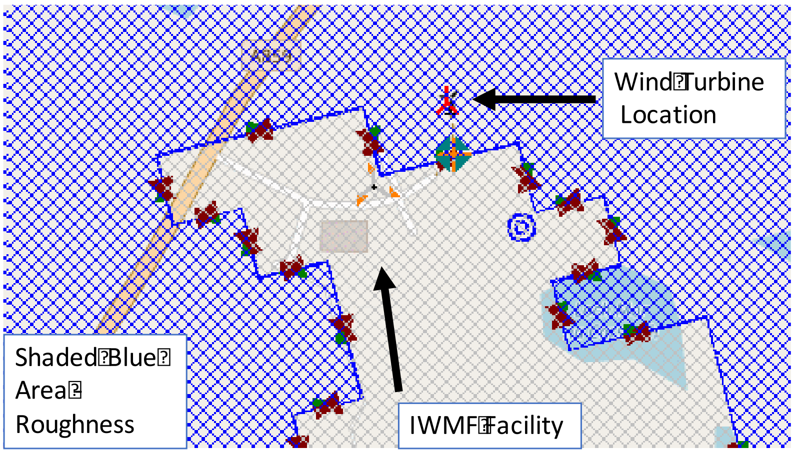


Figure 37: Roughness Map of IWMF (retrieved from WindPRO)

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[3] Mesocale means an intermediate scale between weather systems and microclimates. In this context, it means a time series of wind data generated at any point around the world in 3km resolution by WindPRO.

After setting up the turbine, the mesoscale data is purchased in WindPRO. It is a EMD ConWx mesoscale dataset containing the wind speed data, the Weibull distribution, wind direction and other parameters which are modelled and computed in-house in ConWx and EMD. The mesoscale data is generated at a high spatial resolution of approximately 3x3km with a 1 hour temporal resolution(EMD, 2018). Although longer periods (up to 30 years) can be purchased, this was eventually limited by International Class budget. Therefore, 10-years of mesoscale data is deemed sufficient to finally select the 3 different scenarios. This data includes hourly wind data at different hub heights from November 2007 until October 2017. Figure 38 below illustrates the hourly wind speed of site at different hub heights from the mesoscale data.

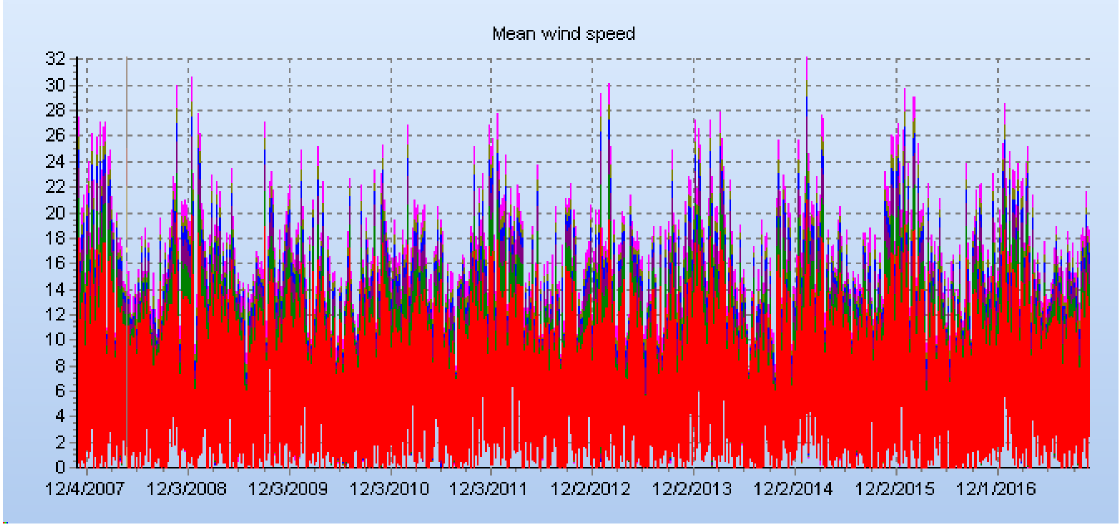


Figure 38: Wind speed of site at different hub height of mesoscale (retrieved from WindPRO)

Figure 39 below shows the wind rose graph and the Weibull distribution at hub height of 50m at the site. It can be concluded that wind blows mostly from south west and the average wind speed for the all the data is 8.4 m/s.

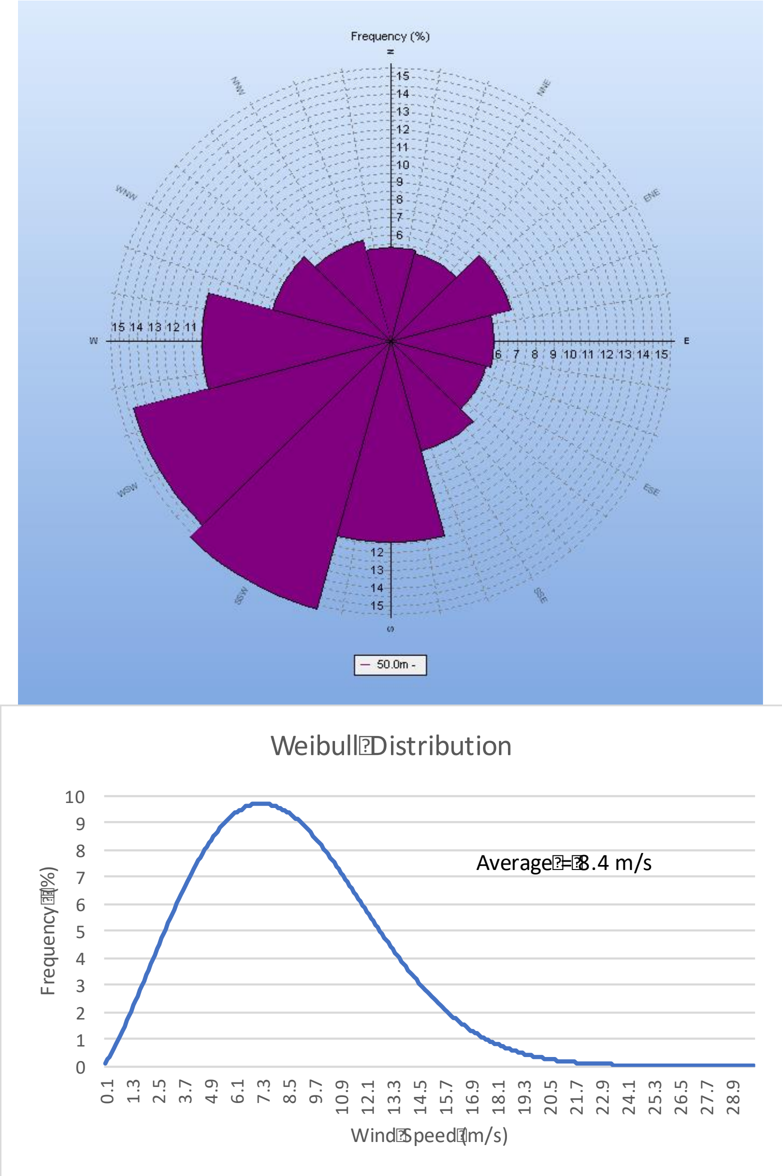


Figure 39: Wind Rose and Weibull graph at 50m hub height (retrieved from WindPRO)

The local data is then correlated with the purchased 10-year mesoscale wind data with using the Measure, Correlate and Predict (MCP) tool inside WindPRO. The objective of MCP is to have long-term correction of local site data based on correlation with mesoscale data, giving us a better picture of the 10-year wind speed for selection of our best, average and worst case scenarios. For this purpose, the local site data (as a site data) was imported into WindPRO. Afterwards, correlation and regression analysis was done by the MCP module based on 10-year data (reference data). The correlation extracts the concurrent measurement point from local time series and 10-year time series to inspect the data. This is done as it was not sure whether the local anemometer is calibrated and there were also some missing data points from the local site data. Figure 40 and Figure 41 show wind speed in 2015 before the correlation and after correlation. As seen below, the generated mesoscale data approaches the local data after MCP is performed.

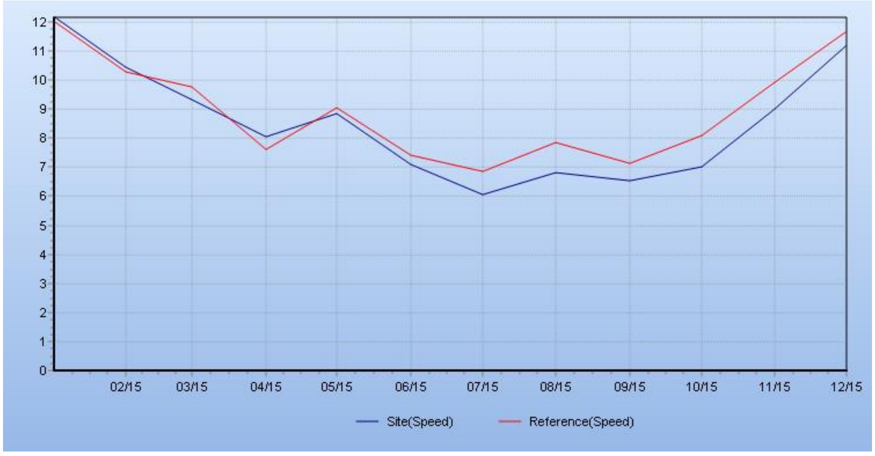


Figure 40: Wind speed in 2015 before correlation

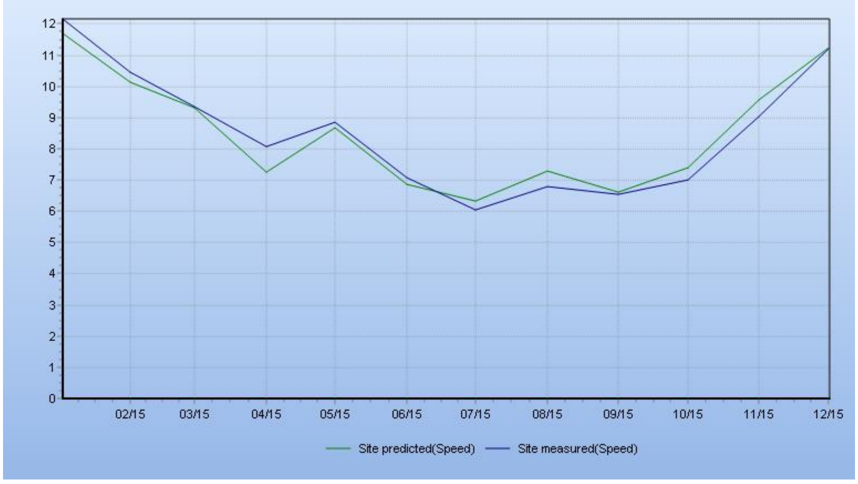


Figure 41: Predicted wind speed in 2015

From the correlated data, the MCP calculation has a correlation coefficient of 0.73 with the measured data, which shows a moderate or acceptable calculation (according to Table 31).

Correlation Coefficient	Quality of Measurement
0.5 to 0.6	Very poor
0.6 to 0.7	Poor
0.7 to 0.8	Moderate
0.8 to 0.9	Good
0.9 to 1.0	Very good

Table 31: Coefficent and quality of correlation(retrieved from Windpro manual)

Figure 42 illustrates the yearly wind speed after and before correlation. It is observed that the correlation reduces the average wind speed by of the modelled mesoscale data by 0.47 m/s (from 8.45 to 7.98 m/s) for the whole 10 years. For the year 2015, the difference in the average wind speed has decreased to 0.2 m/s after correlation, as shown in Table 32. This shows that the correlated wind speed dataset can be used for the wind energy generation.

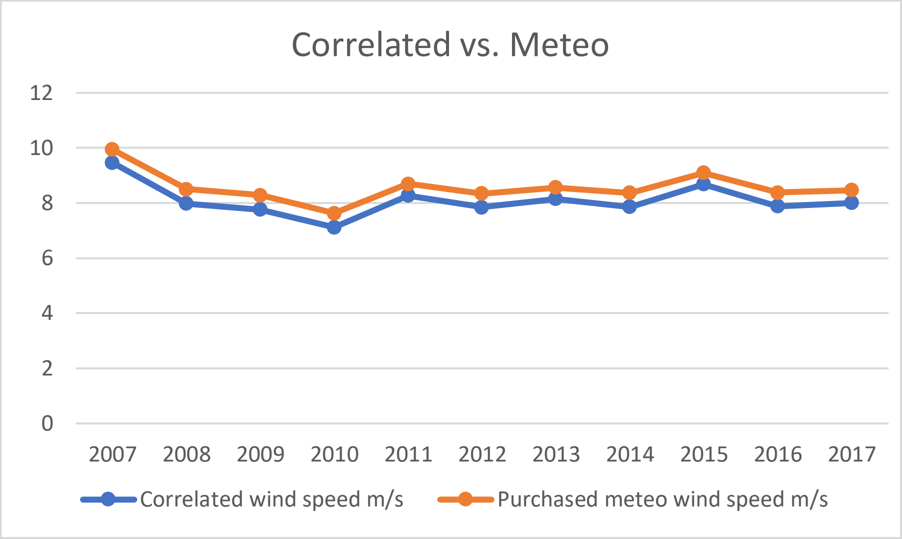


Figure 42: Correlated vs. Meteo wind speed

2015 Data	Average Wind Speed (m/s)
Measured (IWMF)	8.48
Before Correlation	9.09
After Correlation	8.68

Table 32: 2015 2015 Average Wind Speed Comparison- before and after correlation

Finally, the annual electricity generation of the E-33 turbine is simulated using the WAsP tool, developed by Risø National Energy Lab, Denmark(WASP, 2016). The tool estimates the hourly electricity generation of the wind turbine based on wind profiles and considers the roughness and air density (1.241 kg/m^3 in Stornoway) surrounding the wind turbine. The final output for the different years is as shown in Figure 43 below. From the general trend seen below, the wind turbine outputs are higher in winter seasons than in the summer seasons. It is also observed that wind output varies from year to year.

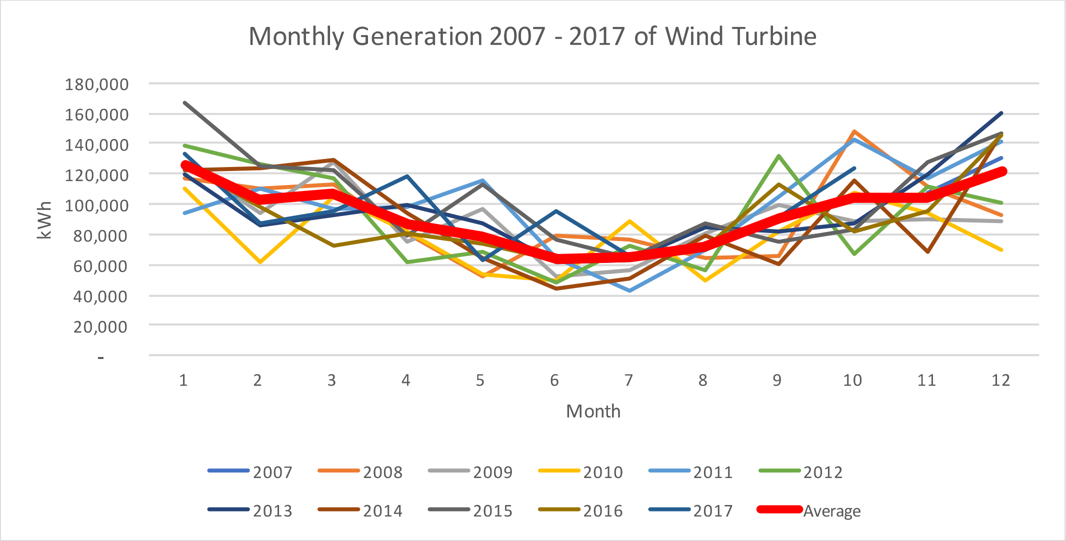


Figure 43: Wind Turbine Output Generation 2007 – 2017 (source: generated from WindPRO)

The results are summarized into the total annual generation and its capacity factor in Table 33 below. The annual average capacity factor for all the years is calculated to be 42.5%.

	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Annual Energy Production (GWh)	1.11	1.08	0.95	1.20	1.10	1.14	1.10	1.27	1.09
Capacity Factor	42.3%	41.0%	36.3%	45.6%	41.9%	43.5%	41.9%	48.4%	41.3%
Case	Average	-	Worst Case	-	Average	-	Average	Best Case	-

Table 33: Annual Wind Generation and Capacity Factors 2008-2016

From Table 33 above, the selected years for worst and best case are 2010 and 2015 respectively. For the selection of the average case scenario wind generation profile, the years 2008, 2012 and 2014 are closest to the average capacity factor of 42.6%. To select the average profile, the monthly average and the median capacity factors for the total 10 years was calculated and correlated with the 3 years. From the correlation factors below shown in Table 34, the year 2014 shows the best correlation at 0.83 than the other years.

Correlation Analysis		
	Average	***p50***
Average	1.00	0.98
p50	0.98	1.00
2008	0.68	0.63
2012	0.75	0.72
2014	0.83	0.83

Table 34: Correlation Analysis for Average Wind Generation Profile

From the capacity factors and the annual generation observed, the final wind profile was selected for the following years. The summary of the wind profiles chosen is shown in

Table 35 below.

Year	Scenario	Annual Generation (kWh)	Capacity Factor (%)	Average Hourly Production (kW)
2010	Worst Case	953,821	**36.29%**	**108.88**
2014	Average Case	1,101,128	**41.90%**	**125.70**
2015	Best Case	1,271,097	**48.37%**	**145.10**

Table 35: Final Selection of Worst, Average and Best Case Scenarios

4.5 Economics

The wind turbine at IWMF enjoys a Feed-in-Tariff incentive for both generation and export of electricity, tabulated as below in Table 36 for 20 years from its commissioning date. The revenues for both tariffs are calculated into the system integration model, where it would vary according to the wind profiles and the scenarios selected. This would especially impact the amount electricity of exported to the grid, according the operational philosophies and scenario selected. An analysis of the impact of the different wind turbine energy contributions can be referred in Chapter 9.

Type of Tariff	Tariff (pence/kWh)	Source
Generation	18.86	CES OHLEH Model from OFGEM
Export to Grid	4.53	CES OHLEH Model from OFGEM

Table 36: FIT incentives for IWMF Park Wind Turbine

Should there be interest in installing additional wind turbines, the total investment cost is estimated as 2000 GBP/kWh(IRENA, 2018).

5. Hydrogen for System Flexibility and Replacement of Fossil Fuels

Constrained capacity of grid to take all the renewable energy produced by wind in the island of Lewis, results in power losses. In the other hand, the island needs to import fossil fuels in order to support mobility. In this OHLEH project the presence of the electrolyser system to produce hydrogen could be an opportunity to improve both issues, using constrained power of the wind. Hydrogen as a green fuel could replace a part of the fossil fuel consumption and the additional benefit of oxygen production could be used by the hatchery, developing a circular economy.

This chapter start with the establishment of demand of hydrogen, continues with the description of the system and analysis of alternatives to improve the production. Finally, a review and comparison of electrolysers and other hydrogen vehicles available in the market is done.

5.1 Hydrogen Demand in IWMF

As a part of OHLEH project, a hydrogen bin lorry has already been ordered by IWMF to utilise the hydrogen production from the Electrolyser. This bin lorry is a Diesel-Hydrogen bi-fuelled Mercedes-Benz Econic Refuse Collection Vehicle(RCV), customized with ULEMCo's H2ICED conversion technology.

This RCV is based on the 26-tonne Mercedes –Benz Econic chassis, with identical Heil Power Link Bodies and Terberg Bin Lifters. In this dual fuel technology, tanks with compressed hydrogen gas at 350 bar are fitted into the vehicle. The hydrogen is injected into the combustion chamber where diesel burning is already taking place. The burning diesel fuel in turn starts burning the hydrogen. When the hydrogen burns, it spreads through the mixture faster than diesel and this in turn ignites the diesel through the entire mix. Hydrogen accelerates the rate at which diesel burn which causes the fuel to burn faster and completely. As a result, less amount of fuel is wasted and results decrease CO_2 emission (Technology, 2017). The vehicle can also operate in diesel-only mode if there is any interruption to the hydrogen supply.

As per the information from ULEMCo, the share for diesel and hydrogen in a dual mode hydrogen vehicle lies between 30% - 40 % but it depends on the specific operation. Taking

30% of Diesel replacement, the respective consumption of hydrogen and Diesel by the RCV is as shown in Table 37 below.

Dual Mode	Hydrogen consumption=0.04kg/km Diesel Consumption=0.28 litres/km
Diesel-only Mode	Diesel Consumption=0.4 litres/km

Table 37: Fuel Consumption of the Bin Lorry. Source: (ULEMCo)

As per the information given by IWMF, the bin lorry is assumed to be travelling a distance of 100km from the facility to collect waste. It is assumed that the RCV would be covering this distance daily. Hence in order to return to the refuelling station it has to overall cover a distance of 200km/day. For covering this daily distance, the bin lorry would consume a diesel of amount 56.8 litres and 7.4 kg of hydrogen, in dual mode.

5.2 Electrolyser Operation Description in OLEH Project

As Per IWMF the electrolyser system is out of operation since 2010. Before that it was operating to produce hydrogen to supply to a dual fuel Ford Transit van operated by the Royal Mail. The actual current configuration of the system As in IWMF is shown below in Figure 44.

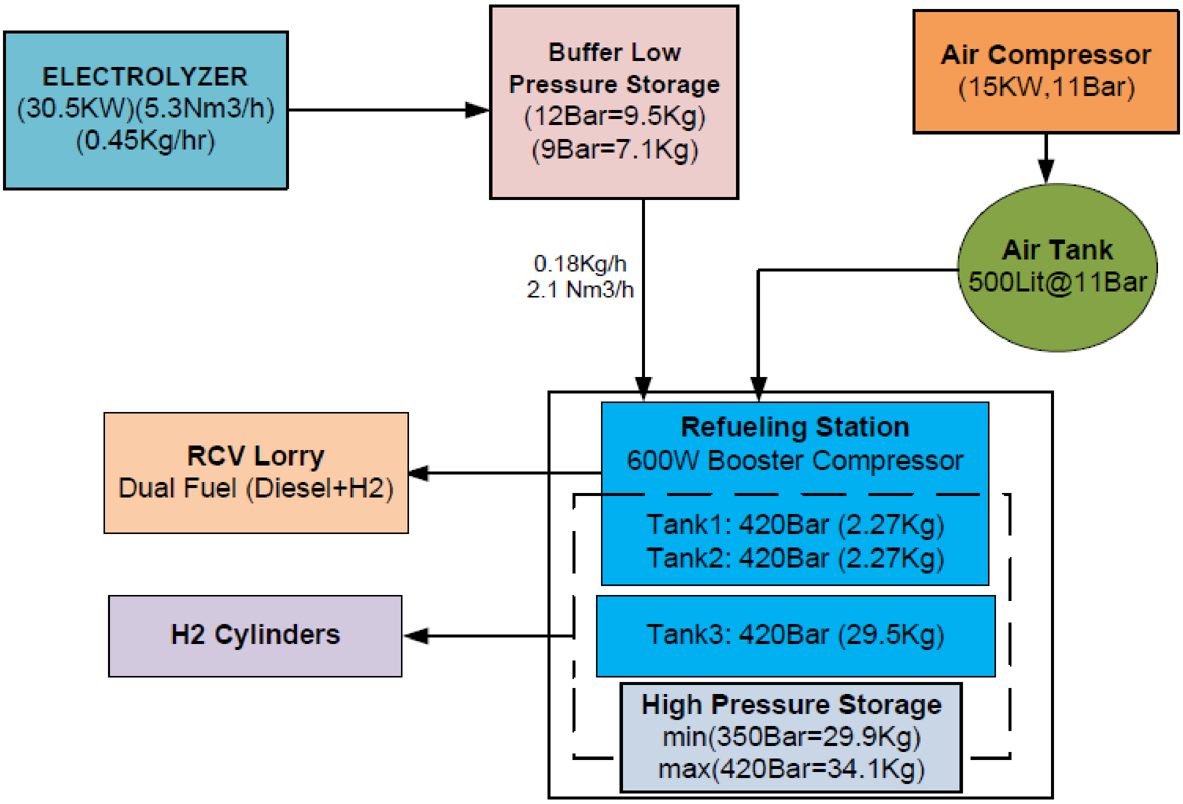


Figure 44 Diagram of existing system, source: own elaboration with information from (Gazey, 2014)

As per the proposed idea by IWMF, the current electrolyser system would be made to produce hydrogen that would be supplied to Dual fuel RCV and the oxygen produced would be supplied to SSC to meet their oxygen demand which are currently met by the bottles imported from Mainland.

5.2.1 Philosophy of Operation

Power supply to the electrolyser system is primarily obtained from renewable energy sources (CHP run by the biogas, and the wind turbine) installed at IWMF. Grid power supply can also be provided to the electrolyser through manual shifting however, is not desirable due to the additional cost of the energy.

Whenever the low-pressure buffer storage is full, the electrolyser stops operating. The air compressors start working, to supply air to the booster compressor inside the fuelling station. Both the air and booster compressors work together to transfer hydrogen from low pressure buffer storage to high pressure storage. The compressors would stop working whenever the high-pressure storage is full i.e. 34.1 kg or the low-pressure storage is less than 9 bar.

The control system of the electrolyser is configured to start only when the available electricity input is 20% of rated capacity which is 6kW for the 30kW electrolyser and hence below 20% of its rated capacity the electrolyser will not operate.

5.2.2 Input / Output Parameters for Electrolyser

For modelling the electrolyser, it was proposed to calculate an efficiency curve from real production data, but due to unavailability of data, a different approach of modelling has been carried out from the available literature (Gazey, 2014). The effect of temperature in the efficiency of the alkaline electrolyser was studied and from there the efficiency curve performance was determined accordingly. Figure 45 below shows how the efficiency increase until the electrolyser reaches a load of 30% and above it the efficiency almost remains constant.

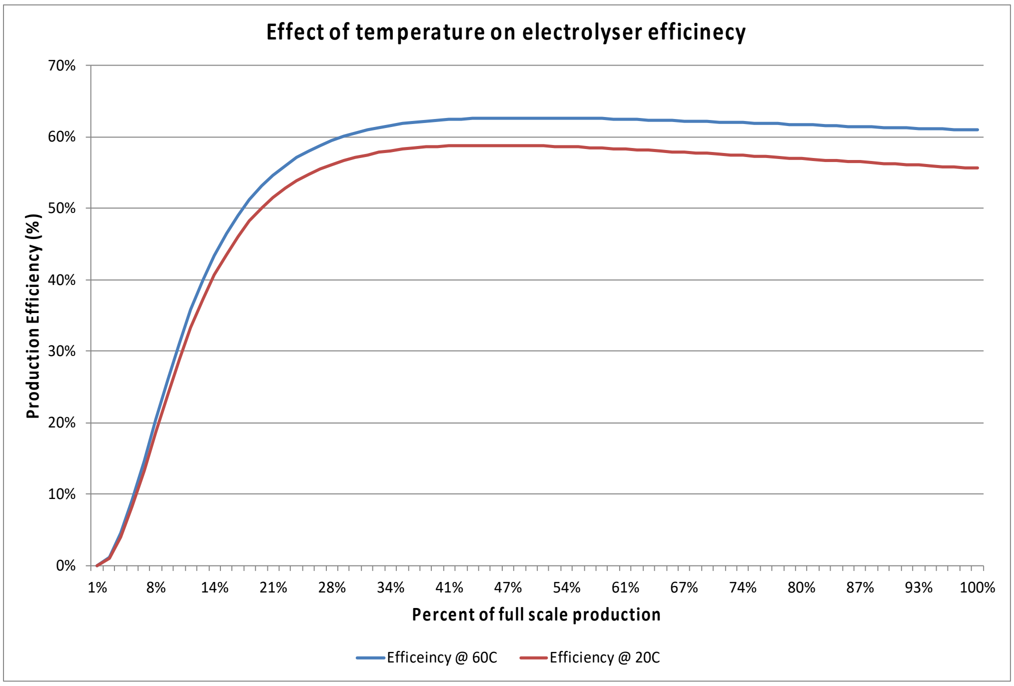


Figure 45 Efficiency of electrolyser, source (Gazey, 2014)m

From technical specifications of the manufacturer of the installed electrolyser it is seen that at 30.5 kW, the hydrogen production is 5.3 Nm^3/hour and the outlet pressure can go up to 12 bar (Pure Energy Centre). As 1 kg of hydrogen is equal to 11.9 Nm^3 at 20°C, the electrolyser produces 0.45kg/hour and the ratio of production at rated power is 0.015 kg/kWh (Community Energy Scotland).

At rated power, the efficiency of the equipment, will be 60% at an operative temperature of 60°C and during the warming up process it will be 55%. According to the literature consulted (Gazey, 2014), the process of warming up for the equipment can take up to1 hour. The changes in efficiency behaviour is included in the excel model for hydrogen and oxygen production. The characteristics of operation for the existing electrolyser are presented in Table 38.The purity of hydrogen produced from the Electrolyser is 99.3%.

Electrolyser 1	**Quantity**	**Unit**	**Source**
Maximum operative power	30	kW	(Pure Energy Center)
Minimum operative power	6	kW	(Pure Energy Center)
Production rate H_2	0.015	kg/kWh	(Pure Energy Center) (Community Energy Scotland)
Production rate O_2	7.94	KgO_2/kgH_2	Own calculation from reaction formula
Auxiliaries	4	kW	(Browne, 2016)

Table 38: 30 kW Electrolyser parameters for model

5.2.3 Hydrogen Buffer storage

The alkaline electrolyser produces hydrogen with an outlet pressure up to 12 bars, and it is directly connected to the buffer storage (Low Pressure Storage), which stores H_2 in the pressure range of 9-12 Bars. The detailed specification of storage is mentioned in Table 39.

Buffer Storage	Quantity	Unit	Source
Maximum storage	9.5	kg @12 bar	(Gazey, 2014)
Minimum storage	7.1	kg @9 bar	(Gazey, 2014)
Inlet flow rate	0.08-0.45	kg/hr	(Pure Energy Center), (Gazey, 2014) and own calculation
Outlet flow rate	0.18	kg/hr	(Gazey, 2014)

Table 39: Low Pressure Hydrogen Buffer Storage Specification

The output of the buffer as shown in Figure 44 is connected to the refueling station. With the given output rate of Table 37, unless the electrolyser is working at the same time as the compressor, the 2.4 kg of H_2 transfer to the high-pressure storage will take approximately 13 hours.

5.2.4 Hydrogen Refuelling Station

The current setup of the fuelling station together with high pressure storage is a cascade type. A high-pressure cascade refuelling station design offers a compromise to the aforementioned configuration. It uses a small compressor, in some instances known as a booster, to replenish the refuelling station's hydrogen store, which can be observed from the details of the three cascade tanks as shown in Figure 44.

The use of a three-stage cascade refuelling station design provides the most efficient refueling station design due to the use of small compressor/booster. As per the Brochure of current refueling station the fueling capacity can increase up to 20Kg/day if a high-pressure hydrogen source is used. (Air Products).

5.2.5 Hydrogen High Pressure Storage

The operation pressure for this storage is between 350 to 420 bars, which give the system an operational mass of 4.2 kg that can flow out, with inlet flow mass rate as shown in the Table 40. For providing the above-mentioned amount of 4.2kg of Transient H_2, the electrolyser has to operate 9.2hours on its maximum rated power. The compressor needs to run 23 hours to transfer this 4.2kg of hydrogen into high pressure storage. The characteristics of the present high pressure storage is shown in Table 40 below.

High pressure storage	**Quantity**	**Unit**	**Source**
Maximum storage	34.1	kg @420 bar	(Gazey, 2014)
Minimum storage	29.9	kg @350 bar	(Gazey, 2014)
Inlet flow rate	0.18	kg/h	(Gazey, 2014)

Table 40: Hydrogen High pressure storage

5.3 Future Planning of the Electrolyser System

5.3.1 Addition of 60kW Electrolyser

Currently, IWMF plans to add a new electrolyser with higher production capacity and to refurbish the existing one. The idea is to operate both as per the constraint available Electricity from Wind and CHP, so that both electrolysers can operate simultaneously, or one will be operating and the second one will be in standby mode. Both electrolysers will be equipped with Oxygen Capture units. CnES plans to purchase of a new electrolyser with higher capacity of approximately 60 kW and the characteristics of the same are shown in Table 41.

Electrolyser 2	**Quantity**	**Unit**	**Source**
Maximum operative power	58	kW	(Pure Energy Centre)
Minimum operative power	12	kW	(Gazey, 2014)
Production rate H_2	0.015	kg/kWh	(Pure Energy Centre)
Production rate O_2	7.940	kgO_2/kgH_2	standard formula
Auxiliaries	4	kW	(Browne, 2016)

Table 41: 60kW Electrolyser parameters for model

5.3.2 Oxygen Production and Handling System

The IWMF has also proposed to retrofit the electrolyser with an Oxygen Handling system which could extract the oxygen produced by the electrolyser to meet the Hatchery demand of imported oxygen. To recover the oxygen produced by the electrolyser, a system consisting of extractor, purification and compressor would be used. The oxygen should be compressed to 230 bar which is the standard available cylinders and Hatchery imports cylinders within the same range of pressure. An oxygen extractor system will extract oxygen from electrolyser at a rate of 2.5Nm^3/h with a maximum outlet pressure of 12 bar and rated power of 500 Watt.

According to information from SSC, the annual imported oxygen demand of hatchery located at Barvas is 53,000Kg. The monthly average demand works out to 4400 kg. The demand is maximum during the summer months which is about 8300 kg as seen in the Figure 46 below.

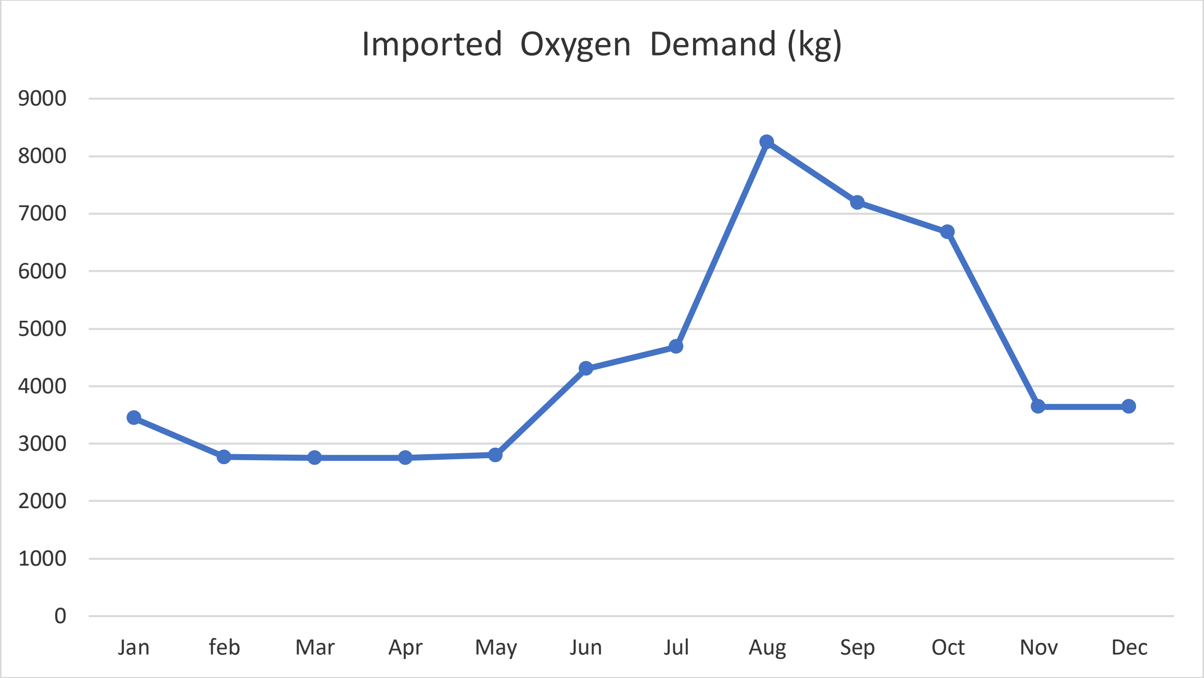


Figure 46: Monthly imported Oxygen Cylinder Demand (Source: SSC)

5.4 Analysis and Recommendations

In the following study, various scenarios have also been analysed using the Energy Model developed by the study team considering the electrolyser in the circular economy concept. The analysis of changes in current configuration is simulated under average wind conditions and AD best Scenario (Scenario 3 Dilution). The various scenarios are mentioned below:

1) **Business as Usual Scenario**: No change in the present electrolyser system configuration

Scenarios	Size of electrolyser	RCV Tank Size(kg)	Annual H_2 production (kg)	Annual Diesel saving by bin lorry (litres)	H_2 surplus for cylinders(kg)	Annual O_2 demand met for hatchery
1	30 kW	4	1330	2880	330	20%

2) **Change in compressor: Flow rate =0.45kg/h, Power consumption=5.5 kW**

Size of electrolyser	RCV Tank Size(kg)	Annual H_2 production (kg)	Annual Diesel saving by bin lorry (litres)	H_2 surplus for cylinders(kg)	Annual O_2 demand met for hatchery
30 kW	4	3310	3120	2230	49%
	8	3310	6140	1240	49%
60 kW	4	3410	3120	2360	50%
	8	3410	6180	1330	50%

3) Change in compressor: Flow rate =0.84 kg, Power Consumption= 7.5kW

Size of electrolyser	RCV Tank Size(kg)	Annual H_2 production (kg)	Annual Diesel saving by bin lorry (litres)	H_2 surplus for cylinders(kg)	Annual O_2 demand met for hatchery
30 kW	4	3340	3120	2230	49%
	8	3340	6140	1240	49%
60 kW	4	5910	3120	4860	88%
	8	5910	6240	3810	88%

The current system has a booster compressor with a low transfer rate of 0.18 kg/h. This forces the compressor to run for more hours than the electrolyser. The electrolyser stops once the low-pressure storage is full but the compressor keeps on running until it transfers 4.2 kg of hydrogen from the low-pressure storage to high pressure storage. To do so it has to run for 23 hours considering the mentioned low transfer rate of 0.18kg/h.

As per business as usual scenario, which is the current electrolyser system configuration, it is seen that dual fuel bin lorry could have 2880kg of diesel saving annually with RCV of 4 kg hydrogen tank and only 20% of annual oxygen demand could be met.

Considering Scenario 2, where a new compressor with flow rate of 0.45kg/hour and rated power of 5.5kW is used, it is found that for both the 30 kW and 60 kW electrolyser, the annual diesel saving for RCV of 4kg tank is approximately same. In this scenario, even the oxygen demand, met by both the electrolyser is same i.e. between 49%-50%. This means with this change in 0.45kg/hr flow rate of compressor, both the electrolyser shows similar performance.

Considering scenario 3, where a new compressor with flow rate of 0.84kg/hour and rated power of 7.5 kW is used, it is found that performance of both the electrolyser varies. With 30 kW electrolyser and RCV of 4 kg, 50 % of oxygen demand was met while with 60 KW electrolyser 88% of annual oxygen demand of the hatchery could be met.

From the above simulations of various scenarios, even when there is higher capacity of electrolyser, the system will try to follow the compressor flow rate. This means that once the buffer storage is between 7.1kg to 9.5 kg, the electrolyser tries to maintain the production at the mass flow equivalent to the mass flow rate of the compressor replenishing the buffer storage tank. Hence, choosing a compressor with mass flow rate equal to the rate of the hydrogen production of the electrolyser would give us the maximum output.

For increasing the transfer rate of the compressor, the possible option is to replace the booster compressor inside the fuelling station together with the air compressor and equip the system with a compressor of high transfer rate of 10Nm^3/h. This would have an inlet pressure of 12 bars and an outlet pressure of 420 bars and an electrical power of 7.5KW. A compressor which matches the above specification is the Oil-free two stages Piston type compressor (C06-10-140/300LX- Hydro-Pac LX-SERIES™). The other technical option with compressors is to have a parallel arrangement of compressors that would allow delivering a higher mass flow to the high-pressure storage, at the same time.

The air compressor presently installed at the IWMF is the rotary screw type with a motor and power rating of 15kW.It compresses the air into max 11 bar and is equipped with a 500 litters' air storage tank of 11bar. If the plan is to use the current setup of compression system it will be a better option to replace the current compressor with a reciprocal diaphragm type having same pressure and flow rate. It has the power consumption of 11kW, which can save 4kW of electricity. (COPCO, 2013).

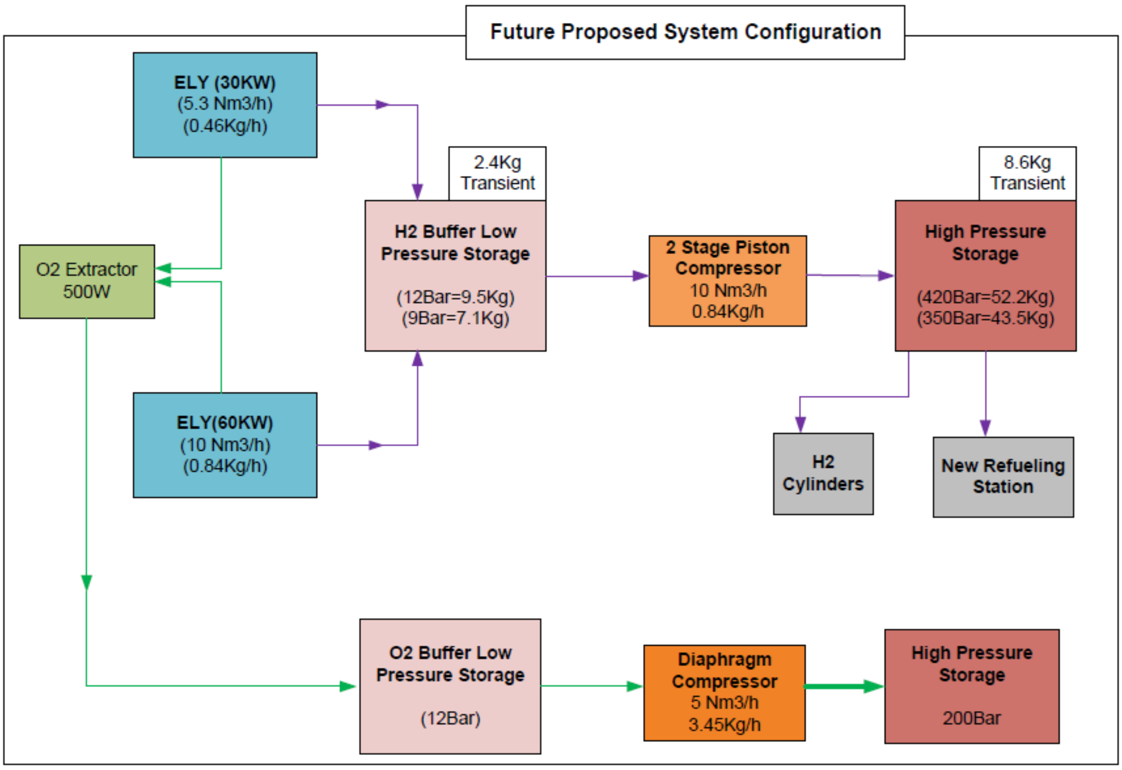


Figure 47 Proposed system configuration

The idea of having a new 60kW electrolyser is to run it together with the old 30KW electrolyser either in stand-alone configuration or in parallel so the better configuration will be to have a common low and high pressure storage with one compression unit for both of electrolysers for each output gas (hydrogen and oxygen) separately as shown in Figure 47 . This configuration will reduce the cost of having two storages and two compressors.

To have a system configuration like this there is a need of high compressor transfer rate (0.84kg/h) together with a new refuelling station that has a fuelling capacity of at least 8kg/day. The capacity of High-pressure storage needs to be increased by adding 8 more cylinders to have a transient ready capacity of 8.6kg storage. The oxygen produced in this simulation was 46,160 kg which can be utilized to meet the 88% of the imported oxygen demand of the hatchery.

5.5 Economic Parameters

The economic parameters of the electrolysers, compressors and storage as well as the operational cost have been integrated in the energy model to carry out the analysis.

Electrolyser OPEX	**Price**	**Unit**	**Source**
HYDROGEN sales price	4	£/kg	BOC online price and calculation to kg
02 price	2	£/kg	BOC online price and calculation to

			kg
Diesel cost	0.124	£/kWh	Refuelling station Stornoway
Electrolyser CAPEX			
Alkaline Electrolyser	2500	£/kW	(Gazey, 2014), chapter 3 page 37
HYDROGEN high pressure storage	909	£/kg	Pure Energy Web site
Refuelling station	85000	£	Pure Energy Web Site
Lifetime	20	Years	(Susan Schoenung, 2011)
Hydrogen Compressor price	80000	£	Pure Energy Web Site
Oxygen Compressor price	50000	£	China Supplier

Table 42: Cost of electrolyser system, sources: detailed in table

5.6 Electrolyser Market Analysis

Electrolyser market can be divided based upon the technology used in the electrolyser such as alkaline water electrolysis and proton exchange membrane (PEM). Currently, in the market alkaline water electrolysers have the highest share of large-scale hydrogen production (MRFR, 2017). In alkaline electrolysers, a diaphragm is used for the purpose of electrolysis which is less expensive than the polymer electrolyte membranes used in the PEM electrolysers (Zeng, 2010).

5.6.1 Efficiency and Lifetime

The efficiency of electrolyser system depends upon many factors such as operation points, boundary conditions and parasitic power requirements. Therefore, it is hard to compare different technologies to define the efficiency of each system exactly. However, efficiency is defined as energy required in kWh electricity per kg of hydrogen. For commercial technologies such as Alkaline and PEM electrolyser, a minimum of 39.4kWh/kgH_2 of electrical energy is required at ambient temperature and pressure. The energy consumption of high temperature electrolyser such as PEM electrolyser is lower than alkaline electrolyser under same conditions. (Bertuccioli, Chan, Hart, Lehner, Madden, & Standen, 2014)

In the figure below, the energy consumption of alkaline and PEM electrolyser is projected.

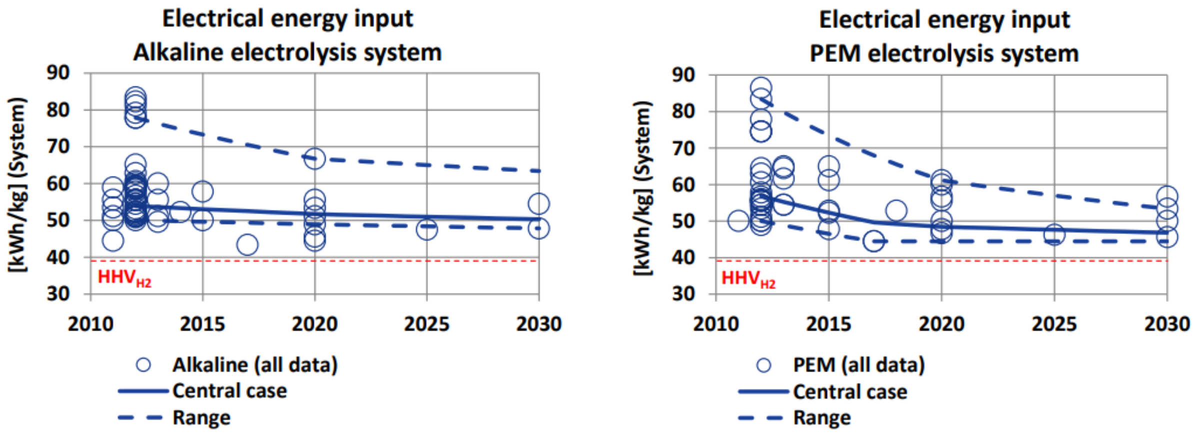


Figure 48: Efficiency trend line for Alkaline and PEM electrolysers

The upper dashed lines indicate the efficiency at full load for commercial electrolyser. However, it can be seen that electrolyser are more efficient at lower loads shown in the lower dashed lines (Bertuccioli L. C., 2014).

Lifetime is affected by efficiency and voltage degradation, according to key performance indicator, for PEM electrolyser is expected 90,000 hours while 100,000 hours are expected for alkaline technology. (Bertuccioli L. C., 2014).

5.6.2 Capital Cost Comparison

In the figure below, the expected cost reduction of the alkaline and PEM electrolysers is shown. It is described in Euros per kW. The PEM electrolysers system cost is currently almost twice the system cost of alkaline electrolysers. In small scale (<100kW), it is reported that the prices of the two electrolyser systems are competitive.

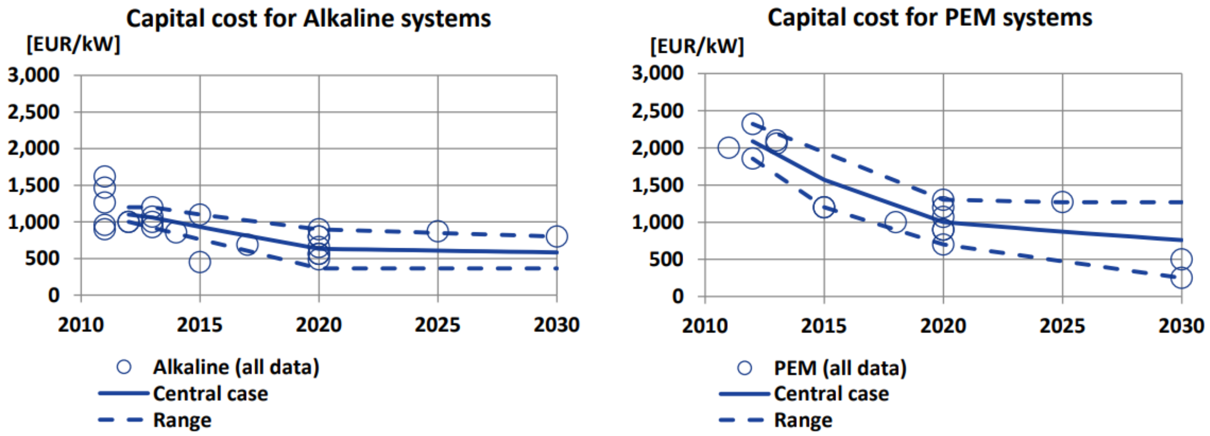


Figure 49: Cost trend line for alkaline and PEM electrolysers

5.7 Market Availability of Hydrogen Vehicles

As of now the IWMF has made decision for the procurement of a single bin lorry as a trial basis to see if the hydrogen production is enough to meet its daily demand. However, with the modification in overall system, there could be surplus production of hydrogen which would give an option to IWMF to replace all its vehicles. Taking this idea into account, market study on availability of different hydrogen vehicles in Scotland was done, if IWMF vehicles would mainly consist of bin lorries, small vans and cars as shown in the Appendix B.

5.8 Conclusion

When production of hydrogen is desired as a part of a project, is vital to stablish the characteristics of the demand, meaning quantity and frequency of the availability required for the product. Once this is done, the following sizing of electrolyser, storage, compressor and refuelling stations can be done. A key factor that affects the dynamic of the system is the mass flow of hydrogen, imposed by the compressor, which oversees meeting the desired pressure of application. Finally, it is an economical compromise between size of storage, mass flow rate of compressor and revenues from the use of hydrogen.

6. Heat equipment

6.1 Thermal Storage

The thermal storage has a volume of 30 m^3. The heat for the thermal storage is supplied by the CHP, electric boiler and the kerosene boiler. The internal piping of the thermal storage leads to heat transfer at correct temperature levels. Furthermore, the piping at the connection point to the store is at larger radius to reduce velocity of water entering and minimizes turbulences. During the site visit on 7th Feb 2018 to IWMF, it was observed that the minimum, average and maximum thermal storage temperature was 71. 4°C, 71.7°C, 78.2°C respectively, as shown in Figure 50 below.

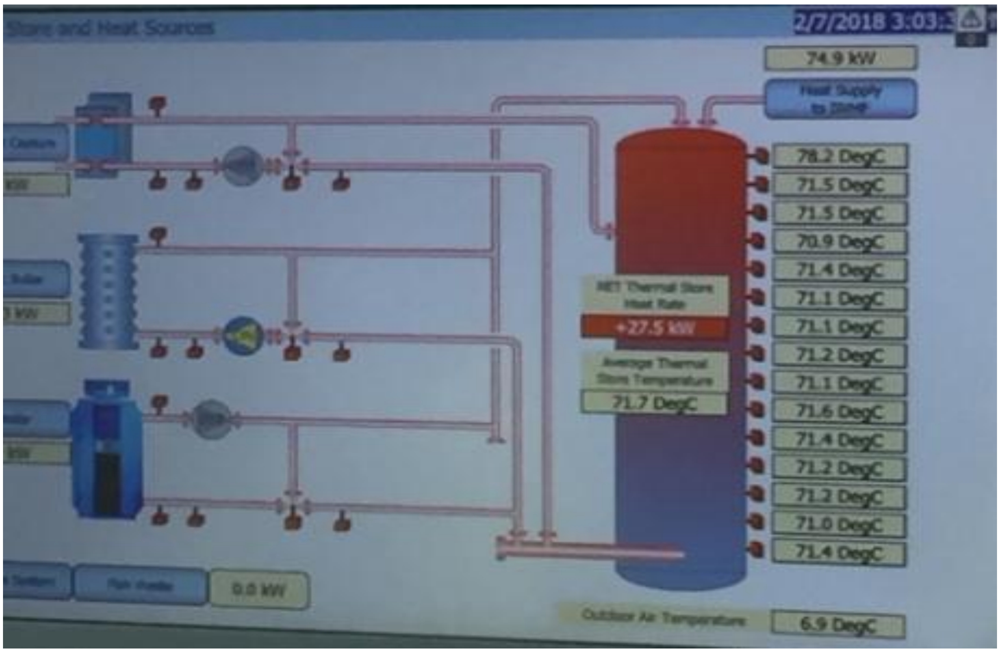


Figure 50: SCADA View of Thermal Storage

Considering the above information, it was decided to neglect the stratification analysis in the system integration model. To supply heat to the AD and the office space a temperature of minimum 70°C is maintained in the thermal storage. The temperature in the storage is increased to an average of 80°C to activate the pasteurization unit when it is needed. Care is also taken to maintain the highest temperature below 97.5°C, which is considered to be the thermal limit of the storage. The thermal loss at rated temperatures considered in the model is 10.465kW equivalent to 0.3°C/hour temperature drop. This is an approximation as per the current operation of the system.

6.2 Combined Heat and Power (CHP) Generator

The CHP engine converts the energy content of the biogas into thermal energy and electrical energy. In the case study, the rated capacity of CHP is 240kW_$_{e}$ and 370kW_$_{th}$ for the maximum input of 125m^3/h of biogas. The corresponding biogas has a methane content of 60%, which is 75m^3/h of methane in order to produce the rated power. The calorific value of methane is 10.45 kWh/m^3 (Agency, 2005). However, in the certificate of performance, the energy content of methane is taken as 10kWh/m^3. Hence, the total energy content of the gas is 750kWh/h considering the lowest calorific value of methane as 10kWh/m^3. The certificate of performance for the whole year 2016 is tabulated below.

Month	Gas Flow to CHP(m^3)	Hours of Run(h)	Gas Consumed (kWh)	Heat Generated (kWh)	Electricity Generated (kWh)	Average Heat Efficiency (%)	Average Electricity Efficiency (%)
Jan	3730	76.5	37300	17862	11675	0.48	0.313
Feb	3923.8	87.5	39238	18791	12282	0.48	0.313
March	2959.2	76.2	29592	14171	9262	0.48	0.313
Apr	5657.5	121.9	56575	27093	17708	0.48	0.313
may	7787.6	137.9	77876	37294	24375	0.48	0.313
June	8313.6	156.3	83136	39813	26022	0.48	0.313
July	8400.5	187.9	84005	40229	26294	0.48	0.313
Aug	6799.2	162.3	67992	32561	21282	0.48	0.313
Sep	5906.5	120.6	59065	28285	18487	0.48	0.313
Oct	5503.4	106	55034	26355	17226	0.48	0.313
Nov	7799.2	139.2	77992	37350	24412	0.48	0.313
Dec	9406.4	178.6	94064	45046	29442	0.48	0.313

Table 43: CHP Certificate of Performance Data 2016 (source: IWMF)

Considering the Table 43above, it is assumed that the electrical efficiency is 31.3% and the thermal efficiency is 48%, producing an electrical and thermal output of 230KW and 360KW respectively (Table 44).

Quality	Electrical Output(kW)	Thermal Output(kW)
Biogas: 125Nm^3/h, 60% methane content	230	360
Biogas: 80Nm^3/h, 60% methane content	150	230

Table 44: Biogas requirements as per CHP rating

In the Energy model, the above data is fed specific to biogas containing 60% methane. However, in the study case the CHP is fed with biogas quality varying from 47% to 55% methane which varies the electrical and heat output from CHP proportionately.

6.3 Electric Boiler

The present electric boiler has the rated power output of 180KW. It takes the electrical power from the wind turbine and converts to thermal power at an efficiency of 100 %(Source: IWMF). The thermal power generated from the boiler is fed to the thermal storage to meet the local heat demands of the systems attached.

6.4 Kerosene Boiler

The kerosene boiler provides heat to the thermal storage when the sufficient heat is not available from CHP or from the Electric boiler. It has an efficiency of 85% (Source: IWMF) and consumes 17.14 litres of kerosene at the rated output of 150KW heat power.

7. The Modelling Tool

7.1 Introduction to Model

The energy system at IWMF has integrated different technologies in order to establish a circular economy which supports the construction of a closed-loop supply chain. Within the OHLEH project the currently operating system is planned to be upgraded by rehabilitation of the existing electrolyser system to use the local resources of the island more efficiently, henceforth further benefiting the entire system. Figure 51 shows the technologies currently working and the ones projected to be established in the short run. The latest plan as expressed by CES has also been considered and incorporated accordingly.

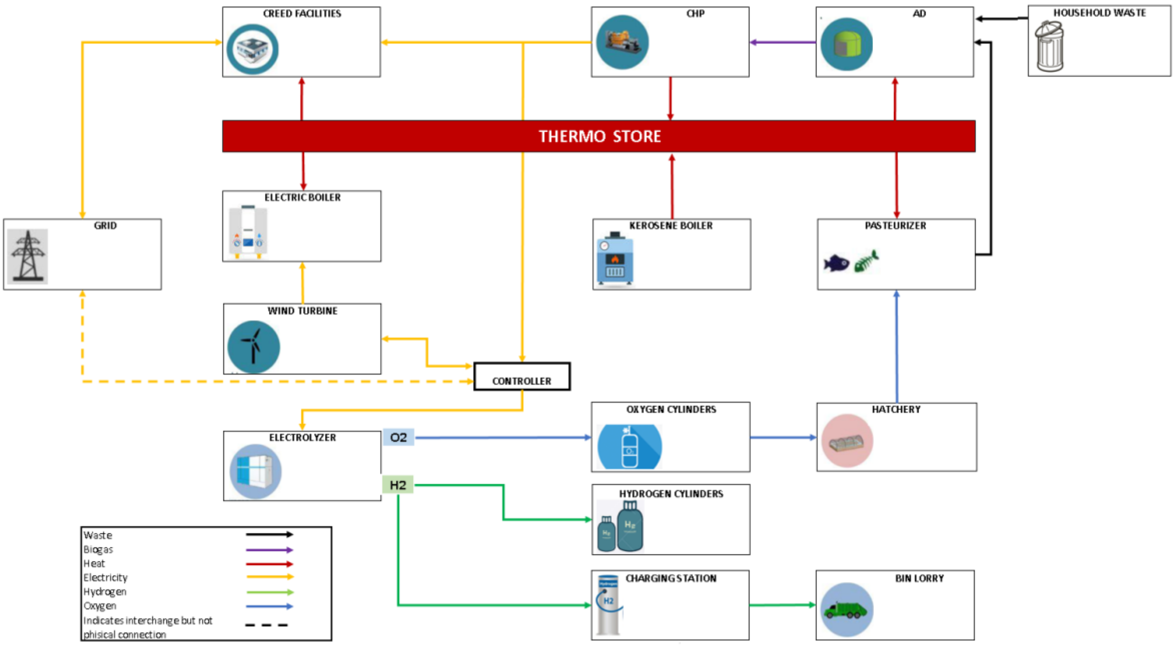


Figure 51: Integrated Energy System at IWMF

The currently structure at IWMF considers different components and technologies, from many suppliers, treating diverse fuels, capacities and with equipment installed at different points in time, each with individual control philosophies and operation modes. This leads to a scenario with low integration. The integration of such an environment is a complex technical problem and, therefore, adds relevance to the main objective of this project, which is to propose a sustainable energy modelling tool.

A model consists in a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions (OXFORD Dictionary, 2018). As the major benefits on developing a model, are the capability to capture and organize the understanding of the system, to permit early exploration of alternatives and evaluation of the system (Brambilla, Cabot, & Wimmer, 2017). Besides that, it helps to understand causes and effects, bringing a better impact analysis by identifying potential consequences of a change. Models are, however, limited in a way that can be considered incomplete, it assumes that future will be like the past, are built on the top of data that might be insufficient or based on uncertain assumptions and the usefulness of a model may be limited by its original purpose, meaning that bigger changes in the real structure might not be covered by the model developed (C. Richardson, 1979).

Therefore, a model that comprehends both technical and financial aspects, can bring an understanding on the behaviour and links between the different components of IWMF Facility. Under the different assumptions and conditions, such a model can be used as a tool for decision making. A reference of the costs used in the model can be found in Appendix C.

The modelling and simulation tool designed for this project and described in this report is a base model of the components shown on Figure 51, where the main variables of the equipment and flow of input/output resources (heat, electricity, biogas, hydrogen and oxygen) are connected to simulate the operation on an 8760-hourly time series for an entire year.

The model brings also the funcitonality of a simulation tool, that allows to modify the particularities of the different components, the control philosophies and thereby is designed to simulate different user-define scenarios

Due to the complexity of the current project, it was decided to adopt a bottom-up approach to carry out the system modelling. That means that the whole system was divided into individual components such as Anaerobic Digester, Pasteuriser Unit, Wind turbine, CHP and others, referred hereafter as modules. This allows more flexibility and freedom for each component to be worked on solutions, scenarios and alternatives that will contribute more to the modelling tool. On the top of the work developed for each equipment or technology, the modelling tool was built with the objective of integrating these modules, defining the communication points and exchanged data between them. On the top of that, the model brings a scheme where all the module’s individual control systems are also integrated, allowing a coordination of the process as a whole.

7.2 Assumptions of the Model

As defined before, a model is a description or a representation of a system or process and, naturally, might differ from reality, where the model needs to be based on information gathered, assumptions and experience. Thus, the modelling tool developed in this project is based on technical assumptions of the energy system operated by IWMF, considering documents analysis, visits on site and conversations with responsible personnel. The main assumptions are listed below:

- The electrolyser and electric boiler are the only available loads to use the surplus of electricity from the wind turbine. In the case of the electricity from the CHP, the only loads managing electricity surplus is the electrolyser.
- The electricity source for the electrolyser is capable to be automatically changed between the wind turbine and the CHP.
- The control system can set priorities for the usage of electricity from the wind turbine between exporting to grid, feeding the electrolyser or running the electric boiler. The electric boiler cannot be set as a priority for the CHP is not an option due to lack of physical connection.
- The input flow of biogas to CHP's inlet is always constant. Variations due to manual interventions are not taken in consideration.
- The feed of waste to the AD is from Monday to Saturday, and the operation of all the equipment is 24/7 except the pasteurizer unit, which only operates during normal working hours.
- All the unit components that compose the system are integrated, and any changes in data and their control philosophies influence each other's operation.
- The electricity demand of the IWMF is assumed fixed to the recorded profile and assumed not affected by changed operation patterns of the plant.

7.3 Modelling Tool Structure

System modelling can be done in several ways. There are many options of software and instruments designed for this purpose, going from costly alternatives to open source ones. For the purpose of the case study, it was decided to use Microsoft Excel® software due to its availability and user-friendly interface.

The main file will be composed of five main parts:

- A spreadsheet with the graphical description of the scenario modelled, as shown in Figure 51.
- An **Input** sheet with the basic parameters of the equipment modelled and different settings for the simulation of scenarios.
- An **Output** sheet to summarize the operation and output of the different components.
- A **Cost** sheet which relates some specifics costs of the simulation.
- Calculation sheets for the different components of the energy system shown on the graphical description. These sheets have the same structure for the name: name of the component/equipment sheet”.

7.4 Modelling Settings

The use of the modelling tool starts with the definition of all equipment parameters, such as capacities, storage sizes, operational set-points, losses, efficiencies, production rates, flow rates and so on. That gives flexibility for simulate scenarios that cover changing of machinery and new operation ranges for the system. A default value is also provided that represents the current operation system.

7.4.1 Electricity Supply Control System

The following approach in the modelling tool relies on defining the control philosophy and priorities for the electricity usage. The main control philosophy for the generated electricity is simplified in Figure 52.

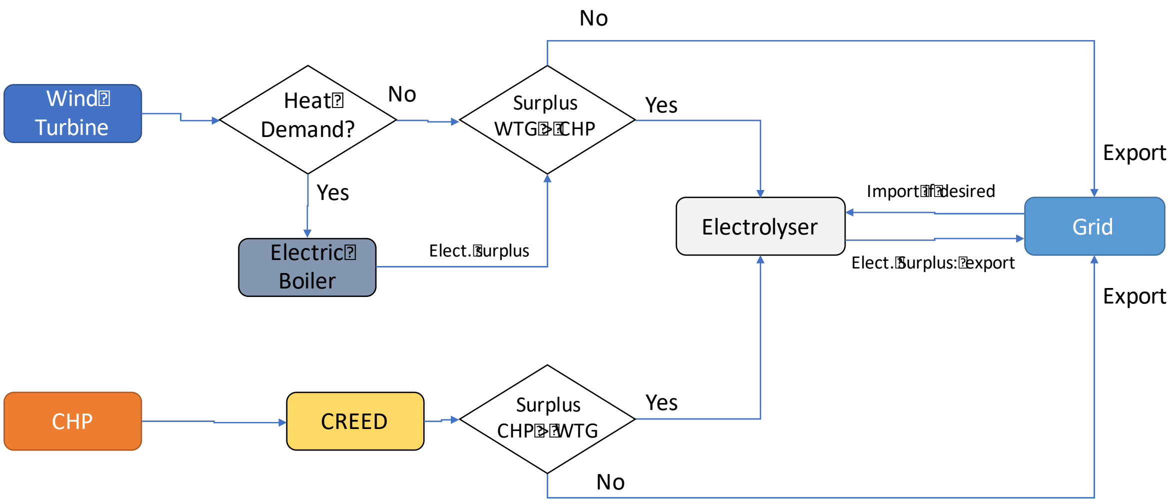
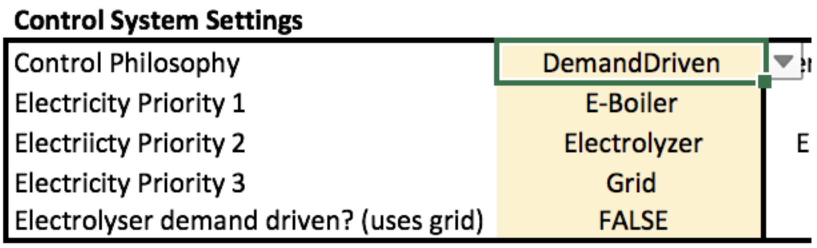


Figure 52. Electricity control flow diagram

As shown, the wind turbine feeds the electric boiler if there is a heat demand from the thermal storage. After feeding the electric boiler, the surplus of electricity from wind, if available, will go through the control system. When there is no need for using the electric boiler, the generated electricity from wind goes straight to the control system. The same happens with the electricity generated by the CHP after meeting the demand of the facility, when its surplus goes through the control system.

The role of the control system is to compare which source has the higher electricity availability to feed the electrolyser unit, while the rest of generated electricity and any surplus, if available, is exported to the main grid. This detail is due to the physical limitation of feeding the electrolyser by the CHP and by the wind turbine simultaneously.

The operation of the control system is defined by the settings specified in the modelling tool. Figure 53 below shows the control system settings that can be defined.



Control System Settings

Control Philosophy	DemandDriven
Electricity Priority 1	E-Boiler
Electriicty Priority 2	Electrolyzer
Electricity Priority 3	Grid
Electrolyser demand driven? (uses grid)	FALSE

Figure 53. Control philosophy settings

The control system designed in the tool comprehends three philosophies possible to be selected. Their descriptions are shown in Table 45 below.

Control Philosophy	Description
Demand Driven	This is designed to supply power to the electric boiler and electrolyser unit as per demanded, looking for export the maximum to the grid at the same time that avoids curtailments due to exporting limit.
Supply Driven	This seeks to work with the electric boiler at the maximum possible power, limited by the thermal storage capacity.
Current	This represents the current philosophy for the electric boiler, that works with the electricity from the wind turbine that extrapolates the maximum export limit to avoid constraining or, when the generation is lower than export limit, explores the maximum possible generation from the boiler.

Table 45. System control philosophies

The next setting to be defined in the modelling tool is the priority of the electricity supply. It is possible to attribute ranked priorities to meeting the electric boiler demand, electrolyser demand or for grid export. An important detail regarding this setting is that the CHP does not supply electricity for the electric boiler, leaving the CHP to only the option of either supplying electricity electrolyser or exporting into the grid. The attribution of priorities is especially important for the **Demand Driven** philosophy that seeks for a better use of constrained electricity according to the system selected as first priority. Finally, if a unit's priority is defined lower than the grid, it means that the control system will pursue the exporting into the grid and the unit will not be powered.

The final setting to be selected is the attribution of a demand driven scenario for the electrolyser. This feature enables the possibility to use the main grid to feed the unit and generate the desired quantity of hydrogen or oxygen. The demand profile for these gases are also variables defined in the system as inputs.

7.4.2 Heat Supply Control System

Another important component modelled in this tool is the thermal storage that acts as the interface point between the heat producing sources and its corresponding demand. It also involves a control system to optimise its usage and run the system within desired operation set-points. Figure 54 simplifies the heat control flow diagram.

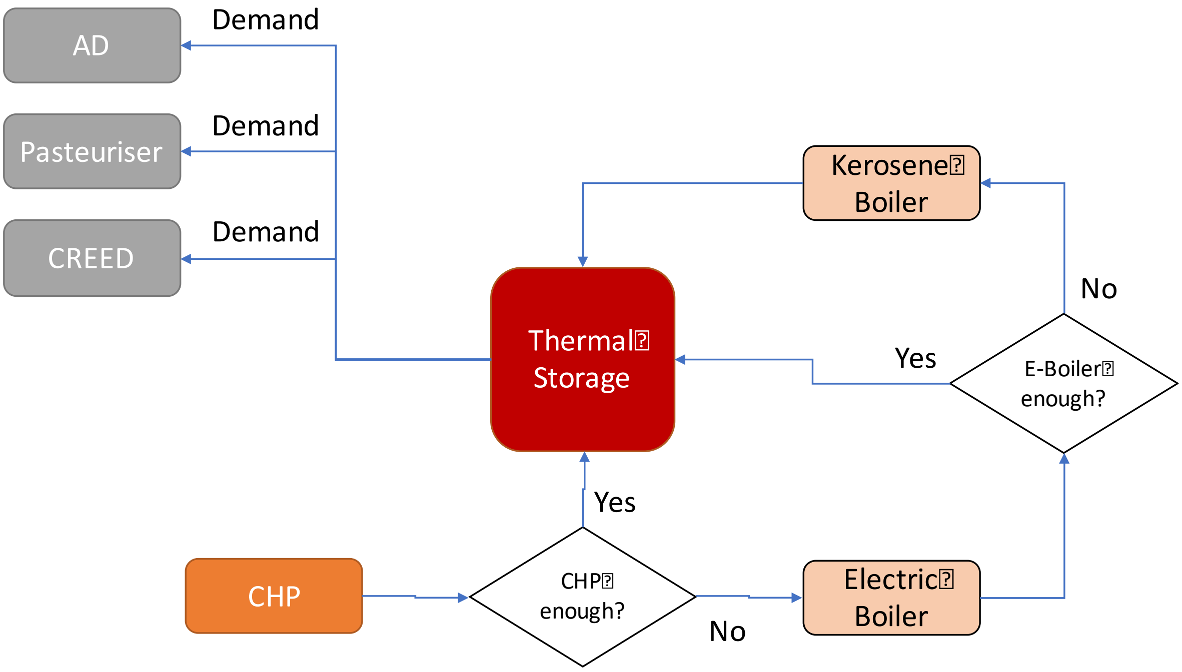


Figure 54. Heat control flow diagram

As shown, the central point of the heating integrated system is the thermal storage. It is responsible for providing heat to the anaerobic digester, pasteurizer and the facility itself. The thermal storage is fed by the CHP and has a control system that perceives differences in its temperature to heat demand. If the CHP cannot provide enough heat energy, additional heat is supplied from the electric boiler to meet the demand. However, in the case of insufficient wind power, the kerosene boiler acts as the residual heat supplier for the system. These actions are performed by the thermal storage's control system.

For the simulation tool, this controller was modelled with a priority to supply enough heat required without exceeding its capacity and maintaining the desired operational set-points. These parameters, capacity and operational set-points are also variables in the modelling tool and can be modified. The model also incorporates the pasteuriser heat demand, that requires a higher temperature (or heat capacity) in the thermal storage to operate. Additionally, by calculating the heat demand necessary during the pasteurisation process according to the amount of fish fed, the controller explores the availability of both electric and kerosene boilers to supply the heat as demanded.

More details regarding the modelling tool can be found in the Modelling Tool User's Guide.

8. Simulation of Scenarios and Results

The simulation of scenarios has been done step-by-step. The simulation of the Business-As-Usual (BAU) as the starting point to reflect the current operational situation, after this scenario the simulations are done based on the BAU with the Electrolyser system operating in order to reflect future plans of the IWMF.

The simulations run have been approached by trial and error. This means that after each scenario is run, the settings were changed with the purpose to find a scenario with higher revenues and less CO_2 emissions compared to the BAU scenario with the Electrolyser system operating. The scenario results are compared both in terms of economic and environmental benefits.

8.1 Business-as-Usual (BAU) Scenario

The Business-as-Usual (BAU) scenario is used to compare further analysis of the resources of the system. This scenario has been simulated with the modelling tool defining the settings on the input sheet as described in the Table 46.

Simulation settings	**BAU**
CHP	Full Capacity
Wind Scenario	Average
Control Philosophy	Current
Electricity Priority 1	E-boiler
Electricity Priority 2	Grid
Electricity Priority 3	ELY
Hydrogen demand driven? (uses grid)	no
Bin lorry demand	0
Hydrogen demand	0
Oxygen demand	0
Anaerobic Digestion Scenario	Status Quo 2017

Table 46. Settings for BAU simulation

The BAU scenario simulated included the fish waste profile in addition to the household waste into the anaerobic digester, which accounts for 68.56 tons for the entire year of 2017. As a result, the Anaerobic Digester produces 501.610 m^3 of biogas, and 239.156 m^3 of it is flared. The operation and outputs of the components are as described in the Figure 55 and Figure 56. With this configuration, the modelling tool calculates a net revenue of 180,785

GBP, this considering revenues due to electricity generated and exported, waste gate fee and the costs of kerosene consumption and the electricity imported.

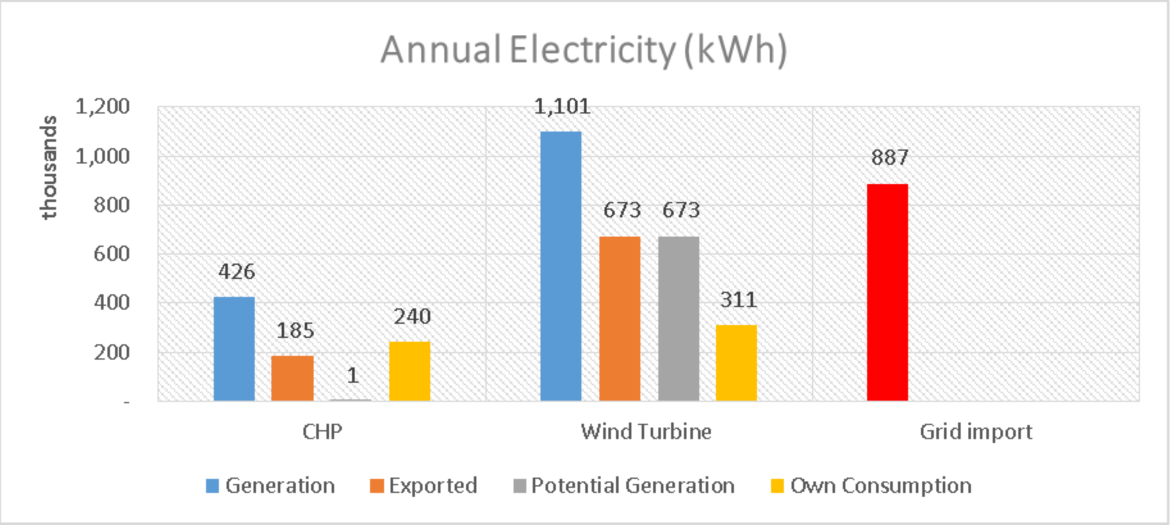


Figure 55. Electricity flow of BAU scenario

In the BAU scenario, the capacity factor of the CHP is 21% and 41.9% for the wind turbine. Since both units do not operate a full capacity during every hour of the year, there are hours where the electricity generated by them is inadequate to meet the demand. Hence, additional electricity is imported from the grid. It is also possible to observe in the Figure 55 that not all what is generated is used in the system, but is exported or curtailed.

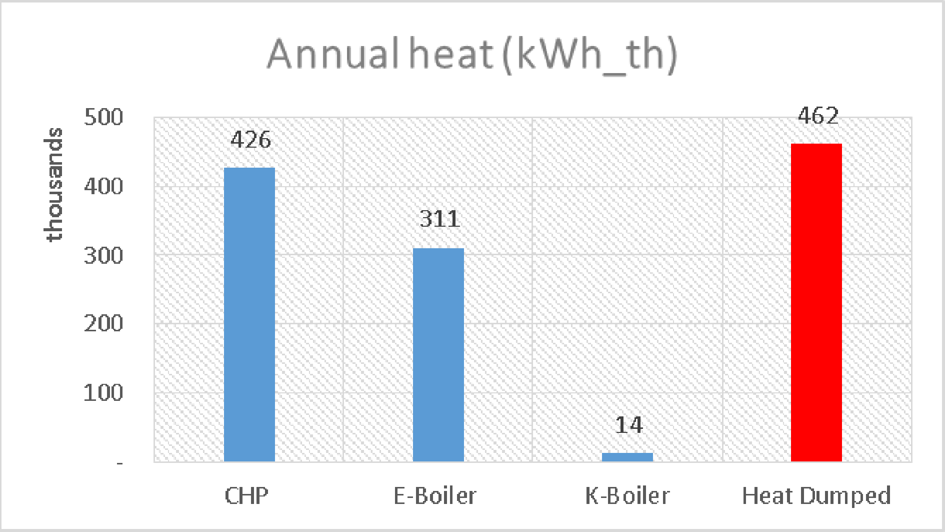


Figure 56. Heat flow of BAU scenario

The heat generation in the BAU scenario is mainly coming from the CHP and at the E-boiler. A smaller amount is contributed by the kerosene boiler, even though a significant amount of heat is being dumped.

8.2 Optimization of BAU Scenario

The necessity to simulate the future system by including the electrolyser unit to supply hydrogen to the Bin Lorry is considered in the next simulations. New simulations were run including the demand for the electrolyser, 4kg for the Bin Lorry every day from Monday to Friday, and maintaining the settings of the BAU.

Simulation settings	Run 2	Run 4	Run 8
CHP	Full Capacity	Full Capacity	Min Requirement
Wind Scenario	Average	Average	Average
Control Philosophy	Demand Driven	Demand Driven	Demand Driven
Electricity Priority 1	Eboiler	ELY	ELY
Electriicty Priority 2	ELY	Eboiler	Eboiler
Electricity Priority 3	Grid	Grid	Grid
Hydrogen demand driven? (uses grid)	no	no	no
Bin lorry demand	4	4	4
Hydrogen demand	0	0	0
Oxygen demand	0	0	0
Anaerobic Digestion Scenario	Status Quo 2017	Status Quo 2017	Status Quo 2017

Balance	Price/unit	Quantity		Subtotal	Quantity		Subtotal	Quantity		Subtotal
Costs										
Kerosene (liter)	£ 0.51	4,849	liters	£ 2,454	6,371	liters	£ 3,224	2,880	liters	£ 1,457
Cow Slurry (qty/week)	£ 400.00	-	Tn	£ -	-	Tn	£ -	-	Tn	£ -
Fresh Water (m3)	£ 0.71	-	m3	£ -	-	m3	£ -	-	m3	£ -
Electricity import (kWh)	£ 0.11	887,432	kWh	£ 97,618	887,432	kWh	£ 97,618	709,381	kWh	£ 78,032
for CREED facility	£ 0.11	887,432	kWh	£ 97,618	887,432	kWh	£ 97,618	709,381	kWh	£ 78,032
for Electrolizer	£ 0.11	-	kWh	£ -	-	kWh	£ -	-	kWh	£ -
Total Costs				£ 100,071			£ 100,841			£ 79,489
Revenues										
WT generation (kWh)	£ 0.19	1,100,630	kWh	£ 207,249	1,100,630	kWh	£ 207,249	1,100,630	kWh	£ 207,249
CHP electricity generation (kWh)	£ 0.08	425,676	kWh	£ 35,842	425,713	kWh	£ 35,845	580,410	kWh	£ 48,871
Gate fee (Tn)			Tn	£ -		Tn	£ -		Tn	£ -
Non-ensiled fish waste	£ 180.00	19	Tn	£ 3,330	19	Tn	£ 3,330	19	Tn	£ 3,330
Ensiled fish waste	£ 130.00	50	Tn	£ 6,508	50	Tn	£ 6,508	50	Tn	£ 6,508
H2 sales (kg) (4)	£ -	-	kg	£ -	-	kg	£ -	-	kg	£ -
O2 sales (kg) (1.8)	£ -	6,828	kg	£ -	7,264	kg	£ -	7,540	kg	£ -
WT export (kWh)	£ 0.05	721,964	kWh	£ 32,922	730,466	kWh	£ 33,309	757,961	kWh	£ 34,563
CHP export (kWh)	£ 0.05	158,160	kWh	£ 8,035	162,117	kWh	£ 8,236	129,476	kWh	£ 6,577
Savings from Diesel (liters)	£ 1.24	2,754	liters	£ 3,414	2,928	liters	£ 3,631	3,039	liters	£ 3,768
Total Benefits				£ 297,299			£ 298,107			£ 310,866
Net				**£ 197,228**			**£ 197,266**			**£ 231,376**
Environmental										
				CO2 emissions			**CO2 emissions**			**CO2 emissions**
Kerosene (kgCO2)				13,021			17,106			7,734
Diesel (kgCO2)				7,357			7,824			8,120
Grid (kgCO2)				2,704			(1,906)			(65,881)
No CH4 to landfill (kgCO2)				(157,688)			(157,688)			(157,688)
Total emissions (kg)				**(134,606)**			**(134,664)**			**(207,715)**

Table 47. Cost results for first phase of simulation

This phase of simulations had three steps with the purpose to find first the optimum control philosophy for the input controller, then look for the best combination of priorities for the control system and finally test if changing the operation of the CHP impacts on the operation of the system. All the trials were evaluated according to the earnings and by the environmental, their environmental benefits in terms of CO_2 savings. The results of the best scenarios found step by step are shown in the Table 47, and the differences in the simulations from step to step are pointed in red colour.

In order to find the optimum control philosophy two scenarios with the CHP at full capacity (heat power 360 kWth and electrical power 230 kW) were run. From these two (Run 2 and Run 4), the best scenario was the "Run 4" by selecting the Demand driven philosophy. This scenario is better because, even when it uses more kerosene, the electricity generated and exported is higher which means greater earnings. Figure 57 shows that the amount of electricity generated and imported, is equal to the BAU scenario. The difference is that more of the electricity generated is used to supply the IWMF system reducing the curtailment.

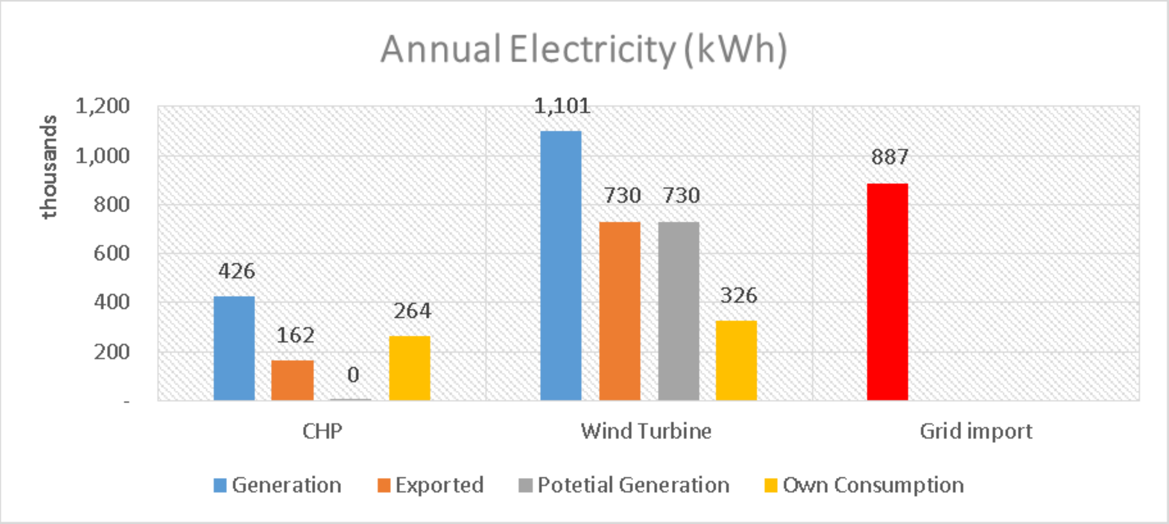


Figure 57. Electricity flow of simulation "Run 4"

On the simulation scenario "Run 4", the kerosene boiler is running more hours (372h), diminishing the electric boiler operation as shown in the Figure 58, therefore the wind turbine can export more.

The carbon dioxide (CO_2) emissions factors per fuel were considered to calculate the total CO_2 emissions. The CO_2 savings when exporting to the grid were calculated as a marginal approach according to the amount of CO_2 emitted to generate a kWh electricity in the UK of 2017, around 0.37 kg CO_2/kWh (Electricitymap.org, 2018), assuming that the exported electricity will replace no renewable generation from the UK electricity mix. In consequence, the CO_2emissions from this scenario are less mainly due to the exports to the grid, as well as the displacement of diesel by the production of hydrogen for the Bin Lorry.

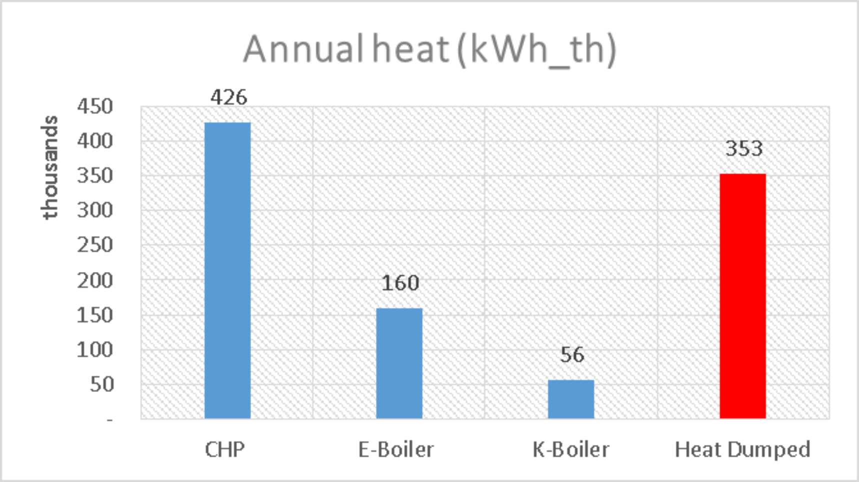


Figure 58. Heat flow of simulation "Run 4"

Once the best philosophy for the system has been selected (Demand Driven) due to the higher revenue and better CO_2 savings, with the priorities Electrolyser, Boiler and Grid. This represent a better option also because of the better production of H_2/O_2, saving more diesel fuel.

Once the philosophy and priorities were defined, the next step is to test the impact of the CHP operation by de-rating it to its minimum capacity (heat power 230 kWth and electricity poser 150 kW). This was done with the simulation "Run 8".

The description of the operation of the equipment are shown in the Figure 59 and Figure 60. It shows that by operating the CHP in the minimum power, the curtailment of electricity decreases, this because the CHP is running 21.2% more (4861 h) than the "Run 4" (2299 h). This decreases hours of the E-boiler and leads to an increase in the electricity export from the wind turbine.

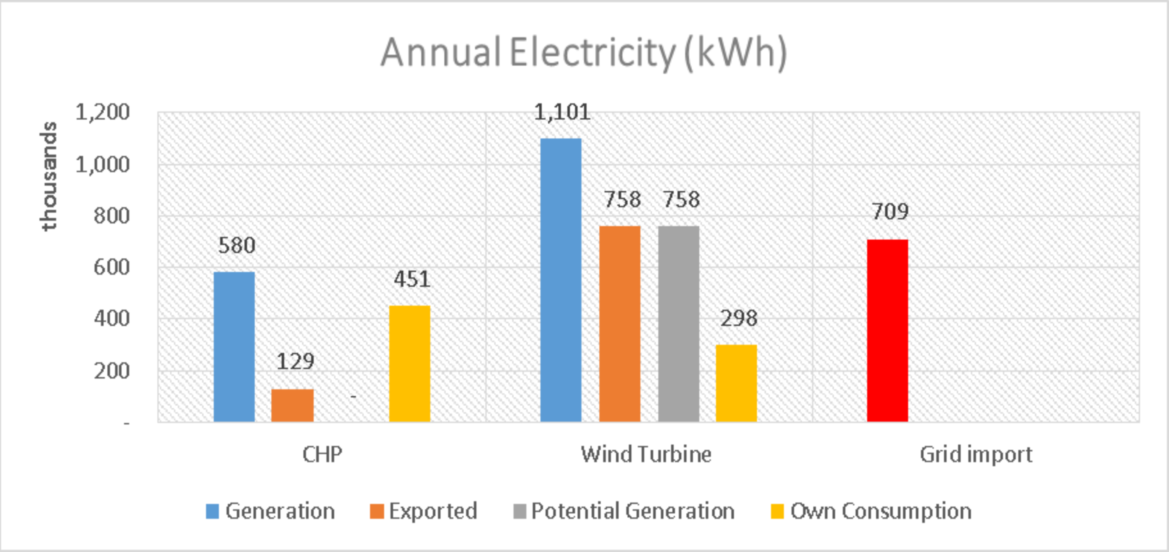


Figure 59. Electricity flow of simulation "Run 8"

With the CHP generating more hours, less kerosene is needed as shown in the Figure 60. The amount of heat being dumped increases, even when the amount of heat required from the electric boiler is less.

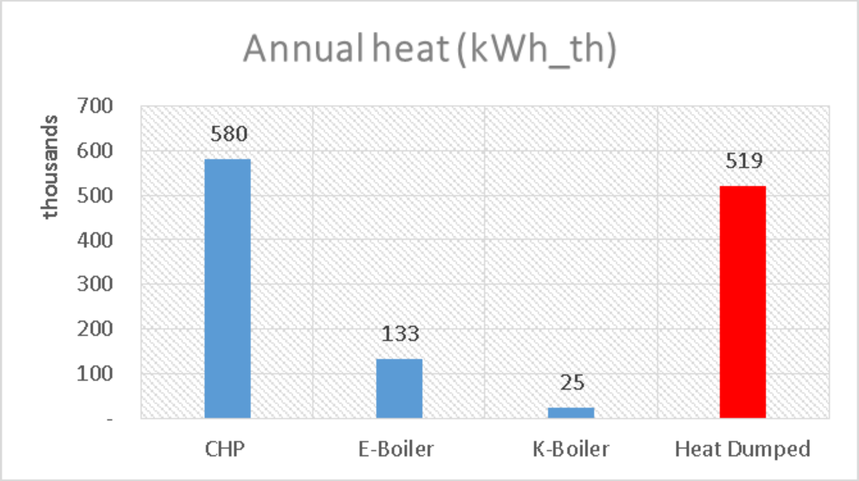


Figure 60. Heat flow of simulation "Run 8"

8.3 Optimization of AD Scenarios

This second phase of simulations also has three steps with the purpose to find the best system operation by testing different scenarios for the Anaerobic Digester. The scenarios are S1 Composition, S1 NF Composition, S1 Meso, S2 Dilution, S3 Composition, S3 Meso, S3 Dilution. Afterwards, when the best AD scenario is chosen, the best combination of priorities for the control system are tested. This is to see whether varying the capacity of the electrolyser system, which has some operational constraints, can impact the overall operation of the system. The results of the best scenarios found in each step are shown in the Table 48, while the input differences in the simulations from step to step are highlighted in red colour.

Simulation settings	Run 10	Run 15	Run 8 (Compressor flow 0.54)
CHP	Full Capacity	Full Capacity	Full Capacity
Wind Scenario	Average	Average	Average
Control Philosophy	Demand Driven	Demand Driven	Demand Driven
Electricity Priority 1	ELY	Eboiler	ELY
Electriicty Priority 2	Eboiler	ELY	Eboiler
Electricity Priority 3	Grid	Grid	Grid
Hydrogen demand driven? (uses grid)	no	no	no
Bin lorry demand	4	4	8
Hydrogen demand	0	100	0
Oxygen demand	0	0	0
Anaerobic Digestion Scenario	3 Dilution	3 Dilution	Status Quo 2017

Balance	Price/unit	Quantity		Subtotal	Quantity		Subtotal	Quantity		Subtotal
Costs										
Kerosene (liter)	£ 0.51	207	liters	£ 105	178	liters	£ 90	214	liters	£ 108
Cow Slurry (qty/week)	£ 400.00	52	Tn	£ 20,800	52	Tn	£ 20,800	52	Tn	£ 20,800
Fresh Water (m3)	£ 0.71	161	m3	£ 114	161	m3	£ 114	161	m3	£ 114
Electricity import (kWh)	£ 0.11	394,231	kWh	£ 43,365	394,231	kWh	£ 43,365	394,231	kWh	£ 43,365
for CREED facility	£ 0.11	394,231	kWh	£ 43,365	394,231	kWh	£ 43,365	394,231	kWh	£ 43,365
for Electrolizer	£ 0.11	-	kWh	£ -	-	kWh	£ -	-	kWh	£ -
Total Costs				£ 64,384			£ 64,369			£ 79,489
Revenues										
WT generation (kWh)	£ 0.19	1,100,630	kWh	£ 207,249	1,100,630	kWh	£ 207,249	1,100,630	kWh	£ 207,249
CHP electricity generation (kWh)	£ 0.08	1,301,730	kWh	£ 109,606	1,301,739	kWh	£ 109,606	1,301,730	kWh	£ 109,606
Gate fee (Tn)			Tn	£ -		Tn	£ -		Tn	£ -
Non-ensiled fish waste	£ 180.00	1,071	Tn	£ 192,832	1,071	Tn	£ 192,832	1,071	Tn	£ 192,832
Ensiled fish waste	£ 130.00	428	Tn	£ 55,602	428	Tn	£ 55,602	428	Tn	£ 55,602
H2 sales (kg) (4)	£ -	-	kg	£ -	365	kg	£ -	-	kg	£ -
O2 sales (kg) (1.8)	£ -	8,128	kg	£ -	10,892	kg	£ -	10,276	kg	£ -
WT export (kWh)	£ 0.05	812,537	kWh	£ 37,052	773,580	kWh	£ 35,275	781,659	kWh	£ 35,644
CHP export (kWh)	£ 0.05	494,784	kWh	£ 25,135	455,378	kWh	£ 23,133	464,787	kWh	£ 23,611
Savings from Diesel (liters)	£ 1.24	3,300	liters	£ 4,092	3,235	liters	£ 4,012	4,106	liters	£ 5,092
Total Benefits				£ 631,567			£ 627,710			£ 310,866
Net				**£ 567,184**			**£ 563,340**			**£ 231,376**
Environmental										
				CO2 emissions			**CO2 emissions**			**CO2 emissions**
Kerosene (kgCO2)				555			479			575
Diesel (kgCO2)				8,817			8,645			10,972
Grid (kgCO2)				(337,843)			(308,849)			(315,320)
No CH4 to landfill (kgCO2)				(3,447,700)			(3,447,700)			(3,447,700)
Total emissions (kg)				**(3,776,172)**			**(3,747,425)**			**(3,751,473)**

Table 48. Cost results for second phase of simulation

For the first step of the second simulation phase, the AD scenario recommended "Scenario Dilution 3" was tested, first with the same settings as the simulation "Run 8". The scenario 3 Dilution had the one of best outcomes ("Run 10"). Since this scenario increases considerably the amount of biogas generated (to 914779 m^3) it was considered important to test this scenario with the CHP at full capacity, resulting in more revenue for the operation. Results from "Run 8" and the "Run 10" are compared by looking at the Figure 59, Figure 61 and Figure 62. Here, it is observed that there is an increase of electricity generated, exported and consumed inside the system, resulting from less electricity import from the grid.

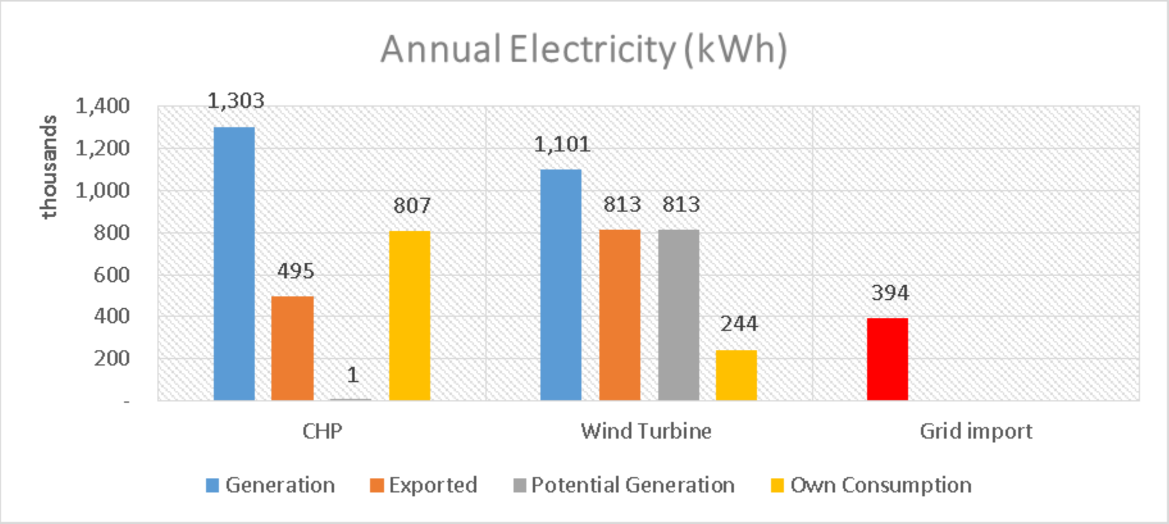


Figure 61. Electricity flow of simulation "Run 10"

In terms of heat, as shown in the Figure 62, the heat generated from the CHP increases and therefore the need for heat from the E-boiler and K-boiler decreases considerably. It is important to note that once more, the amount of heat dumped is significant.

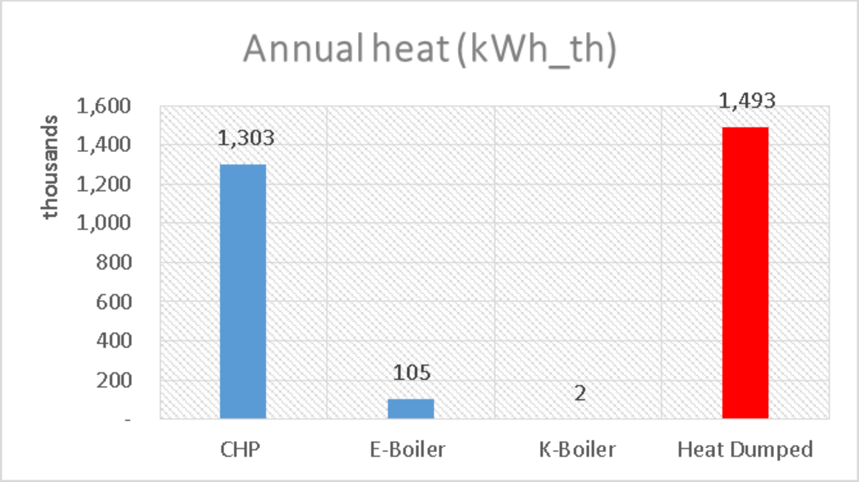


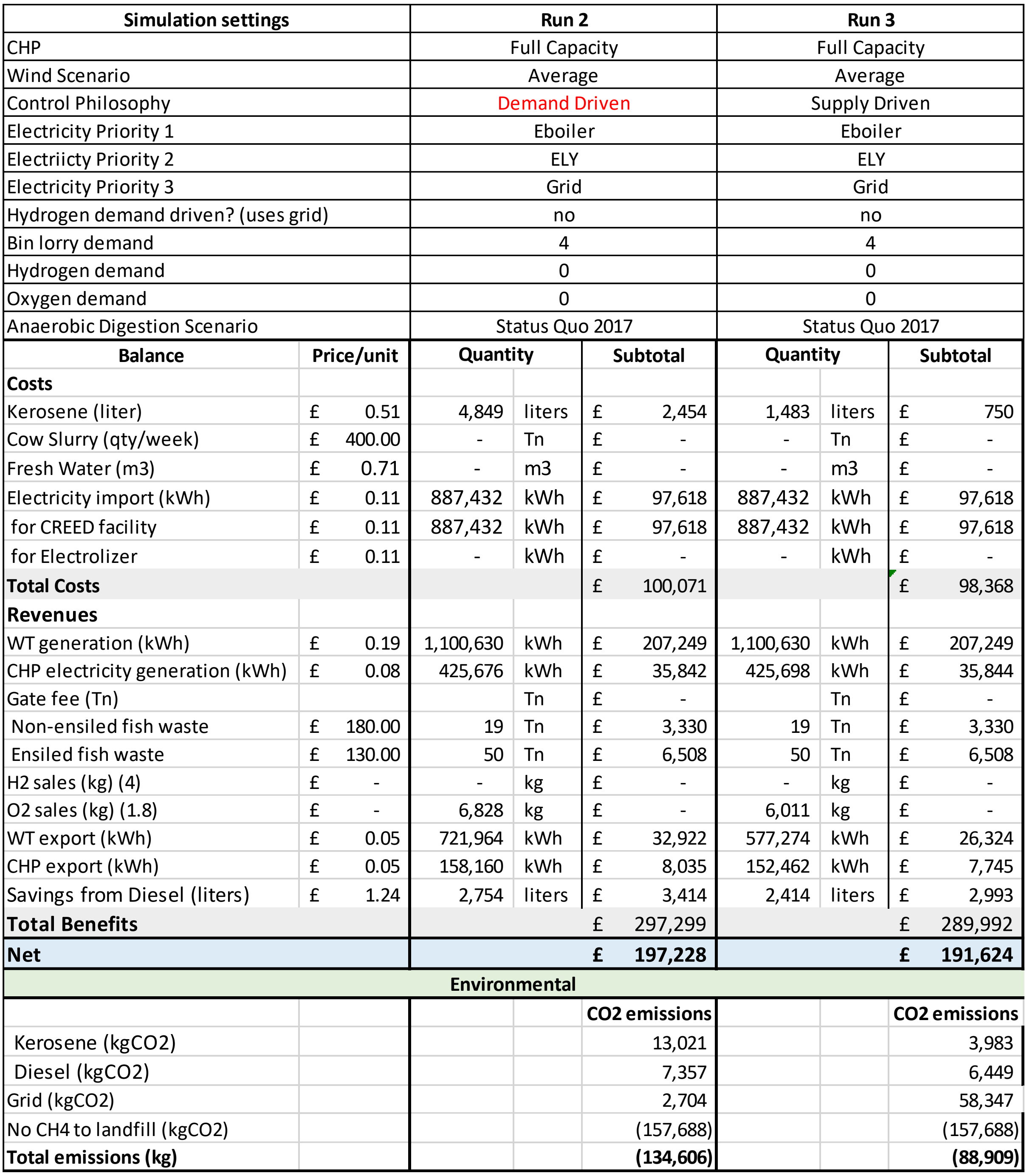
Figure 62. Heat flow of simulation "Run 10"

With the CHP operating at full capacity under the Scenario 3 Dilution, there was still electricity curtailed from the CHP (812 kWh). Therefore, it was necessary to incorporate more demand from the electrolyser to see if the curtailed electricity can be utilised. In this second step, different priorities were tested with a demand of hydrogen of 100kg per week, a demand that is hard to reach but would push the system to produce as much H_2 as it can. From the simulation results, the best results were found with "Run 15". Comparing the simulation “Run 10” and “Run 15”, it is observed that in case there is no market available for oxygen and hydrogen, having only hydrogen demand from the Bin Lorry (no H_2 demand of cylinders), the simulation “Run 10” is better. Even when the “Run 10” results in using more consumption of kerosene, it curtails less electricity from the CHP and therefore more revenue from electricity exports are generated. However, if there is a market for hydrogen and/or oxygen, “Run 15” proves to be a better solution as it uses less kerosene, exports more by curtailing less electricity from CHP. Additionally, more hydrogen and oxygen are produced, resulting in increases of net revenue.

Finally, the last step is to optimise the operation of the electrolyser for the case where there is a market for hydrogen and/or oxygen. For this purpose, the compressor flow was increased to 0.54 kg/h, since this is the component that is limiting the production of hydrogen and oxygen. With this simulation, it was possible to observe that to increase the production of hydrogen and meet a demand of 8kg daily for the Bin Lorry, it is better to set the priorities as shown in the Table 48 for the simulation “Run 18”. This operation allows to use the electricity needed from the electrolyser and would lead to a better revenue even in case of just an oxygen market, which is the larger output from the electrolyser.

8.4 Sensitivity Analysis of Kerosene Price

Changes of the priorities that the control system can have among Electrolyser, E-boiler and Grid, can result in more revenues for the operation of the system. As seen in some simulations before (Run 2 and 4 or Run 15 and 18) the philosophies can be seen as a trade-off between more consumption of kerosene to increase electricity exports or more H_2/O_2 production. As an example, Table 49 shows the comparison of the Run2 and Run 3 simulations. The table shows that it is better to use more kerosene in order to export more electricity to the grid and get more income.



Simulation settings	Run 2	Run 3
CHP	Full Capacity	Full Capacity
Wind Scenario	Average	Average
Control Philosophy	Demand Driven	Supply Driven
Electricity Priority 1	Eboiler	Eboiler
Electriicty Priority 2	ELY	ELY
Electricity Priority 3	Grid	Grid
Hydrogen demand driven? (uses grid)	no	no
Bin lorry demand	4	4
Hydrogen demand	0	0
Oxygen demand	0	0
Anaerobic Digestion Scenario	Status Quo 2017	Status Quo 2017

Balance	**Price/unit**	**Quantity**		**Subtotal**	**Quantity**		**Subtotal**
Costs							
Kerosene (liter)	£ 0.51	4,849	liters	£ 2,454	1,483	liters	£ 750
Cow Slurry (qty/week)	£ 400.00	-	Tn	£ -	-	Tn	£ -
Fresh Water (m3)	£ 0.71	-	m3	£ -	-	m3	£ -
Electricity import (kWh)	£ 0.11	887,432	kWh	£ 97,618	887,432	kWh	£ 97,618
for CREED facility	£ 0.11	887,432	kWh	£ 97,618	887,432	kWh	£ 97,618
for Electrolizer	£ 0.11	-	kWh	£ -	-	kWh	£ -
Total Costs				£ 100,071			£ 98,368
Revenues							
WT generation (kWh)	£ 0.19	1,100,630	kWh	£ 207,249	1,100,630	kWh	£ 207,249
CHP electricity generation (kWh)	£ 0.08	425,676	kWh	£ 35,842	425,698	kWh	£ 35,844
Gate fee (Tn)			Tn	£ -		Tn	£ -
Non-ensiled fish waste	£ 180.00	19	Tn	£ 3,330	19	Tn	£ 3,330
Ensiled fish waste	£ 130.00	50	Tn	£ 6,508	50	Tn	£ 6,508
H2 sales (kg) (4)	£ -	-	kg	£ -	-	kg	£ -
O2 sales (kg) (1.8)	£ -	6,828	kg	£ -	6,011	kg	£ -
WT export (kWh)	£ 0.05	721,964	kWh	£ 32,922	577,274	kWh	£ 26,324
CHP export (kWh)	£ 0.05	158,160	kWh	£ 8,035	152,462	kWh	£ 7,745
Savings from Diesel (liters)	£ 1.24	2,754	liters	£ 3,414	2,414	liters	£ 2,993
Total Benefits				£ 297,299			£ 289,992
Net				**£ 197,228**			**£ 191,624**
Environmental							
				CO2 emissions			**CO2 emissions**
Kerosene (kgCO2)				13,021			3,983
Diesel (kgCO2)				7,357			6,449
Grid (kgCO2)				2,704			58,347
No CH4 to landfill (kgCO2)				(157,688)			(157,688)
Total emissions (kg)				**(134,606)**			**(88,909)**

Table 49. Comparison between Run 2 and 3

In the cases compared above, from a purely economic point of view it is better to buy kerosene to avoid the electricity from the wind turbine to supply the E-boiler but to export it. This is due to the low price of kerosene, therefore, depending on its behaviour the settings of operating the system could change, as it is shown on the Figure 63.

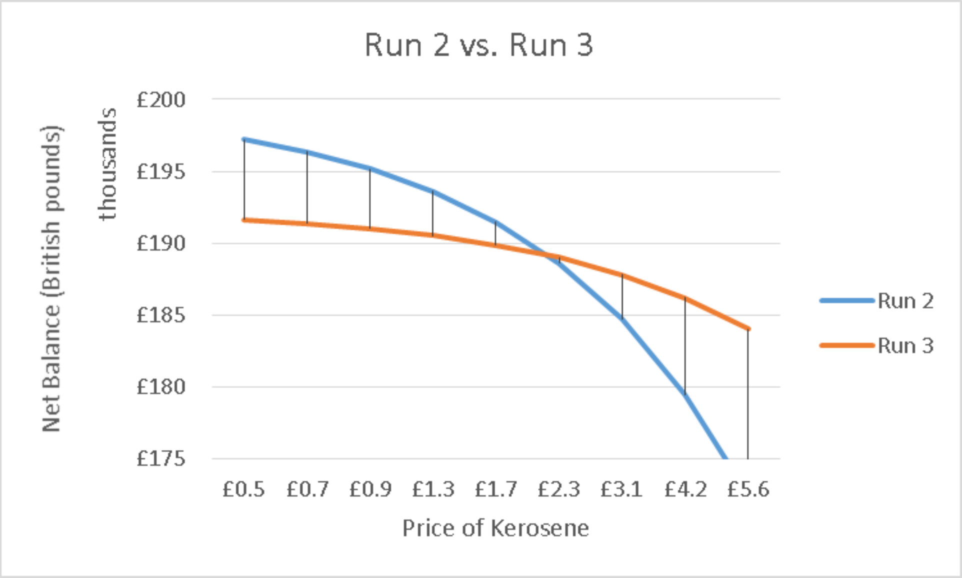


Figure 63. Sensitivity analysis of kerosene price

For the example above, it is possible to observe that when the kerosene price is 2.17 GBP/litre, the priorities of the control system should change. Although, currently this price of kerosene is far from realistic to assume.

9. Summary of Results

9.1 Final Combination of Scenarios

From the results given in Chapter 8, the following combination of scenarios which are chosen to. This combination brings the best results in the model for both economic and environmental benefits, while minimizing curtailment from the wind turbine are as shown in Table 50 below. The full output and costs results can be referred from Table 48 "Run 18" earlier.

AD Scenario	Scenario 3 Dilution
CHP	Full Capacity
Control Philosophy	Demand Driven
Electricity Priority 1	Electrolyser
Electricity Priority 2	E-boiler
Electricity Priority 3	Grid
Hydrogen Demand	8 kg

Table 50: Final Optimized Combination of Scenarios

9.2 Usage of Wind Turbine and Effects of Seasonality

As explained earlier in Chapter 3, the electricity generated at the wind turbine installed can be utilized to supply the electricity demand within the facility, instead of having it all exported to the grid, minimizing losses from curtailment. From the model, the net wind turbine generation under the Average scenario was simulated under various control philosophies of the model, with a fixed AD Scenario 2 Dilution. From the results shown under in Figure 64, it is shown that the electricity usage by prioritizing the electric boiler and electrolyser can be increased. This results in a higher revenue for the whole facility, instead of the operation it at the Current control philosophy. If the facility operation is Demand Driven or Supply Driven, the revenue can further increase while electricity curtailment is significantly reduced. As worst, average, and best wind profile does not significantly change the distribution of the electricity generated used, a comparison of how seasonality can affect the final revenue is also shown in the graph for the Demand Driven scenario.

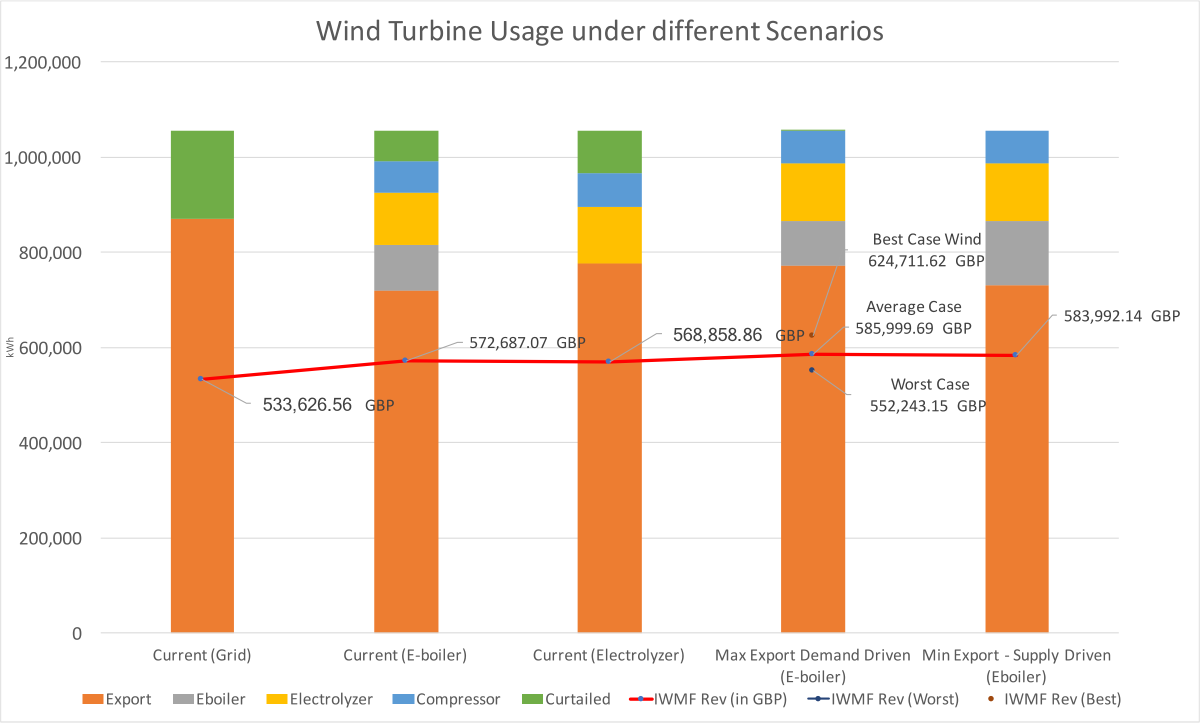


Figure 64: Wind Turbine Electricirty Utilizations under Different Scenarios

9.3 Appropriate Pricing of Gate Fee

From the IWMF perspective, the use of fish waste increases the revenue generation from increased CHP electricity generation as well as the gate fees collected from SSC. On the other hand, SSC can also benefit by increasing their savings of putting the fish waste into AD rather than into landfill. However, it was not clear whether the gate fee stipulated within the agreement between both parties equally benefit both partners. Hence, an analysis of a fair pricing of the gate fee is calculated by using the model. The prevailing costs used for this analysis is shown in Table 51 below.

Type	Fees	Price	Source
Non-Ensiled Fish Waste	AD_Gate Fee	180 GBP/tonne	SSC & IWMF Contract
	Landfill Tax	86.10 GBP/tonne	IWMF
	Disposal Fee at landfill	190 GBP/tonne	IWMF
Fish Waste Ensiled	AD_Gate Fee	130 GBP/tonne	SSC & IWMF Contract
	Landfill Tax	86.10 /tonne	IWMF
	Disposal Fee at land fill	49.82 GBP/tonne	IWMF
	Ensiling Cost	85.48 GBP/tonne	Calculated. Refer to Chapter 3

All Fish Waste	Cost of Transporting Fish Waste to Mainland for Incineration	300.00 GBP/tonne	SSC

Table 51: Fish Waste Related Costs

From running the scenarios, it is found out in all cases, SSC reduces its costs to process fish waste, while IWMF increases its revenue, the highest being in Scenario 2 Dilution. For this scenario, fish waste quantity utilized is 1594 tonnes. This scenario would also include fish ensiling too meet the fish waste demand needed, whose additional costs is described in Chapter 3. The revenue and savings per tonne of fish for the prevailing gate fee is then calculated for both parties, its differences being compared to a Scenario 1 No Fish Composition, is as shown in Table 52 below.

Scenario	Benefit to IWMF £/ Ton	Benefit to SSC £/ Ton
Scenario 2 Dilution	187	56.28

Scenario	Benefit to IWMF £/ Ton	Benefit to SSC £/ Ton
Scenario 2 Dilution	187	56.28

Table 52: Benefit per tonne of fish waste for SSC and IWMF

The above table indicates that for one tonne of fish waste put into AD, the benefit to IWMF is three times as compared to the benefit to SSC. Hence there can be a possibility to reduce the gate fees which in a way would bring parity to the benefits received by each project partner and in a way, encourage more fish waste (and potentially ensiling process) to IWMF. In order to do so, the Pareto principle was applied which tries to ensure equal benefits to the project partners.

It is noteworthy to mention that the benefit of IWMF neither accounts the asset valuation of the pasteurizer nor the operational and handling cost for the incoming fish waste to IWMF. Therefore, the purpose of this assessment is to show in a qualitative rather than a quantitative way of how the issue of gate fee could be approached. Before carrying out the analysis it was assumed to deduct 20% of the benefit to account for the above costs. Hence the benefit to IWMF by using the fish waste is shown in ranges. For analysis, two separate cases have been considered.

Case A: In this case, the local landfill for fish waste dumping is considered as an alternative to the fish waste put into AD. The IWMF benefit curve meets the SSC benefit curve at 2 points indicating the range of reduction in AD Gate fees. It is found that the gate fees can be reduced between 30% -40% to bring parity in the benefits to the both partners, as seen in Figure 65 below.

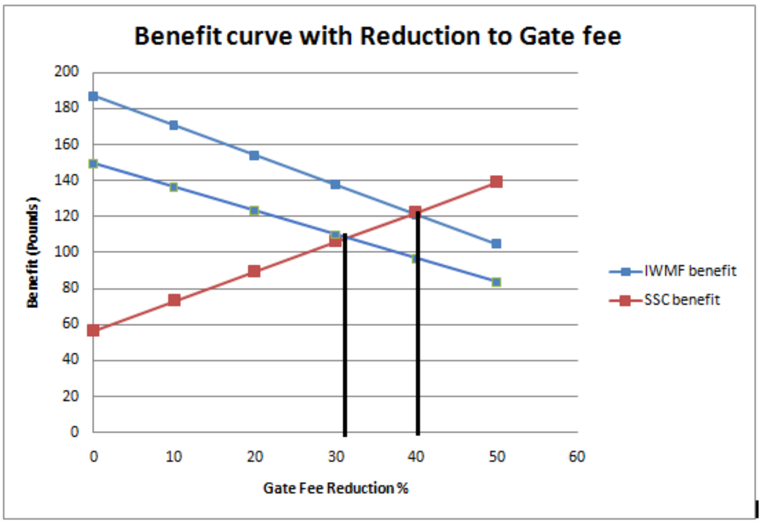


Figure 65: Benefit Curve with Gate Fee Reduction (Case A)

Case B: In this case it is assumed that the local land filling with fish waste is not allowed and considers the only option of sending the fish waste to the main land for incineration. It is found that the gate fees can be reduced between 18%-28% and to bring parity in the benefits to the both partners, as seen in Figure 66 below.

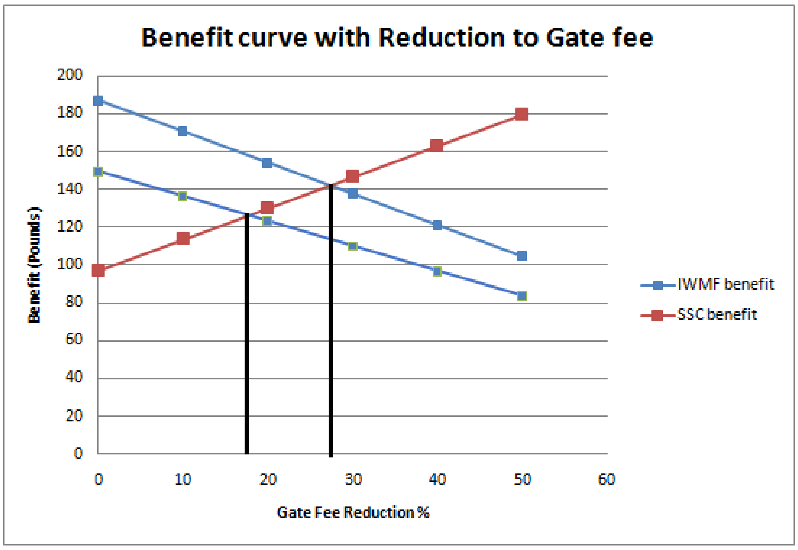


Figure 66: Benefit Curve with Gate Fee Reduction (Case B)

The above conclusion drawn regarding the reduction of gate fees is completely based on the data generated by the model which may not be the reflection of reality.

10. Conclusion

With various studies, field research and meetings with the project partners, the study team has developed an energy model to integrate the various renewable technologies and the local resources of waste. With such a model, it was possible to develop a number of scenarios and describe possible opportunities to meet the local demand of hydrogen and oxygen while analysing various alternate options for improvements for the anaerobic digester and the control philosophies at IWMF.

The study team investigated the current anaerobic digester in operation and found various options to improve the biogas quality and quantity. It was inferred that the introduction of fish waste and cow slurry into the digester, as well as dilution of centrate affects the characteristics of the biogas produced. It was concluded that the best option for running the biogas digester is to dilute the concentrate and use fish waste and cow slurry in appropriate proportions to enhance the quality and the quantity of the biogas.

Considering the importance of fish waste, it is important to find ways to ensure that sufficient flow is available to be used in the co-digestion process of the biogas plant. The waste from fish processing is available in constant volumes, but the same cannot be said for fish mortalities. Any option to ensure or quantify constant volume of fish mortalities will be desirable for proper and regular functioning of the AD. The team explored various technologies to store the fish mortalities and inferred that ensilage can be one of the possible option.

The enhancement in the quantity and quality of the biogas tends to boost the CHP electricity production. Together with the electricity production from the wind turbine, the enables the IWMF to run the electrolyser at higher capacity factor and utilising the electrolyser to produce hydrogen and oxygen to meet the local demands. The team analysed the configuration of the system consisting the electrolyser, compressor, buffer storage and the refuelling station and came to the conclusion that compressor plays a key factor in the whole system. With a 60kW electrolyser and a compressor of0.84kg/h flow rate, the hydrogen production can be as high as 5,910 kg annually, thus saving 6,240 litres of diesel and meeting 88% of the imported oxygen demand of the Barvas fish hatchery.

Finally, the various components and technologies are integrated by developing a model that allows simulation of various scenarios and control philosophies. This enables us to analyse their impact from an economical and environmental perspective, in which the results are outlined in Chapter 8.

It is hoped that the model and the overall results from this project can be used to benefit the project partners for their future collaborations.

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Appendices

Appendix A: Fish and Anaerobic Digester

Year	Scotland's Salmon Production	Prediction of Scotland's Salmon Production (Tonnes)	95% Confidence Interval Maximum (Tonnes)	95% Confidence Interval Minimum (Tonnes)	95% Prediction Interval Minimum (Tonnes)	95% Prediction Interval Minimum (Tonnes)
2007	129,930.0	134,173.1	144,452.5	123,893.8	154,616.5	113,729.8
2008	128,606.0	138,814.6	147,765.4	129,863.8	158,623.2	119,006.0
2009	144,247.0	143,456.1	151,217.8	135,694.3	162,756.6	124,155.6
2010	154,164.0	148,097.5	154,883.6	141,311.4	167,026.8	129,168.3
2011	158,018.0	152,739.0	158,865.6	146,612.4	171,441.9	134,036.1
2012	162,223.0	157,380.5	163,270.8	151,490.1	176,007.3	138,753.6
2013	163,234.0	162,021.9	168,148.5	155,895.3	180,724.8	143,319.0
2014	179,022.0	166,663.4	173,449.5	159,877.3	185,592.6	147,734.2
2015	171,722.0	171,304.8	179,066.6	163,543.1	190,605.4	152,004.3
2016	162,817.0	175,946.3	184,897.1	166,995.5	195,754.9	156,137.7
2017	177,202.0	180,587.8	190,867.1	170,308.4	201,031.1	160,144.4
2018		185,230.0	196,930.1	173,529.9	206,423.3	164,036.7
2019		189,871.5	203,054.7	176,688.3	211,918.3	167,824.7
2020		194,513.0	209,222.8	179,803.2	217,505.2	171,520.8
2021		199,154.5	215,422.1	182,886.9	223,173.3	175,135.7
2022		203,796.0	221,644.6	185,947.4	228,912.5	178,679.5
2023		208,437.5	227,884.5	188,990.5	234,713.9	182,161.1
2024		213,079.0	234,137.9	192,020.1	240,569.8	185,588.2
2025		217,720.5	240,401.9	195,039.1	246,473.1	188,967.9
2026		222,362.0	246,674.4	198,049.6	252,417.9	192,306.1

Table 53: Scotland's salmon production with 95% confidence and prediction interval values until 2026 (Based upon Munro & Wallace, 2017)

S.N.	Ensiler Size	Sty	Rate
1	Minimort (300L)	1	5,282.00
2	Silamort (940L) with discharge pump	1	13,250.00
3	Super Mortalities (2000L)	1	16,533.00
4	Motorize Acid Pump with digital timer control	1	2,942.00
5	Hydraulic Power Pack	1	1,669.00
6	Polyethylene Sealed Tank (10,000L) [a]	1	3,294.00
7	5000 L Ensiler	1	130,000.00
8	85% Formic Acid (metric tonne) [b]	1	250
9	Labour Cost (Per Hour)	NA	7.83

Table 54: The Cost of Ensiler (Norfab Product Ltd, 2018) and (Market Research Future, 2017) [b] and (Tanks for Everything, 2018) [a]

Table 55 Parameters for Simulation

Parameters used for simulations	**Household Waste** (Naroznova, Møller, & Scheutz, 2016)	**Fish Waste** (Table 6, Chapter 2)	**Cattle Manure** (SIMBA Software, 2016)	**Centrate** (IWMF, 2018)	**Potable Water** (IWMF, 2018)	**Units**
Degradable fraction of crude fibre (XF):	0,95	0,62	0,7	1	0,0001	-
Slowly disintegrable fractions of VSS:	0	0	0,5365	1	0,0001	-
Fast disintegrable fractions of VSS:	0,1	1	0,4635	0	0,0001	-
Dissolved inert fraction of COD:	-	0	0,1	0,1	0,0001	kg COD/ kg COD
Particulate inert fraction of COD:	0,02	0,02	0,2	0,2	0,0001	kg COD/ kg COD
Crude Fibre fraction (XF) of TSS:	0,05089	0,0684	0,14	0,05	0,0005	kg TSS/ kg TSS
Crude Protein fraction (XP) of TSS:	0,0574	0,0646	0,035	0,012	0,000112	kg TSS/ kg TSS
Crude Lipid fraction (XL) of TSS:	0,0498	0,026	0,18	0,06	0,00006	kg TSS/ kg TSS
Temperature:	-	57	57	23	10	C
pH value:	-	6	7,1	7,1	7	-
Acid Capacity (pH>4.3):	-	0	80	80	0,632	mol/m3
Volatile fatty acids:	-	30	5	8	0,0001	kg AC/ m3

Table 56 Household Waste Characteristics (IWMF, 2018)

Household Waste						
Month	**TSS (kg/m3)**	**VSS (kg/m3)**	**TSS (kg/m3)**	**VSS (kg/m3)**	**TSS (kg/m3)**	**VSS (kg/m3)**
	2016		**2017**		**2018 (Projected Year)**	
Jan	449	332 (0,74%)	459	358 (0,78%)	373	234
Feb	574	428 (0,73%)	377	317 (0,84%)	373	234
Mar	400	273 (0,68%)	462	370 (0,8%)	373	234
Apr	387	305 (0,787%)	424	318 (0,75%)	373	234
May	490	387 (0,79%)	421	312 (0,74%)	373	234
Jun	419	326 (0,779%)	321	257 (0,8%)	373	234
Jul	294	228 (0,777%)	321	257 (0,8%)	373	234
Aug	323	243 (0,75%)	336	262 (0,78%)	373	234
Sep	311	245	331	255	373	234

		(0,788%)		(0,77%)		
Oct	371	319 (0,859%)	331	255 (0,77%)	373	234
Nov	339	265 (0,783%)	320	211 (0,66%)	373	234
Dec	373	318 (0,853%)	320	211 (0,66%)	373	234

Table 57: Feed for Scenario Status Quo 2016

Household Waste Parameters			
Time	TSS (kg/m3)	VSS(kg/m3)	HH Waste (t)
0	449	332	0
1	449	332	0
2	449	332	0
3	449	332	6
4	449	332	7
5	449	332	12
6	449	332	5
7	449	332	2
8	449	332	0
9	449	332	0
10	449	332	8
11	449	332	3
12	449	332	5
13	449	332	8
14	449	332	5
15	449	332	0
16	449	332	0
17	449	332	7
18	449	332	4
19	449	332	5
20	449	332	6
21	449	332	1
22	449	332	0
23	449	332	0
24	449	332	7
25	449	332	4
26	449	332	5
27	449	332	5
28	449	332	3
29	449	332	0
30	449	332	0
31	574	418	4

32	574	418	5
33	574	418	6
34	574	418	4
35	574	418	5
36	574	418	0
37	574	418	0
38	574	418	8
39	574	418	5
40	574	418	7
41	574	418	8
42	574	418	4
43	574	418	0
44	574	418	0
45	574	418	8
46	574	418	5
47	574	418	6
48	574	418	6
49	574	418	4
50	574	418	0
51	574	418	0
52	574	418	6
53	574	418	5
54	574	418	6
55	574	418	13
56	574	418	3
57	574	418	0
58	574	418	0
59	400	273	8
60	400	273	6
61	400	273	7
62	400	273	4
63	400	273	5
64	400	273	0
65	400	273	0
66	400	273	17
67	400	273	4
68	400	273	9
69	400	273	8
70	400	273	11
71	400	273	0
72	400	273	0
73	400	273	9

74	400	273	6
75	400	273	8
76	400	273	9
77	400	273	4
78	400	273	0
79	400	273	0
80	400	273	9
81	400	273	7
82	400	273	7
83	400	273	10
84	400	273	3
85	400	273	0
86	400	273	0
87	400	273	10
88	400	273	5
89	400	273	8
90	400	273	6
91	387	305	5
92	387	305	0
93	387	305	0
94	387	305	19
95	387	305	7
96	387	305	9
97	387	305	8
98	387	305	4
99	387	305	0
100	387	305	0
101	387	305	9
102	387	305	7
103	387	305	8
104	387	305	8
105	387	305	5
106	387	305	0
107	387	305	0
108	387	305	8
109	387	305	13
110	387	305	10
111	387	305	9
112	387	305	5
113	387	305	0
114	387	305	0
115	387	305	9

116	387	305	6
117	387	305	8
118	387	305	6
119	387	305	6
120	387	305	0
121	490	387	0
122	490	387	0
123	490	387	10
124	490	387	8
125	490	387	3
126	490	387	9
127	490	387	0
128	490	387	0
129	490	387	4
130	490	387	9
131	490	387	6
132	490	387	12
133	490	387	9
134	490	387	0
135	490	387	0
136	490	387	9
137	490	387	9
138	490	387	10
139	490	387	9
140	490	387	12
141	490	387	0
142	490	387	0
143	490	387	7
144	490	387	11
145	490	387	10
146	490	387	10
147	490	387	10
148	490	387	0
149	490	387	0
150	490	387	8
151	490	387	0
152	419	326	9
153	419	326	8
154	419	326	14
155	419	326	0
156	419	326	0
157	419	326	11

158	419	326	11
159	419	326	11
160	419	326	12
161	419	326	10
162	419	326	0
163	419	326	0
164	419	326	11
165	419	326	19
166	419	326	11
167	419	326	13
168	419	326	11
169	419	326	0
170	419	326	0
171	419	326	10
172	419	326	11
173	419	326	10
174	419	326	11
175	419	326	11
176	419	326	0
177	419	326	0
178	419	326	9
179	419	326	14
180	419	326	13
181	419	326	11
182	419	326	12
183	294	228	0
184	294	228	0
185	294	228	17
186	294	228	10
187	294	228	8
188	294	228	8
189	294	228	11
190	294	228	0
191	294	228	0
192	294	228	11
193	294	228	8
194	294	228	6
195	294	228	12
196	294	228	13
197	294	228	0
198	294	228	0
199	294	228	13

200	294	228	16
201	294	228	13
202	294	228	12
203	294	228	12
204	294	228	0
205	294	228	0
206	294	228	8
207	294	228	21
208	294	228	16
209	294	228	10
210	294	228	11
211	294	228	0
212	294	228	0
213	294	228	8
214	323	243	10
215	323	243	11
216	323	243	8
217	323	243	15
218	323	243	0
219	323	243	0
220	323	243	10
221	323	243	10
222	323	243	8
223	323	243	11
224	323	243	10
225	323	243	0
226	323	243	0
227	323	243	10
228	323	243	7
229	323	243	13
230	323	243	12
231	323	243	14
232	323	243	0
233	323	243	0
234	323	243	9
235	323	243	12
236	323	243	10
237	323	243	10
238	323	243	15
239	323	243	0
240	323	243	0
241	323	243	17

242	323	243	8
243	323	243	11
244	323	243	11
245	311	245	9
246	311	245	0
247	311	245	0
248	311	245	8
249	311	245	7
250	311	245	15
251	311	245	2
252	311	245	9
253	311	245	0
254	311	245	0
255	311	245	12
256	311	245	5
257	311	245	11
258	311	245	5
259	311	245	9
260	311	245	0
261	311	245	0
262	311	245	7
263	311	245	7
264	311	245	11
265	311	245	8
266	311	245	11
267	311	245	0
268	311	245	0
269	311	245	3
270	311	245	20
271	311	245	11
272	311	245	6
273	311	245	7
274	311	245	0
275	371	319	0
276	371	319	7
277	371	319	7
278	371	319	1
279	371	319	22
280	371	319	12
281	371	319	0
282	371	319	0
283	371	319	6

284	371	319	7
285	371	319	47
286	371	319	9
287	371	319	6
288	371	319	0
289	371	319	0
290	371	319	9
291	371	319	9
292	371	319	8
293	371	319	10
294	371	319	7
295	371	319	0
296	371	319	0
297	371	319	7
298	371	319	6
299	371	319	4
300	371	319	10
301	371	319	6
302	371	319	0
303	371	319	0
304	371	319	8
305	371	319	6
306	339	265	10
307	339	265	14
308	339	265	6
309	339	265	0
310	339	265	0
311	339	265	7
312	339	265	7
313	339	265	7
314	339	265	9
315	339	265	15
316	339	265	0
317	339	265	0
318	339	265	6
319	339	265	5
320	339	265	7
321	339	265	8
322	339	265	5
323	339	265	0
324	339	265	0
325	339	265	6

326	339	265	6
327	339	265	5
328	339	265	8
329	339	265	5
330	339	265	0
331	339	265	0
332	339	265	9
333	339	265	11
334	339	265	7
335	339	265	6
336	373	318	6
337	373	318	0
338	373	318	0
339	373	318	4
340	373	318	7
341	373	318	8
342	373	318	4
343	373	318	15
344	373	318	0
345	373	318	0
346	373	318	5
347	373	318	7
348	373	318	8
349	373	318	5
350	373	318	5
351	373	318	0
352	373	318	0
353	373	318	6
354	373	318	3
355	373	318	8
356	373	318	6
357	373	318	6
358	373	318	0
359	373	318	0
360	373	318	4
361	373	318	0
362	373	318	0
363	373	318	0
364	373	318	0

Table 58: Feed for Scenario Status Quo 2017

	Household Waste Parameters			Fish Waste Parameters			
Time	**TSS (kg/m3)**	**VSS (kg/m3)**	**HH Waste (t)**	**TSS (kg/m3)**	**VSS (kg/m3)**	**NH4 (kg/m3)**	**Fish Waste (t)**
0	459	358	0	380	359	0,01	0,0
1	459	358	4	380	359	0,01	0,0
2	459	358	4	380	359	0,01	0,0
3	459	358	7	380	359	0,01	0,0
4	459	358	6	380	359	0,01	0,0
5	459	358	3	380	359	0,01	0,0
6	459	358	0	380	359	0,01	0,0
7	459	358	0	380	359	0,01	0,0
8	459	358	11	380	359	0,01	0,0
9	459	358	5	380	359	0,01	0,0
10	459	358	6	380	359	0,01	0,0
11	459	358	6	380	359	0,01	0,0
12	459	358	5	380	359	0,01	0,0
13	459	358	0	380	359	0,01	0,0
14	459	358	0	380	359	0,01	0,0
15	459	358	8	380	359	0,01	0,0
16	459	358	6	380	359	0,01	0,0
17	459	358	7	380	359	0,01	0,0
18	459	358	4	380	359	0,01	0,0
19	459	358	4	380	359	0,01	0,0
20	459	358	0	380	359	0,01	0,0
21	459	358	0	380	359	0,01	0,0
22	459	358	7	380	359	0,01	0,0
23	459	358	7	380	359	0,01	0,0
24	459	358	7	380	359	0,01	0,0
25	459	358	14	380	359	0,01	0,0
26	459	358	4	380	359	0,01	0,0
27	459	358	0	380	359	0,01	0,0
28	459	358	0	380	359	0,01	0,0
29	459	358	7	380	359	0,01	0,0
30	459	358	5	380	359	0,01	0,0
31	377	317	10	380	359	0,01	0,0
32	377	317	6	380	359	0,01	0,0
33	377	317	4	380	359	0,01	0,0
34	377	317	0	380	359	0,01	0,0
35	377	317	0	380	359	0,01	0,0
36	377	317	8	380	359	0,01	0,0
37	377	317	10	380	359	0,01	0,0
38	377	317	7	380	359	0,01	0,0
39	377	317	4	380	359	0,01	0,0
40	377	317	7	380	359	0,01	0,0
41	377	317	0	380	359	0,01	0,0

42	377	317	0	380	359	0,01	0,0
43	377	317	6	380	359	0,01	0,0
44	377	317	6	380	359	0,01	0,0
45	377	317	8	380	359	0,01	0,0
46	377	317	5	380	359	0,01	0,0
47	377	317	5	380	359	0,01	0,0
48	377	317	0	380	359	0,01	0,0
49	377	317	0	380	359	0,01	0,0
50	377	317	8	380	359	0,01	0,0
51	377	317	5	380	359	0,01	0,0
52	377	317	6	380	359	0,01	0,0
53	377	317	5	380	359	0,01	0,0
54	377	317	6	380	359	0,01	0,0
55	377	317	0	380	359	0,01	0,0
56	377	317	0	380	359	0,01	0,0
57	377	317	7	380	359	0,01	0,0
58	377	317	4	380	359	0,01	0,0
59	462	370	6	380	359	0,01	0,0
60	462	370	5	380	359	0,01	0,0
61	462	370	5	380	359	0,01	0,0
62	462	370	0	380	359	0,01	0,0
63	462	370	0	380	359	0,01	0,0
64	462	370	5	380	359	0,01	0,0
65	462	370	5	380	359	0,01	0,0
66	462	370	7	380	359	0,01	0,0
67	462	370	6	380	359	0,01	0,0
68	462	370	5	380	359	0,01	0,0
69	462	370	0	380	359	0,01	0,0
70	462	370	0	380	359	0,01	0,0
71	462	370	0	380	359	0,01	0,0
72	462	370	10	380	359	0,01	0,0
73	462	370	5	380	359	0,01	0,0
74	462	370	8	380	359	0,01	0,0
75	462	370	3	380	359	0,01	0,0
76	462	370	0	380	359	0,01	0,0
77	462	370	0	380	359	0,01	0,0
78	462	370	6	380	359	0,01	0,0
79	462	370	5	380	359	0,01	0,0
80	462	370	5	380	359	0,01	0,0
81	462	370	5	380	359	0,01	0,0
82	462	370	8	380	359	0,01	0,0
83	462	370	0	380	359	0,01	0,0
84	462	370	0	380	359	0,01	0,0
85	462	370	6	380	359	0,01	0,0
86	462	370	5	380	359	0,01	0,0

87	462	370	7	380	359	0,01	0,0
88	462	370	7	380	359	0,01	0,0
89	462	370	4	380	359	0,01	0,0
90	424	318	0	380	359	0,01	0,0
91	424	318	0	380	359	0,01	0,0
92	424	318	10	380	359	0,01	0,0
93	424	318	6	380	359	0,01	0,0
94	424	318	7	380	359	0,01	0,0
95	424	318	7	380	359	0,01	0,0
96	424	318	7	380	359	0,01	0,0
97	424	318	0	380	359	0,01	0,0
98	424	318	0	380	359	0,01	0,0
99	424	318	10	380	359	0,01	0,0
100	424	318	5	380	359	0,01	0,0
101	424	318	10	380	359	0,01	0,0
102	424	318	8	380	359	0,01	0,0
103	424	318	5	380	359	0,01	0,0
104	424	318	0	380	359	0,01	0,0
105	424	318	0	380	359	0,01	0,0
106	424	318	7	380	359	0,01	0,0
107	424	318	5	380	359	0,01	0,0
108	424	318	11	380	359	0,01	0,0
109	424	318	7	380	359	0,01	0,0
110	424	318	8	380	359	0,01	0,0
111	424	318	0	380	359	0,01	0,0
112	424	318	0	380	359	0,01	0,0
113	424	318	7	380	359	0,01	0,0
114	424	318	5	380	359	0,01	0,0
115	424	318	7	380	359	0,01	0,0
116	424	318	8	380	359	0,01	0,0
117	424	318	6	380	359	0,01	0,0
118	424	318	0	380	359	0,01	0,0
119	424	318	0	380	359	0,01	0,0
120	421	312	9	380	359	0,01	0,0
121	421	312	8	380	359	0,01	0,0
122	421	312	11	380	359	0,01	0,0
123	421	312	10	380	359	0,01	0,0
124	421	312	12	380	359	0,01	0,0
125	421	312	0	380	359	0,01	0,0
126	421	312	0	380	359	0,01	0,0
127	421	312	12	380	359	0,01	0,0
128	421	312	8	380	359	0,01	0,0
129	421	312	10	380	359	0,01	0,0
130	421	312	9	380	359	0,01	0,0
131	421	312	9	380	359	0,01	0,0

132	421	312	0	380	359	0,01	0,0
133	421	312	0	380	359	0,01	0,0
134	421	312	8	380	359	0,01	0,0
135	421	312	12	380	359	0,01	0,0
136	421	312	11	380	359	0,01	0,0
137	421	312	6	380	359	0,01	0,0
138	421	312	8	380	359	0,01	0,0
139	421	312	0	380	359	0,01	0,0
140	421	312	0	380	359	0,01	0,0
141	421	312	12	380	359	0,01	0,0
142	421	312	10	380	359	0,01	0,0
143	421	312	11	380	359	0,01	0,0
144	421	312	10	380	359	0,01	0,0
145	421	312	9	380	359	0,01	0,0
146	421	312	0	380	359	0,01	0,0
147	421	312	0	380	359	0,01	0,0
148	421	312	13	380	359	0,01	0,0
149	421	312	10	380	359	0,01	0,0
150	421	312	12	380	359	0,01	0,0
151	321	257	14	380	359	0,01	2,7
152	321	257	0	380	359	0,01	0,0
153	321	257	0	380	359	0,01	0,0
154	321	257	0	380	359	0,01	0,0
155	321	257	13	380	359	0,01	0,0
156	321	257	16	380	359	0,01	0,0
157	321	257	13	380	359	0,01	0,0
158	321	257	10	380	359	0,01	1,7
159	321	257	12	380	359	0,01	0,0
160	321	257	0	380	359	0,01	0,0
161	321	257	0	380	359	0,01	0,0
162	321	257	8	380	359	0,01	0,0
163	321	257	9	380	359	0,01	0,0
164	321	257	15	380	359	0,01	0,0
165	321	257	13	380	359	0,01	3,1
166	321	257	11	380	359	0,01	0,0
167	321	257	0	380	359	0,01	0,0
168	321	257	0	380	359	0,01	0,0
169	321	257	11	380	359	0,01	0,0
170	321	257	14	380	359	0,01	0,0
171	321	257	12	380	359	0,01	0,0
172	321	257	12	380	359	0,01	5,1
173	321	257	12	380	359	0,01	0,0
174	321	257	0	380	359	0,01	0,0
175	321	257	0	380	359	0,01	0,0
176	321	257	5	380	359	0,01	0,0

177	321	257	9	380	359	0,01	0,0
178	321	257	13	380	359	0,01	0,0
179	321	257	12	380	359	0,01	4,6
180	321	257	0	380	359	0,01	0,0
181	321	257	0	380	359	0,01	0,0
182	321	257	0	380	359	0,01	0,0
183	321	257	11	380	359	0,01	0,0
184	321	257	15	380	359	0,01	0,0
185	321	257	11	380	359	0,01	0,0
186	321	257	14	380	359	0,01	6,8
187	321	257	9	380	359	0,01	0,0
188	321	257	0	380	359	0,01	0,0
189	321	257	0	380	359	0,01	0,0
190	321	257	11	380	359	0,01	0,0
191	321	257	9	380	359	0,01	0,0
192	321	257	13	380	359	0,01	0,0
193	321	257	11	380	359	0,01	1,5
194	321	257	12	380	359	0,01	0,0
195	321	257	0	380	359	0,01	0,0
196	321	257	0	380	359	0,01	0,0
197	321	257	11	380	359	0,01	0,0
198	321	257	7	380	359	0,01	0,0
199	321	257	16	380	359	0,01	0,0
200	321	257	10	380	359	0,01	1,3
201	321	257	10	380	359	0,01	0,0
202	321	257	0	380	359	0,01	0,0
203	321	257	0	380	359	0,01	0,0
204	321	257	9	380	359	0,01	0,0
205	321	257	14	380	359	0,01	0,0
206	321	257	14	380	359	0,01	0,0
207	321	257	8	380	359	0,01	0,0
208	321	257	14	380	359	0,01	2,8
209	321	257	0	380	359	0,01	0,0
210	321	257	0	380	359	0,01	0,0
211	321	257	11	380	359	0,01	0,0
212	336	262	7	380	359	0,01	0,0
213	336	262	15	380	359	0,01	0,0
214	336	262	7	380	359	0,01	0,0
215	336	262	7	380	359	0,01	0,0
216	336	262	0	380	359	0,01	0,0
217	336	262	0	380	359	0,01	0,0
218	336	262	8	380	359	0,01	0,0
219	336	262	8	380	359	0,01	0,0
220	336	262	0	380	359	0,01	0,0
221	336	262	0	380	359	0,01	0,0

222	336	262	14	380	359	0,01	0,0
223	336	262	0	380	359	0,01	0,0
224	336	262	0	380	359	0,01	0,0
225	336	262	9	380	359	0,01	0,0
226	336	262	11	380	359	0,01	0,0
227	336	262	13	380	359	0,01	0,0
228	336	262	11	380	359	0,01	0,0
229	336	262	9	380	359	0,01	0,0
230	336	262	0	380	359	0,01	0,0
231	336	262	0	380	359	0,01	0,0
232	336	262	9	380	359	0,01	0,0
233	336	262	11	380	359	0,01	0,0
234	336	262	11	380	359	0,01	0,0
235	336	262	9	380	359	0,01	3,2
236	336	262	8	380	359	0,01	0,0
237	336	262	0	380	359	0,01	0,0
238	336	262	0	380	359	0,01	0,0
239	336	262	12	380	359	0,01	0,0
240	336	262	13	380	359	0,01	1,7
241	336	262	11	380	359	0,01	0,0
242	336	262	10	380	359	0,01	1,3
243	331	255	12	380	359	0,01	0,0
244	331	255	0	380	359	0,01	0,0
245	331	255	0	380	359	0,01	0,0
246	331	255	10	380	359	0,01	0,0
247	331	255	10	380	359	0,01	0,0
248	331	255	15	380	359	0,01	0,0
249	331	255	0	380	359	0,01	3,4
250	331	255	11	380	359	0,01	0,0
251	331	255	0	380	359	0,01	0,0
252	331	255	0	380	359	0,01	0,0
253	331	255	7	380	359	0,01	0,0
254	331	255	3	380	359	0,01	2,9
255	331	255	15	380	359	0,01	0,0
256	331	255	14	380	359	0,01	0,0
257	331	255	10	380	359	0,01	3,2
258	331	255	0	380	359	0,01	0,0
259	331	255	0	380	359	0,01	0,0
260	331	255	6	380	359	0,01	0,0
261	331	255	8	380	359	0,01	0,0
262	331	255	10	380	359	0,01	3,7
263	331	255	13	380	359	0,01	0,0
264	331	255	8	380	359	0,01	2,2
265	331	255	0	380	359	0,01	0,0
266	331	255	0	380	359	0,01	0,0

267	331	255	8	380	359	0,01	0,0
268	331	255	15	380	359	0,01	0,0
269	331	255	8	380	359	0,01	3,9
270	331	255	8	380	359	0,01	0,0
271	331	255	13	380	359	0,01	5,5
272	331	255	0	380	359	0,01	0,0
273	331	255	0	380	359	0,01	0,0
274	331	255	8	380	359	0,01	0,0
275	331	255	12	380	359	0,01	0,0
276	331	255	16	380	359	0,01	7,7
277	331	255	7	380	359	0,01	0,0
278	331	255	7	380	359	0,01	0,3
279	331	255	0	380	359	0,01	0,0
280	331	255	0	380	359	0,01	0,0
281	331	255	6	380	359	0,01	0,0
282	331	255	7	380	359	0,01	0,0
283	331	255	7	380	359	0,01	0,0
284	331	255	7	380	359	0,01	0,0
285	331	255	3	380	359	0,01	0,0
286	331	255	0	380	359	0,01	0,0
287	331	255	0	380	359	0,01	0,0
288	331	255	1	380	359	0,01	0,0
289	331	255	5	380	359	0,01	0,0
290	331	255	0	380	359	0,01	0,0
291	331	255	4	380	359	0,01	0,0
292	331	255	8	380	359	0,01	0,0
293	331	255	0	380	359	0,01	0,0
294	331	255	0	380	359	0,01	0,0
295	331	255	3	380	359	0,01	0,0
296	331	255	5	380	359	0,01	0,0
297	331	255	1	380	359	0,01	0,0
298	331	255	1	380	359	0,01	0,0
299	331	255	2	380	359	0,01	0,0
300	331	255	0	380	359	0,01	0,0
301	331	255	0	380	359	0,01	0,0
302	331	255	4	380	359	0,01	0,0
303	331	255	1	380	359	0,01	0,0
304	320	211	0	380	359	0,01	0,0
305	320	211	1	380	359	0,01	0,0
306	320	211	3	380	359	0,01	0,0
307	320	211	5	380	359	0,01	0,0
308	320	211	0	380	359	0,01	0,0
309	320	211	0	380	359	0,01	0,0
310	320	211	1	380	359	0,01	0,0
311	320	211	1	380	359	0,01	0,0

312	320	211	4	380	359	0,01	0,0
313	320	211	2	380	359	0,01	0,0
314	320	211	0	380	359	0,01	0,0
315	320	211	0	380	359	0,01	0,0
316	320	211	22	380	359	0,01	0,0
317	320	211	1	380	359	0,01	0,0
318	320	211	1	380	359	0,01	0,0
319	320	211	0	380	359	0,01	0,0
320	320	211	2	380	359	0,01	0,0
321	320	211	0	380	359	0,01	0,0
322	320	211	0	380	359	0,01	0,0
323	320	211	0	380	359	0,01	0,0
324	320	211	0	380	359	0,01	0,0
325	320	211	2	380	359	0,01	0,0
326	320	211	0	380	359	0,01	0,0
327	320	211	2	380	359	0,01	0,0
328	320	211	0	380	359	0,01	0,0
329	320	211	0	380	359	0,01	0,0
330	320	211	1	380	359	0,01	0,0
331	320	211	1	380	359	0,01	0,0
332	320	211	0	380	359	0,01	0,0
333	320	211	0	380	359	0,01	0,0
334	320	211	2	380	359	0,01	0,0
335	320	211	1	380	359	0,01	0,0
336	320	211	0	380	359	0,01	0,0
337	320	211	0	380	359	0,01	0,0
338	320	211	1	380	359	0,01	0,0
339	320	211	0	380	359	0,01	0,0
340	320	211	0	380	359	0,01	0,0
341	320	211	2	380	359	0,01	0,0
342	320	211	1	380	359	0,01	0,0
343	320	211	0	380	359	0,01	0,0
344	320	211	0	380	359	0,01	0,0
345	320	211	1	380	359	0,01	0,0
346	320	211	2	380	359	0,01	0,0
347	320	211	0	380	359	0,01	0,0
348	320	211	1	380	359	0,01	0,0
349	320	211	2	380	359	0,01	0,0
350	320	211	0	380	359	0,01	0,0
351	320	211	0	380	359	0,01	0,0
352	320	211	0	380	359	0,01	0,0
353	320	211	2	380	359	0,01	0,0
354	320	211	0	380	359	0,01	0,0
355	320	211	1	380	359	0,01	0,0
356	320	211	5	380	359	0,01	0,0

357	320	211	0	380	359	0,01	0,0
358	320	211	0	380	359	0,01	0,0
359	320	211	0	380	359	0,01	0,0
360	320	211	0	380	359	0,01	0,0
361	320	211	1	380	359	0,01	0,0
362	320	211	3	380	359	0,01	0,0
363	320	211	1	380	359	0,01	0,0
364	320	211	0	380	359	0,01	0,0

Appendix B: Hydrogen Vehicles

Ford Transit Vans	
Type	Hydrogen Hybrid Vans Dual Fuel: Hydrogen and Diesel
Fuel capacity	Hydrogen tank:4.5kg
Hydrogen consumption	1.8kg/100km
Refuelling Pressure	350 bar
Environmental Performance	70% reduction in CO_2 emission 40 % reduction in nitrogen oxide emission
Manufacturer	ULEMCo
Price	Vehicle Price + conversion price =£40000(1) +£30000(aprox.) =£70000

Source**:** (H2 Aberdeen, 2015)
(1) (Lilly, 2018)

Renault Kangoo Maxi Z. E Vans	
Type	Plug-in Hybrid FuelCell Electric vans (Includes hydrogen fuel cell range Extender)
Fuel Capacity	1.78kg hydrogen Tank (1)
Hydrogen Consumption	0.5kg/100km
Refuelling Pressure	350 bar
Environmental performance	No harmful Emission
Manufacturer	SymbioFCell
Price	Vehicle price + Hydrogen kit price =£19,259 (2) + £30000(3) =£49259

Source: (H2 Aberdeen, 2015)
(2) (Lilly, 2018)
(1)& (3) (Symbio, 2016)

Hyundai iX35 Fuel Cell car	
Type	Fuel cell Hybrid
Fuel Capacity	hydrogen Tank:5.6kg
Hydrogen Consumption	0.9kg/100km
Refuelling Pressure	700 bar
Environmental performance	No harmful Emission
Price	£53,105(1)

Source: (Innovate UK -Technology Strategy Board, 2016)
(1) (Lilly, 2018)

Appendix C: Cost Inputs into the Model

No	Item	Description	Unit Price	Source
1	CHP Generator	Electricity Generation	8.42 Pence/kWh	CES OHLEH Model
		Electricity Export to Grid	5.08 Pence/kWh	CES OHLEH Model
2	Wind	Electricity Generation	18.83 Pence/kWh	CES OHLEH Model
		Electricity Export to Grid	4.56 Pence/kWh	CES OHLEH Model
3	Grid	Electricity Import from Grid	11.0 Pence/kWh	IWMF
4	Oxygen	Market Price	4 GBP/kg	SSC – purchase from supplier
5	Hydrogen	Market Price	2 GBP/kg	SSC – purchase from supplier
		IWMF Selling Price to SSC	1.80 GBP/kg	*Assumed sold 10% lower than market price*
6	Fish Waste Non-Ensiled	Gate Fee – to AD	180 GBP/tonne	SSC & IWMF Contract
		Landfill Tax – to Landfill	86.10 GBP/tonne	IWMF
		Disposal Fee – to landfill	190 GBP/tonne	IWMF
9	Fish Waste Ensiled	Gate Fee	130 GBP/tonne	SSC & IWMF Contract
		Landfill Tax	86.10 /tonne	IWMF
		Disposal Fee	49.82 GBP/tonne	IWMF
10	Kerosene	Market Price	0.506 GBP/kWh	(Boiler Juice, 2018) Price as of 22 Feb 2018
11	Diesel	Market Price	0.124 GBP/kWh	(Automobile Association Developments, 2018) Price as of 22 Feb 2018
12	Cow Slurry	Cost Per Transportation Hire	400 GBP/Hire	IWMF
13	Fresh Water	Cost for Dilution of Centrate	0.7068 GBP/Nm^3	IWMF