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Whisky decarbonisation potential using bio-waste

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ABSTRACT

The objective was to investigate the potential of the Scottish Whisky industry to employ the circular economy to decarbonise and reduce costs, using its own bio-waste as a source of energy to power distilleries. The analysis uses a literature review of the fossil fuel energy for heat used in modern distilleries in terms of $MJ/L_{alcohol}$. It then determines the energy content of the whisky distillery bio-wastes: draff, pot ale, spent lees and wash (SLW). Outside the distillery there are bio-wastes in the barley straw on farms and from the malt-house, barley husks, rootlets and dark grains and the maturation barrel preparation area with a wood char waste. The energy in the wastes is also expressed as $MJ/L_{alcohol}$ which then enables the determination of the proportion of the energy to operate the distillery that can be provided from the bio-waste. The distillery wastes all have a high water content, the amount of which is reviewed. The energy to evaporate this water is determined to give the net energy from the bio-wastes. The findings are that in the distillery, including the energy to evaporate water, requires 60 $MJ/ L_{alcohol}$, with half of this used to evaporate water. Most of the energy in wet wastes is used to evaporate the water and there is only 8.7 $MJ/L_{alcohol}$ to contribute to the distillery energy requirements. For dry draff and PAS the energy is sufficient to operate the distillery, but the energy to dry the draff has to be provided at some stage in the process. However, there is enough energy in barley straw and malthouse wastes to provide the rest of the heat required in a distillery and to completely decarbonise the whisky industry. This is the first time that all the bio- wastes have been assessed in whisky manufacture, from the farm to the maturation barrel stores. It is proposed that the best way to use these diverse bio-wastes is gasification of the solid wet waste to produce a biomass gasification gas (BGG) with direct burning of the BGG to generate the heat to burn the PA and SLW and evaporate the water.

Keywords: Decarbonisation Draff Distillery Biomass Gasification

1. Introduction

The Scottish whisky industry has 151 whisky distilleries in May 2024 [1,2]. The food and drink industrial sector is the largest in the UK [3] and whisky accounts for 77 % of this in Scotland and 22 % of this in the UK. The Scottish whisky industry exports 5.6 Bn of whisky per year and the gross value added, GVA, is £7.1Bn. This is larger than aerospace, automotive, industrial metals and food processing in the UK [3]. Whisky is 25 % of all UK food and drinks exports and 2 % of UK total exports [2]. Whisky is a very energy intensive manufacturing process and each distillery is a major point source of Green House Gas (GHG) emissions. Scottish Distilleries use 10 % of all energy in Scotland and so decarbonisation of the distillery industry is essential if Scotland and the UK is to decarbonise [4–6].

The potential of bio-waste from the Whisky industry to provide a large proportion of the heat for the distillery is reviewed in this paper. Most of the bio-waste are also a waste disposal problem for the industry and many distilleries pay farmers to take the waste away [7], for animal feed and for spraying onto fields as a fertilizer, where it becomes a significant source of river and air pollution. Using the whisky industry bio-waste to displace fossil fuel use for heat in the industry is an example of the circular economy [8–10], where less fossil fuel is used and less farm-based pollution of rivers occurs. Fig. 1 gives a schematic of whisky manufacture and the wastes that result from the various processes involved in the manufacture of whisky.

Fig. 1 shows schematically that there are four sources of bio-waste from the whisky industry: the distillery; draff, pot ale (PA) and pot ale syrup (PAS), which is the PA with the water evaporated off and spent lees with wash water (SLW)); the malt house (dark grains, rootlets or malt culms and barley husks or chaff); the farm that grows the barley (barley straw) and the barrel maturation, that uses a NG flame to char the barrels and prior to charring removes the spent char from the previous whisky maturation to produce a char waste. This paper reviews the quantities of these wastes that are available from the whisky industry. It is shown in this review that all the wastes identified, if combined could decarbonise heat and reduce heat costs in distilleries, but none on their own are sufficient to decarbonise distilleries. There are two techniques to utilise biomass for heat that can cope with mixed sources of biomass and these are: air combustion and air gasification. The advantage of air gasification is that it produces a Biomass Gasification Gas (BGG) that can be used directly to fire a burner in the existing steam boiler at the distillery and the authors are developing this technology [11].

The combustion of bio-waste leaves a high temperature ash and the gasification of bio-waste leaves a low temperature ash. The ash retains the minerals in the bio-waste and makes a useful fertiliser [8]. This is a good example of the circular economy [9,10] with the farm producing the biomass (barley) and bio-waste (barley straw) that is used for alcohol production and potentially for distillery energy production. The ash returns to the farm to offset the cost of the production of the barley, by reducing the need for expensive chemical fertilizers. Recycling the distillery waste for energy production is also an example of the circular economy [12]. However, Duffy et al. [12] model the use of whisky distillery bio-waste in AD plants with the gas used to generate electricity. They show that 5 % of Scottish domestic electricity requirements could be generated this way. However, the main energy use in distilleries is natural gas, NG, or fuel oil for heat, mainly using steam heat with on-site steam boilers. This work is directed at the potential use of distillery bio-waste to directly fire the on-site steam boilers. However, the same burners could be used for direct fired distilleries (2 % of UK distilleries).

There is currently no use of malt house or farm waste bio-energy for heat in distilleries [5,8,9], although some malthouses use their waste for conventional biomass combustion heat for the malthouse processes [13].

The distillery wastes have a high-water content problem, which is included in this review of the distillery bio-wastes. To utilise this wet waste the water has either to be evaporated using a fossil fuel (hydrogen burners could be used for complete decarbonisation) or the energy release process has to be capable of coping with a high-water content of the bio-waste. Two possible ways of doing this are gasification of the waste and injecting the wet waste into the flame output of the BGG burner (hydrogen for complete decarbonisation). The former is more likely to be suitable for wet draff and the latter for pot ale; both are being developed by the authors for these wastes [11].

Two methods of using bio-waste for heat in the whisky industry are conventional biomass CHP for draff and straw [14,15] and anaerobic digestion (AD) to produce bio-gas and a digestate [16,17]. Both applications require the draff and PA waste to be dried and the cost of this and the GHGs released in the drying process from using fossil fuels, make their use unattractive financially. There are 9 AD plants [16] in the 151 Whisky distilleries and most distilleries are not using AD plants, partially due to the cost of drying the draff. Currently, a large proportion of distilleries have wet draff and PA as wastes, that farmers are paid by distilleries to dispose of as fertiliser (draff) and for spraying onto farmland for PA [7]. Draff and pot ale if dried can be combined and sold as a cattle feed, but the drying process makes this expensive [7].

Combustion of gaseous fuels can cope with a high-water level being injected into the flames, as this is a common way of reducing NO_x emissions from burners [18,19]. Water to fuel mass ratios of 1 have been shown capable of > 90 % NO_x reductions in burner trials [19]. It will be shown in this review that water in draff and PA is greater than a ratio of 1 with water/dry fuel ratios of 3 and 7 respectively. Water injection for NO_x control is done into the flame stabilisation zone of a near stoichiometric diffusion flame burner and W/F ratios greater than 1 risk extinguishing the flame. If lean well mixed combustion is used and the PA injected downstream of the completion of combustion, much larger quantities of water in the second stage fuel can be accommodated and this axially staged combustion process is a route to releasing the energy from liquid bio-wastes with a high-water content. This is a technique being developed by the authors [11] combined with hydrogen burners to generate the high temperatures to release the energy in pot ale.

Gasifiers for biomass [20] are potentially capable of gasifying bio-fuels with a high-water content [21] and are a potential method of releasing energy from raw draff in a distillery. They are also capable of utilising a wide range of bio-fuels [20] and hence potentially could use all the distillery industry wastes identified in this review. The authors [22] have shown in a small-scale gasification rig that dry draff is capable of being gasified and have identified the optimum gasifier equivalence

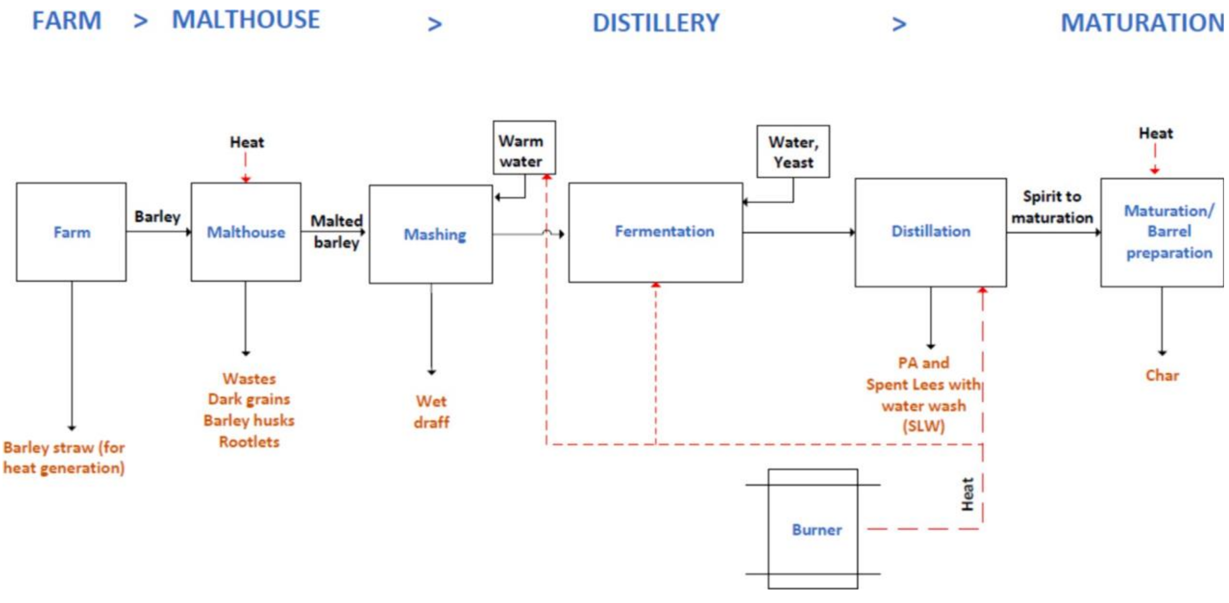

Fig. 1. Schematic of whisky manufacture from the farm to barrel maturation with the bio-wastes and heat input requirements shown.

ratio for maximum biomass gasification gas (BGG) energy yield [22]. The steam from the water can combine in the gasifier with CO to generate more hydrogen, by the water gas shift reaction, if the gasifier temperature is above 700 °C [23]. Commercial uses of the water gas shift reaction in dedicated hydrogen production use a catalyst to lower the reaction temperature [23], but the reaction can occur naturally in gasifiers if the temperature is high enough. Another advantage of using wet bio-waste in the heating process is that the steam released passes through the boiler and with a suitable flue gas condenser the latent heat could be recovered and used within the process heating requirements. If the draff and PA are dried in an external fossil fuel drier the steam and flue gas heat is usually wasted, although heat recovery is possible if the drier is on the distillery site.

2. The energy required in a whisky distillery to manufacture alcohol

The baseline NG or fuel oil energy used to manufacture the whisky needs to be known, for the potential contribution of bio-waste in the whisky industry to the total energy requirements for the distillery is to be evaluated. It is the convention in the Whisky industry to undertake energy balances on the basis of the total energy used to produce one litre of alcohol in units of MJ/$L_{alcohol}$, not per 70 cc bottle of whisky. This requires the alcohol production of a distillery to be known as well as the total fossil fuel use and electricity use. As these are commercially confidential quantities for a distillery, it is not easy to access the data unless a distillery is willing to give this data and two distilleries did this for this work [26,27]. The little information in the open literature on the energy required to manufacture alcohol is reviewed and it is shown to be variable. The distillery energy consumption depends on the energy conservation technologies used in a distillery.

The Scottish Whisky Association in 2012 found that the average energy requirement for the distilling and maturation process was 22.6 MJ/L per litre of whisky produced per annum, an improvement of 6 % on the 2008 figure of 24.1 kWh [74]. Meadows [29] also reported the energy per L of whisky for 8 distilleries and the ratio of the highest to the lowest was 1.89 and this was for two distilleries of similar production capacity. It is more useful to refer to the energy consumption per litre of alcohol produced at the distillery and this is what is reviewed here, If the average alcohol content of the whisky was 50 % then the SWA figures would double, which will be seen to be high relative to direct measurements of MJ/L of alcohol. As the alcohol content of whisky is variable, the energy to produce alcohol is the relevant measurement. Also, the SWA figures includes the maturation energy requirements or charring of barrels and warehouse heating. This makes them higher that the distillery energy consumption.

Fruh et al. [4], stated that the typical energy requirement for a whisky distillery is 17 kWh/L or 61 MJ/$L_{alcohol}$. However, it will be shown in this review that this figure is likely to include the energy to dry draff and to dry PA to generate PAS. Duguid [28] and Meadows [29] reported the thermal energy used and alcohol produced for 8 whisky distilleries on Islay, including the fuel and electricity use, although the fuel use dominated. All these distilleries on Islay used fuel oil for heat. The results in MJ/$L_{alcohol}$ were 33.5, 50.3, 30.6, 33.3, 26.3, 32.0, 36, 31.5 and the average was 34.2 MJ/$L_{alcohol}$ with a range from 26.3 to 50.3. The larger production distilleries usually had a lower energy consumption. Only the small Islay distillery with 50.3 MJ/$L_{alcohol}$ is near the value reported by Fruh et al. [4]. Allardyce et al. [69] have reported energy use data for Balmenach distillery and their data can be shown to give the energy consumption as 30.5 MJ/L. Schestak et al. [67] have measured the energy consumption at the Arbikie distillery, which uses fuel oil for heat, at 28.8 MJ/L, consistent with the above data.

The authors have visited two distilleries as part of this research: Kingsbarns [26] and Inchdairnie [27]. At Kingsbarns the energy consumption was 31.4 MJ/$L_{alcohol}$. This is in the range found for the 8 Islay distilleries [28,29]. At Inchdairnie the energy consumption was 7.8 MJ/$L_{alcohol}$. Inchdairnie has one of the lowest energy consumptions in Scottish whisky distilleries and is an example of best practice [30]. Palmer [27] stated that the range of energy use in Scottish distilleries was 6–8 kWh/$L_{alcohol}$, which is 22–29 MJ/$L_{alcohol}$. The Inchdairnie and Kingsbarns energy consumption exclude the energy to vaporise the water in draff, PA and SLW, but Inchdairnie counts the green bio-gas generated at an AD plant (where dry draff and PAS is the feedstock) as deducted from its energy use [27], which is why the 15.8 MJ/$L_{alcohol}$ is much lower than for other distilleries in this review. Palmer [27] stated that Inchdairnie is 40–50 % lower energy consumption than other distilleries, which implies an industry average of 26 to 32 MJ/$L_{alcohol}$. This is in reasonable agreement with the above data for other distilleries. Dalmunnach distillery [70] gave their energy use as 19.1 MJ/L, but stated then they had one of the highest efficiency distilleries, 38 % less than the industry average. This gives an industry average energy consumption of 31 MJ/L, within the range given by Palmer [27].

Kvaalen et al. [31] reviewed alcohol distillation technology and gave (converted from USA units) between 30 and 34 MJ/$L_{alcohol}$. Kang et al. [9] gave for a 2 million litre per year distillery a 'typical' energy (thermal and electric) consumption of 8.82 kWh/L which is 31.75 MJ/L. Dalton et al. [16] gave for a 2 million litre per year distillery a thermal energy use of 16.92 GWh, which converts to 30.46 MJ/L.

The SWA [30] in 2021 stated that a 53 % reduction in GHGs had been achieved in whisky distilleries from 2008 and 20 % renewable energy achieved. This indicates that about 40 % of the GHG reduction came from the use of biomass and 60 % from process thermal efficiency improvements. The range of energy use will vary from no reduction in GHGs to more than the average reduction and this is likely to give a variation of a factor of at least 2.

The above review shows a range of whisky distillery energy consumption from 25 to 35 MJ/$L_{alcohol}$. The average energy consumption of the above data is 30 MJ/$L_{alcohol}$ and this will be used as the energy that needs to be supplied from a bio-waste source, if decarbonisation using whisky distillation bio-wastes is to be viable. This value excludes the energy to evaporate the water in draff, PA and SLW, which is shown in this paper to double the total energy requirements to 60 MJ/$L_{alcohol}$, which is close to the figure given by Fruh et al. [4] as the typical energy use in whisky distilleries. Also, the data from Inchdairnie [27] at 17.8 MJ/$L_{alcohol}$ is an outlier, which reflects its high thermal efficiency design and its use of an AD plant to generate bio-methane, which directly reduces its NG use. The AD plant requires dry draff and PAS and so these wastes are dried and the energy for this is not in the above 17.8 MJ/$L_{alcohol}$. The drying is normally done outside the distillery for off-site AD plants and not normally counted as distillery energy consumption.

Clearly, the proportion of energy that can be satisfied from the distillery bio-waste is greater if the energy consumption is lower. This paper will present the contribution that wet bio-waste could make to a 30 MJ/$L_{alcohol}$ distillery, as well as determining the energy that would be required to dry the wet bio-waste, in addition to the 30 MJ/L distillery energy requirements excluding the energy to dry the bio-waste.

The energy to manufacture alcohol for whisky is the key component on its GHG emissions, as all distilleries use fossil fuels to generate the energy (1/3 fuel oil and 2/3 Natural Gas, NG). The average GCV of NG and fuel oil, weighted in the above proportions is 48 MJ/kg and so 30 MJ/L is 0.625 kg/L. Methane produces 2.76 kg of CO_2 per Kg of methane and the average production for NG with 4 % inerts and 4 % higher hydrocarbons is 2.67 kg CO_2 per kg NG. Fuel oil produces 3.3 kg CO_2/kg fuel. The average production for the industry with the above fuel weighting is then 2.9 kg CO_2 per kg fuel used. With an average GCV of 48 MJ/kg this gives 1.81 kg CO_2 per L. The 2018 estimated CO_2 production from the whisky industry was 518,792 tonnes CO_2 [5] and production was 792 ML/year so 0.67 kg CO_2 were emitted per L of alcohol, which is well below the 1.81 kg/L based on 30 MJ/L. Schestak et al. [67] used data from the Arbikie distillery, fuelled by fuel oil, to give 2.3 kg CO_2 per L alcohol for the heating system, which is in reasonable agreement with the present calculations based on 30 MJ/L.

The energy used in this distillery was 28.8 MJ/L. They also calculated the total CO_2 emissions as 4.4 kg CO_2/L with 21 % coming from the barley farm and 14 % from malting. They also pointed out that draff and pot ale spread on farmland as fertilizer would produce methane and N_2O emissions and it is not clear whether these effects were included in the distillery net CO_2 emissions. They conclude that using the distillery waste as cattle food was preferable as this displaced soya for cattle food and the GHG emissions connected with soya production outweighed the emissions of draff and pot ale spread on farmland. Destruction of draff and pot ale by recovering their energy, as advocated in the present work, was not considered. If this is done then the methane and N_2O emissions from spreading draff and pot ale on farmers' fields does not exist and the overall GHG savings are larger as less NG or fuel oil use results, when the energy to dry distillery biowaste is taken into account.

3. Energy required to dry wet bio-waste

It takes 2.274 MJ/kg$_{water}$ to change from water at 100 °C to steam (latent heat of vaporisation). It takes 0.336 MJ/kg$_{water}$ to heat liquid water from 20 to 100 °C, using the specific heat of liquid water as 4.2 kJ/kg^{o}C. For materials with absorbed water (wood and plants and draff) it takes about 0.020 MJ/kg$_{water}$ to extract the water from the plant structure [24]. Thus, for the water in Pot Ale it takes 2.560 MJ/kg$_{water}$ to evaporate the water. For draff it takes 2.580 MJ/kg$_{water}$ to evaporate the water from the wet draff, due to the extra energy to extract water from solid draff. Uzukwu et al. [25] assessed the energy to dry draff, a heat of evaporation of water of 2.20 MJ/kg$_{water}$, was assumed. This is too low, mainly due to ignoring the energy to heat water from ambient temperature.

4. Draff

4.1. *The production of draff per litre of alcohol*

The published estimates for the production of draff in whisky distilleries are summarised in Table 1. Where data in the literature has values a factor of 10 below the levels in Table 1, the data has been ignored as it will be data for dry draff. The average of the data in Table 1 is 2.39 kg$_{wetdraff}$/L$_{alcohol}$ with a range from 1.79 to 2.5 and it is recommended that a design value of 2.4 kg$_{wet\ draff}$/L$_{alcohol}$ is used. There is much less variation in the production of wet draff data then there is in the energy use for the production of alcohol.

4.2. *The water content of draff*

Draff does not have surface water and is not wet to touch, but it has absorbed water. The authors have used thermal gravimetric analysis (TGA) of draff to determine the water content using a draff sample from Inchdairnie distillery [25] and full details are given by Olanrewaju et al. [22]. The sample was heated in nitrogen and the weight loss determined as a function of temperature. The water content was taken as the weight loss to 105 °C, which for wet draff was 73 % water [22]. Table 1 summarises the literature on the water content of draff, but most of the data is not based on a measurement and has 'about' before the value. Table 1

Table 1
Review of open literature data on the production of wet draff per liter of alcohol, its water content, pot ale (PA) production, pot ale syrup (PAS) as a % of PA and production of spent lees with water wash (SLW).

Refs.	Distillery/Author	Kg$_{wetdraff}$/L$_{alcohol}$	% water in wet draff	Pot Ale, L$_{PA}$/L$_{alcohol}$	PAS % of PA by vol.	SLW L$_{SLW}$/lL$_{alcohol}$	PA/SLW
[26]	Kingsbarns	2.42 Measured		8.06 Measured		4.0 Measured	2.0 Measured
[27]	Inchdairnie	1.79	About 75 %	6.75 Year Average			
[22]	Inchdairnie		73 % measured		4.7 TGA		
[7]	Industry Ave. White et al.	2.5		8		8.5	0.94
[10]	2013 Average Arnison, R and Carrick, R.	1.92	About 80 %	3.2	10	1.31	2.45
[10]	10 year average Arnison, R and Carrick, R.	2.5					
[32]	Irish Whisky Hamill	2.37	74.2 % measured	8.8 Measured		3.3	2.67
[34]	2012 Average Leinonen, I. et al.	2.24	75 % water assumed				
[36]	2002 Average Pass and Lambert	2.4		10		5.0**	2
[37]	Diageo Roseilsle Edwards et al.	2.46		7.9 Measured	6.0*		
[38]	Annual average	2.37					
[33]	Gandy and Hinton		About 80 %		9		
[14]	Bell et al.		77 % measured				
[39]	Duncan McNab Stewart		74–80 %				
[3544]	J. C. Akunna1 and G. M. Walker Musatto et al.		80 %				
[38]	Schreiberg			9			
[28,29]	9 Distilleries in Islay			7.7 Measured			
[44]	Musatto et al. Diageo			8			
[47]	Mohana, Indian Distilleries Mohana et al	2.5–3.0	35 %	8.75 8–15	11–19		
[25]	Uzukwu				20		
[47]	Saha Centrifugal separation				9.55		
[50]	*Goyal et al.				10.5–15.5		
[52]	Barrena					0.89	
[72]	Balmenach 2.3 ML/year	2.47	70–80 %	6.0 Kg/L Measured5.8 L/L		1.78 kg/L Measured 1.78 L/L	3.35
[71]	Price et al.		75.3 % Measured		5.6 Meas		
[67]	Schestak et al. Arbikie Distillery	2.73 Measured	78 Measured		5.0 Dry	2.9	
	Recommended value	**2.4**	**75 %**	**8**	**13**	**3.8**	**2.1**$^{\flat}$

*22 distillery PAS samples analysed by component. Result may be low as not all components were measured.

**Spent Lees only.

$^{+}$This is the ratio of the average values of PA and SLW.

has only three measured values of the water content 73, 74 and 77 % and the other values are not referenced to specific measurements. It is recommended that the water content of draff is taken as 75 %. This gives the dry draff production rate as

$$kg_{\text{wet draff}} \times 0.25 = 0.60\ kg_{\text{dry draff}}/L_{\text{alcohol}}.$$

4.3. *The energy content of dry draff*

Olanrewaju et al. [22] measured, using a bomb calorimeter, the gross calorific value (GCV) of Inchdairnie dry draff as 20.5 $MJ/kg_{\text{dry draff}}$. The wet draff was dried on a pan heater and the water was reduced to 6.7 %. The wet draff had a GCV of 5.2 MJ/kg. The ratio of the wet to dry GCV should be the water content, which is 74.5 % wet, similar to the TGA measurement. Duncan McNab Stewart [39] measured the wet draff GCV as 6.5 MJ/kg and the dry draff as 21.7 MJ/kg, which is close to the measured values of Olanrewaju et al. [22]. The 0.60 $kg_{\text{dry draff}}/L_{\text{alcohol}}$ with a GCV of 20.5 $MJ/kg_{\text{dr draff}}$ gives 12.3 MJ/L_{alcohol} which is 41 % of the distillery energy.

4.4. *The composition of dry draff*

The wet draff composition determined by Olanewwaju et al. [22] using TGA was 23 % volatile matter and 4 % fixed carbon, in addition to the 73 % water. This gives the dry draff composition as 14.8 % fixed carbon and 85.2 % volatiles.

Foltanyi et al. 2020 [43] gave the elemental analysis of dry draff and this is compared with the authors elemental analysis [22] on a dry ash free (daf) basis in Table 2. The stoichiometric A/F by mass (Ø=1) has been computed from this elemental analysis and the results are shown in Table 2. This is a critical parameter for designing burners or gasifiers for draff. The mean of the three values for the stoichiometric A/F of dry draff in Table 2 is 5.78, which is close to the 5.91 result for barley straw in Table 2.

Foltanyi et al. [43] have given the cellulose, hemicellulose and lignin in dry draff using the data of Mussato [40,44]. The composition was:

Cellulose	17–25 %
Hemi-cellulose	22–28 %
Lignin	12–28 %
Protein	15–24 %
Lipid	10 %
Ash	5 %

This composition is similar to wood with only protein and lipid being different. The composition is also similar to that of Bennet [41].

Akunna and Walker [35] have measured the composition of the 20 % of draff that is not water i.e. dry draff as:

Cellulose	20 %
Hemi-cellulose	25 %
Protein	15 %
Lignin	25 %
Ash	10 %
Starch	5 %

This is quite similar to the composition of Mussato et al. [40,44], and only ash has a higher value. The range of compositions measured by Mussato will result in a range of H/C and O/C which is the source of the variability in these in Table 2. More data is needed on this variability as there is only one publication in addition to that published by Olanrewaju et al. [22].

The high level of nitrogen in draff in Table 2 is due to proteins, as in the above compositions. Fuel nitrogen is a potential problem for NO_x emissions as if they were burnt lean, as in a biomass combustor, the fuel nitrogen converts to NO. However, if the fuel is gasified (which is rich burning) the fuel nitrogen is converted to N_2 and there should not be high levels of NO_x in the gasifier outlet gases. This would be important as the burning of draff with wood in a biomass combustor will have a NOx problem, as these levels of nitrogen in draff would lead to high NO_x in conventional biomass combustors.

Table 2 shows that for a real biomass the composition is influenced by the relative proportion of cellulose, hemicellulose and lignin. A high stoichiometric A/F for a real biomass indicates high lignin and a low A/F indicates high hemi-cellulose. Table 2 shows that the composition of draff is similar to that of barley straw in terms of the H/C, but with a lower oxygen (lower O/C) content than straw, which indicates higher lignin in draff. Table 2 also shows that dry draff is quite close to the composition of pitch pine wood [42].

4.5. *The energy to evaporate the water in wet draff*

The above review has shown that wet draff is produced at 2.4 kg per litre of alcohol and with 75 % of water in wet draff this is 0.6 $kg_{\text{dry draff}}$. Dry draff has a GCV of 20.5 $MJ/kg_{\text{dry draff}}$ and so the energy content is 12.3 MJ/L_{alcohol}, which is 41 % of the 30 MJ/L_{alcohol} required to operate the distillery. Murthy and Power [45] gave this energy as 35 % of the energy to operate a distillery, which is 10.5 MJ/L_{alcohol} lower than the present estimate. Whether the water in draff is dried in an external drier or in-situ in combustion or gasifier equipment, the energy required to evaporate the water is the same. If the drying is external the water is lost as steam, if it is internal in the furnace or gasifier then potentially the latent heat can be recovered in a flue gas condenser, which is the objective in the present work. In a gasifier the water in draff would produce steam and if the temperature is high enough, then steam and CO can combine to yield more hydrogen [23].

The water in wet draff is 1.8 $kg_{\text{water}}/L_{\text{alcohol}}$ and this takes 1.8 × 2.56 = 4.61 MJ/L_{alcohol} to evaporate. The energy in wet draff in the gasifier can provide a net contribution to heat release, after evaporation of the water in draff, of 7.69 MJ/L_{alcohol} which is 25.6 % of the energy required to operate the distillery. Kang et al [9] estimated that wet draff could produce 22.2 % of the energy to operate a whisky distillery, if the wet draff was sent to an AD plant to produce a biogas for heat. This is close to the 25.6 % maximum possible contribution estimated above and implies a very high AD plant thermal efficiency, which is unrealistic. Poschl et al. [51] have presented a review of the AD plant thermal efficiency as the ratio of the external energy used in the process (excluding the energy in the biomass feed) to the energy in the biogas produced. The range was 10.5 to 64 %. However, the practical thermal efficiency of an AD plant is the ratio of the energy in the biogas to that in the biomass feedstock.

Table 2

Elemental composition of dry draff by mass on a daf basis, with a comparison with pine wood and straw and computation of the stoichiometric A/F by mass.

Ref.	C%	H%	N%	O%	O/C	H/C	N/C	A/F at Ø=1 by mass
Foltanyi et al. [42]	49.87	7.19	4.44	38.51	0.579	1.73	0.077	6.44
Olanrewaju [22] Sample 1	61.50	8.49	4.0	26.00	0.316	1.66	0.056	5.16
Olanrewaju [22] Sample 2	54.64	7.63	3.69	34.04	0.468	1.68	0.058	5.75
Pitch Pine [15]	59.00	7.19		32.68	0.42	1.46		8.09
Barley Straw [42]					0.705	1.68		5.91
Cellulose					0.833	1.5		5.12
Hemicellulose					1.167	1.67		3.15
Lignin					0.222	1.11		9.57

Taking a typical GCV for biomass as 15 MJ/$kg_{biomass}$ the data of Poschl [51] can be used to show that for straw with 20 % water the thermal efficiency is 27 %, but for a wet biomass with 40 % water the thermal efficiency is 8 % and a water content higher than this, does not produce sufficient biogas to heat the wet biomass drier. This is why AD plants that use draff as a feedstock require this to be provided dry. Wet draff is currently regarded as of no positive value to a distillery [26] and is currently a negative value as farmers are paid to take the waste draff offsite [7].

For more efficient distilleries, such as Inchdairnie [27], where the energy use is much lower, dry draff could be more important and would be about half of the required energy. These results show that wet draff can never be a gasification or combustion fuel on its own, as there is insufficient net energy after vaporising the water to provide all the heat requirement of the distillery. However, wet draff could in principle deliver a quarter of the distillery energy which is a significant renewable heat contribution.

5. Pot ale (PA)

5.1. *Pot ale production per litre of alcohol*

The Scottish distillery industry produces 1.6 billion L_{PA} per year [37] and the review in Table 1 shows that the dry PA, known as Pot Ale Syrup (PAS), is 13 % of PA and its energy is 19 MJ/kg_{PAS}. The density of PA is 1.0325 kg/L_{PA} which is based on 13 % of PA being PAS with a density of 1.25 kg/L_{PAS} which are values for these parameters reviewed later. Thus, the mass of PA per year is 1.652 billion kg and this has an energy of 4.08 TJ/year which is a substantial potential energy resource.

There is significant variation in the $L_{PA}/L_{alcohol}$ between different distilleries as shown in Table 1. There are very few open literature measurements at specific distilleries and the recommended design value is 8 $L_{PA}/L_{alcohol}$.

5.2. *The density of PAS and PA*

The density of PAS is greater than water and greater than most hydrocarbons and this is because it has a solid content. The density of PAS is 1,250 kg/m^3 or 1.25 kg/L_{PAS}. [54]. This is from a manufacturer's product property list for PAS, but no other reference has been found. This density is close to that of glycerol which is 1,263 kg/m^3, which is why glycerol might be a surrogate for the volatile content of PAS [21], that is not associated with the solid content of PAS. It is this density difference from water that allows PAS to be separated from PA by gravity in a vertical column, as shown in Fig. 2a. Also, the centrifugal separation method relies on this density difference from water. The gravity separation does not leave clear water as the water above the PAS in gravity separation is still visibly polluted as shown in Fig. 2b. With PAS as 13 % of PA by mass and a PAS density of 1250 kg/m^3 and a water density of 1000 kg/m^3, the density of PA is 1033 kg/m^3.

5.3. *PAS as a proportion of PA*

Pot ale has solid and organic (bio-oil) compounds in it that contain energy. If pot ale has the water evaporated there is a syrup that remains, known as pot ale syrup (PAS). To determine the energy content of PA the proportion of PA that is PAS has to be known and the GCV of PAS determined. There are very few published measurements of this and these are summarised in Table 1. There are 8 references with measurements of total PAS (not solid fraction of PA) in the range 9 % to 20 % with an average of 13.07 % which will be rounded to 13.0 % by mass. This is using the ranges as two separate measurements. This is the most uncertain of the distillery bio-waste properties, as can be seen by the variations in Table 1. Part of the uncertainty is the method of measurement which may be evaporation, centrifugal separation [49], thermal gravimetric analysis (TGA), chemical species analysis or simply gravity separation.

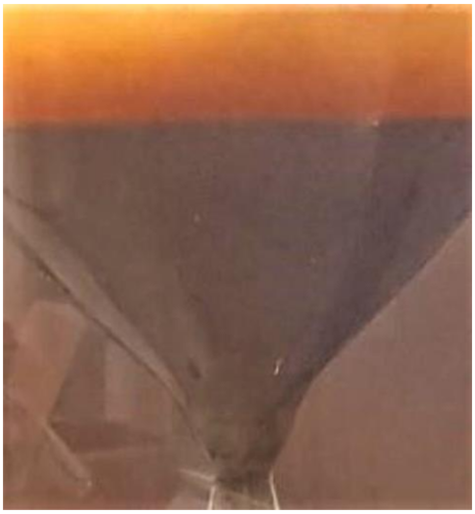

Fig. 2a. Gravity separation of PAS from PA.

Fig. 2b. PA after gravity separation of PAS.

5.4. *Dry matter in PAS as a proportion of PA*

The authors [53] have used TGA analysis of PA, which gave a very low fraction of PAS of PA at 4.7 % and 20 % of the PAS was determined to be solid carbon using TGA. This would give the carbon fraction of PA as 0.94 % of PA. This does not agree with other data in this review, which may be because carbon is not the only component of the solid fraction of PAS. The literature below shows other components such as carbohydrates and protein.

Luna-delRisco et al. [49] analysed a range of biomass waste resources including 'distillery slop' which will be assumed to be Pot Ale. They gave results for the raw sample dry mass which will be assumed to be part of PAS. After centrifugal separation, which was the method used of removing water to leave PAS, the dry fraction of this PAS was 5.54 % of the original PA compared with 9.55 % after centrifugal separation.

Hamill et al. [32] have PA as 4 % solid (40 g/kg_{PA}) and PAS should be > 4 % as a consequence. Hamill et al [32] also reported that PAS is 25–50 % solid, depending on the distillery. White et al. 2020 [7] further analysed PA for solid material and the total analysed amounted to 5.01 % of the pot ale. Uzukwu et al. [25] showed that dry solid PAS was 3.5 % by mass of PA.

Barrena et al. [52] measured insoluble solids in PA at 1 % on a dry matter basis and soluble protein at 1 % of PA on dry matter basis. There was also 3.0 % of soluble carbohydrates. Total solids were determined as 3.02 %. Berrena et al. [52] analysed data from four distilleries and the solid fraction of PA varied from 3.5 to 4.2 % and the volatile content of these solids varied from 88.8–93 %. The present results agree with this work. Bennet et al., 2015 [41] gives a wider range for the solid fraction of pot ale as 4–7 %.

Mohana et al. [48] give the total dissolved solids as 9–15 % of PA. This would give the dry solids as 2–4 % of PA by mass, but the volatile solid measurement would give a dry solid fraction as 3–7 %. The implication of the difference is that some of the dissolved solids are not released on heating. The 3–7 % solid range will be used as the solid fraction. Dionisi et al. [53] reported that the total solids in PA was 5.3 g/L_{PA} which with a density for PA of 1.0325 kg/L_{PA} is 5.13 g/kg_{PA}.

Edwards et al. [37] have undertaken the detailed composition of the PA from 22 distilleries in Scotland. They did not report the total solids as a proportion of the PA, but analysed the individual components. There was considerable variability in the individual composition but the mean value was 6 % total solids identified. Wisniewski [55] has reported data from Alasdair Anderson of Glenrothes that the solid fraction of PA is 4.2 % of the PA.

There are 14 measurements referred to above for the solid fraction or dry matter fraction of PA (taking the limits of ranges as separate data points) and the average of these is 4.7 % of PA and the range is 3.5–7%. The recommended design value is a 4.7 % solid fraction PA.

5.5. Pot ale to wet draff ratio

Arnison and Carrick [10] give the whisky industry production of PA at 1.6 billion litres with 500,000 tonnes of draff a year. This gives a PA/draff ratio of 1.6 billion L_{PA}/0.5 billion kg draff = **3.2 L_{PA}/kg draff** and this will be assumed to be wet draff. Grandy and Hinton [33] has 3.3 kg_{PA}/kg_{draff}. Pot ale is 87 % water and 13 % PAS with a PAS density of 1.25 kg/L_{PAS} which gives the density of pot ale as 1.0325 kg/L_{PA}. The ratio of PA/draff is then 3.20 L_{PA}/kg_{draff} in agreement with Arnison and Carrick [10]. White et al. [7] also has 3.2 $L_{PA}/kg_{wet\ draff}$.

Kingsbarns distillery [26] has 5 L_{PA}/kg_{draff}. Inchdainie distillery [27] has 3.86 kg_{PA}/kg_{draff} which is 3.78 $l_{PA}/kg_{wet\ draff}$. Edwards et al [37] gives for the Diageo Roseisle distillery a PA/draff ratio of 3.28 l_{PA}/ kg_{draff}. Five data sources have the PA/draff ratio in the range 3.2–3.78 and the Kingsbarns ratio of 5 looks rather high. It is recommended that 3.2 is the design ratio as there are 4 references close to this value. Also, the mean recommended pot ale production of 8 $L_{PA}/L_{alcohol}$ and the mean draff production of 2.5 $kg_{draff}/L_{alcohol}$ gives 3.2 $L_{PA}/kg_{wet\ draff}$,. With PAS at 13 % of PA and draff with 75 % water, the PAS to dry draff ratio is 0.55 $L_{PAS}/kg_{dry\ draff}$, which is 0.69 $kg_{PAS}/kg_{dry\ draff}$.

5.6. The dry matter as a proportion of PAS

For the above total PAS content of 13 % and solid content of 4.7 % of PA, there are 8.3 % of PA as bio-oils. This gives PAS as 36 % solid and 64 % bio-oils. There have been attempts to measure these proportions in PAS, which are review here.

The TGA analysis of Inchdairnie PAS [53], showed that this was 80 % volatile materials and 20 % solid carbon. No ash fraction was measured. However, this proportion of dry matter in PAS is lower than other data in the literature which indicates that the solid matter is not all carbon. Wainman [55] gave the dry matter (DM) as 48.3 % of PAS. Luna-del Risco et al. [49] analysed a range of biomass waste resources, they determined the dry fraction of PAS as 58 %. Bell et al., [14] gave 42–45 % dry mass in PAS for a specific distillery and 30–50 % of PAS depending on the distillery. United Mollases [59] gave a dry mater PAS content of 43–44 %. A commercial specification of Pot Ale composition [60] has the dry matter of PAS at 42 %. According to a commercial datasheet for pot ale syrup from Scottish malt whisky distilleries [57] PAS is typically 42 % dry matter. Hamill et al. [32] reported that PAS is 25–35 % solid, depending on the distillery and this is in agreement with the 36 % solid from the above PA composition review.

The above review has 12 data points (assuming the limits of the ranges are based on actual measurements) and the average is 43 % dry matter in PAS. The above PA analysis gave the solid fraction of PAS as 36. It is considered that the recommended mean value for the solid fraction of PAS should be 40 %, as an average of the data for solid fraction based on PA and PAS analysis.

Taking the solid fraction of PAS as 40 % by mass, the solid fraction based on 13.0 % total PAS is 5.2 % solid fraction of PA, which is close to the 4.7 % average of actual PA solid fraction measurements. The solid fraction of PA is recommended to be taken as the average of these at 5.0 % of PA.

5.7. The GCV of PAS dry matter and of the total PAS

Wainman [56] gave the GCV of dry (solid fraction) PAS as 20 MJ/kg dry matter, with a solid fraction of 48 %. This is the only reference that gives the thermal energy of dry PAS. All the other measurements are for the energy content of PAS as an animal feed – the metabolisable energy (ME). Grandy and Hinton [33] gave the ME in PAS as 14.5 MJ/$kg_{PAS\ DM}$. Bell et al. [14] have the metabolisable energy of PAS dry Matter as 14.2 MJ/$kg_{PAS\ DM}$. United Mollases [58] gave the ME as 14.2 MJ/$kg_{PAS\ DM}$. It is considered that from a thermal energy point of view Wainman's value for dry PAS of 20 MJ/kg should be used and that the animal feed energy values are not valid for thermal release calculations.

The dry matter of PAS is 40 % of PAS and there is no measurement of the GCV of the total PAS. This is a difficult area as knowing the energy content of PAS is crucial to the evaluation of it as an energy source. It is likely that the biomass liquid organics (bio-oils) that form the rest of the PAS are similar in GCV to other compounds in this class with a COH elemental composition. Glycerol for example has a GCV of 19 MJ/kg and solid agricultural residues have a GCV of 18 MJ/kg for Wheat straw, 15 MJ/kg for rice straw, 19 MJ/kg for miscanthus grass. It would thus seem reasonable to take the GCV of the 'liquid' portion of PAS as 18 MJ/kg. Thus, for 40 % solid and the rest of PAS liquid the mean GCV of PAS would be 19 MJ/kg_{PAS}. This is the recommended value to use for PAS energy, but is an uncertain value.

PAS is 13 % of PA and PA is 8 L/$L_{alcohol}$ which gives 1.04 $L_{PAS}/L_{alcohol}$. Using the density of PAS as 1.25 kg_{PAS}/L this converts to 1.30 $kg_{PAS}/L_{alcohol}$. For a PAS GCV of 19 MJ/kg_{PAS} this gives the PAS energy as 24.7 $MJ_{PAS}/L_{alcohol}$, which is a potentially significant contribution to the energy to operate a distillery. However, the water in PA has to be evaporated using this energy, as discussed below. and the energy in PAS after evaporation energy has been used is much smaller than for PAS.

5.8. The composition of PAS

The average solid fraction of PAS is 40 % and this means that there is 60 % of other material in the volatile fraction of PAS. This material will be liquid organics with some energy, so the GCV of the solid fraction of PAS is not necessarily the GCV of total PAS as a fuel. The TGA analysis of Pot Ale determined the volatile composition of PAS as 80 % [53]. Luna- del Risco [49] determined that the volatile content of PAS was 91.2 %. This low solid content of the PAS at 8.8 % supports the low solid content of PAS at 20 % [53], even though other data reviewed above give a larger solid content.

Steffan et al. [60] analysed Ferment slops, which have been taken as equivalent to Pot Ale. The total PAS was not determined, only the solid content, which was1-5 % of PA. If total PAS is taken as 13 % of PA, from the above review, then the solid content of PAS would be 8 % − 38 %. The volatility of this solid fraction was 80–95 %, which is in agreement with Maxfield et al. [53], which has the volatiles in PAS at 80 %. The C/N ratio of the solid fraction of PAS was 4–10, due to high levels of protein. The variability was due to different processes at distilleries.

This review shows that PAS has a high proportion of volatiles in the solid fraction and in the non-solid fraction. However, there has been little analysis of these volatiles and most investigations of the composition of PAS is for the solid fraction. Hamill et al. [32] showed that PA has 350 g/kg of crude protein, which is 3.5 % by mass and indicates that their 5 % solid fraction of PA is mainly protein (70 %). White et al. 2020 [7] further analysed PA for solid material at 3.45 tonnes of insoluble solids, 3.45 tonnes of soluble protein and 10.4 tonnes of soluble carbohydrates. This is a total of 17.3 tonnes which is 5.01 % of the pot ale and protein was 20 % of the total solids. There were other alcohols and related organic compounds that were not quantified. A commercial specification of Pot Ale composition [59] has 13.4 % crude protein, 1 % oil, 2 % sugar, this is 16.4 % of PA. Uzukwu et al. [25] showed that the composition of the produced solids in PAS was high in magnesium (24–28 % w/w) and phosphorus (16–19 %), and the solids also contain nitrogen (4–6 %), from proteins, and calcium (5–7 %). Therefore, the produced solids in PAS are probably suitable as fertiliser [48] and this is why the disposal of PA on land is used as it acts as a fertiliser.

Edwards et al. (2022) [37] have undertaken the detailed composition of the PA from 22 distilleries in Scotland. There is considerable variability in the individual composition but the mean values of the main constituents of pot ale (apart from water) are given in Table 3.

Table 3 is probably the most definitive publication on the composition of PAS. There was considerable variability in the data, but a value for PAS of 6.0 % of PA would be reasonable from this data. However, this assumes that there are no other compounds present that have not been analysed for. 6 % is low for the total PAS, as the above review concluded that total PAS was 13 % of PA. This would indicate that the compounds not analysed for are significant. More work is required on the composition of PAS and the proportion of PA that is PAS, as this is where the energy content of PA is and so evaluating the GCV of PAS is difficult, as discussed above.

5.9. *The energy to evaporate water in PA*

For Pot Ale it takes 2.560 MJ/kg_{water} to evaporate the water. There is from the above review 8 $L_{PA}/L_{alcohol}$ which with 87 % of water in PA gives 6.96 $L_{water}/L_{alcohol}$ which is 6.96 $kg_{water}/L_{alcohol}$ and this takes 17.82 MJ/$L_{alcohol}$ to evaporate the water in PA. This is 59.4 % of the energy to operate a distillery, excluding the energy to dry the PA. Higher energy would actually be required, as the efficiency of the evaporator has not been taken into account. This explains why pot ale is seen as a waste of no value in distilleries. The 9 distilleries on Islay [17] for example all discharge pot ale into the sea. If the PA is sent to an AD plant which wants PAS as the input, the energy to evaporate the water is not counted in the distillery carbon footprint or energy consumption (confirmed by Inchdairnie [27]). Kang et al. [9] also estimated the thermal production from dry draff and PAS, but ignored the energy to dry the draff or pot ale drying to produce PAS. Their improved contribution to the energy requirement of distillation is then false information.

Table 3
Mean composition of PA for 22 distilleries in Scotland.

Substance	Average concentration (g/L)
Protein	20
Free Amino Acids e.g. Proline	1.626
Organics acids e.g. Lactic acid	2.5
Inorganic anions e.g. Phosphates	1.8
Magnesium	0.188
Total organic carbon	12.7
Total carbohydrates hydrated e.g. mono-sacharin	18.4 (0.6 unhydrated)

The energy in PAS was shown above to be 24.7 MJ/$L_{alcohol}$ and the energy to produce the PAS from the pot ale is 17.8 MJ/$L_{alcohol}$, which gives a net contribution of useful energy of 6.9 MJ/$L_{alcohol}$ or 22.7 % of the distillery energy requirements. If this is combined with the 25.6 % of the distillery energy requirements from wet draff, then the total contribution of wet draff and PA to the distillery energy production is 48.3 %. Kang et al. [9] estimated that if the wet pot ale was sent to an AD plant then 23.6 % of the energy to operate the distillery could be generated from the biogas used for distillery heat. This is similar to the current estimate (22.7 %) of the maximum energy from pot ale. However, as for their similar estimate for the energy from wet draff, discussed above, this requires an unrealistic thermal efficiency assumption for AD plants.

Uzukwu et al. [25] estimated the amount of energy to be spent for the PA to PAS evaporation process to be approximately 17,600 GJ/year, based on the need to evaporate 8,000 m^3 of water per year (8 million kg). These figures with 2.56 MJ/kg_{water} evaporation energy result in an annual evaporation energy of 20,480 GJ/year, higher than the estimate by Uzukwu et al. [14]. This was for a 1,250 m^3/year production of alcohol. On this basis the energy to vaporise water is 16.4 MJ/$L_{alcohol}$, which is close to the 17.8 MJ/$L_{alcohol}$ from this review.

Hamill et al. [32] gives the electrical consumption for the fan power to dry the PA and this is 16–28 kWh/tonne of PA, which is 0.58–1.18 MJ/kg_{PA}. If we take PA production as 8 $L_{PA}/L_{alcohol}$, which is ~ 8 $kg_{PA}/L_{alcohol}$ we have the maximum electrical consumption for air fan evaporation as $1.18 \times 8 = 9.44$ MJ/$L_{alcohol}$. This value from Hamill [38] is low relative to the theroretical energy based on boiling the PA of 17.8 MJ/$L_{alcohol}$, probably because the energy to heat the PA is additional to the fan energy to remove the water vapour.

6. Spent lees and water wash (SLW)

Spent Lees (SL) is the second stage distillation waste water. It is common practice to mix the wash water for the two distillation vessel in with the SL making a spent lees plus wash liquid (SLW). It is the practice at many distilleries [26] to combine pot ale with spent lees and wash water to produce a single liquid waste discharge. This means there is more water to vaporise and much less energy content in SLW per litre. However, both PA and SLW represent large quantities of contaminated water which cannot simply be disposed of in sewers and the days when direct river or sea water discharges were used are largely over. Currently, much of the SLW and PA is spread on farmland and farmers are paid to do this and £250,000 per year by a distillery is typical of the annual payments for PA and SLW disposal by farmers [38]. In 2020 the cost of disposal of pot ale was £20 per tonne. The selling price of pot ale syrup to the farmer for animal feed is about £40 per tonne, but only 0.13 tonnes of PAS are produced per tonne of PA and 7.7 tonnes of PA are required to produce 1 tonne of PAS worth £40 and the disposal costs of the 7.7 tonnes of PA would be £154 [53]. However, a fossil fuel is used to evaporate the water in PA to produce PAS and the cost of this fossil fuel makes the sale of PAS uneconomic.

Farmers paid to dispose of PA spread it on farmland as a fertilizer. The rainwater run-off then pollutes rivers and this is undesirable. Thus, destroying these distillery wastes at the distillery would be preferable and any energy that could be extracted would be a bonus. If the water can be recovered (in a condenser in the flue gases of the steam boiler) then this can be returned to rivers and deducted from the net use of water from the distillery. The Scottish Whisky Industry [1] has a policy to reduce the quantity of water used per litre of alcohol produced and so recovery of the condensed evaporated water is also desirable.

The average spent lees and washings per litre of alcohol in Table 1 was 3.0 $L_{SLW}/L_{alcohol}$ and this was the average of 5 publications with a range 1.31–4.03. The average ratio of the pot ale production of 8.0 $L_{PA}/L_{alcohol}$ to the average spent lees plus washings production of 3.0 $L_{SLW}/$

Total mass	57.214	
		5.7 % of PA=Solid PAS

$L_{alcohol}$ is 2.7 L_{PA}/L_{SLW}.

6.1. The composition of spent lees and the role of lactic acid in whisky distilleries

SLW does have some energy content that is much lower than for PA, but still needs evaluating as it adds to the energy from PA that helps in the water vaporisation energy. Spent lees typically contains a dilute solution of a range of organic acids and alcohols, alongside high levels of copper and low levels of phosphorus and sulphur [35].

Spent lees is an oily, cloudy liquid, with a slightly oily aroma. Water accounts for the majority of the liquid, together with some 'oily fats' in liquid form (created during distillation), and the level of alcohol is around 0.1 % ABV [63]. However, the level of ethanol in a modern distillery is 0.5 % [52]. Quantifying the 'oily fats' is difficult as there are few publications. However, Hou et al. [61] for a rice-based spirit has identified lactic acid as the main component in the 'oily fats'. Lactic acid is $C_3H_6O_3$ or in molar ratio terms relative to carbon this is CH_2O and is clearly related to ethanol C_2H_6O or $CH_3O_{0.5}$. Lactic acid has a BP of 122 °C and a molar mass of 90. It has a GCV of 15.1 MJ/kg. Hou et al. [61] determined the average of five samples that there was 1–1.7 % of Lactic acid in distillery water wash. It is likely that Lactic Acid is the 'oily fats' mentioned above [63]. They showed that all other components were at a much lower level and not significant in the content of the samples. Beek and Priest (2002) [65] for the Glenkinchie distillery found that the final Lactic Acid concentration after the second distillation i.e in the spent lees and wash, was 0.4 % by mass. They showed that lactic acid reacts with ethanol during distillation to produce ethyl lactate, and spirits derived from long fermentations (greater than 55 h) in which lactic acid bacteria have flourished tend to have higher ester concentrations.

Priest [62] summarised the role of Lactic Acid bacteria in whisky distillation and its small contribution to whisky flavour. During the final stages when the yeast is dying, a homofermentative bacterium, related to Lactobacillus acidophilus, often occurs in the spent lees and wash [62]. Some American Bourbon distillers embraced this many decades ago by adding their own mixtures of lactic acid bacteria to their fer- mentations to provide consistency of flavour [55]. However, Priest [56] gives no quantitative information on the amount of Lactic Acid in the distillery spent lees and wash. Graham et al. [46] showed that lactic acid was < 0.1 % by mass in pot ale and it is in the second distillation tank spent lees that lactic acid forms [64,65].

6.2. Energy in ethanol and lactic acid in SLW

Very little data is available, but the above review suggest that 0.5 % ethanol and 0.5 % Lactic Acid in SLW would be reasonable. The density of ethanol is 789 kg/m³ and lactic acid is 1206 kg/m³, which gives the mass proportion of ethanol as 0.0039 kg/Kg_{SLW} and for lactic acid the mass proportion is 0.006 kg/kg_{SLW}. The density of the organic fraction in SLW is 1000 kg/m³ as the higher density of lactic acid cancels out the lower density of ethanol. The rest of SLW is water and so the overall density of SLW is 1000 kg/m³. The GCV of ethanol is 29.8 MJ/$kg_{ethanol}$ and Lactic Acid 15.1 MJ/$kg_{lactic\ acid}$. This gives 0.116 MJ/kg_{SLW} from ethanol and 0.091 MJ/kg_{SLW}. from lactic acid, which combined is 0.207 MJ/kg_{SLW} and 20.7 MJ/kg_{SLW} on a dry basis (as SLW has a moisture content of 99 %). The production of SLW is 3L_{SLW}/$L_{alcohol}$ which is 3kg_{SLW}/$L_{alcohol}$ and the energy content is 0.621 MJ/$L_{alcohol}$.

6.3. Energy to vaporise the water in SLW

The water in SLW is 99 % and it takes 2.56 MJ/kg_{water} to vaporise the water. This is 7.67 MJ/$L_{alcohol}$ and the energy in SLW is 0.621 MJ/$L_{alcohol}$, which is 8.1 % of the energy to vaporise SLW. This is useful but leaves 92 % of the energy to vaporise SLW to come from Pot Ale or Draff or 7.06 MJ/$L_{alcohol}$.

It has been shown above that there is 2.6 MJ/$L_{alcohol}$ spare energy from PAS in PA after vaporisation of water in PA. It was shown that Draffhas 8.3 MJ/$L_{alcohol}$ surplus energy after vaporising the water in draff. This is a total of 10.9 MJ/L available to vaporise the water in SLW, which requires 7 MJ/L. Thus, potentially there is 3.9 MJ/$L_{alcohol}$ remaining after all the water in PA, SLW and draff has been evaporated, this is 13 % of the energy to operate the distillery. This means that potentially there is no loss in thermal efficiency through injecting all the PA and SLW alongside a green fuel for the main steam boiler in a whisky distillery. At present if the PA, SLW or draff are dried, a fossil fuel is used with associated GHG emissions, which would be avoided if these distillery bio-wastes were used in the process to dry and burn the biomass. Two green fuels are being investigated for burning the PA and SLW: hydrogen and a biomass gasification gas (BGG), generated from the gasification of draff and other farm waste biomass (barley straw). For the PA and SLW these liquid wastes would be burnt in a two-stage burner downstream of the BGG or hydrogen first stage burner. The BGG burner would fire a steam boiler and if the water is recovered by condensation, then a greater contribution to the distillery energy requirement could be made from draff, PA and SLW.

7. Total energy to evaporate water in Draff, PA and SLW

The total energy to evaporate the water in PA is 17.8 MJ/$l_{alcohol}$ and Draff is 4.6 MJ/$L_{alcohol}$ giving a total energy to evaporate water in draff and PA as 22.4 MJ/$L_{alcohol}$ and if SLW is added, 7.67 MJ/$L_{alcohol}$, then the total evaporation energy is 30.1 MJ/$L_{alcohol}$. This is the same as the energy to operate the distillery and so twice as much energy is required to produce alcohol for whisky if the water in the biomass by-products is recovered and dry draff and PAS produced. This is why few current distilleries dry the waste on site and are prepared to pay farmers to take these wastes away for cattle feed or spraying onto farmland.

The total energy in PAS is 20.4 MJ/$L_{alcohol}$ and in Draff is 13.1 MJ/$L_{alcohol}$ and in SLW is 0.7 MJ/$L_{alcohol}$ which is a net energy in all three wastes of 34.2 MJ/$L_{alcohol}$. This implies that there is 4.1 MJ/$L_{alcohol}$ potential contribution to the distillery boiler energy requirements. Thus, evaporating all the water in PAS and SLW and Draff should not deteriorate the thermal efficiency of the process. However, at least 26 MJ/$L_{alcohol}$ has to be provided by an additional fuel and this will be the gasifier preheater fuel and straw (or other biofuel) added to the draff in a gasifier. An alternative would be to use a low-cost waste bio-oil crude glycerol, from bio-diesel manufacture. This is difficult to burn but could be used in an axially staged hydrogen or BGG burner as the second stage fuel. With the BGG burner the crude glycerol could be injected in the same location as the PA+SLW injection. This design is currently being developed as part of a 100 % decarbonisation demonstration for the whisky industry, using all the distillery, malthouse and barley farming wastes.

The total energy supplied to the system will be 60 MJ/$L_{alcohol}$ and this is double that for the fuel to operate the distillery, leaving all the waste in a wet state. Fig. 1 shows that if the view of whisky manufacture is extended beyond the distillery, then there are wastes produced at the malthouse, at the barrel preparation phase of maturation, and at the farm that supplies the barley that can provide additional biomass to provide the additional bio-energy to complete decarbonisation of the production of alcohol for whisky.

8. Bio-waste energy from the malthouse

There is currently no use of malt house or farm waste bio-energy for heat in distilleries. The malt house has three bio-wastes: dark grains and rootlets or malt culms and barley grain husks. About 15 % of the mass of barley processed in the malthouse is rejected as dark grains and culm with a typical NCV of 10 MJ/kg [14]. Barley production for distilleries is 800,000 tonnes per year which would yield 120,000 tonnes of dark grains and culm [14]. This has an energy content of 1.2 PetaJ. For an annual alcohol production of 320 million L this is 0.375 kg/$\mathrm{L_{alcohol}}$ and 3.75 MJ/$\mathrm{L_{alcohol}}$ which is a significant bio-energy resource, but still insufficient to provide the 26 MJ/$\mathrm{L_{alcohol}}$ required to provide all the energy to operate all whisky production. A further bio-energy resource capable of providing > 22 MJ/$\mathrm{L_{alcohol}}$ is required and barley straw from the farm that provided the barley to the malthouse is an obvious source of some of that bio-energy.

Barley husks are 10–13 % of barley [66], which taking the lower figure is 80,000 tonnes per year, which is 0.25 kg/$\mathrm{L_{alcohol}}$. Taking the GCV of Barley husks as 16 MJ/kg, similar to that for three other seed husks reported by Xyradakis et al. [64], the energy that could be generated from barley husks is about 4 MJ/$\mathrm{L_{alcohol}}$. This is about 10 % of the distillery energy requirements.

9. Farmers waste barley straw

Barley straw has the potential to be produced at the same mass as barley, 800,000 tonnes per year [14] with a water content of 14.5 % [14] gives 684,000 tonnes of dry barley straw and 116,000 tonnes of water. This water is 0.36 kg/$\mathrm{L_{alcohol}}$. Using a GCV of 17 MJ/kg for barley straw [42]. This gives a potential energy of 11.6 PJ and for an annual alcohol production of 320 million L [2] this is a potential bio-energy of 36 MJ/$\mathrm{L_{alcohol}}$, which is more than sufficient to complete the decarbonisation of whisky production. The energy to evaporate the water is 2.56 MJ/$\mathrm{kg_{water}}$ × 0.36 Kg/L=0.92 MJ/$\mathrm{L_{alcohol}}$.

22 MJ/$\mathrm{L_{alcohol}}$ is the additional bio-energy requirement to complete the decarbonisation of the distillery and so only 61 % of barley straw is required. This is practical, as there are other uses for barley straw. Currently, farmers supply barley to the Malthouse and there are very few distilleries with their own malt house. However, currently the price of straw is too low for farmers to harvest the full crop. If barley straw was an energy crop, then farmers would benefit financially. Distilleries would also be able to decarbonise completely, using annual renewable bio-energy. Also, wet draff, wet pot ale and wet SLW would be consumed at the distillery, so that no river pollution occurs as a result of their disposal on farmland.

10. Maturation barrel preparation char removal.

Whisky barrels are flame charred before being used to mature whisky. At the end of the whisky maturation period (3–10 years typically) and the bottling of the whisky, the char is removed from the barrel by machining to produce a char waste. The barrel is then flame charred again, ready for a second life of whisky maturation. This can happen typically 5 times in the life of a barrel, the barrel is then too thin to have more char machined off and is retired, typically after a 30-year life of whisky maturation. The bio-char [68] removal in this process is a potential renewable energy fuel. Typically, the char thickness that is removed is 2 mm deep and a barrel is approximately 1.5 m high and 1 m diameter, with a density of 700 kg/$\mathrm{m^3}$ the mass of char removed is about 5 kg of char per barrel. Bio-char has a high GCV of about 30 MJ/kg [68] and so 150 MJ of energy is potentially produced for each barrel char renewal. There are in Scottish maturation facilities 22 M barrels [2] with about 4 M barrels renewed each year. This is 80L per barrel and about 0.0625 $\mathrm{kg_{char}}$/$\mathrm{L_{alcohol}}$ of bio-char. This is a potential energy per year of 600TJ. There are 320 M L of alcohol produced per year [2] and so the energy available from barrel char removal is 1.88 MJ/$\mathrm{L_{alcohol}}$, which is 6 % of the required energy to operate a distillery on a dry bio-waste basis.

11. Conclusions

Table 4 summarises the bio-energy resource mass, kg/$\mathrm{L_{alcohol}}$ or volume L/L of Whisky Industry.

Table 4 shows that in terms of dry bio-waste, using an average bio-waste GCV of 15 MJ/kg, there would be 65 MJ/$\mathrm{L_{alcohol}}$ available to operate the distillery, which is more than adequate. However, 49 % of this is from straw and not all straw produced would be available for energy use. Even without the straw there is 32 MJ/$\mathrm{L_{alcohol}}$ available, which is sufficient to operate a distillery. However, the need to evaporate the water in the waste at 2.56 MJ/$\mathrm{kg_{water}}$ adds 31 MJ/$\mathrm{L_{alcohol}}$ to the energy requirements and most of this could be provided by straw, if it was all available. Table 5 shows the individual components of the bio-waste energy, using the GCV for each component that was detailed in this review.

Table 4

Summary of Whisky Industry bio-energy resource mass, kg/$\mathrm{L_{alcohol}}$ or volume L/L.

Bio-waste Source	Wet	Water	Dry
Distillery: Draff kg/L	2.4	1.8	0.6
Pot Ale L/L	8	6.9	1.1
Pot Ale kg/L	8.26	6.9	PAS 1.36
Spent Lees Wash (SLW) kg/L	3.0	2.97	0.03
Malthouse: Dark grains + rootlets	0.375	0	0.375
Husks	0.25	0	0.25
Farm: Barley Straw kg/L	2.5	0.36	2.14
Maturation barrel bio-char kg/L	0.063	0	0.063
Total kg/L	15.5	12.97	4.318

Table 5 shows that the distillery wet waste biomass could be used to provide 24 % of the 60 MJ/$\mathrm{L_{alcohol}}$ distillery heat requirements, including the heat to dry draff and pot ale/SLW.

Malthouse bio-waste. farm barley straw and maturation bio-char could be additional bio-wastes from the whisky industry and these would increase the decarbonisation of the distillery industry to 89 % decarbonisation. However, this assumes that all the barley straw could be used for heat in distilleries and it is likely that only 50 % would be available. For bio-wastes to be a low-cost route to decarbonising the whisky industry other bio-wastes would have to be used. Crude glycerol from bio-diesel manufacture is one waste that is in plentiful supply and is low cost. Also, any waste straw could be used, not just barley straw. The key conclusion is that there is insufficient bio-waste in the whisky industry to operate a distillery and dry the wet bio-waste, so that other bio-waste resources would have to be used. Alternatively, hydrogen could be used to provide the missing energy and effectively the use of bio-waste would reduce the amount and cost of hydrogen for decarbonisation.

To utilise this wide range of bio-wastes an energy conversion system is required that can cope with this wide range of bio-wastes from solid to liquid and with a high-water content of the solid and liquid bio-wastes. Both AD and biomass combustion could use some of the wastes, but not all. Gasification of wet draff and barley straw to produce a biomass gasification gas, BGG, is the recommended route to utilisation of the wet draff, bio-char, malthouse bio-wastes and straw. The BGG gas burnt with air in a burner enables the PA, SLW and crude glycerol to be injected into the BGG burner hot outlet gases, using an axially staged burner with the PA and SLW injected downstream of the BGG flame to evaporate the water and release the energy in PAS and SLW and crude glycerol.

Gasifiers require heating during the process start up and to control the gasification temperature and for 100 % decarbonisation hydrogen burners would be used and about 20 % of the total energy would be supplied for process heating during cold start. An alternative way of looking at this is that the 100 % hydrogen solution to the decarbonisation of whisky distilleries has a reduced demand for and cost of hydrogen, if waste bio-mass is the source of say 80 % of the energy. The use of waste biomass in Whisky distilleries is the low-cost way for decarbonisation of heat and the problem of the disposal of draff, PA and SLW at the distillery is solved.

Table 5

Summary of Whisky Industry bio-energy resources, in MJ/$L_{alcohol}$.

Energy required for the distillery, MJ/L			30	%	60	%
Bio-waste Source	Water Evaporation	GCV MJ/kg_{dry}	Dry	Dry %	Wet	Wet
Distillery: Draff	4.6	20.5	12.3	41 %	7.7	12.8
Pot Ale	17.8	PAS 19	PAS 25.8	86 %	PA 8.0	13.3
Spent Lees Wash (SLW)	7.67	0.116 MJ/kg_{SLW}	0.62	2.1 %	−7.05	−11.8
Malthouse: Dark grains + rootlets	0	10	3.75	12.6	3.75	6.25
Husks	0	16	4.0	13.3 %	4.0	6.7 %
Farm: Barley Straw	0.92	17	36.4	121 %	35.5	59.1
Maturation barrel bio-char	0	30	1.88	6.3	1.89	3.1
Total	31.0		84.75	282 %	53.8	89.45

Wet = Energy after water removal (dry) − Energy to evaporate water.

Dry = Energy after water removal (dry). For PA this is PAS.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] Al O'Conner A. Brewing and Distilleries in Scotland – economic facts and figures. The Scottish Parliament SPICe Briefing SB18.64, 11 Oct. 2018.

[2] The Scottish Whisky Association, Facts and Figures 2024.

[3] Office of National Statistics, ONS.gov.uk, 2023.

[4] Früh WG, Hillis J, Gataora S, Maskell D. Heriot-Watt U. Reducing the carbon footprint of Whisky production through the use of a battery and heat storage alongside renewable generation. 19th International Conference on Renewable Energies and Power Quality (ICREPQ'21) Almeria (Spain), 28th to 30th July 2021. Also in: Renewable Energy and Power Quality Journal (RE&PQJ) ISSN 2172-038 X, Volume No.19, September 2021.

[5] Sibille R., Scotch Whisky Pathways to Net Zero. Report for the Scottish Whisky Association, 11th May 2020, Ricardo.

[6] Scottish Government. Scottish Energy Hub. (2021). https://scotland.shinyapps.io/Energy/.

[7] White S, Stewart KL, Maskell DL, Diallo A, Traub-Modinger JE, Willoughby NA. Characterization of Pot Ale from a Scottish Malt Whisky Distillery and Potential Applications. ACS Omega 2020. https://doi.org/10.1021/acsomega.9b04023.

[8] Silva FC, Cruz NC, Tarallo LAC, Rodrique CM. Use of biomass ash-based material as soil fertilizers: literature review of the existing regulatory framework. J Cleaner Production 2019;214:112–24.

[9] Kang X, Lin R, O'Shea R, Deng C, Li L, Sun Y, et al. A perspective on decarbonizing whiskey using renewable gaseous biofuel in a circular bioeconomy process. J Clean Prod 2020;255:12021.

[10] Arnison, R. and Carrick, R. Circular Economy: Sector Hub – Beer, Whisky and Fish. Final Report June 2015, Scottish Government, Ricardo-AEA.

[11] UK BEIS (now DESNZ) Green Distilleries: Contract GD166. BatGasDW: Batch Gasification of Distillery Waste Biomass for renewable distillery fuel.

[12] Duffy C, Styles D, Black K, Schestak I, Macgregor K, Iannetta PPM. Optimising sustainability: Circular pathways for Scotch Whisky distillery co-products. J Clean Production 2023;395:136436.

[13] Waste reduction | Boortmalt.

[14] Bell J, Farquhar J, McDowell M. Distillery by-products, livestock feed and bio-energy use in Scotland. A Review commissioned under the Scottish Government RESAS Policy Underpinning: Special AEconomic Studies. Prepared by SRUC; July 2019.

[15] Erikssona G, Grimm A, Skoglundc N, Bostro¨mc D, O¨ hmanb M. Combustion and fuel characterisation of wheat distillers dried grain with solubles (DDGS) and possible combustion applications. Fuel 2012;102:208–20.

[16] Dalton C, Okolie JA, Davis P, Gunes B. Design of a pre-treatment integrated anaerobic digestion treatment facility for decarbonising whiskey industry: A circular economy perspective. Heliyon 2022;8(5):e09522.

[17] Leinonen, I., MacLeod, M., & Bell, J. (2018). Effects of alternative uses of distillery by-products on the greenhouse gas emissions of Scottish malt whisky production: a system expansion approach. Sustainability, 10(5), 1 - 18. [1473]. https://doi.org/10.3390/su10051473.

[18] Bowman, C.T. Control of combustion-generated nitrogen oxide emissions: technology driven by regulation, 24th Combustion Symposium 1992 p.859 - 878.

[19] Baukal CE, editor. The John Zink Combustion Handbook. CRC Press; 2001.

[20] Basu P. Biomass Gasification and Pyrolysis. Academic Press; 2010.

[21] Quinonez Arce JR, Andrews GE, Maxfield JD, Phylaktou HN, Smith SB, Wakeman R. Glycerol and Glycerol/water Gasification for the Decarbonisation of Industrial Heat. Chem Eng Trans 2023;105:199–204. https://doi.org/10.3303/CET23105034.

[22] Olanrewaju FO, Andrews GE, Phylaktou HN, Li H, Smith S, Maxfield JD, et al. Renewable Energy from Whisky Distillery By-products. Chem Eng Trans 2023;105: 211–6. https://doi.org/10.3303/CET23105036.

[23] Chan, W-H and Chen, C-Y, Water gas shift reaction for hydrogen production and carbon dioxide capture: A review. Applied Energy 258 (2020) 1140724. Tillman DA, Rossi AJ, Kitto WD. Wood Combustion, Academic Press 1981, p.29.

[24] Uzukwu CC, Barraclough MJ, Davide DD. Experimental investigation of a new process for treatment and valorisation of pot ale wastewaters 2017;75:5.

[25] Holroyd P. 2022 Distillery Manager, Kingsbarns Distillery. Private Communication27. Palmer I. 2022. Distillery Manager, Inchdairnie Distillery, Private Communication.

[26] Duguid L. Sustainable Energy using Anaerobic Digestion of By-Products: Islay Whisky Industry Case Study. A thesis submitted in partial fulfilment for the requirement of the degree Master of Science Sustainable Engineering: Renewable Energy Systems and the Environment 2016, University of Strathclyde.29. Meadows S. 2015. Anaerobic Digestion and Resource Use within the Scotch Whisky & UK Beer Industries. MSc project report. http://www.esru.strath.ac.uk/Documents/MSc_2015/Meadows.pdf.

[27] Scottish Whisky Association (SWA) newsroom. Sustainability numbers add up for green whisky strategy. 01 November 2021.

[28] Kvaalen E, Wankat PC, McKenzie BA. Alcohol distillation: basic principles, equipment, performance relationships, and safety. Purdue University. AE: CPD Lecture notes; 1983. p. 117.

[29] Hamil A. improved treatment of distillery wastes. Project Ref 2013-ET-CP-47 Date: 28th September 2015.. National Waste Prevention Programme 2014–2018 Final Report For Green Enterprise Programme (GEP) Phase 2.

[30] Gandy S, Hinton S. 2018. Whisky by-products in renewable energy, Ricardo Energy.

[31] Leinonen I, MacLeod M, Bell J. Effects of alternative uses of distillery by-products on the greenhouse gas emissions of Scottish malt whisky production: a system expansion approach. Sustainability, 2018: 10(5), 1 - 18. [1473]. https://doi.org/10.3390/su10051473.

[32] Akunna JC, Walker GM. (2017). Co-products from malt whisky production and their utilisation. In: Walker, G.M., Abbaas, C., Ingledew, W.M. & Pilgrim C. (Eds.). The alcohol textbook: a reference for the beverage, fuel and industrial alcohol industries (6 edn. 529-537). Ethanol Technology Institute, Duluth, Georgie,Whisky

technology, production and marketing (Stewart, G., Bamforth, C. and Russell, I., eds). Academic Press: London, 2003.

[33] Pass B, Lambert I. Co-products. In: Whisky technology, production and marketing (Stewart G, Bamforth C, Russell I, eds). Academic Press: London, pp 245-270. 2003.

[34] Edwards C, McNerney CC, Lawton LA, Palmer J, Macgregor K, Jack F et al. Recoverable resources from pot ale & spent wash from Scotch Whisky production. J. Resources, Conservation and Recycling, 179 (2022) 106114.

[35] Schrieberg. Putting whisky waste to good use. Scotch Whisky. 27 March 2017.

[36] Stewart DM, “co-products” In: Whisky technology, production and marketing (Stewart G, Bamforth C, Russell I, eds). Academic Press: London Chapter 21 2021.

[37] Mussatto SI, Dragone G, Roberto SI. Brewers’ spent grain: generation, characteristics. J Cereal Sci 2006;43:1–14.

[38] Bennett J. 2013. The application of ultrasound in the bioconversion of brewers’ and distillers’ spent grains to bioethanol. Ph.D Thesis. Abertay University.

[39] Wil´en, C., Moilanen, A., Rautalin, A., Torrent, J., Conde, E., Lo¨del, R., Carlson, D., Timmers, P and Brehm, K. Safe handling of renewable fuels and fuel mixtures. VTT Publication 394, Finland 1999.

[40] Foltanyi FF, Hawkins JE, Panovic I, Bird EJ, Gloster TM, Lancefield CS, Nicholas J. Westwood NJ. Analysis of the product streams obtained on butanosolv pretreatment of draff. Biomass and Bioenergy 2020. v.141 105680. St. Andrews and Napier Universities.

[41] Mussatto SI, Roberto IC. Chemical characterization and liberation of pentose sugars from brewer’s spent grain. J Chem Technol Biotechnol 2006;81:268–74. https://doi.org/10.1002/jctb.1374.

[42] Murthy JD, Power NM. How can we improve the energy balance of ethanol production from wheat? Fuel 2008;87:1799–806.

[43] Graham J, Peter B, Walker GM, Wardlaw A, Campbell E. Characterisation of the pot ale profile from a whisky distillery. Distilled Spirits: Science and Sustainability. Chapter 43, 1-7.

[44] Saha NK, Balakrishnan M, Batra VS. Improving industrial water use: case study for an Indian distillery. Resources, Conservation and Recycling 43 (2005) 163–174 (India).

[45] Mohana S, Acharya BK, Madamwar D. 2008. Distillery spent wash: Treatment technologies and potential applications. Journal of Hazardous Materials. 163 (2009) pp. 12-25. This refers to Indian Distilleries.

[46] Luna-delRisco M, Normak A, Orupo˜ld K. Biochemical methane potential of different organic wastes and energy crops from Estonia. Agron Res 2011;9(1–2): 331–42.

[47] Goyal K, Seth R, Handa BK. Diphasic Fixed-Film Biomethanation of Distillery Spentwash. Bioresour Technol 1996;56:239–44.

[48] Poschl M, Ward S, Owende P. Evaluation of energy efficiency of various biogas production and utilisation pathways. Appl Energy 2010;87:3305–21.

[49] Barrena R, Traub JE, Gil CR, Goodwin JAS, Harper AJ, Willoughby NA, et al. Batch anaerobic digestion of deproteinated malt whisky pot ale using different source inocula. Waste Manag 2018;71:675–82.

[50] Maxfield, J., Andrews, G.E. and Palmer, I., Green Distlleries: Phase 1 Final Report (TRN 2564/08/2020). BatGasDW: Batch Gasification of Distillery Waste Biomass for renewable distillery fuel. UK BEIS (now DESNZ) Aug. 2020.

[51] Dionisi D, Bruce SS, Barraclough MJ. 2022. Effect of pH adjustment, solid-liquid separation and chitosan adsorption on pollutants’ removal from pot ale wastewaters.Accepted Paper, University Aberdeen staff.

[52] Wisniewski I. Pot Ale and Spent Lees. Whisky Magazine.

[53] Wainman FW, Dewey PJS, Brewer AC. 1984. Feeding stuffs Evaluation Unit - Fourth report 1984. Rowett Research Institute, DAFS, Edinburgh. Also, in Feedipedia - Animal Feed Resources Information System, 6.11.2014.

[54] www.gpfeeds.co.uk/analysis/pot_ale_syrup.htm.

[55] United Molasses Data Sheet for PAS.

[56] Pot Ale Specification, www.glw-feeds.co.uk.

[57] Steffen R, Szolar O, Braun R. Feedstocks for Anaerobic Digestion. Institute for Agrobiotechnology Tulln University of Agricultural Sciences Vienna 1998-09-30.

[58] AB Agri Group, UK. Spey syrup. https://www. tridentfeeds.co.uk/products/spey-syrup/.

[59] Priest FG. Lactic acid bacteria – the uninvited but generally welcome participants in malt whisky fermentation. MICROBIOLOGYTODAY VOL 31, p.16-18, FEB 2004.

[60] https://www.sruc.ac.uk/download/downloads/id/1057/distillery_feed_by-products_briefing.

[61] Hou W, Linga J, Xu Y, Li K, Wang F. Liquid chromatography-tandem mass spectrometry analysis for identification and quantification of antimicrobial compounds in distillery wastewater. MethodsX 2021;8(2021):101470.

[62] Beek SV, Priest FG. 2002. Evolution of the Lactic Acid Bacterial Community during Malt Whisky Fermentation: a Polyphasic Study. J. Applied and Environmental Microbiology, 0099-2240/02/$04.000 DOI: 10.1128/AEM.68.1.297–305.2002 Jan. 2002, p. 297–305 Vol. 68, No. 1.

[63] Krawczyk H, Persson T, Andersson A, Jansson A-S. Isolation of hemicellulose from barley husks. Food and Bioproducts Process 2008;80:31–6.

[64] Xyradakis, P., Kateris, D., Gialamas,T., Bartzialis, D., Giannoulis, K. An Experimental Determination of Gross Calorific Value of Different Agroforestry Species and Bio-Based Industry Residues Ioannis Gravalos1,.

[65] Kumar A, Bhattachonga T. Biochar: A sustainable solution. Environmental Development and Sustainability 2021;23:6642–80.

[66] UK DEFRA and National Statistics, Cereal and Oilseed products in the UK 2023, 21.12.23.

[67] Schestak, I. Styles, D., Black, K. and Prysor Williams, A., Circular us of feed bu-products from alcohol production mitigates water scarcity. Sustainable Production and Consumption 30 (2022) 158-170.

[68] Price, R., MacDonald, L., Gillies, N., Day, A., Brightman, E. and Li, J., Utilisation and valorisation of distillery whisky waste streams via biomass electrolysis: electrosynthesis of hydrogen. Faraday Discuss. 2023. **247**.268-288.

[69] Allardyce S, Baster E, Kirk C, Lamond W. Balmenach Distillery Case Study: An investigation of Energy Production from Distillery Co-Products for Balmenach Distillery, Speyside. Scotland: University of Strathclyde MSc Report; 2016.

[70] Dalmunnach Distillery. How Dalmunach Distillery became one of the most energy efficient in Scotland. The Scotsman, 2023.

[71] Scottish Whisky Association. (2012). *Environmental Strategy Report 2012*. Retrieved from http://www.scotch-whisky.org.uk/news-publications/publications/documents/environmentalstrategy-report-2012/#.Vdndu_lVhBe.