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Anaerobic Digestion and Resource Use within the Scotch Whisky & UK Beer Industries

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A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2015

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Abstract

This project assesses resource use within the Scotch whisky and UK beer industries. It focusses on water and energy usage and the potential of using the by-products from whisky and beer production as a feedstock for Anaerobic Digestion (AD) systems. Using data provided by breweries and distilleries it looks to validate values from literature or understand why they are different.

The average energy demand was found to be 8.83kWh per litre of whisky produced and 0.52kWh per litre of beer produced. On average three litres of water are used by a brewery for every litre of beer produced. On average a total of 296 litres of cooling water and 17 litres of process water were used for every litre of whisky produced. The economic results suggest that distillery and brewery by-products are well suited for AD-based energy generation. Using by-products for AD instead of selling it to third parties has more potential for generating income.

The average carbon dioxide emissions were 2.3kg of carbon dioxide for every litre of whisky produced and 0.16kg for every litre of beer produced. AD technology has the potential to greatly reduce carbon dioxide emissions and was found to reduce emissions in one case by as much as 97%.

Acknowledgements

I would like to thank my industrial contact Neil Phillips for his time, advice and guidance on this project.

I would also like to thank Robert Kennedy at Stathendrick Biogas for helping me with his extensive knowledge of Anaerobic Digestion systems.

A special thanks to my academic supervisor Paul Strachan and the other lecturers for creating and organising a truly fantastic course.

Thanks to my friends and family that have supported and encouraged me throughout the past year.

And finally to everyone on the Renewable Energy Systems & the Environment course for making my time at the University of Strathclyde fun, memorable and enlightening. I wish you all the best for your future endeavors.

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Acronyms

ABV: Alcohol by Volume

AD: Anaerobic Digestion

CAPEX: Capital Expenditures

CHP: Combined Heat & Power

COD: Chemical Oxygen Demand

DECC: Department for Energy and Climate Change

DM: Dry Matter

GHG: Greenhouse Gas

HFO: Heavy Fuel Oil

KWh: Kilowatt-Hour

LPA: Litres Per Annum

LPG: Liquefied Petroleum Gas

MFO: Medium Fuel Oil

NNFCC: National Non-Food Crops Centre

OFGEM: Office of Gas and Electricity Markets

OPEX: Operational Expenditures

SWA: Scotch Whisky Association

WRAP: Waste & Resources Action Programme

1. Project Overview

1.1 Project Background

The Scotch whisky and UK Brewing industries are big contributors to the UK economy. Scotch whisky is worth more than £5bn[1] whilst beer and pubs contribute £22bn to UK GDP and generate £13bn in tax revenue.[2] They employ thousands of people directly through the manufacturing process and indirectly through the supply chain. It is of great importance that these industries are regularly assessed in every aspect.

Resource use such as water and energy consumption is continually improving in these sectors as knowledge and technology improve. Continuous evaluation of this area will lead to further improvements, and as such, will help to increase profits for companies, reduce greenhouse gas emissions, create more jobs and help the UK meet its future energy targets.

1.2 Project Aims

This project focusses on resource use within the Scotch whisky and UK beer industries.

The aims of this project are to:

- Collect and analyse data on energy and water use and compare against values from literature.
- Understand why differences in resource consumption occur.
- Access the feasibility (economic and practical) of integrating Anaerobic Digestion (AD) systems within breweries and distilleries.
- Investigate carbon dioxide emissions within this sector and look at ways of how they can be reduced.

2. Scotch Whisky

2.1 Background and Statistics

The appetite for Scotch whisky is not only massive in the UK but also worldwide. Scotch whisky accounts for approximately a quarter of all UK food and drink exports (85% of Scotland's) and in the past year it generated £3.95 billion for the UK balance of trade.[3] This is equivalent to £125 every second. There are 98 active malt distilleries in Scotland[4], which are spread around the country, and they produce a cumulative total of over a 600 million litres of whisky a year.

Figure 1. Scotch Whisky map [Hart Brothers[6]]

Scotland is divided up into whisky producing regions as illustrated by Figure 1. The division of regions is mainly historical with old regulations and different taxation systems being used in each region in the past.[5] Many of the regions do produce whisky which is more similar in taste compared with whiskies in other regions. For example whiskies from Islay are often more heavily peated in flavor in comparison to the commonly lighter whiskies from the mainland's. Mainly though the flavor is determined by the way it's made and how the ingredients are treated rather than to do with the geographical location of where the whisky is produced.

2.2 How Whisky Is Made

Whisky is made with only a few ingredients: barley, water and yeast. The way whisky is made has changed very little in the last couple of centuries. Improved technology has helped refine the process but in principle it is still the same. The process runs in the following order: malting, mashing, fermentation, distillation and maturation.

Malting

In the first step the barley is mixed with warm water and then allowed to germinate, traditionally by spreading it out onto the floor of a malting house. The germinating barley is then dried in a large oven called a kiln which halts the process of germination and prepares the barley for the next stage. Often the kiln is fired by peat which gives some whiskies their smoky flavours. Once the barley, now called 'malt', is dry it is ground in a mill.

Figure 2. Malt on the floor of a malting house [Credit: Wingclipped]

Mashing

The milled barley is then mixed with hot water in a large vessel called a mash tun and stirred for several hours to begin the process of extracting the soluble sugars. The water is often taken from a local source such as a river or a loch. This is why most distilleries are in rural locations: so that they have access to a clean and reliable source of water. The malted barley and water mixture is called the 'mash'. During the period in the mash tun the sugars in the malt dissolve in the water and then the liquid, called 'wort' is drawn off leaving behind the malt. The process is often repeated two or three times with higher temperatures each time in order to extract the maximum amount of sugar. The liquid from the 3rd repetition is put back into the next batch of malt. The left over unused malt from the process is called 'draff' and is usually sold to farmers to use as animal feed.

Fermentation

The wort is cooled and then transferred into large vats called washbacks. Yeast is then added to begin the fermentation process. During fermentation the yeast converts the worts sugars into a low strength (5-10% ABV) alcoholic liquid called ‘wash’. This process usually takes about 48 hours but some distilleries run the process for longer to create different characteristic flavours in the final product.

Distillation

The wash is traditionally distilled twice in two large copper stills which act like giant kettles. Copper is used as it is the preferred choice for extracting impurities from the alcohol. The stills have a wide bowl-shaped base which rises up to a thin neck at the top. All stills work in the same way but different shapes of stills will change how the final whisky tastes. The wash enters the first still, called the ‘wash still’, where it is heated, most often by gas or steam. The liquid vapourises and passes up the still where it condenses in the neck into a liquid called ‘low wines’ and passed on to the second smaller still called the ‘spirit still’. The leftover liquid from the wash still is called ‘pot ale’ and like draff it is often used by farmers for animal feed. The liquid that runs off from the second still is divided into three parts. Alcohol from the beginning of distillation, called ‘foreshots’, is too high in alcohol and therefore too strong tasting to be used in the final product. Alchohol from the end of distillation, called ‘feints’, is too weak to be used and they also have a strong taste which would ruin the whisky. The middle, desirable part of the distillation is called ‘the heart’. The separation of parts is done by sight alone since whisky at this stage is under lock for legal reasons to make sure that every drop of whisky is taxed.

Figure 3. Whisky stills [Credit: Forsyth]

Maturation

Once the distillation process is complete the new spirit is poured into casks and left to mature for a minimum of three years before it can legally be called Scotch. Scotch whisky is often matured for much longer: some whiskies are left to mature for over a decade. The casks used for whisky are either sherry or bourbon oak casks and during maturation, the whisky takes on the flavours from the wood of the casks. Since wood is porous overtime the whisky 'breathes' in the surrounding air which adds to its final colour, character and flavour. Air quality, temperature and humidity will all also affect the final product. Over the time the whisky spends maturing some of the whisky evaporates through the porous wood. This is called the 'angels share'. Each year about 2% of the whisky in the cask is lost through this process and it contributes to the reasons why older whiskies are more expensive, since there is less of it available than younger whiskies.

Figure 4. Whisky maturing in casks [Laphroaig[7]]

2.3 Energy Use

Producing whisky is energy intensive mainly due to the large quantities of heat energy required for the heating of liquids at the different process stages. Reducing energy consumption will be good for both economic and environmental reasons.

The Scotch Whisky Association (SWA) works to "sustain Scotch Whisky's place as the world's leading high-quality spirit drink and its long-term growth worldwide". Part of this responsibility involves regularly assessing energy use within the industry. They have a number of goals set for the industry that they hope to achieve that will help reduce energy consumption and GHG emissions:[8]

- To reduce greenhouse gas emissions and increase energy efficiency
- By 2020, 20% of primary energy requirements will be met with from non-fossil fuels sources, reaching 80% by 2050
- 10% reduction in the weight of the materials made to produce the product packaging by 2020
- 40% of the product packaging will be made from recycled material by 2020
- To make all of the product packaging reusable or recyclable by 2020
- No packaging waste sent to landfill by 2020
- All of the whisky casks to be made from oak wood that comes from sustainable forests

The SWA published 'Environmental Strategy' reports in 2010, 2012 and 2013 to monitor the progress the industry is making in reducing resource consumption and greenhouse gas emissions. Their most recent report, published in 2013, indicates that significant progress has been made:

- Non-fossil fuel primary energy usage rose from 3% in 2008 to 16% in 2012
- GHG emissions have reduced by 10% since 2008 despite an increase of 11% in spirit production
- Only 5% of waste was sent to landfill in 2012 compared to 13% in 2008

In some areas the same advancements haven't been made. For example the average weight of packaging materials for a 9 litre case increased from 6.62kg to 6.82kg. This can be partly attributed to a higher demand for the more prestigious, intricate glass designs in places like Asia where the demand for Scotch whisky is rapidly growing. These generally require thicker glass in order to be made more aesthetically pleasing and to avoid the bottles from being too delicate where they could be susceptible to breakage.

2.4 Water Use

Water is another resource that is extensively used within the Scotch whisky industry. The SWA, as well as energy use, have also been assessing distillery water use and have been presented their findings in their environmental strategy reports.[8] They also have set a number of water usage goals for the industry to achieve:

- To "manage (their) water more effectively"
- To work with Scotland's River Basin Management Plans to ensure that a "sustainable and good quality water supply is maintained"

The total water usage in 2012 amongst the 100 or so distilleries was about 52 million cubic metres.[8] Much of this is used as cooling water during manufacture of the whisky and is returned to the water system since it is uncontaminated. Excluding cooling water the total water used by distilleries in 2012 was ~15 million cubic metres. This is equivalent to filling an Olympic sized swimming pool 6,000 times. Since 2008 a growing number of companies have been installing water meters to more effectively manage their water usage.

3. UK Beer

3.1 Background and Statistics

Beer is one of the oldest beverages produced by mankind and dates back to 5000BC where evidence of its manufacture and consumption can be found in ancient Egyptian and Mesopotamian history. It is the most popular alcoholic drink in the UK with annual sales over £18 billion a year.[9] The UK also has the most breweries per head of population than any other country in the world[10] with a reported 1,285 breweries in operation. A surge in popularity of craft beer can be attributed to the rise in number of breweries opening up in recent years - the annual growth rate of breweries in the UK is currently at 10% highlighting the appetite UK dwellers have for this type of product.

A Scottish company called BrewDog undisputedly lead the way in the craft beer surge. They have been the fastest growing food and drinks company in the UK for the past 3 years in a row.[11] With small brewery numbers on the rise their market share of the UK economy will rise with it. It is therefore of growing importance that, as well as for the larger beer companies, resource use within the industry is regularly assessed in order to identify areas where improvements can be made. This will help lead to reducing unnecessary resource consumption, thus saving money and reducing greenhouse gas emissions.

3.2 How Beer Is Made

Beer is made from only a few ingredients: barley or wheat, water, yeast and hops. The basic principle is to extract the sugars from the barley so that they can be converted into alcohol by the yeast cells. The process is similar to making whisky but without the distillation stages and longer maturation times and runs in the following order: malting, mashing, boiling, fermentation, bottling & aging.

Malting

The barley is mixed with warm water to start the process of germination. Germination is stopped after a while by drying the barley in hot air. In doing this it prepares the barley, now called 'malt', so that the sugars can be extracted from it and used by the yeast to produce alcohol.

Mashing

The malted barley is then mixed with fresh, clean water and heated in a process known as 'mashing'. This process lasts for about an hour and during this time the sugars are extracted from the malt. Once this is finished the liquid, now called 'wort', is drained and collected leaving behind the leftover spent grain. The spent grain is usually sold to farmer for use as animal feed.

Boiling

The liquid is passed onto another tank where it is boiled for about an hour while hops and sometimes other ingredients are added for flavour. The hops also provide bitterness to the beer to balance out the sweetness from the sugars in the beer.

Fermentation

After the boiling period, the wort is cooled, filtered and put into fermentation vessels where the yeast is added. The yeast acts on the sugars in the wort to produce alcohol and carbon dioxide. It's the carbon dioxide that gives beer its characteristic fizz. This process happens at room temperature (for ales) or at cold temperatures (for lagers) for about a couple of weeks

Bottling & Aging

The beer is then put into bottles or casks where it is either artificially carbonated, like soft drinks are, or if it is to be 'bottle conditioned' it is allowed to naturally carbonate. The aging process can take anywhere from a few weeks to a few months.

Figure 5. Making beer [photo credit: The Malt Miller, Skyline Hop Shop, The Idle Loaf]

3.3 Energy Use

Making beer requires large quantities of heat energy. Energy consumption is equal to 3 – 8% of the production costs of beer.[12] Because of this breweries are particularly vulnerable to volatile energy prices. Understanding how energy is used within breweries and knowing ways of reducing consumption will help to reduce overall costs.

Most of the energy consumption happens in the brew house. This involves the processes from milling through to the cooling of the wort before it goes into the fermentation tanks. This is understandable since these are the most heat demanding processes, particularly mashing and wort boiling. Development of new processes technology has helped reduce the energy expenditure on these processes[13] over the years, for example from using dynamic wort boiling with an internal boiler[14] and use of waste heat recovery.[15] Majority of the electricity expenditure in breweries is on refrigeration[15] (44%), packaging (20%), and compressed air (10%).

Energy consumption and carbon dioxide emissions have been falling as time has progressed. Since the 70's energy consumption has fallen by 47% and emissions have fallen by 63%.[16] The major reduction in carbon dioxide emissions is largely due to the increased use of renewable technologies within the industry such as use of photovoltaic and thermal energy collectors[17]. Renewable Anaerobic Digestion (AD) technology is also being used to displace fossil fuels and reduce carbon emissions (more about this in section 4).[41]

3.4 Water Use

Since the main ingredient of beer is water it comes as no surprise that water use within breweries is extensive. There are four main areas where water is used: the brew house, cellars, packaging and utilities.[18] Water usage among breweries differs depending on how efficient their equipment is and how closely they monitor their water usage.

The amount of waste water from each process is variable. Bottle washing produces a high volume of waste water but it contains low levels of organic matter where as wastewater from the fermentation and filtering stages are high in organic matter. Water that is high in organic content often needs treated before it can be discharged therefore incurring additional costs. The true cost of water is often much greater than the amount displayed on the water bill as figure 6 illustrates.

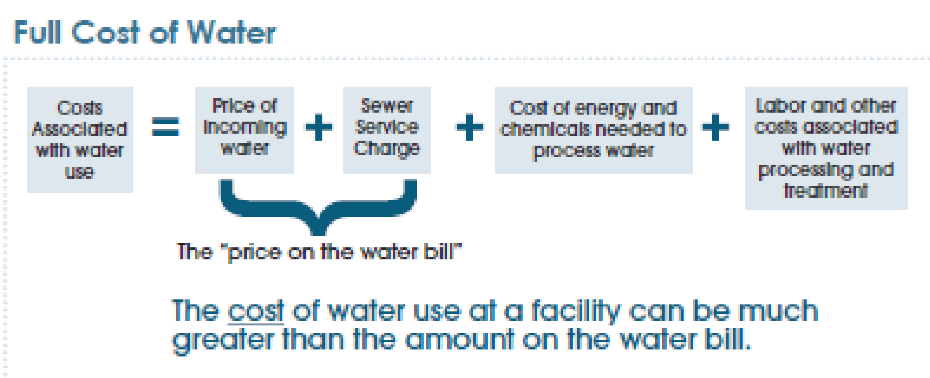

Figure 6. The full cost of water [Brewers Association]

Installation of proper watering monitoring equipment will often quickly pay for itself through rapid detection of costly water leaks. Figure 7 shows estimates on how much water could be saved from using different water saving measures.

Typical Reductions In Water Use

Water saving measure	Possible application	Typical reduction in process use (%)
Closed loop recycle	Fermentor cooling	>90
Cleaning-in-place (CIP)	New CIP set	60
Re-use of wash water	Cask washer	50
Countercurrent rinsing	CIP set	40
Good housekeeping	Hose pipes	30
Cleaning-in-place	Optimisation of CIP set	30
Spray/jet upgrades	Cask Washer	20
Brushes/squeegees	Fermentor cleaining	20

Figure 7.Typical reductions in water use [Brewers Association]

4. Anaerobic Digestion

4.1 What is Anaerobic Digestion?

Anaerobic Digestion (AD) is the process of using micro-organisms to break down organic matter in the absence of oxygen. The products of this process are:

- Biogas – a methane-rich gas
- A nutrient-rich solid called 'digestate'
- A liquid liquor that can be used as fetiliser

Typically AD involves sealing biodegradable organic matter, called a 'feedstock' in an airtight container, adding the appropriate bacteria and creating the right environmental conditions for the process to occur. AD occurs naturally in some parts of nature but has been used by man to process sewage sludge as early as the 19th century.[19]

Figure 8. Anaerobic Digester vessels [Stuart Michael Associates[20]]

4.2 Benefits of AD

Environmental Benefits:[21,22]

- Reduced volumes of waste going to landfill - these would decompose there and produce methane, a greenhouse gas with a global warming potential 21 times higher than carbon dioxide.
- Production of biogas, a renewable source of energy that can be used to replace fossil fuels
- Can be used to treat wastewater systems by lowering the levels of organic matter within them and killing pathogens.
- AD is a low energy process and therefore has low running costs.
- Production of nutrient-rich digestate and fertiliser. This is also an economic advantage.

Economic Benefits:[21,22]

- Biogas can be used to displace fuels therefore offsetting costs.
- Income potential when biogas is used as fuel for energy generation from fuel savings and income from government incentives such as the FIT and RHI tariffs for AD systems in the UK.

Government Benefits:

- Can help meet the Landfill Directive by reducing the amount of organic waste sent to landfill.
- Will help meet national renewable energy targets.
- Helps Local Waste Authorities tackle the Landfill Allowance Trading Scheme.

Some disadvantages of AD:[21,22,23]

- It can only be used to treat organic matter. Therefore they cannot treat non-organic material in, for example, wastewater streams such as nutrients or disease-causing micro-organisms.
- Biogas may have to be cleaned before being used as a fuel since it can be corrosive to equipment.

4.3 Government Incentives to Encourage AD

4.3.1 Feed-In-Tariff

The Feed-In-Tariff (FIT) is a government introduced scheme which means you get paid for generating your own electricity from a renewable or low-carbon source.[24] Most renewable technologies apply to this scheme including AD. Payments are made per kWh generated even if it used by yourself and payments are also made per kWh exported to the national electricity grid. The UK government's Department for Energy and Climate Change (DECC) make all the governmental policy decisions around FIT payments. The energy regulator Ofgem manages and is responsible for running the scheme.[25]

Your energy supplier is required by law to make the FIT payments to you if they are a large energy supplier but smaller suppliers are not, although many of them have chosen to opt in with the scheme. For an AD system to qualify for FIT payments it must be certified through the ROO-FIT process.

The FIT tariff received is dependent on the output capacity of the system and on the date of registration since the tariffs often change with time.

4.3.2 Renewable Heat Incentive

Similar to the FIT, the Renewable Heat Incentive (RHI) is a government introduced payment scheme but pays people for generating their own *heat energy* from a renewable source.[26] For the non-domestic sector e.g. distilleries and breweries this subsidy is payable for 20 years and how much is money is given is dependent on which renewable heat systems are used, the output capacity of the installed system and on the date of registration.

4.4 Size of UK AD Industry

A survey[27] of the UK Anaerobic Digestion industry in 2013 showed that the uptake of AD systems within the UK has been increasing rapidly. The number of operational sites increased by 34% compared to 2012. The survey classified AD plants into four categories:

- Commercial: "sites which accept waste from off-site, on a commercial basis (i.e. for a gate fee). Such sites may be based on a farm."
- Industrial: "sites which process their own wastes, typically on a large scale, such as food and drink manufacturers."
- On-farm: "sites which are both located on a farm and process only material generated on-farm (including energy crops)."
- Demonstration: "demonstration/R&D sites. AD sites that process feedstock for demonstration or feasibility purposes. Such sites may contract in waste but not on a large scale."

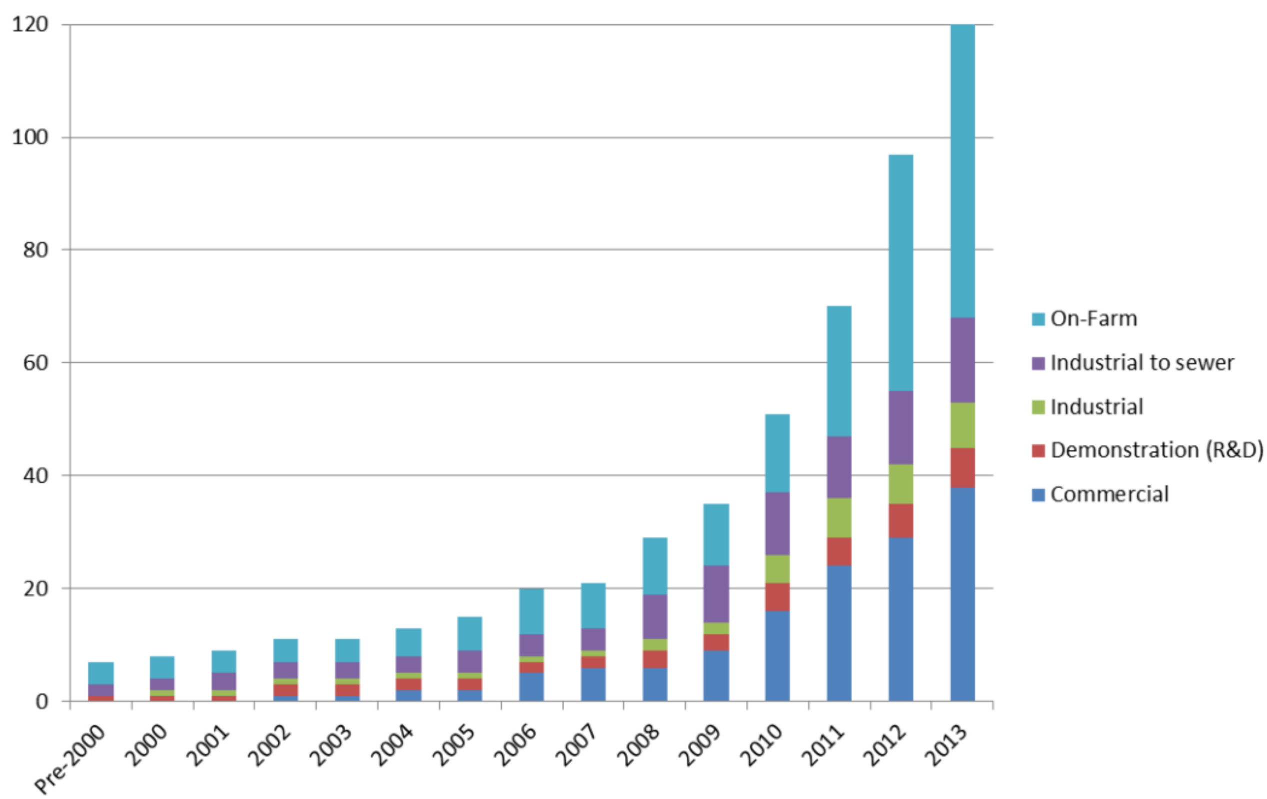

Figure 9. Year AD facilities started operation – cumulative number of facilities [WRAP]

The recent explosion in growth can be attributed to the UK government's action on encouraging the uptake of AD with the introduction of the FIT and RHI payments schemes in the past few years. Also the wealth of support and advice that's available now will likely be contributing to the uptake of AD. There continues to be significant investment made in the industry with an estimated £160 million made in the 18 months before March 2015.[28]

4.5 The Chemical Process of AD

Ultimately the AD process involves putting organic feedstock into an airtight container, adding the appropriate bacteria, creating the right environmental conditions and then the bacteria will digest the feedstock and release the methane-rich biogas. The process in reality is slightly more complex than this simplified description. There are four main stages in AD:

- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

The overall process can be described by this chemical reaction:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

This chemical reaction describes organic matter such as glucose ($C_6H_{12}O_6$) being biochemically digested into carbon dioxide (CO_2) and methane (CH_4). The biogas produced from AD is approximately 60% methane and 40% carbon dioxide with a few other trace elements and compounds.[41]

Hydrolysis is the process of breaking up the large organic polymers which the biomass is made of (in most cases). If this is not done the bacteria cannot access the energy potential of the material. The larger polymers are broken down into smaller parts, called monomers. These consist of simple sugars, amino acids and fatty acids as well as other things. This is the process that takes the longest so determines the retention time the feedstock needs in the digester.

After this stage acidogenesis takes place which involves breaking down the compounds into acetic acid by acidogenic (fermentative) bacteria. Following this the products from acidogensis are further broken down to produce mainly acetic acid, as well as carbon dioxide and hydrogen, in a process called acetogenesis.

Methanogenesis, the final stage, involves methanogenic bacteria using the intermediate products from the previous stages and converting them into methane, carbon dioxide and water.

The indigestible material that remains after the entire process is called the digestate.

4.6 Types of AD

Anaerobic digesters can be classified in several different ways depending on their configuration:

- Moisture Level: Wet system (5-15% dry matter) or dry system (>15% dry matter)
- Temperature: Mesophilic (25-45 degrees Celsius) or Thermophilic (50-60 degrees Celsius)
- Process type: batch or continuous flow
- Complexity: numbers of digesters, layout

The configuration chosen will depend on a number of things. Factors affecting which AD system should be chosen include:

- Type and volume of available feedstock.
- Money available for investment
- Space available
- Potential income from RHI and FIT tariffs
- Existing infrastructure

4.6.1 Wet or Dry

Wet AD

Wet AD is AD with a dry matter content of 5-15%.

Advantages[29,30]:

- Lower capital costs
- Easy filling and emptying of digester since contents can be pumped in and out
- Well suited for slurry and vegetable wastes

Disadvantages:

- More space required and less gas produced per unit volume
- Higher operating costs since there is more water to heat
- Higher maintenance costs since there is more moving parts
- Less volume reduction of feedstock
- More complex system compared to dry AD

Dry AD

Dry AD is AD with a dry matter content of 15 – 50%. Despite the name there is still moisture within the digester as the microorganisms involved in the process require moist conditions.

Advantages:

- Less space required
- Less volume required to produce the same quantities of gas compared to wet AD
- More volume reduction of feedstock
- Less energy required since there is less water to heat
- Smaller maintenance costs
- Less complex system compared to wet AD
- More suitable for high dry matter content feedstock's

Disadvantages:

- Higher capital costs
- Special equipment is needed for filling and emptying the digester since the content cannot be pumped.
- In many cases there are lower methane yields than in the wet case.

4.6.2 Mesophilic or Thermophilic

<u>Mesophilic</u>

Mesophilic AD occurs at temperatures of 25-45°C

Advantages:

- Lower maintenance requirements
- Lower capital costs per m^3 capacity
- Lower operating costs particularly since less heat energy is needed
- Less management required

Disadvantages:

- Longer digestion period
- Slower rate of biogas production per unit of feedstock
- More space required per unit of feedstock

<u>Thermophilic</u>

Thermophilic AD occurs at temperatures of 50-60°C

Advantages:

- Quicker digestion period

- Higher rate of biogas production per unit of feedstock
- Less space required per unit of feedstock
- Better at killing pathogens

Disadvantages:

- Higher operating costs
- Higher capital costs per m^3
- More management required

4.6.3 Batch or Continuous Flow

In a batch process the feedstock is loaded into the digester, sealed and left for digestion to occur. In continuous flow digestion processes the feedstock is continuously added to the digester during the process at an appropriate rate. Whilst the feedstock is continuously added the end products of the process are continuously being removed. Therefore a constant production of biogas will result. The vast majority of AD digesters are continuous flow.

Batch

Advantages:

- Lower organic loading rate

Disadvantages:

- Lower gas production per unit of feedstock
- Higher operating costs
- More management required
- Higher capital cost
- More space usually required
- Can only have a level output of gas if multiple digesters are used since the process has to be stopped and started.

Continuous

Advantages:

- Higher gas production per unit of feedstock
- Lower operating costs
- Less management required
- Lower capital cost
- Less space usually required
- Level output of gas

Disadvantages:

- Higher organic loading rate

4.6.4 Number of Digester Tanks

As described in section 4.5 The Chemical Process of AD' the process of AD involves four chemical stages. Each stage has slightly different optimum conditions such as pH. By using a separate digester tank for each stage and creating the appropriate optimum conditions the process of AD can be fully exploited. The result is higher gas yields per cubic metre of feedstock as well as a quicker rate of production.

Single Digester

Advantages:

- Less space required
- Lower maintenance costs
- Less management required
- Lower capital and operating costs

Disadvantages:

- Lower gas yields per cubic metre of feedstock as well as a slower rate of production.

Multiple Digesters

Advantages:

- Higher gas yields per cubic metre of feedstock as well as a quicker rate of production

Disadvantages:

- More space required
- Higher maintenance costs
- More management required
- Higher capital and operating costs

4.7 Maximizing Biogas Yields

To achieve the maximum possible biogas yields from a feedstock the following should be adhered to:

Keeping the digester airtight: This will ensure that no biogas escapes and that no oxygen will enter which would reduce methane yields.

Maintaining the optimum pH: The microorganisms involved in AD operate best between a pH of 6.8 to 8.0. Outside of this range they do not operate optimally and at extreme ranges they will die, stopping the production of biogas. Adding the feedstock at too high a rate can raise the pH excessively.

Ensuring the correct moisture levels: This is dependent on the feedstock and whether wet or dry AD systems are being used. If the mix is too dry then the feed stock will not mix with the microorganisms effectively. If the mix is too wet there will be too small a concentration of organic matter in the water for effective biogas production.

Carbon:Nitrogen Ratio Balance: The bacteria in the digester consumes about 30 times more carbohydrate than protein. The closer the feedstock is to this difference i.e. contains 30 times more carbohydrate than protein, then the more optimized biogas production will be.

Retention Time in the Digester: Different feedstocks have different susceptibility to the bacteria involved in the chemical process of AD. Therefore some feedstocks will need longer time in the digester than others. Depending on the availability of the feedstock the digester operator may wish to cut the digestion process short and add in new feedstock in order to create higher revenue.

4.8 Energy Generation using Biogas

The biogas generated from AD can be used to run a boiler, electrical generator or combined heat and power (CHP) unit in place of regular gas. Generally the most common option used is CHP since both electricity and heat energy are produced. Energy generation using biogas can offset fuel bills, generate income and reduce greenhouse gas emissions.

4.9 Digestate Applications

After the AD process is complete a nutrient-rich substance called digestate is left over and, particularly from wet AD, nutrient-rich liquor. These can be used as compost and fertiliser for agricultural applications and therefore they have a certain market value as farmers will often pay for them. How much they are worth depends on the nutritional content and the market value at the time of purchase. One estimate[31] of the price of digestate puts it at around £5 per tonne of digestate. While this may seem low it is preferable to making no money or having to pay for sending the digestate to landfill.

4.10 Suitability of Distillery and Brewery By-Products for AD

Breweries and distilleries produce large quantities of organic by-product from the process of making beer and whisky. This free access to feedstock makes them suitable candidates for AD systems. The by-products from this process are used grain and pot ale[1] and they produce some of the best yields of biogas per tonne of feedstock compared to other feedstocks.[32] Furthermore the by-products are ideal feedstocks since they have already been broken down from the alcohol making processes and therefore they are more susceptible to the bacteria in the digester thus producing higher yield rates of biogas.

The biogas produced from the by-products can be used to generate electricity and heat energy that can be used on-site to offset fuel costs and generate income for the company. A CHP unit is particularly useful here since breweries and distilleries have both an electricity demand and a large heat demand.

[1] Pot ale is from distillation process only and is not available from the brewing process.

5. Data Collection

While there is some literature data available quantifying and describing different aspects of the UK beer and Scotch whisky industry, it was clear that to proceed with the analysis these numbers needed validated or amended since a range of figures exist. A questionnaire was sent to the brewery and distillery companies willing to participate in the project. The questions within the document were formulated on the basis of areas of interest within the industry and on what would be relevant to the analysis. In total 9 distilleries and 7 breweries provided enough data to be included within the project. A few of these were not able to answer every question and therefore in some sections they have not been included in the analysis. For legal reasons the company names have been omitted from this paper and instead they have been assigned a corresponding letter e.g. 'Distillery A', 'Brewery A', etc. The companies have been informed which letter they have been assigned so they can note their results.

The questions given to the distilleries and breweries were as follows:

- What volume of beer/whisky do you produce a year?
- How much spent grain/draff do you produce a year? If you know the dry weight please enter this if not please specify otherwise.
- What do you currently do with your spent grain/draff? For example if you give it to a local farmer do they come and pick it up and how far away is their farm from your site? If you sell it on how much do you sell it for? If you dispose of it how much does this cost?
- How much pot ale do you produce a year?
- What is your main source for heating? E.g. electric, gas hot water etc.
- What is your annual electricity demand?

- What is your annual gas demand?

- What is your annual oil demand? (If you know please specify if this is light fuel oil, medium fuel oil, heavy fuel oil or gas oil)

- What is your annual LPG (Liquefied Petroleum Gas) demand?

- If you derive energy from any other sources what are they and how much do you use annually?

- What is your annual water usage?

- Where does your water come from and how much do you pay for it?

Analysis of the answers to these questions was carried out in relation to different areas of the industry. More specifically the areas of interest were:

- Water usage
- Energy required to produce whisky and beer
- Energy saving potential of using biogas derived from Anaerobic Digestion of by-products
- Carbon dioxide emissions

At times in the following sections large amounts of data are presented. This is mainly for the benefit of the distillery and brewery companies so they can take note of their results and to see how they perform against one another and against averages.

6. Results

6.1 Water Usage

6.1.1 Brewery Water Usage

The annual volume of water used by each brewery was divided by the annual volume of beer produced to determine the water to beer ratio.

Table 1. Brewery water usage

Brewery	Annual volume of beer produced (litres)	Annual volume of water used (m^3)	Source	Water to beer ratio
Brewery A	12,900,000	51,600,000	Mains	4:1
Brewery B	1,000,000	2,500,000	Mains	2.5:1
Brewery C	84,000	300,000	Mains	3.6:1
Brewery D	700,000	3,000,000	Mains	4.3:1
Brewery E	1,350,000	3,700,000	On-Site Borehole	2.7:1
Brewery F	24,000	80,000	Mains	3.3:1
Brewery G	2,600,000	5,922,000	Mains	2.3:1
			Average ------->	**3:1**

It was found that on average three litres of water are used by a brewery for every litre of beer produced. This appears to be slightly lower than values from literature. A study[33] by the Waste and Resources Action Programme (WRAP) found that the average water use was 4.4 litres to every litre of beer produced. Another study[34] puts the figure anywhere between 3 and 10 litres of water per litre of beer. The breweries in Table 1 are therefore on average performing well when it comes to conservative water use. Furthermore no correlation was found between the size of the brewery and water to beer ratio as can be seen by *Figure 10*. It would be expected that the larger breweries would have better water management in place. However in this case of range 20,000 to 13 million litres of beer produced annually this appears untrue.

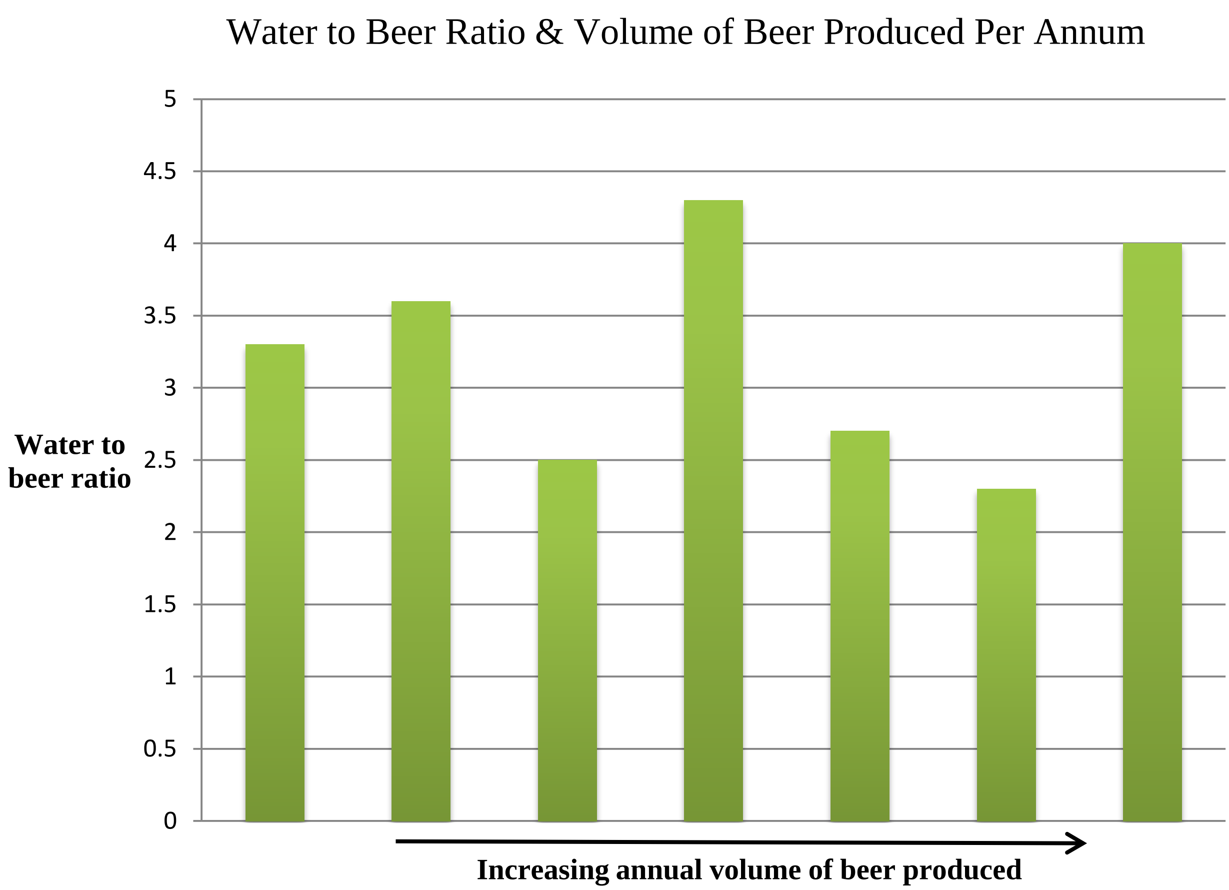

Figure 10. Water to beer ratio and volume of beer produced

6.1.2 Distillery Water Usage

The results for water use in the whisky industry are presented below in *Table 2*. Water use can be divided into two different areas: cooling water and process water.

The cooling water is, as it suggests, used for cooling at different stages of the whisky making process. Use of heat exchangers allows the cooling water to pass through the system uncontaminated thereby negating the need for water treatment. In most cases, given the rural locations of the distilleries, cooling water is simply taken from a nearby water source, such as a stream or river, and after passing through the cooling network returned to the water source. This takes the pressure off the mains water system, making the process more environmentally friendly, and greatly reduces the overall costs for the distilleries. If the average price of mains water is taken at 70 pence per m^3 (since this is the average price of mains water as supplied by the breweries and distilleries) this will save on average 20 pence per litre of whisky produced.

This may not sound significant but for a distillery producing 1,000,000 litres of whisky a year this equates to a £200,000 a year saving.

Process water is the water that is directly used in making the whisky i.e. in the malting, mashing, fermentation and distillation stages. The water for process often comes from a local source as well for financial reasons but also because it can influence the final character of the whisky since it contains minerals after passing over things like peat, granite or other surfaces.[35]

Table 2. Distillery water usage

Distillery	Annual volume of whisky produced (litres)	Total volume of water used per annum (litres)	Water used for cooling per annum (litres)	Water used for process per annum (litres)
Distillery D	920,600	98,424,000	87,290,000	11,134,000
Distillery E	6,200,000	134,986,000	N/A	N/A
Distillery F	140,000	6,000,000	N/A	N/A
Distillery G	2,400,000	1,410,000,000	1,360,000,000	50,000,000
Distillery I	10,000,000	2,438,767,000	2,260,967,000	177,800,000
Distillery	**Annual volume of whisky produced (litres)**	**Ratio of water to whisky -total volume of water (litres)**	**Ratio of water to whisky -cooling water (litres)**	**Ratio of water to whisky - process water (litres)**
Distillery D	920,600	107:1	95:1	12:1
Distillery E	6,200,000	22:1	N/A	N/A
Distillery F	140,000	43:1	N/A	N/A
Distillery G	2,400,000	588:1	567:1	21:1
Distillery I	10,000,000	244:1	226:1	18:1
	Average ----->	**201:1**	**296:1**	**17:1**

The results displayed in Table 2 show that on average a total of 201 litres of water were used for every litre of whisky produced. Since not every distillery was able to provide separate process and cooling water data this has skewed the results making the average cooling water ratio higher than the total: On average 296 litres of cooling water were used for every litre of whisky produced. And finally on average 17 litres of process water were used for every litre of whisky made.

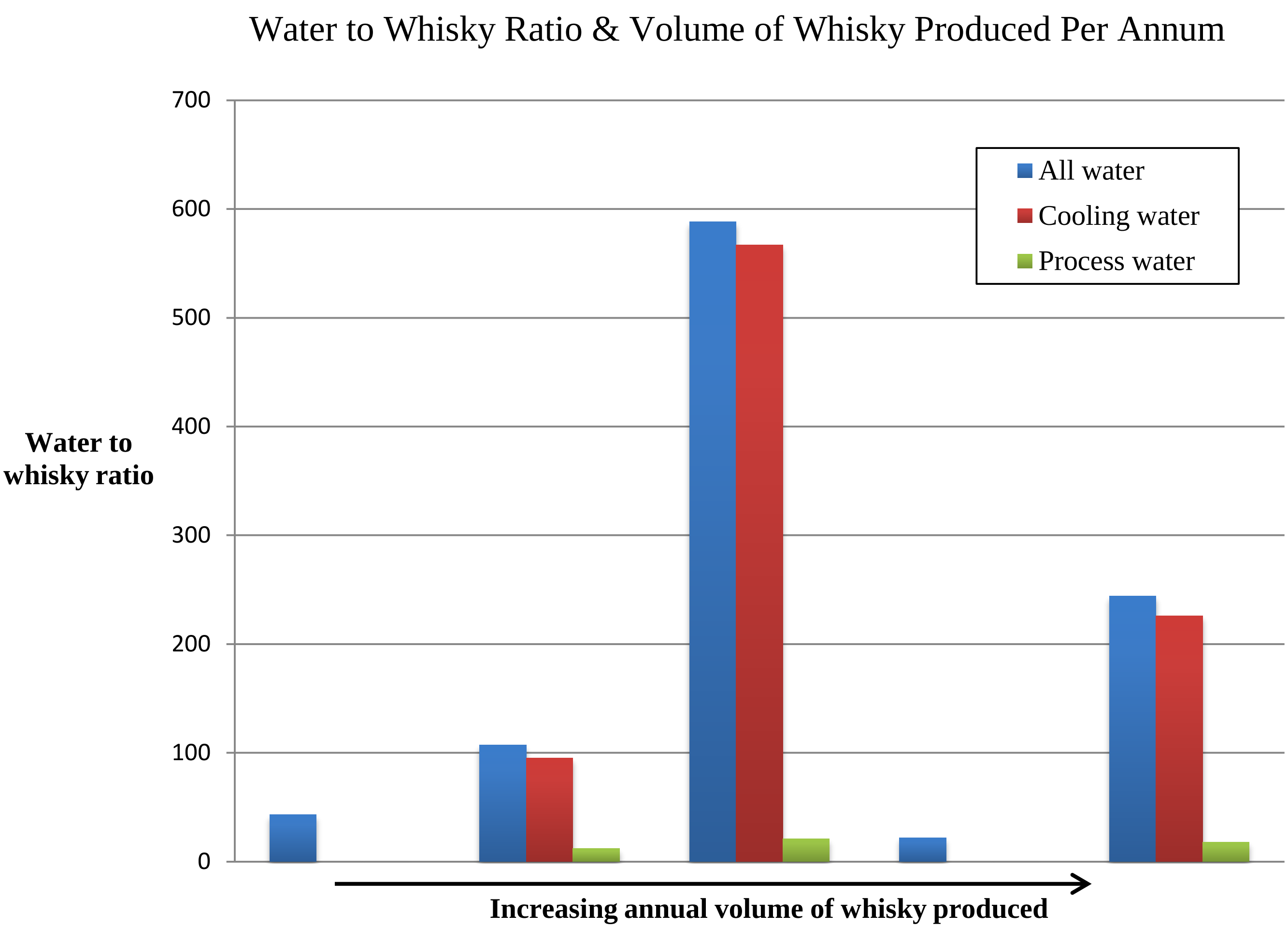

Figure 11. Water to whisky ratio and volume of whisky produced per annum

Similarly with the breweries it was found that there is no correlation between the annual volume of whisky being produced and the water to whisky ratio as can be seen in figure 11. It might be expected that a larger distillery would be more efficient at using water and therefore would have smaller water to whisky ratios but in this scenario this is not the case. It could be that the cost of water is so little, since it nearly always comes from a free source that the distilleries don't place too much emphasis on conservative water usage and therefore it varies without correlation to whisky output.

6.2 Energy Required to Produce Whisky

Whisky making is a fairly energy intensive process that requires lots of heat energy at different stages of manufacture from malting to distilling. The energy required to produce whisky is often described by the Specific Energy Consumption (SEC) which is the energy directly required to produce new-make whisky. A study[36] by the Scottish Whisky Association in 2012 found that the average energy requirement for the distilling and maturation process was 6.29 kWh per litre of whisky produced per annum, an improvement of 6% on the 2008 figure of 6.69 kWh. One of the reasons for improvements in efficiency is that the global demand for whisky has doubled in the past decade[37] and therefore the distilleries are outputting higher volumes of whisky which means they can be more efficient with the way they produce it. Additional energy requirements come from the packing process with the same study citing that it takes 3.30 kWh of energy to package one 9 litre case or 0.37kWh per litre of whisky. In total this means that they found that it takes about 6.66kWh to make and package 1 litre of whisky.

However this figure does not incorporate other energy requirements of the distillery. And given that distilleries main profitable commodity is the whisky itself for a fuller understanding of the costs to produce whisky these energy requirements should be taken into account or at least quantified to verify if they can be assumed to be negligible within the contexts of economic analysis. The distilleries require energy also for space heating, lighting, power to offices etc. It could argued that there is no ‘one size fits all’ way of quantifying this given that distilleries will have different requirements in regards to these areas which are dependent on things such as distillery location (average weather – temperature, humidity, etc), levels of building insulation and if they have an on-site office or other facilities. Irrespective of this variability it may be interesting to see if there is any convergence of numbers when other energy requirements are taken into account.

Results

The majority of the whisky distilleries that responded produced large volumes of whisky per annum falling in the range of about 920,000 lpa – 6,200,000 lpa but one small distillery produced just 20,000 lpa. Every distillery had an electricity demand but the main source of heating in all cases came from other energy means which differed from distillery to distillery. Since many of the distilleries were in rural locations with no connection to the mains gas network they relied mostly on some form of oil with one distillery using kerosene as the basis to generate their heat.

To determine the energy (indirect and direct) required to produce a litre of whisky the total annual energy demand of each distillery was summed. In the case of electricity and mains grid gas the units were already given in kWh but for other means conversion factors were used. See *Table 3* for conversion factors.

Table 3. Energy conversion factors[38,39]

Energy Source	Unit	To obtain energy in kWh multiply by
Gas Oil	Litres	10.6
Light Fuel Oil	Litres	11.2
Medium Fuel Oil	Litres	11.3
Heavy Fuel Oil	Litres	11.4
Kerosene	Litres	9.8
Propane	Litres	13.8
Diesel	Litres	11

The total annual energy demand was then divided by the annual volume of whisky produced to give the total energy demand per litre of whisky of produced. The results are shown in *Table 4*.

Table 4. Total energy demand per litre of whisky produced

Distillery	Total annual energy demand (kWh)	Annual volume of whisky produced (litres)	Total energy demand per litre of whisky (kWh/l)
Distillery A	13,960,000	1,500,000	**9.31**
Distillery B	270,300	20,000	**13.97**
Distillery C	11,898,820	1,400,000	**8.5**
Distillery D	8,505,500	920,600	**9.24**
Distillery E	45,208,000	6,200,000	**7.3**
Distillery F	*N/A*	140,000	*N/A*
Distillery G	21,551,700	2,400,000	**8.98**
Distillery H*	26,220,000*	2,700,000	**9.71***
Distillery I	87,600,000	10,000,000	**8.76**

**No given electricity demand though will be small % compared to heating so figure still given. Actual value would be higher 10 kWh/l approximately.*

From *Table 4* it can be seen that a range of energy demands per litre of whisky exist. The lowest found was 7.3 kWh/l belonging to a distillery with the second largest output of 45 million litres of whisky produced per annum whilst the highest energy demand was 13.97 kWh/l that belonged to the distillery with the lowest output of 270,000 litres of whisky per annum. This is what would be expected since distilleries with a larger output would be able to be more efficient in the way they manufacture their whisky. The average energy demand per litre of whisky produced was 8.83kWh/l. This applies for distilleries of annual output of about one million litres of whisky per annum or more and therefore doesn't include distillery B[2].

Figure 12 shows a trend of decreasing energy demand per litre of whisky as the volume of whisky produced per annum increases. The red horizontal line represents the average value given by the Scottish Whisky Association of 6.66kWh/l. As can clearly be seen when all of the energy demands of the distillery are taken into account the actual value is significantly higher by about 2kWh/l. Therefore the other energy demands of the distillery not included in the Specific Energy Consumption *should* be taken into account to understand how much energy it takes to produce whisky.

[2] Distillery B excluded since it is an exceptional case compared to the others and would change the average in a way that would be less insightful.

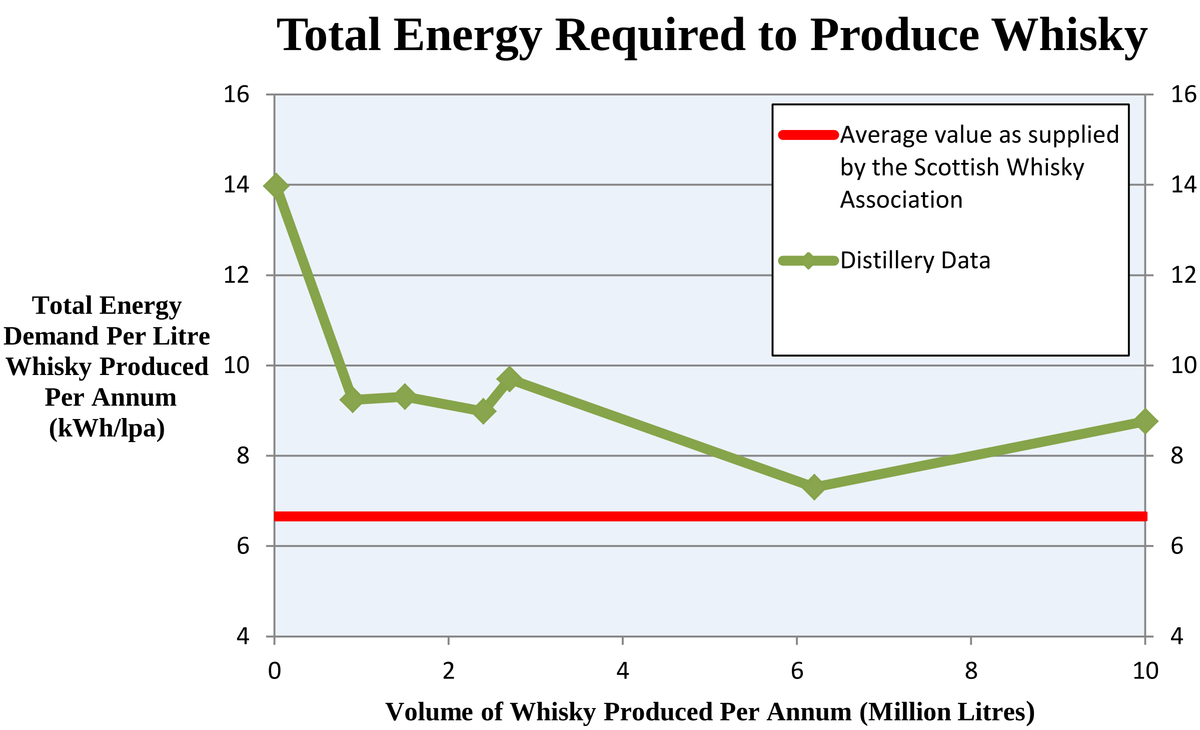

Figure 12. Total energy required to produce whisky

The electricity requirements of the distillery were also investigated. The results are shown in *Table 5*.

Table 5. Electricity demand per litre of whisky produced

Distillery	Total annual electricity demand (kWh)	% of total energy demand	Annual volume of whisky produced (litres)	Electricity demand per litre of whisky (kWh/l)
Distillery A	400,000	2.9%	1,500,000	**0.27**
Distillery B	9,000	3.3%	20,000	**0.45**
Distillery C	411,120	3.5%	1,400,000	**0.29**
Distillery D	427,800	5.0%	920,600	**0.46**
Distillery E	1,888,000	4.4%	6,200,000	**0.3**
Distillery F	*N/A*	*N/A*	140,000	*N/A*
Distillery G	1,011,500	4.7%	2,400,000	**0.42**
Distillery H	*N/A*	*N/A*	2,700,000	*N/A*
Distillery I	3,600,000	4.1%	10,000,000	**0.36**

The average electricity demand was 0.36kWh/l. This makes the average electricity demand about 4% of the total energy demand of the distillery. Unlike the total energy demand there was no correlation found between the electricity demand per litre of whisky produced and the annual volume of whisky produced as can be seen by Figure 13. This may be due to the variability between distilleries on what on-site facilities they have for example offices, visitor centres and levels of lighting used.

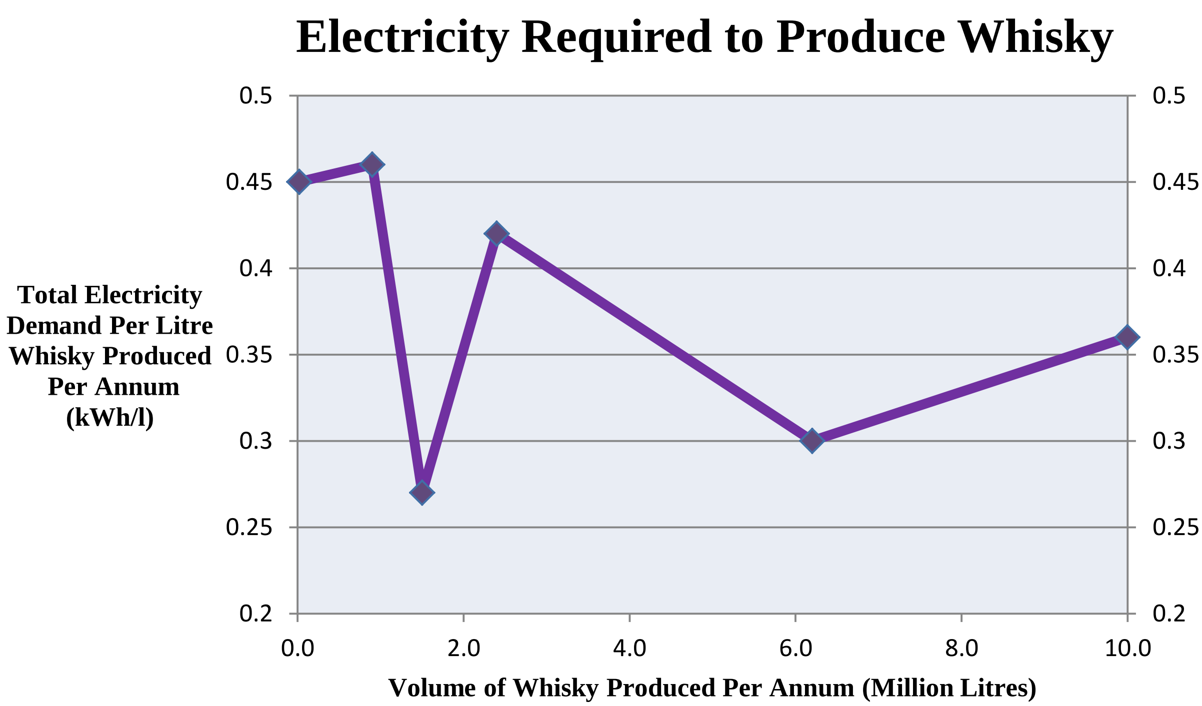

Figure 13. Electricity required to produce whisky

Therefore it is the heat energy demand per litre of whisky produced that is related to the annual output of whisky of the distillery. Refer to *Table 65* in the appendix for data on heat energy demand. Since majority of the heat demand is directly involved in the process of manufacturing the whisky at higher volumes of whisky output the process will be more efficient therefore lowering the heat energy demand per litre of whisky.

6.3 Energy Required to Produce Beer

Like whisky, making beer is an energy consuming process that requires large amounts of heat energy. However it is a less complex process than whisky making, has less overall stages and therefore requires significantly less energy to produce than whisky does.

A survey[40] by Campden BRI involving 32% of the world's beer production found that between the periods of 2008 to 2012 breweries reduced their energy consumption by 10%. They found that the average energy it took to produce beer reduced from 0.64kWh/l to 0.57kWh/l during this period. A study[41] carried out back in 1977 found that it took 1kWh to produce a litre of beer. Therefore significant progress has been made since then in terms of reducing energy consumption. The breweries involved with these studies were on average large scale breweries with the survey by Campden BRI only involving breweries which produced more than 50 million litres of beer a year. The breweries in

Table 6 all produced less beer than this annually so it would be expected that on average they would be less energy efficient at making beer than the larger companies. However the average energy consumption was found to be 0.52kWh/l which is lower than the average value of the larger breweries suggesting that, by comparison, small scale breweries perform better than average when it comes to energy required to produce beer.

Table 6. Total energy demand per litre of beer produced

Brewery	Total annual energy demand (kWh)	Annual volume of beer produced (litres)	Total energy demand Per litre of Beer (kWh/l)
Brewery A	6,358,400	12,900,000	**0.49**
Brewery B	426,900	1,000,000	**0.43**
Brewery C	66,200	84,000	**0.79**
Brewery D	556,000	700,000	**0.79**
Brewery G	248,911	2,600,000	**0.1**

Table 6 also shows that there was no correlation between the annual volume of beer produced and the total energy demand per litre of beer.

The electricity demands of the breweries were also investigated. A study[42] cites the European benchmark for breweries is to use between 0.075kWh and 0.115 kWh of electricity for each litre of beer produced.

Table 7. Electricity demand per litre of beer produced

Brewery	Total annual electricity demand (kWh)	% of total energy demand	Annual volume of beer produced (litres)	Electricity demand per litre of beer (kWh/l)
Brewery A	2,128,000	33.5%	12,900,000	**0.16**
Brewery B	77,000	18.0%	1,000,000	**0.08**
Brewery D	115000	20.7%	700,000	**0.16**
Brewery E	55,788	N/A	1,350,000	**0.04**
Brewery G	194,307	78.1%	2,600,000	**0.07**

The average electricity demand from the results displayed in *Table 7* was 0.1kWh per litre of beer produced putting it about in the middle of European best practice. As with the total energy demand no correlation was found between the annual volume of beer produced and the electricity demand per litre of beer. The average heating demand was also investigated and was found to be 0.44 kWh per litre – the results can be viewed in *Table 66* in the appendix.

6.4 Anaerobic Digestion - Energy Potential of Draff & Pot Ale

As discussed in chapter 2 the process of making whisky involves extracting sugars from barley and fermenting these and distilling off the alcohol. From this process large quantities of unused barley called draff are left over from the early stages of whisky making as well as large quantities of pot ale which is the leftover liquid from the distillation process. Pot ale in particular is of low value to the industry and can cause problems with disposal since it contains large amounts of organic matter preventing it from being passed into water systems without substantial treatment. Currently most of the distilleries sell or simply give their spent draff to third parties such as farmers to use for animal feed.

Anaerobic digestion (AD) provides the opportunity for distilleries to use their draff and pot ale to produce biogas which can then be used to generate their own energy. This energy has the potential to reduce their reliance on other fuels and electricity, reduce their greenhouse gas emissions and ultimately save them money by offsetting their fuel bills.

Table 8. Quantities of draff produced by distilleries

Distillery name	Annual volume of whisky produced (litres)	Draff weight (tonnes/annum)	Weight per litre (kg)
Distillery A	1,500,000	3,750	2.5
Distillery B	20,000	5.4	2.5
Distillery C	1,400,000	3,164	2.26
Distillery D	920,600	2,234	2.43
Distillery E	6,200,000	14,500	2.34
Distillery F	140,000	360	2.57
Distillery G	2,400,000	6,166	2.57
Distillery H	2,700,000	8,280	3.07
Distillery I	10,000,000	25,000	2.5

Table 9. Quantities of pot ale produced by distilleries

Distillery Name	Annual volume of whisky produced (litres)	Annual volume of pot ale produced (litres)	Volume of pot ale per litre of whisky produced (litres)
Distillery C	1,400,000	5,300,000	3.79
Distillery E	6,200,000	50,688,000	8.18
Distillery F	140,000	1,100,000	7.86
Distillery G	2,400,000	19,125,000	7.97
Distillery I	10,000,000	75,413,000	7.54

Table 8 and *Table 9* show the quantities of draff and pot ale produced by each distillery respectively. An average value of 2.53kg of draff was produced from each litre of whisky made. Excluding 'Distillery C' [3] the average volume of pot ale produced per litre of whisky made was 7.89 litres.

6. 5 Biogas Production from Distillery Draff and Pot Ale

Since the chemical make-up of draff and pot ale is different they require separate anaerobic digestion treatment in order to produce the highest yield rate of biogas.[43] This is mainly to do with draff being more resistant to biochemical breakdown from the methane producing bacteria and therefore draff requires a longer time in the digester than pot ale does. Pot ale requires dilution prior to AD treatment since it has too high a chemical oxygen demand (COD) to begin with.[44] The chemical oxygen demand is a measure of the concentration of organic matter within water. It is a good indicator of the volume of biogas that can be produced from the liquid if it undergoes anaerobic digestion.

Pot ale has COD of about 60-70 kg/m3. As it stands this is too high for AD since at this concentration substrate inhibition will occur[41]. To make this suitable for AD it can be mixed with the spent lees (another liquid by-product from the whisky making process) which have a COD of

[3] Distillery C was excluded because the volume of pot ale by comparison to other distilleries appeared to be abnormally low therefore there may have been an error with data collection.

3-5 kg/m3 to produce a liquid of about 35 kg/m3. This will require roughly a 1:1 mixture of pot ale to spent lees. Since there is about three times more pot ale produced than spent lees additional waste water will be needed to dilute the pot ale to the desired COD concentration. From the water data provided by the distillery companies in *Table 2* there is more than enough of this available on site. This solution may be preferable to cut down on extra water charges if water was to be used directly from the mains. If waste water recovery is difficult or expensive many distilleries have a free water source that could be used to dilute the pot ale in the digester.

The volumes of the digesters needed for the draff and pot ale were calculated from the data provided by the distilleries. For the digester holding the draff a loading rate of $4.2kg$ of draff per metre cubed of water per day was needed in order to maintain a COD of $45kgm^{-3}$.To calculate the volume of the digester needed the annual weight of draff was divided by the number of days in a year to get the daily amount of draff available, and this was then divided by the loading rate.

$$Volume\ of\ digester\ required\ for\ draff\ (m^3) = \frac{Annual\ weight\ of\ draff\ (kg)}{365}/4.2$$

This set up in theory should produce about 1.8 litres of methane per litre of liquid in the digester per day.[41] The results are shown in Table **10**.

Table 10. Biogas production from anaerobic digestion of distillery draff

Distillery	Spent grain weight per day (kg/day)	Volume of digester needed (m^3)	Biogas production (litres/day)
Distillery A	10274	2446	4,354,207
Distillery B	15	4	7,200
Distillery C	8668	2064	3,673,790
Distillery D	6121	1457	2,593,947
Distillery E	39726	9459	16,836,269
Distillery F	986	235	418,004
Distillery G	16893	4022	7,159,478
Distillery H	22685	5401	9,614,090
Distillery I	68493	16308	29,028,050

A similar calculation was done for the digester holding the pot ale. The diluted pot ale needs to remain in the digester for about 3 days before being emptied and refilled. Therefore the volume of digester needed is:

$$Volume\ of\ digester\ required\ for\ pot\ ale\ mix\ (m^3)$$
$$= \frac{Annual\ volume\ of\ pot\ ale\ mix (m^3)}{365} \times 3$$

The biogas produced per tonne of effluent in the pot ale digester is $25m^3$. The potential volumes of biogas produced from pot ale by each distillery are shown in Table 11.

Table 11. Biogas production from anaerobic digestion of distillery pot ale

Distillery	Annual volume of diluted pot ale (m^3)	Volume of digester needed (m^3)	Annual volume of biogas produced (m^3)
Distillery A	2,200	18	55,000
Distillery C	38,250	314	573,750
Distillery E	101376	833	1,520,640
Distillery F	2200	18	33,000
Distillery G	38250	314	573,750
Distillery I	150826	1,240	2,262,390

6.6 Biogas Production from Brewery Spent Grain

One of the major by-products from beer making is the left over grain. Like distillery draff and pot ale this can be used as a feedstock for anaerobic digestion to produce biogas. The quantities of spent grain produced by the breweries that were able to supply this data are shown in *Table 12*

.

Table 12. Quantities of spent grain produced by breweries

Brewery	Annual volume of beer produced (litres)	Spent grain weight (tonnes/year)	Spent grain weight per litre of beer (kg/litre)
Brewery A	12,900,000	3,137.5	0.24
Brewery B	1,000,000	170.0	0.17
Brewery C	84,000	12.0	0.14
Brewery D	700,000	120	0.17

The average value of spent grain produced was 0.18 kg per litre of beer made. The volumes of the digesters needed for the spent grain was calculated from the data provided by the breweries. For the digester holding the spent grain a loading rate of $4.2kg$ of spent grain per metre cubed of water per day was needed in order to maintain a COD of $45kgm^{-3}$.To calculate the volume of the digester needed the annual weight of spent grain was divided by the number of days in a year to get the daily amount of spent grain available, and this was then divided by the loading rate.

$$Volume\ of\ digester\ required\ for\ spent\ grain\ (m^3) = \frac{Annual\ weight\ of\ spent\ grain\ (kg)}{365}/4.2$$

Theoretically this should produce 1.8 litres of methane per litre of liquid in the digester.[41] The results are shown in Table 13.

Table 13. Biogas production from anaerobic digestion of brewery spent grain

Brewery	Spent grain weight per day (kg/day)	Volume of digester needed (m^3)	Methane production per day (litres)
Brewery A	8596	2,046.7	3,643,043
Brewery B	466	110.9	197,391
Brewery C	33	7.8	13,933
Brewery D	329	78.3	139,335

6.7 Further Comments on Biogas Production

Since the by-product outputs are synchronised with the production profiles of the breweries and distilleries, to obtain a constant feed rate into the digester some form of storage will be needed to store the draff, pot ale and spent grain when its becomes available. If this is not done the anaerobic digester cannot be sized optimally to make full potential of the annual by-product yields. If the distillery or brewery wanted to digest the by-product immediately when it became available the actual volume of digesters would need to be bigger than the ones calculated in Table 10, Table ***11*** and Table 13.

6.8 Energy Generation Using Biogas

The biogas produced from AD can be used to generate heat and/or electricity via a biogas boiler, electrical generator or a combined heat and power (CHP) engine. To determine the energy potential of each device the biogas data from each distillery and brewery was input through a series of calculations. Typical efficiencies were used to model the calculations:

Table 14. Typical efficiencies of biogas boiler, generator and CHP

Energy Source	Typical Efficiency
Biogas Boiler	90%
Biogas Electrical Generator	35%
Biogas CHP	50% (thermal) 35% (electrical)

The combustion of biogas (60% methane 40% carbon dioxide) produces roughly 6kWh of energy per metre cubed of biogas. The actual energy delivered will be subject to the efficiencies of the boiler, generator and CHP units. For the distilleries supplied heat energy demand data 90% efficiency has been assumed since this is typical for steam boilers. This allows the direct energy requirements to be estimated. The boiler, generator and CHP unit can roughly be sized by from the energy produced on combustion and the typical efficiencies of each device.

Additional heat energy is needed to maintain the mesophilic temperatures within the digester throughout the year. This is hard to quantify since it is dependent on a number of things such as the levels of insulation of the digester, surrounding air temperatures, the temperature the feedstock enters the digester and the makeup of the feedstock mix. As a rough guide, low DM feedstock mixes, like the ones from brewery and distilleries, can be modelled approximately as water. If the digester is located in UK (average UK weather conditions) then approximately 400kWh of heat energy is needed per m^3 of the digester size for the digesters with spent grain and draff as the feedstock and 1MWh of heat energy is needed per m3 of the digester size for the digesters with pot ale as the feedstock.[45] For example a $100m^3$ digester feed with draff would require ~40MWh of heat energy a year to maintain mesophilic temperatures and a $100m^3$

digester fed with pot ale would require ~100MWh. In all of the following relevant calculations this has been accounted for.

The potential heat and electrical energy outputs were calculated and measured against the annual requirements of the breweries and distilleries to see what percentage of the demands were met.

Table 15. Biogas from distillery draff AD – Biogas boiler energy statistics

Distillery	Total Annual Heating Demand (kWh)	Annual volume of biogas available (m^3)	Energy produced on combustion (kWh)	Boiler (90% efficiency) output capacity (kW)	Heat output from 90% efficient boiler (kWh)	% Heating demand met
Distillery A	14,538,000	1,589,286	9,535,714	980	8,582,143	66%
Distillery B	272,000	2,628	15,768	1.8	14,190	5.9%
Distillery C	12,313,000	1,340,933	8,045,600	827	7,241,040	65%
Distillery D	8,660,800	946,790	5,680,743	584	5,112,669	66%
Distillery E	43,320,000	6,145,238	36,871,429	3,788	33,184,286	79%
Distillery F	*N/A*	152,571	915,429	94	823,886	N/A
Distillery G	20,539,890	2,613,210	15,679,257	1,611	14,111,331	70%
Distillery H	26,220,000	3,509,143	21,054,857	2,163	18,949,371	74%
Distillery I	84,000,000	10,595,238	63,571,429	6,531	57,214,286	65%

Table 15 shows the results from the biogas boiler using distillery draff. Excluding 'Distillery B', since their demand data appeared to be far outside the norm, the average percentage of heating demand met using this set up was found to be 75%.

Table 16. Biogas from distillery draff AD – Biogas electrical generator energy statistics

Distillery	Total Annual Electricity Demand (kWh)	Annual volume of biogas available (m^3)	Energy produced on combustion (kWh)	Generator (35% efficiency) - output capacity (kW)	Electricity output from 35% efficient generator (kWh)	% Electricity demand met
Distillery A	400,000	1,589,286	9,535,714	381	3,337,500	834%
Distillery B	9,000	2,628	15,768	0.5	5,520	61%
Distillery C	411,120	1,340,933	8,045,600	321	2,815,960	685%

Distillery D	427,800	946,790	5,680,743	227	1,988,260	465%
Distillery E	1,888,000	6,145,238	36,871,429	1,473	12,905,000	684%
Distillery F	*N/A*	152,571	915,429	37	320,400	*N/A*
Distillery G	1,011,500	2,613,210	15,679,257	626	5,487,740	543%
Distillery H	*N/A*	3,509,143	21,054,857	841	7,369,200	*N/A*
Distillery I	3,600,000	10,595,238	63,571,429	2,540	22,250,000	618%

Table 16 indicates that the distillery electrical demand can more than be met using an electrical generator that runs off of biogas produced from draff AD. With the average % demand met being 638%**.** *Table 17* shows the results of a CHP unit being used and indicates that the electricity demand can easily be covered and the average heating demand met was found to be 42%.

Table 17. Biogas from distillery draff AD – Biogas CHP energy statistics

Distillery	Electricity output from CHP unit with 35% electrical efficiency (kWh)	% Electricity demand met	Heat output from CHP unit with 50% heat energy efficiency (kWh)	% Heating demand met	Output capacity (kWe,kWth)
Distillery A	3,337,500	834%	4,767,857	33%	381, 545
Distillery B	5,520	53%	7,872	3%	0.5, 0.7
Distillery C	2,815,960	685%	4,022,800	33%	321, 459
Distillery D	1,988,260	465%	2,840,371	32%	227, 325
Distillery E	12,905,000	684%	18,435,714	39%	1,473, 2106
Distillery F	320,400	N/A	457,714	N/A	37, 53
Distillery G	5,487,740	543%	7,839,629	35%	626, 895
Distillery H	7,369,200	N/A	10,527,429	37%	841, 1203
Distillery I	22,250,000	618%	31,785,714	35%	2,540, 3632

Table 18, Table 19 and Table 20 show the boiler, electrical generator and CHP unit results using biogas from pot ale AD.

Table 18. Biogas from distillery pot ale AD – Biogas boiler energy statistics

Distillery	Total Annual Heating Demand (kWh)	Annual volume of biogas available (m^3)	Energy produced on combustion (kWh)	Boiler (90% efficiency) output capacity (kW)	Heat output from 90% efficient boiler (kWh)	% Heating demand met
Distillery A	13,580,000	600,000	3,600,000	370	3,240,000	26%
Distillery C	11,800,000	159,000	954,000	98	858,600	8%
Distillery E	44,150,000	1,520,640	9,123,840	937	8,211,456	21%
Distillery F	*N/A*	33,000	198,000	20	178,200	N/A
Distillery G	20,854,000	573,750	3,442,500	354	3,098,250	17%
Distillery I	85,240,000	2,262,390	13,574,340	1,395	12,216,906	16%

The average % heating demand met from using a boiler running on biogas from pot ale AD was found to be 18%.

Table 19. Biogas from distillery pot ale AD – Biogas electrical generator energy statistics

Distillery	Total Annual Electricity Demand (kWh)	Annual volume of biogas available (m^3)	Energy produced on combustion (kWh)	Generator (35% efficiency) - output capacity (kW)	Electricity output from 35% efficient generator (kWh)	% Electricity demand met
Distillery A	400,000	600,000	3,600,000	144	1,260,000	315%
Distillery C	411,120	159,000	954,000	38	333,900	81%
Distillery E	1,888,000	1,520,640	9,123,840	365	3,193,344	169%
Distillery F	*N/A*	33,000	198,000	8	69,300	*N/A*
Distillery G	1,011,500	573,750	3,442,500	138	1,204,875	119%
Distillery I	3,600,000	2,262,390	13,574,340	542	4,751,019	132%

The average % electricity demand met from using an electrical running on biogas from pot ale AD was found to be 163%.

Table 20. Biogas from distillery pot ale AD – Biogas CHP energy statistics

Distillery	Electricity output from CHP unit with 35% electrical efficiency (kWh)	% Electricity demand met	Heat output from CHP unit with 50% heat energy efficiency (kWh)	% Heating demand met	Output capacity (kWe,kWth)
Distillery A	1,260,000	315%	1,800,000	13%	144, 206
Distillery C	333,900	81%	477,000	4.3%	38, 54
Distillery E	3,193,344	169%	4,561,920	10%	365, 522
Distillery F	69,300	*N/A*	99,000	*N/A*	8, 11
Distillery G	1,204,875	119%	1,721,250	8.3%	138, 197
Distillery I	4,751,019	132%	6,787,170	8%	542, 775

The average % electricity demand and % heating demand met from using a CHP engine running on biogas from pot ale AD was found to be 163% and 10% respectively.

A combination of using biogas from pot ale and draff anaerobic digestion will provide the most energy potential. However separate digesters will be needed to produce the methane since, as stated earlier, the by-products have different susceptibility to the methane producing bacteria. The combination results are shown in the appendix in Table 67, Table 68 and Table 69.

Similarly analysis was carried out on the brewery data. Only four breweries provided sufficient data to allow for analysis.

Table 21. Biogas from brewery spent gain AD – Biogas boiler energy statistics

Brewery	Total Annual Heating Demand (kWh)	Annual volume of biogas available (m^3)	Energy produced on combustion (kWh)	Boiler (90% efficiency) output capacity (kW)	Heat output from 90% efficient boiler (kWh)	% Heating demand met
Brewery A	5,049,000	1,329,711	7,978,265	820	7,180,439	160%
Brewery B	394,000	72,048	432,286	44	389,057	110%
Brewery C	69,000	5,086	30,514	3	27,463	44%
Brewery D	472,000	50,857	305,143	31	274,629	65%

Table 22. Biogas from brewery spent gain AD – Biogas electrical generator energy statistics

Brewery	Total Annual Electricity Demand (kWh)	Annual volume of biogas available (m^3)	Energy produced on combustion (kWh)	Generator (35% efficiency) - output capacity(kW)	Electricity output from 35% efficient generator (kWh)	% Electricity demand met
Brewery A	2,128,000	1,329,711	7,978,265	319	2,792,393	131.2%
Brewery B	77,000	72,048	432,286	17	151,300	196.5%
Brewery C	N/A	5,086	30,514	1	10,680	N/A
Brewery D	115000	50,857	305,143	12	106,800	92.9%

Table 23. Biogas from brewery spent gain AD – Biogas CHP energy statistics

Brewery	Electricity output from CHP unit with 35% electricity efficiency (kWh)	% Electricity demand met	Heat output from CHP unit with 50% heat energy efficiency (kWh)	% Heating demand met	Output capacity (kWe,kWth)
Brewery A	2,792,393	131.2%	3,989,133	80%	319, 456
Brewery B	151,300	196.5%	216,143	55%	17, 24
Brewery C	10,680	N/A	15,257	22%	1, 1.4
Brewery D	106,800	92.9%	152,571	32%	12, 17

The results indicate that a large proportion of the distillery and brewery heating and electricity demands can be met with using the different AD systems. What this means economically will be discussed in the next section.

7. Economic Analysis

The potential monetary savings a distillery or brewery can make by installing an anaerobic digestion and biogas energy generation system depend on a number of things. Generally it is the bigger sized companies that are the most suited for these systems since the total costs involved are not linearly proportional to size and instead follow a relationship similar to the one in *Figure 14.*.

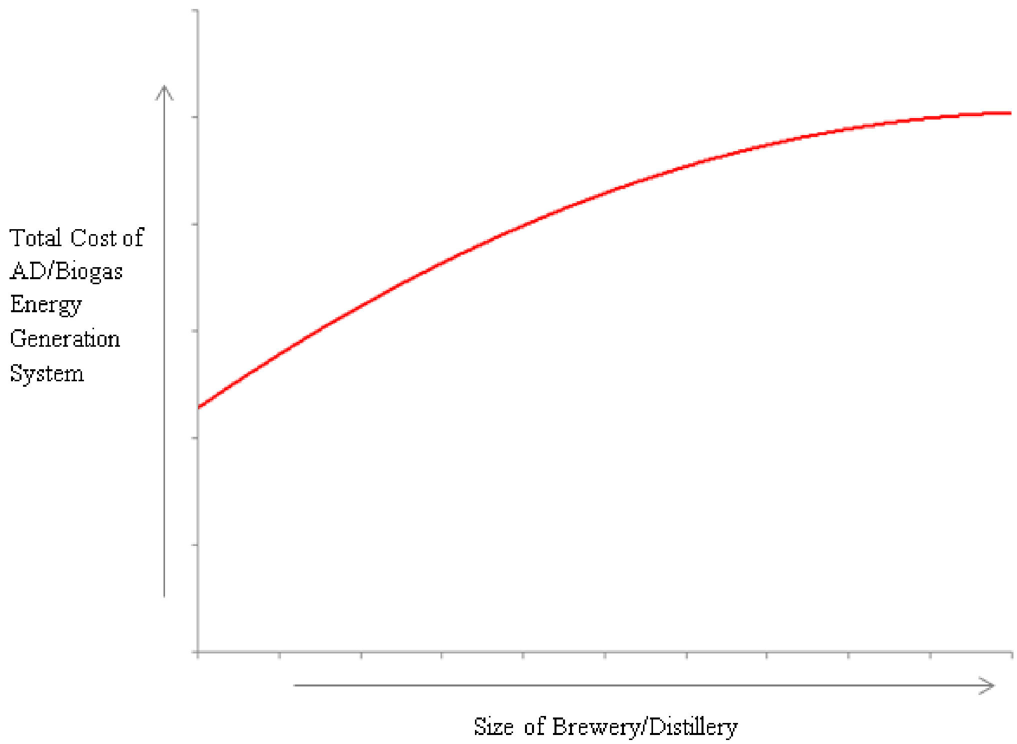

Figure 14. Relationship between the total cost of an AD/biogas energy generation system and the size of the brewery/distillery

The main sources of economic saving come from a reduced need on buying fuel and energy from an external provider since a proportion of the total heat energy and/or electricity demand are being generated and used on site. The money saved will depend on the amount of fuel displaced and the cost of the fuel to the company. Average UK industrial fuel prices were used in calculating the money saved from the fuel displaced for each brewery and distillery company. A full breakdown of the fuel costs can be found in the appendix.

Further sources of savings come from payments via the UK governments Renewable Heat Incentive (RHI) and Feed-In-Tariff (FIT) payment schemes which will give the companies money for the heat and electricity the generate via their AD system. The RHI payments are made for every kWh of heat energy generated and the FIT payments for every kWh of electricity generated. The FIT export tarrif is a bonus payment for the electricity generated that's exported to the national grid. This is a fixed payment of 4.85 pence per kWh[46] exported whilst the FIT generation tariff and RHI tariff are related to the size of the installed AD system. *Table 24* and *Table 25* show the tariffs in relation to the size of the AD system.

Table 24. FIT payments in relation to installed capacity of AD system. As of 1st April 2015 .[47]

Installed Capacity	Tariff (p/kWh)
≤250kW	10.13
>250-500kW	9.36
>500kW	8.68

Table 25. RHI payments in relation to installed capacity of AD system. As of 1st July 2015[48]

Installed Capacity	Tariff (p/kWh)
<200kW	7.62
200-600kW	5.99
≥600kW	2.44

Since a biogas boiler will only produce heat energy it is only eligible to receive RHI payments and not FIT payments. Likewise, since a biogas electrical generator will only produce electricity it will only receive FIT payments and not RHI payments. A biogas CHP unit will receive both since it produces both electricity and heat energy.

The following tables show the annual savings that can be made for each system setup based on savings from displaced fuel and income from RHI and FIT payment schemes. **NOTE** that they **DO NOT** represent overall annual profit since the costs involved have not yet been taken into account. The true cost for each system in relation to each distillery and brewery will be discussed further on. Note also that when the columns are summed they will always be slightly less than the total. This is because money has been deducted to account for the costs of heating the digester over the year.

Table 26. Biogas from draff AD – Biogas boiler - Potential savings

Distillery	Annual savings from displaced fuel	RHI Income	Total annual savings
Distillery A	£306,000	£209,404	**£513,000**
Distillery B	£760	£942	**£1,700**
Distillery C	£205,000	£176,681	**£382,000**
Distillery D	£145,000	£306,249	**£451,000**
Distillery E	£1,032,000	£809,697	**£1,840,000**
Distillery G	£493,000	£344,316	**£837,000**
Distillery H	£664,000	£462,365	**£1,126,000**
Distillery I	£1,334,000	£1,396,029	**£2,730,000**

Table 27. Biogas from draff AD – Biogas electrical generator - Potential savings

Distillery	Annual electricity savings	Money made from selling surplus electricity to the grid	FIT income	Total annual savings
Distillery A	£47,440	£142,469	£312,390	**£481,000**
Distillery B	£566	£0	£487	**£1,100**
Distillery C	£39,601	£116,635	£263,574	**£404,000**
Distillery D	£50,737	£75,682	£201,411	**£316,000**
Distillery E	£223,917	£534,325	£1,120,154	**£1,798,000**
Distillery G	£119,964	£217,098	£476,336	**£758,000**
Distillery I	£345,960	£904,525	£1,931,300	**£3,079,000**

Table 28. Biogas from draff AD – Biogas CHP - Potential savings

Distillery	Annual savings from displaced fuel and electricity savings	Money made from selling surplus electricity to the grid	FIT income	RHI income	Total annual savings
Distillery A	£200,000	£142,469	£312,390	£285,595	**£940,000**
Distillery B	£907	£0	£487	£523	**£1,900**
Distillery C	£143,000	£116,635	£263,574	£240,966	**£764,000**
Distillery D	£121,000	£75,682	£201,411	£170,138	**£568,000**
Distillery E	£804,000	£534,325	£1,120,154	£449,831	**£2,908,000**
Distillery G	£367,000	£217,098	£476,336	£191,287	**£1,251,000**
Distillery H	£328,000	N/A	£639,647	£256,869	>**£1,224,000**
Distillery I	£1,011,000	£904,525	£1,931,300	£775,571	**£4,622,000**

Table 29. Biogas from pot ale AD – Biogas boiler - Potential savings

Distillery	Annual savings from displaced fuel	RHI Income	Total annual savings
Distillery A	£123,000	£215,640	**£338,000**
Distillery C	£26,000	£72,695	**£99,000**
Distillery E	£311,000	£222,622	**£534,000**
Distillery G	£117,000	£206,206	**£324,000**
Distillery I	£307,000	£331,214	**£637,000**

Table 30. Biogas from pot ale AD – Biogas electrical generator - Potential savings

Distillery	Annual electricity savings	Money made from selling surplus electricity to the grid	FIT income	Total annual savings
Distillery A	£47,440	£41,710	£127,638	**£208,000**
Distillery C	£39,601	£0	£33,824	**£72,000**
Distillery E	£223,917	£63,309	£298,897	**£559,000**
Distillery G	£119,964	£9,379	£122,054	**£244,000**
Distillery I	£345,960	£55,824	£412,388	**£791,000**

Table 31. Biogas from pot ale AD – Biogas CHP - Potential savings

Distillery	Annual savings from displaced fuel and electricity savings	Money made from selling surplus electricity to the grid	FIT income	RHI income	Total annual savings
Distillery A	£107,000	£41,710	£127,638	£107,820	**£384,000**
Distillery C	£53,000	£0	£33,824	£36,347	**£123,000**
Distillery E	£370,000	£63,309	£298,897	£273,259	**£1,005,000**
Distillery G	£178,000	£9,379	£122,054	£131,159	**£440,000**
Distillery I	£519,000	£55,824	£412,388	£165,607	**£1,152,000**

Taking the total annual savings from the distilleries and presenting them graphically in *Figure 15* raises some interesting points.[4] For every distillery an AD system using draff as the feedstock for biogas production and then a CHP unit to generate heat and electricity provided the largest total annual savings. Also for every distillery using any type of draff-based AD system (boiler, generator, CHP) will have the biggest possibility for savings on displaced fuel and money generated by FIT and RHI payments. This is because the annual quantities of biogas produced from draff are larger than that of the biogas produced from pot ale. CHP units were the best option for both draff and pot ale cases. There was a split of monetary outcome between the distilleries when using either a boiler or generator. This was due to a number of things such as distilleries falling into different output capacities affecting what RHI and FIT tariff bracket they fell into, and also if they had any surplus electricity which they could sell back to the grid.

[4] Only distilleries which provided data for both draff and pot ale are presented graphically

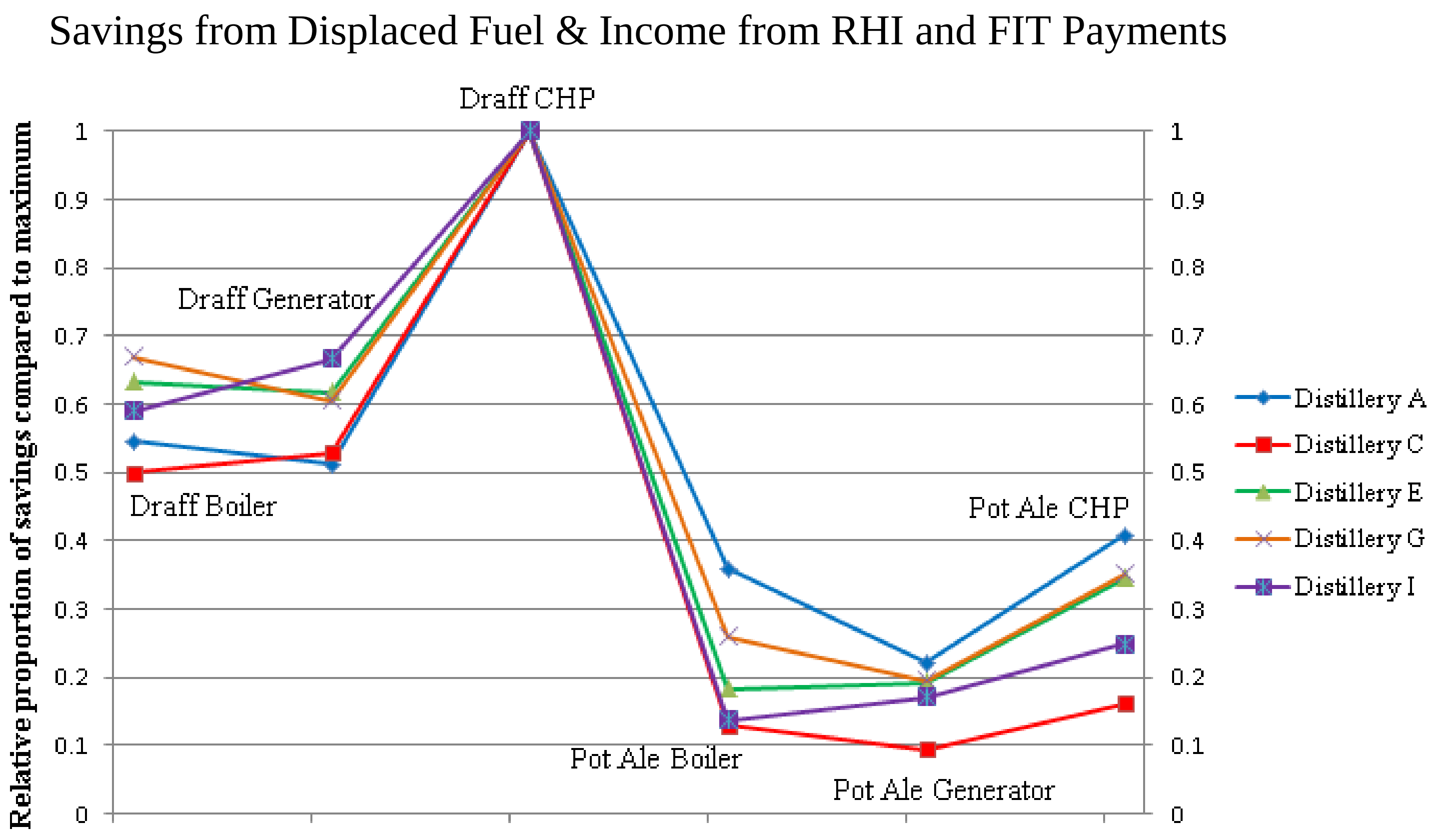

Figure 15. Distillery savings from displaced fuel and income from RHI and FIT payments (1)

The results for using a combination of biogas from pot ale and draff AD are shown in the following tables. A combination of all the distillery results is presented in *Figure 16.*

Table 32. Biogas from pot ale and draff AD – Biogas boiler - Potential savings

Distillery	Annual savings from displaced fuel	RHI Income	Total annual savings)
Distillery A	£415,000	£288,460	**£703,000**
Distillery C	£225,000	£197,631	**£423,000**
Distillery E	£1,330,000	£1,010,056	**£2,340,000**
Distillery G	£602,000	£419,914	**£1,022,000**
Distillery I	£1,552,000	£1,694,121	**£3,246,000**

Table 33. Biogas from pot ale and draff AD – Biogas electrical generator - Potential savings

Distillery	Annual electricity savings	Money made from selling surplus electricity to the grid	FIT income	Total annual savings
Distillery A	£47,440	£203,579	£399,063	**£628,000**
Distillery C	£39,601	£132,829	£294,827	**£451,000**
Distillery E	£223,917	£689,202	£1,397,336	**£2,199,000**
Distillery G	£119,964	£275,534	£580,919	**£930,000**
Distillery I	£345,960	£1,134,949	£2,343,688	**£3,719,000**

Table 34. Biogas from pot ale and draff AD – Biogas CHP - Potential savings

Distillery	Annual savings from displaced fuel and electricity savings	Money made from selling surplus electricity to the grid	FIT income	RHI income	Total annual savings
Distillery A	£321,000	£203,579	£399,063	£160,256	**£1,084,000**
Distillery C	£201,000	£132,829	£294,827	£109,795	**£738,000**
Distillery E	£1,209,000	£689,202	£1,397,336	£561,142	**£3,856,000**
Distillery G	£556,000	£275,534	£580,919	£233,285	**£1,646,000**
Distillery I	£1,581,000	£1,134,949	£2,343,688	£941,178	**£6,000,000**

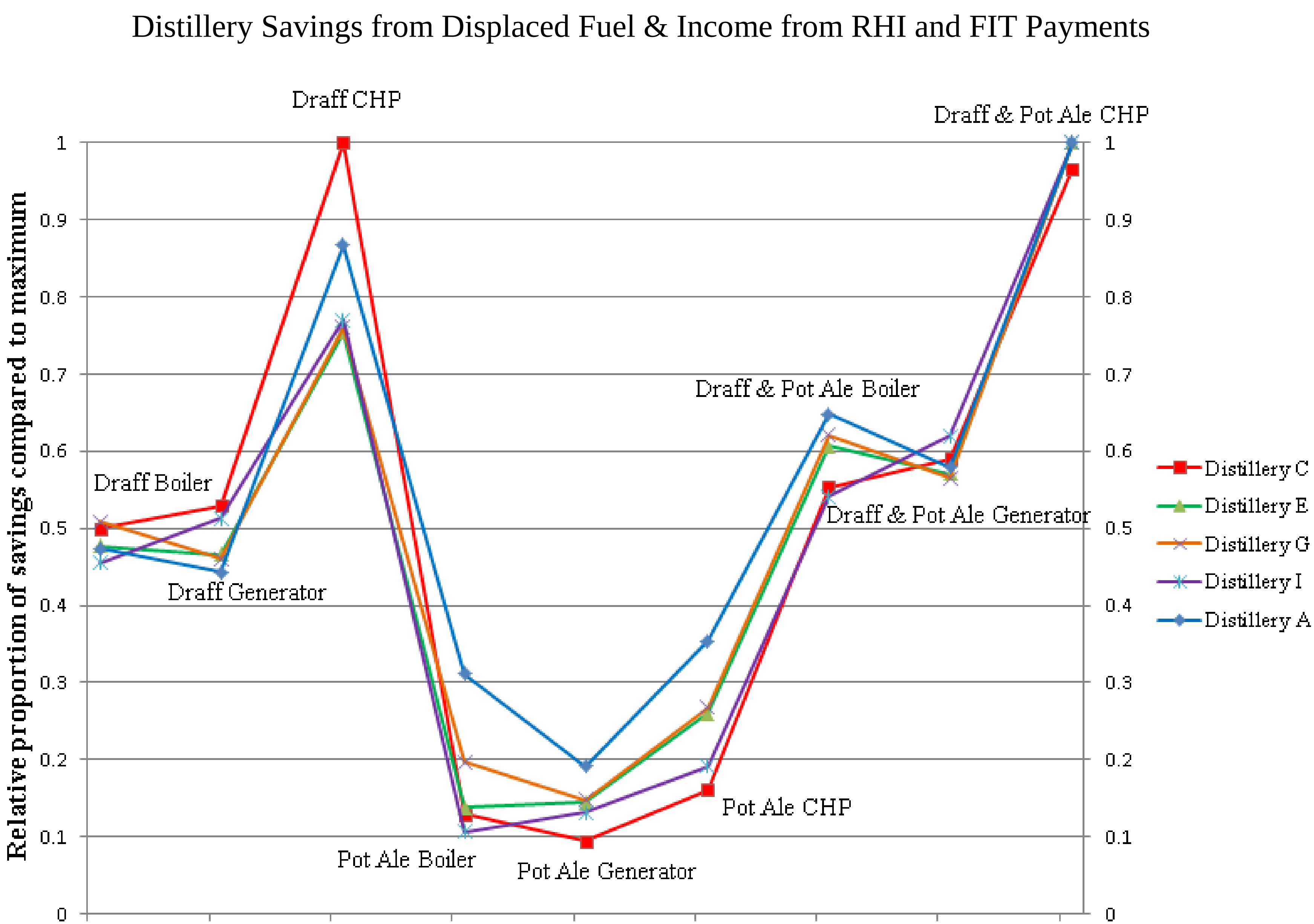

Figure 16. Distillery savings from displaced fuel and income from RHI and FIT payments (2)

From *Figure 16* it can be seen that using a CHP based AD system always presents the best opportunity for the greatest earnings from FIT and RHI payments and money saved from the fuel displaced. An interesting point arises when the results for Distillery C are looked at. It is actually more profitable for only the draff to be used to generate biogas and run the CHP unit rather than including the pot ale also. This is because the thermal output capacity of the CHP unit in the former case is lower and puts the unit in a better RHI tariff bracket. For distilleries close to a 600kW thermal output capacity of either a boiler or CHP unit it is worth considering dropping the thermal output capacity slightly below 600kW so as to receive significantly better payment for the heat energy generated. The increase in tariff is by 245% from 2.44p/kWh to 5.99p/kWh, by far the biggest difference between all tariff brackets including FIT tariff brackets.

The brewery results were analysed in the same way and are presented in the following tables.

Table 35.Biogas from spent grain AD – Biogas boiler - Potential savings

Brewery	Annual savings from displaced fuel	RHI Income	Total annual savings
Brewery A	£116,000	£175,000	**£259,000**
Brewery B	£11,000	£30,000	**£40,000**
Brewery D	£29,000	£21,000	**£48,000**

Table 36. Biogas from spent grain AD – Biogas generator - Potential savings

Brewery	Annual electricity savings	Money made from selling surplus electricity to the grid	FIT income	Total annual savings
Brewery A	£205,000	£32,000	£261,000	**£466,000**
Brewery B	£9,000	£4,000	£15,000	**£26,000**
Brewery D	£14,000	£0	£11,000	**£22,000**

Table 37. Biogas from spent grain AD – Biogas CHP - Potential savings

Brewery	Annual savings from displaced fuel and electricity savings	Money made from selling surplus electricity to the grid	FIT income	RHI income	Total annual savings
Brewery A	£270,000	£215,000	£261,000	£239,000	**£955,000**
Brewery B	£15,000	£12,000	£15,000	£16,000	**£57,000**
Brewery D	£25,000	£0	£11,000	£12,000	**£48,000**

Brewery Savings from Displaced Fuel & Income from RHI and FIT Payments

Figure 17. Brewery savings from displaced fuel and income from RHI and FIT payments

Table 35, Table 36, Table 37 and *Figure 17* indicate that a CHP based AD system for the breweries has the biggest potential for money savings from fuel displaced and income from FIT and RHI payments. The reason for this is, since *both* electricity and heat are generated and used, savings are incurred from displaced fuel and electricity but also because both RHI and FIT payments can be received.

So far none of the costs associated with an AD system have been discussed. In reality it is difficult to quantify these as they vary from case to case and are dependent on many different factors as will be discussed further on. Because of the variability it is often useful to calculate the maximum possible loan a company could receive in order to break even over a certain loan repayment period. This is calculated based on the savings each company make from the annual amount fuel displaced and the total annual FIT and RHI payments. In essence this calculation allows the company to see how much money they have to 'play with' and to cover things like capital, installation, maintenance and running costs of the AD system.

For the calculations a fixed repayment period of 7 years was used since this is a fairly typical repayment period. A range of interest rates on the loan were applied ranging from 2% to 10%.[5]

The formula used for the calculation:

$$C = \frac{T((1+R)^P - 1)}{(R(1+R)^P)}$$

Where

C = The maximum loan possible in order to break even over the payback period

T = Total annual savings from displaced fuel and RHI and FIT payments

R = Interest rate on loan

P = Payback period (in this case 7 years)

[5] It is possible that a governmental grant could be used to finance the project with a low or no interest rate on it.

The results are displayed in the flowing tables:

Table 38. Biogas from draff AD – Biogas boiler maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Distillery A	£3,320,000	£3,079,000	£2,864,000	£2,671,000	£2,497,000
Distillery B	£11,000	£10,000	£9,000	£9,000	£8,000
Distillery C	£2,472,000	£2,293,000	£2,132,000	£1,989,000	£1,860,000
Distillery D	£2,919,000	£2,707,000	£2,518,000	£2,348,000	£2,196,000
Distillery E	£11,908,000	£11,044,000	£10,272,000	£9,580,000	£8,958,000
Distillery G	£5,417,000	£5,024,000	£4,672,000	£4,358,000	£4,075,000
Distillery H	£7,287,000	£6,758,000	£6,286,000	£5,862,000	£5,482,000
Distillery I	£17,669,000	£16,386,000	£15,240,000	£14,213,000	£13,291,000

Table 39. Biogas from draff AD – Biogas electrical generator maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Distillery A	£3,113,000	£2,887,000	£2,685,000	£2,504,000	£2,342,000
Distillery B	£7,000	£7,000	£6,000	£6,000	£5,000
Distillery C	£2,615,000	£2,425,000	£2,255,000	£2,103,000	£1,967,000
Distillery D	£2,045,000	£1,897,000	£1,764,000	£1,645,000	£1,538,000
Distillery E	£11,637,000	£10,792,000	£10,037,000	£9,361,000	£8,753,000
Distillery G	£4,906,000	£4,550,000	£4,231,000	£3,946,000	£3,690,000
Distillery I	£19,927,000	£18,480,000	£17,188,000	£16,030,000	£14,990,000

Table 40. Biogas from draff AD – Biogas CHP maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Distillery A	£6,084,000	£5,642,000	£5,247,000	£4,894,000	£4,576,000
Distillery B	£12,000	£11,000	£11,000	£10,000	£9,000
Distillery C	£4,945,000	£4,586,000	£4,265,000	£3,978,000	£3,719,000
Distillery D	£3,676,000	£3,409,000	£3,171,000	£2,957,000	£2,765,000
Distillery E	£18,821,000	£17,454,000	£16,234,000	£15,140,000	£14,157,000
Distillery G	£8,096,000	£7,509,000	£6,984,000	£6,513,000	£6,090,000
Distillery H	£7,922,000	£7,347,000	£6,833,000	£6,373,000	£5,959,000
Distillery I	£29,914,000	£27,741,000	£25,802,000	£24,064,000	£22,502,000

Table 41. Biogas from pot ale AD – Biogas boiler maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Distillery A	£2,188,000	£2,029,000	£1,887,000	£1,760,000	£1,646,000
Distillery C	£641,000	£594,000	£553,000	£515,000	£482,000
Distillery E	£3,456,000	£3,205,000	£2,981,000	£2,780,000	£2,600,000
Distillery G	£2,097,000	£1,945,000	£1,809,000	£1,687,000	£1,577,000
Distillery I	£4,123,000	£3,823,000	£3,556,000	£3,316,000	£3,101,000

Table 42. Biogas from pot ale AD – Biogas electrical generator maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Distillery A	£1,346,000	£1,248,000	£1,161,000	£1,083,000	£1,013,000
Distillery C	£466,000	£432,000	£402,000	£375,000	£351,000
Distillery E	£3,618,000	£3,355,000	£3,121,000	£2,910,000	£2,721,000
Distillery G	£1,579,000	£1,465,000	£1,362,000	£1,270,000	£1,188,000
Distillery I	£5,119,000	£4,748,000	£4,416,000	£4,118,000	£3,851,000

Table 43. Biogas from pot ale AD – Biogas CHP maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Distillery A	£2,485,000	£2,305,000	£2,144,000	£1,999,000	£1,869,000
Distillery C	£796,000	£738,000	£687,000	£640,000	£599,000
Distillery E	£6,504,000	£6,032,000	£5,610,000	£5,232,000	£4,893,000
Distillery G	£2,848,000	£2,641,000	£2,456,000	£2,291,000	£2,142,000
Distillery I	£7,456,000	£6,914,000	£6,431,000	£5,998,000	£5,608,000

Table 44. Biogas from pot ale and draff AD – Biogas boiler maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Distillery A	£4,550,000	£4,219,000	£3,924,000	£3,660,000	£3,422,000
Distillery C	£2,738,000	£2,539,000	£2,361,000	£2,202,000	£2,059,000
Distillery E	£15,144,000	£14,045,000	£13,063,000	£12,183,000	£11,392,000
Distillery G	£6,614,000	£6,134,000	£5,705,000	£5,321,000	£4,976,000
Distillery I	£21,008,000	£19,483,000	£18,120,000	£16,900,000	£15,803,000

Table 45. Biogas from pot ale and draff AD – Biogas electrical generator maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Distillery A	£4,064,000	£3,769,000	£3,506,000	£3,270,000	£3,057,000
Distillery C	£2,919,000	£2,707,000	£2,518,000	£2,348,000	£2,196,000
Distillery E	£14,232,000	£13,199,000	£12,276,000	£11,449,000	£10,706,000
Distillery G	£6,019,000	£5,582,000	£5,192,000	£4,842,000	£4,528,000
Distillery I	£24,069,000	£22,322,000	£20,761,000	£19,362,000	£18,106,000

Table 46. Biogas from pot ale and draff AD – Biogas CHP maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Distillery A	£7,016,000	£6,506,000	£6,051,000	£5,644,000	£5,277,000
Distillery C	£4,776,000	£4,430,000	£4,120,000	£3,842,000	£3,593,000
Distillery E	£24,956,000	£23,144,000	£21,526,000	£20,076,000	£18,773,000
Distillery G	£10,653,000	£9,879,000	£9,189,000	£8,570,000	£8,013,000
Distillery I	£38,832,000	£36,012,000	£33,494,000	£31,238,000	£29,211,000

And the results for the breweries:

Table 47. Biogas from spent grain AD – Biogas boiler maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Brewery A	£1,676,000	£1,555,000	£1,446,000	£1,348,000	£1,261,000
Brewery B	£259,000	£240,000	£223,000	£208,000	£195,000
Brewery D	£311,000	£288,000	£268,000	£250,000	£234,000

Table 48. Biogas from spent grain AD – Biogas electrical generator maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Brewery A	£3,016,000	£2,797,000	£2,601,000	£2,426,000	£2,269,000
Brewery B	£168,000	£156,000	£145,000	£135,000	£127,000
Brewery D	£142,000	£132,000	£123,000	£115,000	£107,000

Table 49. Biogas from spent grain AD – Biogas CHP maximum capital investment

Interest Rate -->	2%	4%	6%	8%	10%
Brewery A	£6,181,000	£5,732,000	£5,331,000	£4,972,000	£4,649,000
Brewery B	£369,000	£342,000	£318,000	£297,000	£277,000
Brewery D	£311,000	£288,000	£268,000	£250,000	£234,000

The results indicated that large savings are possible but they need to be put into context with the costs involved with an AD system in order. As stated earlier this can be hard to quantify but it can be roughly approximated and understood by looking at the economics of currently operating AD systems.

One example, which for legal reasons cannot be named, cites a 1MWe AD/CHP systems capital expenses (CAPEX) being in the region of £4m all in. This includes planning, legal, civil and costs of equipment.

There are also operational expenses (OPEX) to consider. For this example the OPEX are:

- **Feedstocks**: This site buys in all of its feedstock at a cost of £25-45/MWh, about £700k a year, putting the breweries and distilleries at an advantage since they generate their own feedstock.
- **CHP maintenance:** ~£19/MWh which equates to ~£150k per year
- **Digestate disposal:** This is hard to quantify since farmers will often take this away for free.
- **AD equipment maintenance:** This is a bit more ad hoc as it depends on equipment lifespans and breakdowns. For this example it roughly costs them £20-£30k per year

There are lots of other costs and for this example they are:

- **Insurance** ~ £20k/year
- **Trace elements** ~ £10k/year
- **Analysis** ~ £5k/year

- **Wages** ~£30-£50k/year (depending on number of staff needed)
- **Site lease** (if not owned by the developer) ~ £25k/year

All of these combined put the OPEX at ~£1m/year. Excluding feedstock costs this would be £300k/year for a 1MWe AD/CHP system.

For comparison Distillery E running an AD/CHP system using draff as the feedstock for the digester has an output capacity of 1.47MWe can break even over a 7 year period with a loan of £16.2m with 6% interest on it (see *Table 40*). Going off this example case and scaling it up[6] the running costs would be around £440k/year, a total of ~£3m for the 7 year period. The CAPEX would be ~£5.9m. Therefore the total cost over the 7 year period would be ~£9m. This suggests that not only would Distillery E be able to comfortably break even over this period but also incur healthy profits. Beyond this point once the CAPEX costs have been covered and the only expenses would be OPEX costs. *Table 28* estimates the annual savings for distillery E as £2.9m therefore subtracting OPEX costs the distillery would make yearly savings of ~£2.4m.

An AD/CHP system for Brewery A using spent grain as the feedstock can have an output capacity of 319kWe. If the CAPEX and OPEX costs are scaled for this CAPEX costs can be expected to be £1.3m and the OPEX costs will be around £100k/year. Therefore the total costs will be at least £1.4m over a 7 year period. Going off the figures in

*Table **49*** this configuration can cover the costs and make profits over a 7 year period with a loan of £5.3 million. This gives a profit margin of £3.9m. It is likely that the actual total cost will be larger than £1.4m because of the relationship in *Figure 14* but even if the total cost over the 7 years was three times larger than the one calculated the brewery would still be able to break even. After CAPEX costs have been paid for Brewery A should make yearly savings of ~ £850k.

It is very likely then that AD/CHP systems of capacity of 300kWe and upwards should be financially viable and generate savings for a brewery or distillery. It becomes less economical as it is implemented on a smaller and smaller scale. One of the contributing financial difficulties is

[6] Costs are scaled from 1MWe to 1.47MWe by multiplying by a scale factor of 1.47. In reality it is likely that the scale factor would be smaller since the cost of an AD/CHP system relative to the size of the output follows a relationship similar to the one in *Figure 14*. However in order to be certain that a system can be economical and to leave room for cost uncertainties the scale factor will remain so.

that there is no FIT tariff bandings below 250kW for anaerobic digestion like there is for other renewable technologies such as hydro, solar PV and wind energy. This adds to making micro-scale AD more financially vulnerable. Introduction of better FIT tariffs for micro-scale AD would help bolster the chances of economic success.

For lower capacity sites rough estimations can be based off another study[49] which looked at the costs of AD when applied to farming and waste systems:

OPEX:

- **Maintenance and repairs:** The costs of maintaining the digester are relatively low when compared to the capital costs. Budgeting costs for this are usually around 2% of its capital value. Good maintenance practice and investment will ensure long lifetime of equipment and prevent higher cost incursions further down the line. The maintenance of the CHP unit will cost around 1p/kWh_e. Most CHP manufacturers recommend a major rebuild after 15-20,000 hours (2-3 years) of operation. This cost of this is often covered in the purchasing deal but not always so care should be taken around this area. The CHP unit will not last as long as the AD digester which will last for around 8-12 years. Repair procedures often mean the system needs to be shut down incurring heavy additional costs until the system is repaired.
- **Insurance:** Often insurance is covered within the purchase agreement of equipment from the suppliers but if not a good budgeting figure is around 1% of the capital investment.
- **Labour:** These costs are not proportional to the output capacity but instead to the complexity of the system in place. This makes it unique from case to case. On small sites only one or two hours a day might be needed. This could be covered by someone already employed by the brewery or distillery although additional training will likely be required to ensure they have the knowledge of how to operate it. Labour requirement will also heavily depend upon the levels of automation the system has. Going off of the previous economic model approximately £50/year per kW_e will be needed.

CAPEX:

As previously stated there are many costs associated with CAPEX. A good rule of thumb figure is that it will cost ~£2,500-£6,000 for every kW of electricity generating capacity. The range is reflective of the size of the installed system. Smaller systems will cost more per kW since they do not benefit from the same economics of scale that the larger systems do. The Good Practice Guide[50] states that a 10kWe capacity system using animal slurry as the feedstock would cost about £60,000 - £70,000 although this costs should be less than this for breweries and distilleries since the draff, spent grain and pot ale feedstock's have a much better biogas yield rate per m^3 in the digester than from animal slurry.[49] Additional capital expenses can come from electrical grid connections and any grounds preparation that needs to take place.

'Brewery B' using an AD/CHP system has an output capacity of ~17kWe. From

*Table **49*** it has the potential to break even over a 7 year period with a £268,000 loan with 6% interest on it. Using the economic model just discussed the estimated costs for this system will be as follows:

CAPEX:

£6,000 x 17 = £102,000

OPEX:

Maintenance and repairs: In 7 years a total potential of 1GWhe of electricity can be produced. The model says the CHP maintenance costs will be ~1p/kWe therefore the total of 7 years will be ~£10,000.

Insurance costs ~ £7,000

Labour ~£7,000

Therefore the total cost is around £126,000. This suggests that the system should be economically viable with plenty of wiggle room to account for uncertainties like how many hours in the year will the system be operational for and any hidden costs.

7.1 Selling Digestate to Third Parties

The price that breweries and distilleries can sell their spent grain and draff to third parties for is hard to be specific about since the agreement is often based on individual circumstances rather than based on average market values. It is also often given away for free since as it avoids the companies having to pay for sending it to landfill. One estimate[31] puts the price at £5 per tonne. One of the distilleries in this report sells their draff for £17 per tonne, another sells theirs for £7 per tonne and one has variable prices dependent on demand which can range from £0 - £6.

If the highest figure of £17 is used with Distillery E's economic results how does it compare economically to sell the draff versus using it to produce biogas and run a CHP unit with?

Distillery E produces approximately 14,500 tonnes of draff a year. Selling it at £17 per tonne would provide £247,000 a year in income. From the analysis earlier using the draff as the feedstock for an AD/CHP system would result in yearly savings of £2.4m. Therefore the distillery would still be at least £2m better off a year using the draff to feed the AD/CHP system instead of selling it on to a third party.

8. Carbon Dioxide Emission Results

The total annual carbon dioxide emissions were calculated for each brewery and distillery from their annual fuel consumption and electricity demand. Emission conversion factors were applied for each fuel type used. For the electricity demand the average UK carbon dioxide emissions per kWh of electricity were used. This was reflective of the current energy mix in the UK e.g. percentage mix of fossil-fuel power stations, renewables etc.

Table 50. Carbon dioxide conversion factors based on fuel type

Fuel Type	Kg CO_2 per kWh
Mains Electricity	0.462
Natural Gas	0.185
Gas Oil	0.274
Fuel Oil[7]	0.263
Propane	0.234
Diesel	0.252
LPG	0.244

Table 51. Carbon dioxide emissions from distilleries

Distillery	Annual volume of whisky produced (litres)	Total annual electricity demand (kWh)	Total annual heating demand (kWh)	Heating source(s)	Annual CO_2 emissions (tonnes)	CO_2 emissions per litre whisky produced (kg/l)
Distillery A	1,500,000	400,000	13,560,000	MFO	3,751	2.50
Distillery B	20,000	9,000	270,300	Gas Oil	78	3.90
Distillery C	1,400,000	411,120	11,487,700	Natural Gas	2,315	1.65
Distillery D	920,600	427,800	8,077,800	Natural Gas	1,692	1.84
Distillery E	6,200,000	1,888,000	43,320,000	HFO	12,265	1.98
Distillery F	140,000	*N/A*	*N/A*	Kerosene	N/A	N/A

[7] Medium fuel oil (MFO) and heavy fuel oil (HFO) have approximately the same carbon dioxide emission factors.

Distillery G	2,400,000	1,011,500	20,539,890	Biomass[8] + MFO	6,135	2.56
Distillery H	2,700,000	*N/A*	26,220,000	HFO	6,896	2.55
Distillery I	10,000,000	3,600,000	84,000,000	Natural Gas	17,203	1.72

The average carbon dioxide emissions for distilleries were found to be 2.3 kg CO_2 per litre of whisky produced. Literature values[36,51] from 2010 state that on average 1.5kg CO2 per litre of whisky made were produced. Since this is an old figure, and improvements in efficiency and an increased integration of renewable technologies with the whisky sector have occurred, we can expect more recent figures conducted in the same way to be lower than this. This could be due to distilleries A to I performing worse than average when it comes to CO_2 emissions or that the way in which data is gathered is different. Furthermore emissions from transport and packaging have not been included in calculating the emissions figure therefore the average would actually be higher than 2.3 kg CO_2 per litre of whisky produced were these factors taken into account.

Table 52. Carbon dioxide emissions from breweries

Brewery	Total annual electricity demand (kWh)	Total annual heating demand (kWh)	Heating source(s)	Anuual CO_2 emissions (tonnes)	Annual volume of beer produced (Litres)	CO_2 emissions per litre beer produced (kg/litre)
Brewery A	2,128,000	4,230,400	Natural Gas	1,766	12,900,000	0.14
Brewery B	77,000	350,000	Natural Gas	100	1,000,000	0.10
Brewery C	N/A	66,200	Propane Gas	>15	84,000	>0.18
Brewery D	115000	441,000	LPG & Diesel	159	700,000	0.23

The average carbon dioxide emissions for breweries were found to be 0.16 kg CO_2 per litre of beer produced. A paper[52] by the Carbon Trust puts the figure at 0.1kg CO_2 per litre of beer produced. Similar to the whisky case the value calculated is higher than the one from literature. This may also be due to differences in the way data is gathered or that distilleries A-D

[8] Biomass is wood which comes from sustainable source therefore zero net carbon emissions from biomass component of heating.

on average perform less well. However this seems unlikely since the breweries better than average when it came to the energy demand per litre of beer produced. It is more likely because the breweries use less renewable energy than the UK average.

Reductions in carbon dioxide emissions can be made with the integration of an anaerobic digestion system. The distillery and brewery biogas is carbon neutral since it only contains CO2 taken up during the growth of the plant material that makes the feedstock (i.e. grain, etc). The subsequent grain which is grown will consume an equivalent amount of CO_2 of that released during the combustion of the biogas. Therefore effectively zero net CO_2 is released into the atmosphere. Calculations were made from the figures in section 6 to see what the reduction in CO2 emissions would be from using each system.

Table 53. Distillery carbon emission reductions from using biogas (from draff) boiler

Distillery	**Annual CO_2 emission reduction (tonnes)**	**% Reduction of CO_2 emissions**
Distillery A	2,508	66.9%
Distillery B	4	4.8%
Distillery C	1,488	64.3%
Distillery D	1,051	62.1%
Distillery E	9,697	79.1%
Distillery G	4,326	70.5%
Distillery H	5,537	80.3%
Distillery I	11,761	68.4%

Table 54. Distillery carbon emission reductions from using biogas (from draff) electrical generator

Distillery	**Annual CO_2 emission reduction (tonnes)**	**% Reduction of CO_2 emissions**
Distillery A	185	4.9%
Distillery B	2	2.6%
Distillery C	190	8.2%
Distillery D	198	11.7%
Distillery E	872	7.1%
Distillery G	467	7.6%
Distillery H	N/A	N/A
Distillery I	1663.2	9.7%

Table 55. Distillery carbon emission reductions from using biogas (from draff) CHP

Distillery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Distillery A	1,968	52.5%
Distillery B	39	50.0%
Distillery C	1,253	54.1%
Distillery D	945	55.8%
Distillery E	6,569	53.6%
Distillery G	3,301	53.8%
Distillery H	N/A	N/A
Distillery I	9,433	54.8%

Table 56. Distillery carbon emission reductions from using biogas (from pot ale) boiler

Distillery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Distillery A	947	25.2%
Distillery C	176	7.6%
Distillery E	2,400	19.6%
Distillery G	950	15.5%
Distillery I	2,511	14.6%

Table 57. Distillery carbon emission reductions from using biogas (from pot ale) electrical generator

Distillery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Distillery A	185	4.9%
Distillery C	154	8.2%
Distillery E	872	7.1%
Distillery G	467	7.6%
Distillery I	1,663	9.7%

Table 58. Distillery carbon emission reductions from using biogas (from pot ale) CHP

Distillery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Distillery A	711	19.0%
Distillery C	288	12.4%
Distillery E	2,205	18.0%
Distillery G	995	16.2%
Distillery I	3,058	17.8%

Table 59. Distillery carbon emission reductions from using biogas (from pot ale & draff) boiler

Distillery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Distillery A	3,455	92.1%
Distillery C	1,665	71.9%
Distillery E	11,393	92.9%
Distillery G	5,276	86.0%
Distillery I	14,272	83.0%

Table 60. Distillery carbon emission reductions from using biogas (from pot ale & draff) electrical generator

Distillery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Distillery A	185	4.9%
Distillery C	190	8.2%
Distillery E	872	7.1%
Distillery G	467	7.6%
Distillery I	1663	9.7%

Table 61. Distillery carbon emission reductions from using biogas (from pot ale & draff) CHP

Distillery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Distillery A	2,104	56.1%
Distillery C	1,115	48.2%
Distillery E	7,202	58.7%
Distillery G	3,399	55.4%
Distillery I	9,592	55.8%

Table 62. Brewery carbon emission reductions from using biogas boiler

Brewery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Brewery A	782	44%
Brewery B	65	65%
Brewery C	7	47%
Brewery D	74	47%

Table 63. Brewery carbon emission reductions from using biogas electrical generator

Brewery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Brewery A	983	56%
Brewery B	35	35%
Brewery C	N/A	N/A
Brewery D	49	31%

Table 64. Brewery carbon emission reductions from using biogas CHP

Brewery	Annual CO_2 emission reduction (tonnes)	% Reduction of CO_2 emissions
Brewery A	1721	97%
Brewery B	76	75%
Brewery C	>3.5	>23%
Brewery D	117	73%

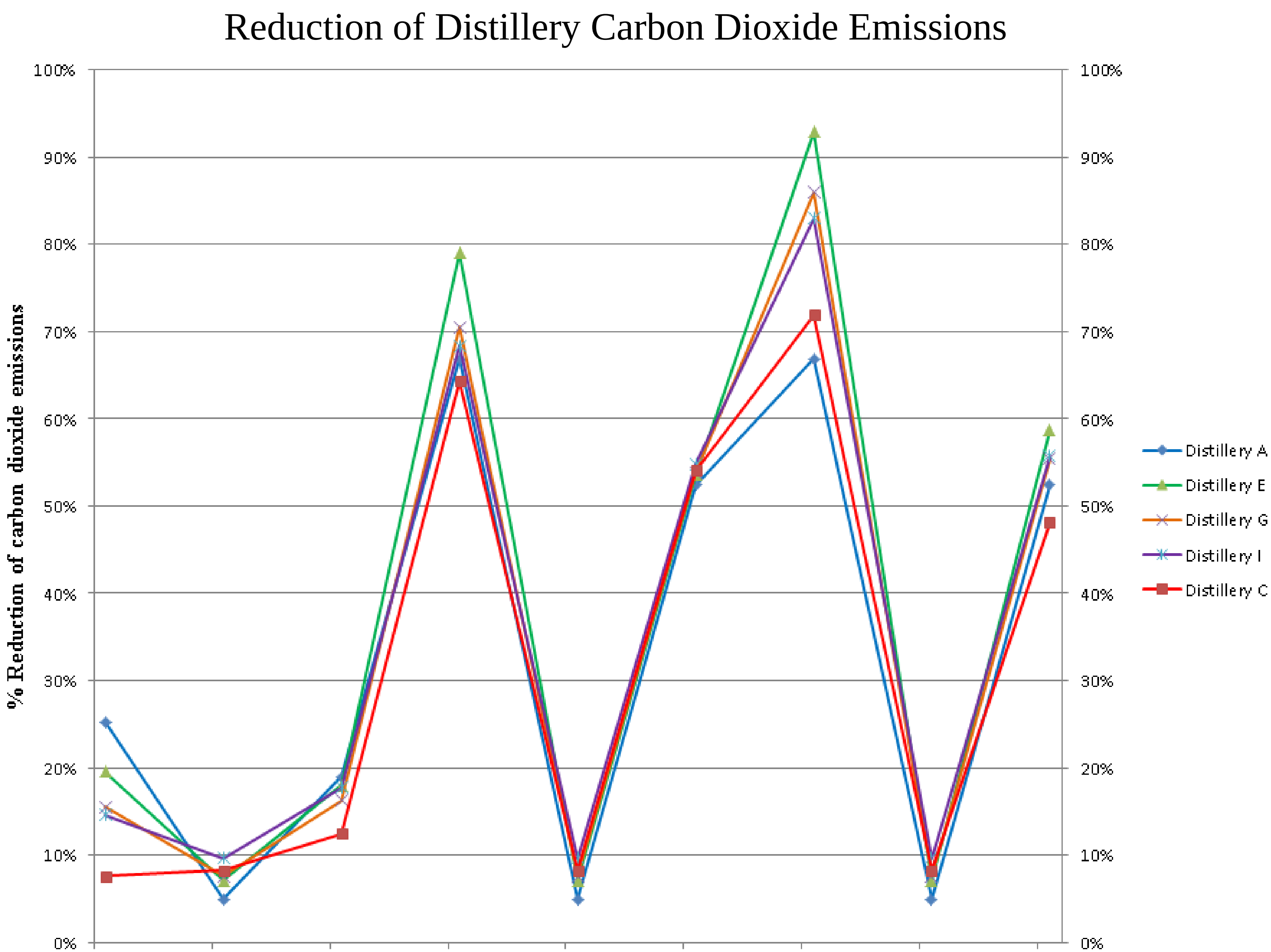

Figure 18. Reduction of distillery carbon dioxide emissions

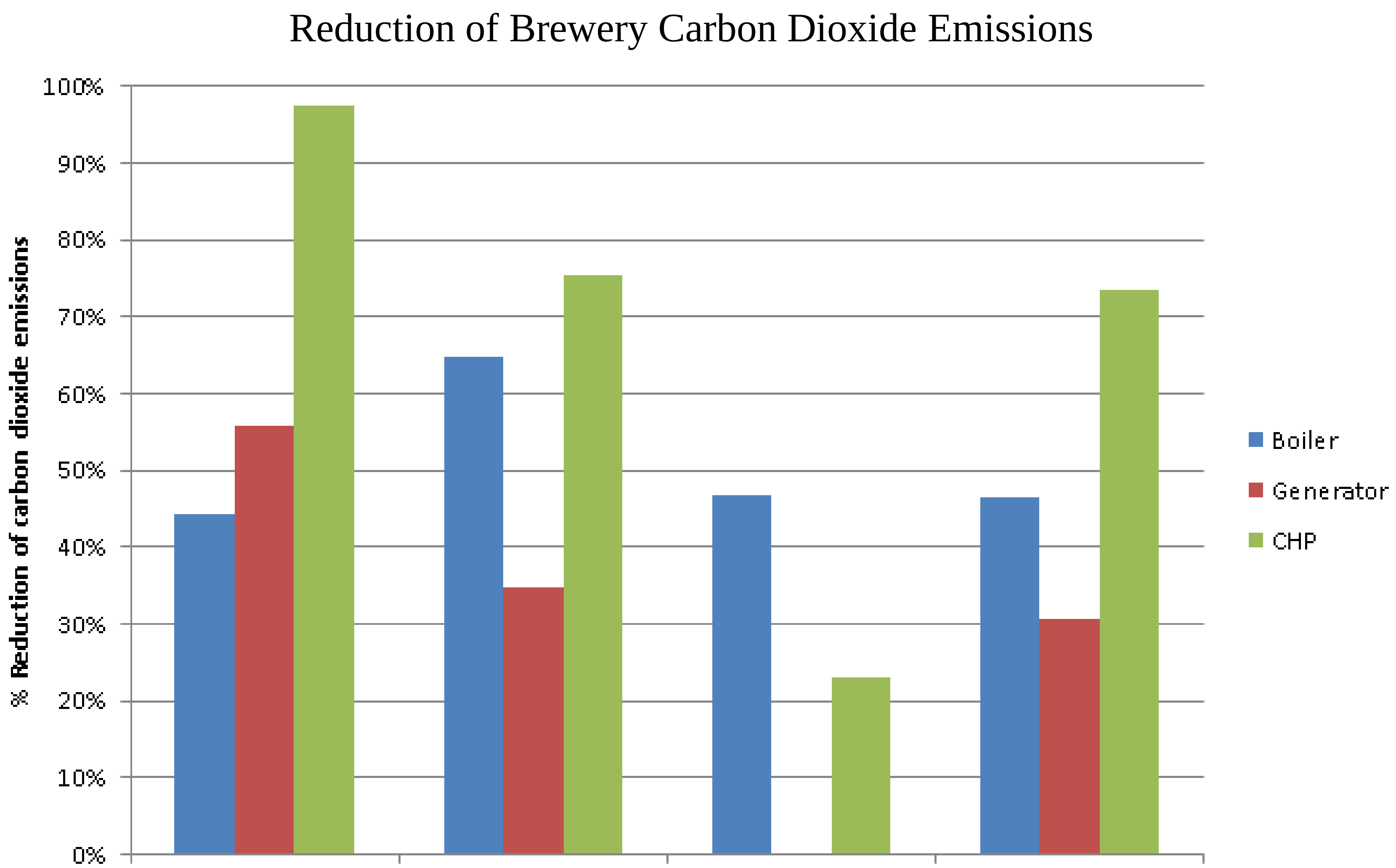

Figure 19. Reduction of brewery carbon dioxide emissions

9. Conclusions

It was found that on average three litres of water are used by a brewery for every litre of beer produced. On average a total of 296 litres of cooling water and 17 litres of process water were used for every litre of whisky produced.

When all of the distillery energy demands are taken into account, other than just the Specific Energy Consumption (SEC), the values of energy required per litre of product are significantly higher than the ones from literature. The average energy demand for producing whisky was found to be 8.83kWh per litre made and the value from literature states that it takes 6.66kWh per litre made i.e. a third more energy is required to make whisky if all of the distillery energy demands are taken into account. However this was not the same case when assessing brewery performance. The average energy demand per litre of beer produced was found to be 0.52kWh and the 2012 value from literature was 0.57kWh which may have reduced since then. Therefore the methods of calculating the energy requirements of producing beer do not need to be reassessed.

The energy demand per litre of whisky produced decreased as the annual volume of whisky produced by the distillery increased. No similar correlation was found with the breweries – this may been due to the smaller micro-brewery sizes of the breweries involved in the analysis compared with their larger counterparts. Therefore there may have been more variation in the way they produced beer and on the type of equipment they used, thus having a greater spread of energy demands per litre of beer produced.

The economic results suggest that distillery and brewery by-products are well suited for AD based energy generation. Larger capacities sites have more economic potential whilst lower capacity sites still appear to be economically viable. The access distilleries and breweries have to a free feedstock greatly increases the economic potential of implementing AD within their company. Using by-products for AD instead of selling it to third parties has more potential for generating income.

More needs to be done to encourage the uptake of smaller sized AD plants particularly by introducing new RHI and FIT tariff brackets that extend to lower output capacities. Tariff brackets for other renewable energy sources such as wind, solar PV and hydro already exist therefore it would be a rational, progressive decision to implement them for AD technology also.

It was found that on average 2.3kg of CO_2 is produced for every litre of whisky made**.** Literature values[36,53] state that this figure is closer to 1.5kg. This could be attributed to not all of the distilleries energy demands being taken into account in the literature case. The average carbon dioxide emissions for breweries were found to be 0.16kg CO_2 per litre of beer produced, higher than the average literature value of 0.1lkg. This was probably mainly due to less renewable energy being used by the breweries than the national average.

AD technology has the potential to greatly reduce carbon dioxide emissions and was found to reduce emissions by as much as 97% in one case.

10. Possible Further Work

Further work on this subject could include looking at how RHI and FIT tariffs affect the economic success of using AD technology within breweries and distilleries. RHI and FIT tariffs are regularly reassessed and as more renewable technology gets installed in the UK the payments tend to get less and less. Therefore it would be beneficial to see at what tariff does the economic success of an AD system become unlikely.

A similar sensitivity analysis could also be carried out with the industrial costs of fuel and electricity. This could be done in tandem with the RHI and FIT sensitivity analysis.

Appendix

Table 65. Heating demand per litre of whisky produced

Distillery	Main heating source	Total annual heating demand (kWh)	% of total energy demand	Annual volume of whisky produced (litres)	Heating demand per litre of whisky (kWh/l)
Distillery A	MFO	13,560,000	97.1%	1,500,000	**9.04**
Distillery B	Gas Oil	270,300	96.7%	20,000	**13.5**
Distillery C	Natural Gas	11,487,700	96.5%	1,400,000	**8.2**
Distillery D	Natural Gas	8,077,800	95.0%	920,600	**8.77**
Distillery E	HFO	43,320,000	95.6%	6,200,000	**6.99**
Distillery F	Kerosene	*N/A*	*N/A*	140,000	*N/A*
Distillery G	Biomass (Wood)	20,539,890	95.3%	2,400,000	**8.56**
Distillery H	HFO	26,220,000	*N/A*	2,700,000	**9.71**
Distillery I	Natural Gas	84,000,000	95.9%	10,000,000	**8.4**

Table 66. Heating demand per litre of beer produced

Brewery	Main heating source	Total annual heating demand (kWh)	% of total energy demand	Annual volume of beer produced (litres)	Heating demand per litre of beer (kWh/l)
Brewery A	Natural Gas	4,230,400	66.5%	12,900,000	0.33
Brewery B	Natural Gas	350,000	82.0%	1,000,000	0.35
Brewey D	LPG	441,000	79.3%	700,000	0.63

Table 67. Biogas from distillery draff and pot ale AD – Biogas boiler energy statistics

Distillery	Total Annual Heating Demand (kWh)	Annual volume of biogas available (m^3)	Energy produced on combustion (kWh)	Boiler (90% efficiency) output capacity (kW)	Heat output from 90% efficient boiler (kWh)	% Heating demand met
Distillery A	14,556,000	2,189,286	13,135,714	1,350	11,822,143	90%
Distillery C	12,627,000	1,499,933	8,999,600	925	8,099,640	71%
Distillery E	47,937,000	7,665,878	45,995,269	4,726	41,395,742	96%
Distillery G	22,463,000	3,186,960	19,121,757	1,965	17,209,581	86%
Distillery I	91,763,000	12,857,628	77,145,769	7,926	69,431,192	84%

Table 68. Biogas from distillery draff and pot ale AD – Biogas electrical generator energy statistics

Distillery	Total Annual Electricity Demand (kWh)	Annual volume of biogas available (m3)	Energy produced on combustion (kWh)	Generator (35% efficiency) - output capacity(kW)	Electricity output from 35% efficient generator (kWh)	% Electricity demand met
Distillery A	400,000	2,189,286	13,135,714	525	4597500	1149.4%
Distillery C	411,120	1,499,933	8,999,600	360	3149860	766.2%
Distillery E	1,888,000	7,665,878	45,995,269	1838	16098344	852.7%
Distillery G	1,011,500	3,186,960	19,121,757	764	6692615	661.7%
Distillery I	3,600,000	12,857,628	77,145,769	3082	27001019	750.0%

Table 69. Biogas from distillery draff and pot ale AD – Biogas CHP energy statistics

Distillery	Electricity output from CHP unit with 35% electricity efficiency (kWh)	% Electricity demand met	Heat output from CHP unit with 50% heat energy efficiency (kWh)	% Heating demand met	Output capacity (kWe,kWth)
Distillery A	4,597,500	1149.4%	6,567,857	50%	525, 751
Distillery C	3,149,860	766.2%	4,499,800	40%	360, 515
Distillery E	16,098,344	852.7%	22,997,634	53%	1838, 2628
Distillery G	6,692,615	661.7%	9,560,879	47%	764, 1093
Distillery I	27,001,019	750.0%	38,572,884	47%	3082, 4407

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