WATER DEMAND AND WASTE HEAT EMISSION IN SCOTTISH DISTILLERIES

Chemical Engineering Study Project 4(U04634)

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Contents

Covid-19 Statement

Acknowledging the impact of Covid-19 on this report including, but not limited to, significant difficultly in communication with a large number of industrial contacts for the acquisition of data to analyse. This includes constraints on the side of the industrial contacts as I personally invested significant time to reach out to a large number of contacts to no avail. This led to a slight sway from the initial direction of the project from a data analysis of the whisky industry to both a literature review and a data analysis.

1. Abstract

This paper evaluates the presence and usage of process water in the Scottish malt whisky distillery industry. Further evaluation will address the ultra-low grade waste heat at temperatures of less than 80 °C and the co-location of waste heat and process water. The basis for this review is to provide both a critical survey of existing literature on the Scottish malt whisky manufacturing process and to evaluate qualitative summaries of the industrial sector of malt whisky production. The estimates provided found a total energy usage of 3.384 TWh/yr, an annual process water volume of 1.135×10^8 m^3/yr and a corresponding waste heat emission across various sections of the manufacturing process, including 147 GWh from heating and cooling duty performed, 73.2 GWh from convection of the still and 23.7 GWh carried by process water streams back to their source.

2. Introduction

Across the globe, there are few Scottish exports more famous than whisky. An age-old tradition, the word whisky stems from the Gaelic *uisge beatha* meaning 'water of life' [1] and had its earliest literature reference from 1494 in the Scottish Exchequer Rolls [2]. Within the whisky manufacturing process, there are various key ingredients and a variety of preparation stages to arrive at the final bottle, though few elements are hailed as more important than the water.
The whisky distillery industry is a significant asset to the overall UK economy and contributed approximately 1.5 billion GBP in exports to the European market in 2019 alone [3]. With the Scottish variety steeped in tradition and worldwide reputation, Scotch whisky is protected by Geographical Indication (GI) status and provides a gross value added (GVA) to the UK economy of 4.9 billion GBP, with a direct impact of 3.2 billion GBP [4]. In 2019, there were 160 operational distilleries in Scotland manufacturing a variety of spirits, mostly whisky and gin. Of the 160 distilleries, 122 manufacture malt whisky and each employ traditional methods governed by the protection status of Scotch malt whisky, though each employ their own unique measures across 5 major regions, as shown in figure 1. [5]

The protection status of Scotch whisky prevents adulteration of the process of manufacturing and inhibits corner-cutting to minimise excess expenditure, so adaptation within the Scottish distillation industry is a slow process. The dedication to tradition exhibited throughout the industry is one of the defining features of the industry, and undoubtedly remains within the interest of all Scottish distilleries in order to uphold worldwide reputation. Thus, the utilisation of low-grade heat recovery and techniques to minimise water demand must be implemented in a manner which maintains respect to tradition.

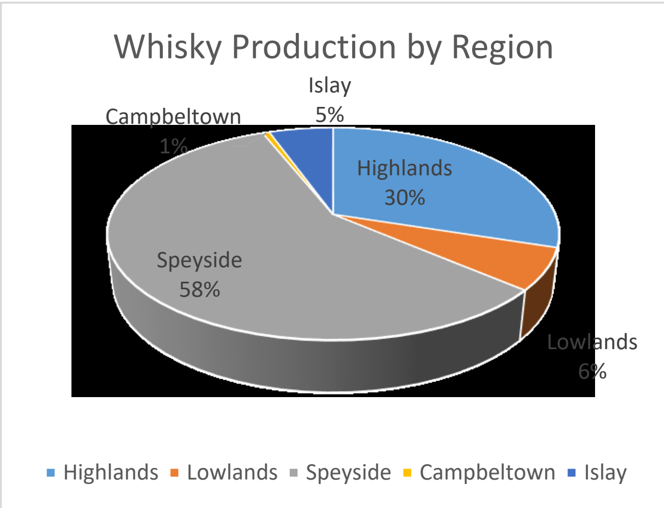

Figure 1: Whisky production by manufacturing region, [5].

The future holds increasing uncertainty for the worldwide distillery industry as global water utilisation increases at twice the rate of population growth [6] and responsible water usage will be a critical consideration for sustainability of both the industry and wider humanity. The existence of the 'energy-water nexus' which considers the concurrent existence of unutilised energy in water streams, is an ongoing challenge to 'disentangle' or separate each constituent for utilisation or responsible discharge from the process, and a progressive approach can include a variety of strategies.

There is an inherent cooling requirement involved in the distillation process of whisky, and waste heat from process cooling water falls into the ultra-low heat grade at less than 80 °C. The potential waste energy carried in such streams is vast, and is estimated later in the report. Techniques to exploit the heat are valuable for reducing operating costs by minimising wasted energy, but must respect the constraints of tradition. Investigation of existing technology is currently implemented by few distilleries, but those under larger corporate umbrella companies may experience furthering of existing technology into waste heat capture and exploitation from process water streams, and smaller distilleries may target more creative, community-focussed solutions to ensure utilisation of valuable energy. Current utilisation of waste heat is controlled solely by the initiative of each individual distillery. The capacity of each distillery, and by consequence amount of waste heat available to distilleries, is dependent not only on distillery production volume, but also considerations such as existing heat exploitation by well-designed heat exchanger networks.

There exists major gaps in literature due to the proprietary nature of information in whisky manufacturing, and trade secrets are treasured and protected. The conventional practices characterised across the industry perhaps require refreshing by ongoing inspection, whilst recognising the most important asset of all in the final product. This review will address the ongoing use of water in the distillation process, provide analysis of energy and water usage throughout the malt whisky distillation sector and outline the relevance of ongoing research into the water-energy nexus evaluating its applicability to the Scottish malt whisky distillery industry.

2.1 Whisky manufacturing process

The process of production of whisky is a protected practice and follows many traditions. Figure 2 shows a typical whisky distillery layout from wash onwards. The process begins with barley being heated in water at around 16 °C. This increases the moisture content in the barley from around 12% to between 43-46%; thus preparing the barley for germination. The process of germination occurs when the barley is spread across large floors, known as 'malting halls'. After malting, the barley is dried before being ground into a fine powder known as 'grist' by milling. It is desirable to have a grist with variable particle sizes. The grist is then added to a large vat, either a mash-tun or lauter-tun, to heat with water from temperature ranges of 62 °C – 95 °C while being macerated by rotating blades or rakes. The mashing process allows the synthesis of fermentable sugars from the starch using the natural enzyme amylase present in the barley. The resulting fluid is known as 'wort', and the solid matter and particulates are separated and sold to local farms as fertiliser or burned to provide heat in alternate areas of the distillery. The wort is cooled using heat exchangers to around 34 °C and fermented by adding yeast to the wort in large 'washback' vessels for around 48-60 hours. The wort is then distilled in pot-stills twice, firstly from around 7-8% alcohol content to 'low wines' of 21-30% alcohol content then to around 70% to be stored in wooden casks to age. There are various customs with distillation process, including the initial and final distillate being discarded at a cut point determined by the distillery's brewer, as well as variable aging times. [8]. Denis A. Nicol evaluates further some of the opportunities for disparity between different distilleries within the industry to a detailed extent in the text 'Whisky: Technology, Production and Marketing'. Various authors contribute to sections of the text with specific analysis of history, fermentation, coproducts and marketing; providing an excellent analysis of each area involved from barley to dram. [7]

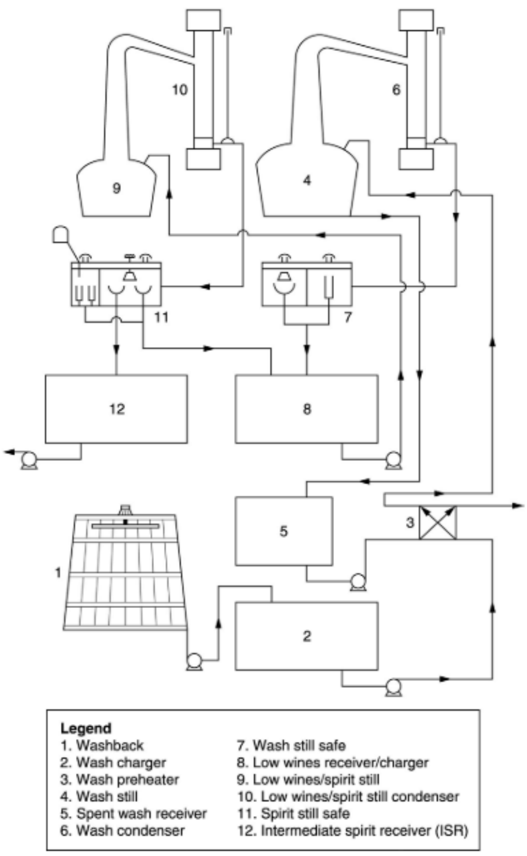

Figure 2: Whisky Distillery Layout [7]

2.2 Distillation methods

In all Scottish whisky distilleries, large, beautiful copper pot stills have been a staple of the industry, and are one of the GI protecting factors – batch distillation is one of the defining features of Scottish malt whisky. In older times, the stills were heated externally by fire in furnace, but modern stills are heated by internal steam heating coils, powered by gas burners [7]. There is an element of neglect for traditional 'good practice' chemical engineering for the heating elements in stills, as a certain degree of burning allows for mild charring of the malt products, known in the food industry as the 'Maillard reaction' [31] and gives rise to complex notes of sulphur and smoke in the final product. Before modern adaptations, old stills used air cooling condensers, with long lye pipes to allow for sufficient cooling duty to condense the vapours into drinkable liquid, and through time as understanding of the cooling requirement developed, worm-tubs, and later shell and tube condensers were utilised to perform the cooling duty to condense the distillate. The widely accepted method for utilisation of the cooling water after performing cooling duty is to preheat wash or to be used in larger distilleries in the mashing process.

2.2.1 Worm-tub condensers

Low-grade heat emission is prevalent within the whisky production industry, with various traditional practices inhibiting energy optimisation of the distillation process. One example of this is the usage of worm-tub condensers to cool the distillate from pot-still columns. Widely praised for the subsequently produced whisky, worm-tub condensers are large, wooden vats with the copper coils from the lyne-arm of the distillation column coiling around the vat, filled with water, as shown in Figure 3. They perform a less intense cooling duty than the more efficient counterpart, shell and tube condensers, and thus allow for the retention of desirable sulphurous compounds in the whisky [7]. The stagnant surrounding water to the copper coil of vapours gives rise to a temperature driving force that changes as the process water heats up, when compared to shell and tube which maintains a constant temperature profile throughout the exchanger as the constant counter current flow of water maintains the colder inlet temperature of water and thus consistent temperature profile. In general, the cooling water in worm-tub condensers cannot be subsequently utilised, instead is slowly dissipated to surrounding environment through the wooden body. Worm-tub condensers are utilised in 15 Scottish distilleries, with obvious beauty in visual design but inhibit the usage of the energy transferred to the cold water, which is addressed if utilising shell and tube heat exchangers. The energy trade-off for a more desirable tasting whisky is an important financial decision, with payback of increased energy costs dependent primarily on the sale of the product.

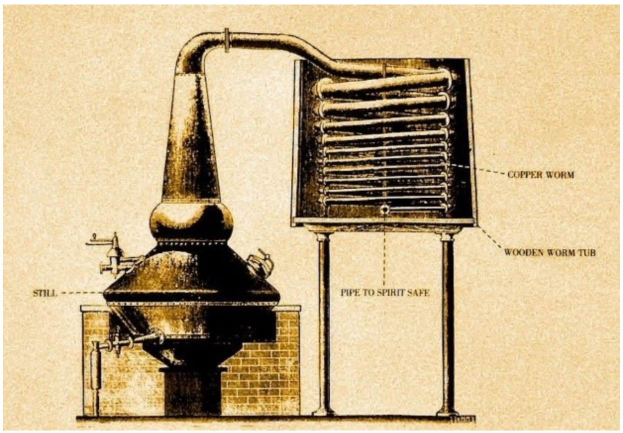

Figure 3: Pot still with worm-tub condenser setup [32].

3. Water demand

3.1 Process water usage

Throughout the distillation process, there are various uses of both process and production water. Production water is utilised for final consumption, for example the making of wort when water is mixed with grist, and will not be the focus of this investigation. Process water is used in many regions of the plant to perform necessary duty functions, such as cool distillate from the pot still by operating as the shellside fluid in worm-tub condensers. The energy carried by the process water is large, and volumes utilised greatly exceed the volumes of production water. In many distilleries, process water is extracted from local sources such as lochs, rivers or burns, and utilised directly for cooling. Once the water has performed its cooling function, it is often expelled back to the same source it came from, with very little risk of contamination from chemicals in violation of overarching SEPA regulation having been solely employed for heating or cooling duty. [9]

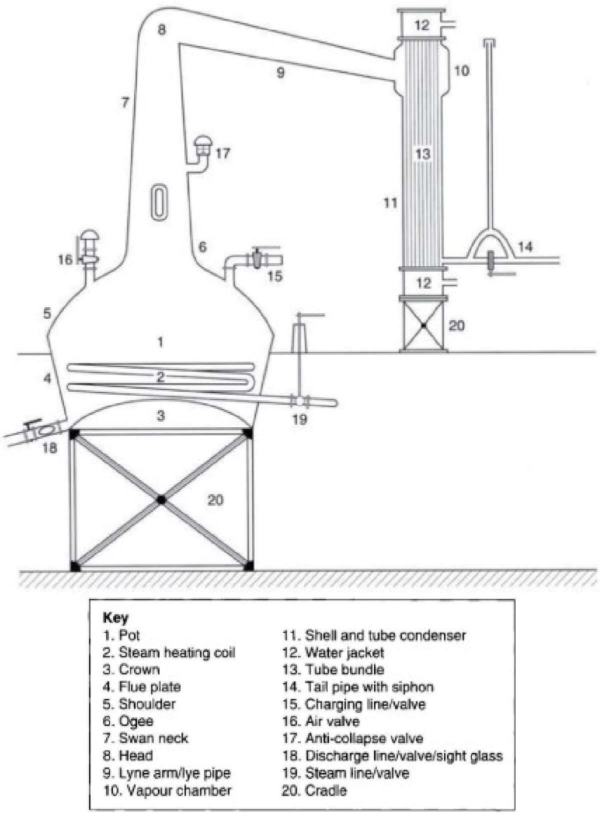

Figure 4: Pot-still distillation column setup [7]

A brief analysis of available literature shows studies such as S.G. Haile et al. into the energy efficiency of distilleries and wider industrial alcohol production facilities demonstrate the main energy consuming elements of an alcohol manufacturing plant are the boiler, distillation columns, pumps, and air compressors. Associated heat losses within the constituent elements of the boiler can be contributed to convective and radiative heat transfer from the surface of the boiler and distillation columns themselves, as well as the effluent from the column carrying excess heat that is not recovered by heat exchangers. These are prevailing issues worldwide, but particularly appropriate to the Scottish whisky process considering the batch nature of processes and atempering of each batch between respective regions of the process, which leads to implications of any advances in capture of heat being utilised at a variety of points of the plant through the journey of whisky production. [10]

One of the GI indication factors for Scottish distilleries is the requirement to use pot-still distillation techniques, thus a non-continuous process, with the setup of a column is shown in Figure 4. It is desirable for large scale processes to maintain operation through continuous processes, but part of the beauty of the batch process whisky production is maintenance of attention to important details such as cut-point of when the initial feints from distillation are discarded and collection of the main spirit begins, albeit hindering overall volumes of whisky production when compared to continuous distillation. [7]

3.2 Existing systems for heat integration

Whisky distilleries recognise the potential for adaption and monetary incentive with heat recovery. Bruichladdich Distillery harness waste heat capacity to heat a visitor centre, meeting rooms and halls adjacent to the distillery with a simple 750L tank and a saving of £7333 per year for heating. This saving also rendered two oil-burning boilers surplus, and had significant savings of carbon dioxide emissions [11]. Various commercial entities which specialise in heat capture have targeted distilleries due to the inherent presence of heat for utilisation. With promised payback times of 2-3 years, the initial investment is a lucrative prospect and one which has sound environmentally responsible grounding. [12]

There also exists growing governmental incentive to maximise heat recovery. Allardyce et al. investigated the feasibility of implementation of the Renewable Heat Incentive which allows generation of renewable energy by utilising waste heat. The heat integration systems utilised in distilleries such as the Balmenach facility in Speyside which utilises steam generation to produce energy. The feasibility of such projects are assisted by government tariffs in place, which reduced the payoff time for such investment to as little as 4.6 years, whilst reducing carbon dioxide emissions significantly though holds limitations in applicability at ultra-low heat level. [13]

At Tamdhu Distillery in Speyside, a heat integration system is utilised with heat exchangers recovering heat from cooling the distillation column, with process water drawn from the adjacent Knockando Burn. In conversation with Sandy McIntyre, Distillery Manager at Tamdhu, their focus is more on meeting SEPA demands for biological oxygen demand (BOD) and chemical oxygen demand (COD) [40], as well as other minimising other pollutants present rather than maximising potential heat recovered. McIntyre describes the heat integration process as, “This water is effectively used once only, and is drawn from the burn and then released back into it albeit slightly warmer.” [9] As a consequence of the cooling water utilised in the condenser heating up following basic thermodynamic and heat transfer principles, Tamdhu employ techniques to recover some of the heat, now carried by process water. They utilise the heat in this stream to preheat other liquids across the facility in heat exchangers, which also serves to re-cool the process water before release back into Knockando Burn. One significant consideration with the process water is that it only flows through pipes, heat exchangers and intermediate tanks, thus requiring no further treatment prior to discharge, and net volume of water drawn from the burn for cooling is discharged back to the burn after use. For some smaller distilleries, the operational cost saved by recovering more of the heat dispelled by process water is outweighed by the significant capital cost of investment to maximise heat recovery utilising water treatment units.

Efficient heat exchange processes and the practicality of reuse of waste heat including heat integration of distillation columns and vapour recompression offer significant potential for the future of the industry. Within the Scotch whisky industry, the regulatory body for environmental protection and regulation of emissions is SEPA. To fall within the SEPA ‘de Minimis’ for heat regulations, the temperature of water being dispelled by a distillery must be below 20 °C and less than 5 m^3/day [14]. Given medium capacity distilleries such as Tamdhu Distillery use in the region of 3300 m^3/day of cooling water in full capacity operation, so meeting ‘de Minimis’ is clearly not feasible [15]. Due to the nature of usage of process water in the distillery, during normal operation there are not any concerns with increased BOD or COD unless contaminants are introduced, as the water is utilised solely for heating or cooling duty. Good practice, regular maintenance and inspection of streams for contaminants remains essential. The ease of daily operation when not requiring consideration of complex regulatory standards on for the abatement of compounds such as NO_x or SO_x on wastewater emission streams is desirable, and there exist various solutions which avoid pollutants to utilise the heat responsibly. District heating, where the water stream would carry waste heat into a centralised heating system for local communities through a system of insulated pipework [16] [17], would be particularly suitable for the small, isolated communities surrounding distilleries in the north of Scotland, albeit requiring a significant investment cost to implement initially, the payback would be covered by local residents in a community scheme. Particular successes of such heating systems are evident at new distilleries such as grain whisky producer North British Distillery in Edinburgh, and adjacent Tynecastle High School, where heat is captured at the distillery using 1.5 MW heat exchangers and transferred to the schools heating system at 85 °C. For an initial investment of £45,000 and an annual reduction of the schools carbon dioxide emissions by 500 tonnes per year, the project is widely lauded as successful and achieved excellent status from sustainability assessment organisation BREEAM [19].

The ‘Energy from Waste’ scheme by SEPA to promote the use of combustible waste, such as spent wash, could be used to provide heating capacity on site and suggests water around 40 °C to be generated, but in general, SEPA suggests that for wider use, heat must be over 60 °C for utilisation outside the distillery [20]. More likely for distilleries is the potential for anaerobic digestion systems, and various resources delve into greater detail such as the investigation by Allardyce et al. into the case study of Balmenach Distillery. An example of a Sankey diagram is shown for Balmenach Distillery in Figure 5, where a well-optimised process with the opportunity for investment in an anaerobic digestion unit is explored [13]. Due to the proprietary nature of data in the whisky industry, the ability to construct Sankey diagrams mapping energy streams is unique to every distillery and difficult to obtain for maintenance of fiscal efficacy. The opportunities for each distillery is wholly dependent on individual setup for capacity and of monetary budgets for investment opportunity, as such to judge the opportunity for heat recovery is unique to each and every distillery. A significant advancement currently is the aforementioned anaerobic digestion units which synthesise biogas from spent streams of the distillery, providing alternate uses for spent streams which are usually utilised by local farming for crop fertiliser.

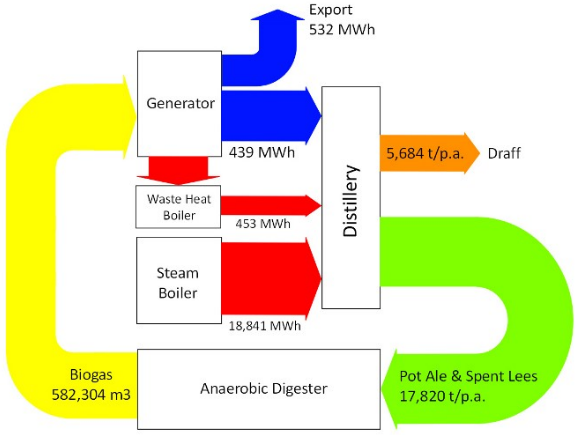

Figure 5: Balmenach Whisky Distillery Energy Sankey [13], [21]

4. Energy water nexus

Water is a crucial consideration in the distillation industry and the availability of both production and process water is a major consideration for each respective distillery. Within the whisky industry, the tendency of dispelling ultra-low grade waste heat, at temperatures lower than 80 °C, is generally rare without heat integration for basic utilisation of the heat, but there is still large amounts of heat dispelled to ambient or surrounding sources without utilisation of energy carried by water streams. The energy-water nexus describes the co-location of heat and water, and summarises the challenges to separate one from the other. The intertwined usage of both can be seen in the widespread usage of water requirement for development and delivery of energy, and energy usage for delivery, treatment and distribution of water [22]. At present, the nexus does not prove to be a significant concern within the distillery industry, but the potential of future water scarcity dictates a necessity to understand available methods to capitalise on recovery of waste heat and water, as well as demonstrate responsible utilisation of resources to ensure a favourable global perspective of the Scottish whisky industry and thus a more marketable product [23]. A critical consideration for the distillation industry is to preserve the traditions of the trade, whilst also implementing responsible, economical and environmentally-responsible methods.

The existence of the energy-water nexus is a pressing concern for future generations. The trend of significant urbanisation coupled with a growing global population [6] dictates that there must be techniques utilised for responsible usage of industrial resources, including implementation of techniques to minimise wasted energy through optimisation techniques to control the ‘nexus’. J. Dai et al. evaluate the extent of current research into the nexus, with studies on a variety of geographical scales as well as thorough analysis of models to describe the nexus. The interlinkages between energy for water systems and water for energy systems precisely describes the prospective methods for exploitation and succinctly summarises wider areas for targeting, with city-level ‘urban nexus conceptual frameworks’ including hydropower generation utilising waste heat in water streams [24]. Utilisation of the WEAP-LEAP integrated modelling system can be used to forecast demand and supply of water for industrial usage across specific areas such as the Scottish Highlands, and can be useful for informing future decisions on implementation of energy-systems such as the anaerobic digestion system being widely introduced across Scotland – most recently at Scotland largest beer manufacturer, Tennant’s Wellpark brewery in Glasgow. [25]

The tight interdependence of water, food and energy is particularly evident in ethanol production, as evaluated by M. Bazilian et al. A succinct summary can be provided by evaluation of M. Bazilian’s ‘Schematic of Ethanol production and energy/water/food interactions’ via IAEA (International Atomic Energy Agency) from 2009, demonstrating the difficulty in defining the nexus due to complex interdependence of various factors including initial resources, primary and secondary operations, transport and finally utilisation. Greater understanding of such a complex system can be utilised to develop parameters in development of a wider model for the overall nexus when applied to Scottish distilleries. Bazilian holds the opinion that coherent analysis considering interdependence of factors is a necessary approach, and when considering factors in isolation, there are significant penalties [26]. Models such as the BEWM model developed by Zhang et al. developed a tiered decision making process utilising fuzzy logic to help better substantiate areas where clear considerations are not available [27]. At the time of writing, the BEWM model, nor any similar alternatives, has not been applied to any other industrial areas aside from power plants. Distilleries require similarly large cooling water demands, with slightly lower cooling duty requirements, thus presenting a logical ‘next step’ to apply wider models to and maximise recovery of waste heat.

Future outlooks into the nexus with relevance to the Scottish alcohol industry include targeted and specific evaluation of individual processes. Examples of such optimisation could include the optimisation of hydrodynamic efficiency of the overall water flow through distilleries to minimise NPSH required; thus minimise pumping duty or utilising the expulsive flow of water to power turbines used for the milling phase of a continuous whisky manufacturing process. Thorough analysis of either demand specific research applied to individual distilleries.

Almost all available literature on the nexus evaluated was based upon areas with great concern for water scarcity, in a manner which the Scottish climate does not suffer. Although water and energy is abundant currently, the potential for large scale distilleries to develop or purchase complex models to forecast water availability and maximise funding to energy recovery, despite initial CapEx considerations, could cement Scotland's distilleries as an industry leader in worldwide environmental attitude, as well as a bastion for traditional, time honoured practices.

4.1 Quantifying impact of existing solutions

To circumvent the nexus is a multifaceted problem. In a similar manner to the shift from reliance on GHG production of energy, the development of alternative methods requires time, extensive trials and investment. G McBoyle et al. evaluated the valuable potential of 'green tokens' and the belief that the Scottish distillery tourism industry has grown in popularity with the help of a responsible industry as well as the lure of world class alcohol [28]. The visitor centres at whisky distilleries present an image of responsibility and respect for the environment, which only proves to increase the societal esteem in return. Disparity amongst different players within the industry would create inconsistency in the global image of Scotch whisky, as such a coherent approach to environmentalism is beneficial for all players. McBoyle later mentions that one of the major factors of consideration in Scottish distilleries is the surplus heat. Generated from the cooling process, the traditional process for utilisation of this heat it to allow the hot process water to remain stagnant in cooling ponds to dissipate heat to the surrounding environment before being re-introduced to local water sources, and this acclimation process is assisted by the 'rigours of Scottish weather'. McBoyle summarises some of the creative utilisation for such warm water previously by distilleries, for various spurious side-projects such as raising young eels at Tomatin Distillery, crayfish rearing at Glenfarclas and tomato plant growth at Glen Garioch. Across these three projects at three different distilleries, success was limited with the downtime between batches and technical availability of sufficient technology to utilise the heat. Perhaps a more widely accepted method of re-purposing the surplus heat is to focus on utility in minimising input of heat by heat integration using recovery condensers, however the characterisation of unique projects allows significant community involvement and development of local economies.

Venkatesh, G. et al mention that minor incremental improvements to existing industrial practice and infrastructure can develop sustained GHG emission reduction, and ethical objectives could become intertwined with profitable practices. The existence of a water-energy nexus implicitly implies a co-reliance on carbon with the current utilisation of fossil fuel based energy production, and thus a GHG emissions cost for the wider alcohol industry [29]. It is precisely due to this carbon dioxide cost that the whisky industry were fast to convert to renewable power sources [9] and the future implementation of progressive technology will see further reduction of such emissions. Combined heat and power generation on-site at distilleries as well as anaerobic digestion systems are steps that distilleries are taking to become self-sufficient in terms of power usage, and are particularly suitable for remote, isolated facilities with limited grid access.

4.1.1 Developmental techniques to exploit ultralow heat emission

Garimella et al explored the feasibility and design of regeneration of power when utilising gaseous streams at 120 °C. The gaseous stream was utilised in an absorption cycle to generate both hot and cold water, and focused on the feasibility of industrial exploitation of gaseous exhaust streams at low temperatures [30]. Garimella discusses the various styles of applicable cycles, like single-effect cycles, multiple-effect cycles and half-effect cycles. The only realistic option for low-grade heat utilisation is single-effect, with the expense of half-effect cycles leading to reduced feasibility despite suitability for low-grade heat, and multiple-effect requiring greater heat sources. Significant benefits explored include the increase of overall efficiency and thus decreased GHG emissions as well as help processes meet ever-increasing environmental standards. Albeit slightly higher than the temperature range previously quoted, distillery waste water at 80 °C can be forced into vapour phase by operating under vacuum conditions, or any pressure less than 0.467 atm and a reduced temperature driving force across the absorber model, this could be countered by increasing residence time in the exchanger to maximise heat utility or increase the surface area exchanger. Otherwise, the waste water could remain in liquid phase and thus possess a lower overall heat transfer coefficient, so cannot perform the same heating duty over the same exchanger and again, would require greater heat transfer area for the same duty.

Perhaps the greatest advancement available to the distillery industry would be the widespread introduction of heat pump technology utilised to capture low grade heat. Currently technology is allowing greater utilisation of low grade temperatures such as open-loop water source heat pumps, which utilises a refrigerant to transfer heat from water for use in other applications, by utilising the water to vaporise a liquid refrigerant, which is then compressed to increase its temperature and condensed over a heat exchanger. Current coefficients of performance are in the region of 4-6 and are being implemented across Scotland such as in the River Clyde in Glasgow [36], and it seems only a matter of time before such heat pumps can capture heat at a slightly higher temperature than currently exploited. Such practices would be ideal for process water streams being reintroduced to their source after extensive heat integration, being below a temperature feasible for preheating though still carrying excess heat; water source heat pumps provide the ideal mechanism for utilisation of such low grade waste heat.

5. Waste heat emission

5.1 Process water analysis of Scottish Malt Whisky Industry

To determine some of the annual totals for the Scottish whisky distillery industry, data was collected from a variety of sources. Firstly the Scottish Whisky Association annual report gave annual production volumes of whisky produced in Scotland from 2000 – 2015 [37]. There is an inherent disparity between production volume and sales volume due to the minimum of 3 years delay caused by GI defined ageing process. As such, sales volume represents the production volume manufactured with a delay of between 3 and 20 years ago. The trend of reducing volumes of whisky is not considered for the purposes of this investigation, as it involves geopolitical factors such as the closure of Jonny Walker production by Diageo in Kilmarnock. [35]

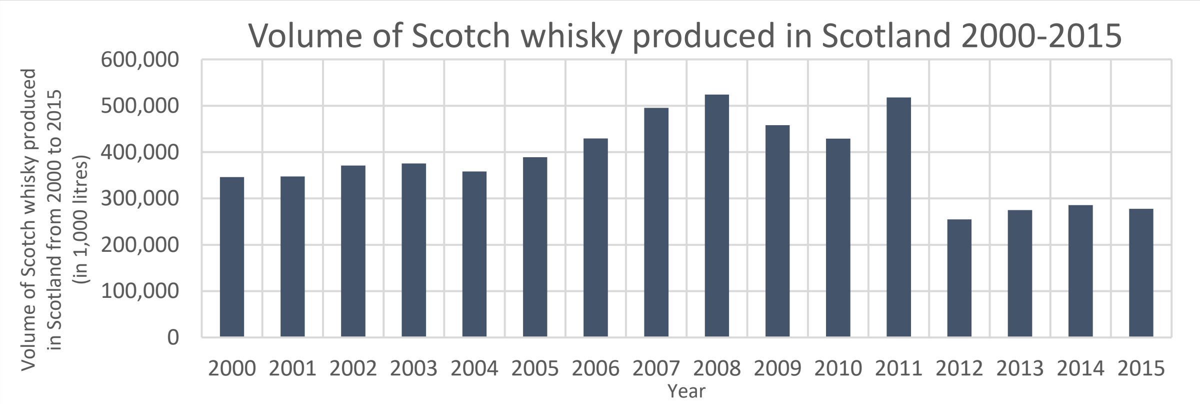

Figure 6: Graph of Volume of Scotch Whisky production, 2000-2015. [37]

The average total volume of whisky produced per year between 2000 and 2015 was 383,306,875 L.

Meadows et al. investigated some of the associated energy and process water requirements per litre of whisky manufactured across a sample of 8 Scottish distilleries [33]. To achieve the total volume of process water utilised across the whisky distillation industry, the volume of process water per litre of whisky produced was collected from Meadows et al., and simply evaluated as described in equation 1. Note, Meadows et al. refers to process water as 'production water.' The value of 296 L of cooling water per litre of whisky produced is used.

$$Process\ water\ volume = Process\ water\ per\ litre\ of\ whisky\ produced\ \times\ litres\ of\ whiskey\ produced$$

Equation 1: Process water volume from process water intensity

$$Process\ water\ volume = 296\frac{L}{L} \times 383306875\ \frac{L}{yr}$$

$$Process\ water\ volume = 113{,}458{,}835{,}000\ \frac{L}{yr}$$

This gave an overall volume of process water as 1.135×10^8 m^3/yr across Scotland.
A particularly interesting finding is that Meadows et al. reaches no conclusions on correlations between distillery capacity and water usage, hypothesising the availability of water for no fiscal charge gives rise to non-conservative usage of cooling water. This was reinforced by McIntyre of Tamdhu [9] confirming the vast availability of seemingly endless cooling water from local sources enforces little pressure for distilleries to adapt for optimised efficiency in cooling water usage.

5.2 Energy Intensity analysis of Scottish Malt Whisky Industry

Meadows et al. also evaluates the total energy usage of a typical distillery per litre of whisky produced, with the average value found to be 8.83 kWh per litre of whisky produced. The total energy utilised by the whisky industry can thus be found by Equation 2.

$$Annual\ Energy\ usage = Energy\ intensity\ per\ litre\ of\ whisky\ produced\ \times\ litres\ of\ whisky\ produced$$

Equation 2: Annual energy usage from energy intensity

$$Annual\ Energy\ usage = 8.83\frac{kWh}{L} \times 383306875\frac{L}{yr}$$

$$Annual\ Energy\ usage = 3{,}384{,}599{,}706\frac{kWh}{yr}$$

This gave an overall energy usage of 3.384 TWh/yr across Scotland each year. This energy intensity does not account for the facility requirements of each distillery, only the associated energy costs of the process for producing whisky. Meadows et al. performs further analysis on the basis of energy usage and associated carbon cost, which is provides interesting perspective to sustainable energy sources. Findings were in line with other estimates provided by Xodus Group [34] leading to reasonable confidence in the figures quoted by Meadows and thus a representative sample was selected.

5.3 Analysis of energy losses throughout whisky manufacturing process

5.3.1 Heating and Cooling Duty required between processes

A simple analysis of the energy requirements through the process can be conducted, subject to an elementary heat balance from thermodynamic principles.

$$\dot{Q}_{Overall} = \dot{m}\ C_p \Delta T$$

Equation 3: Heat transfer equation

$\dot{Q}_{Overall}$ = overall rate of heat transfer, W.
$\dot{m}$ = mass flow of liquid, kg/hr.
C_p = specific heat capacity of respective component, kJ/(kg.K).
ΔT = temperature difference, K.

$$\dot{Q}_{Overall} = \left(\dot{m}_{ethanol}C_{p,ethanol} + \dot{m}_{water}C_{p,water}\right) \times (\Delta T)$$

Given between each phase of the process, each mixture is brought to atemper from 80 °C to 20 °C [7] and for a known production volume per distillation batch, the overall heat required to bring the mixture to temperature in the still can be found, subject to a total whisky volume per year of 383306875 L/yr. Note 80 °C lies between the boiling points of water and ethanol at standard atmospheric pressure, with data utilising shown in the appendix.

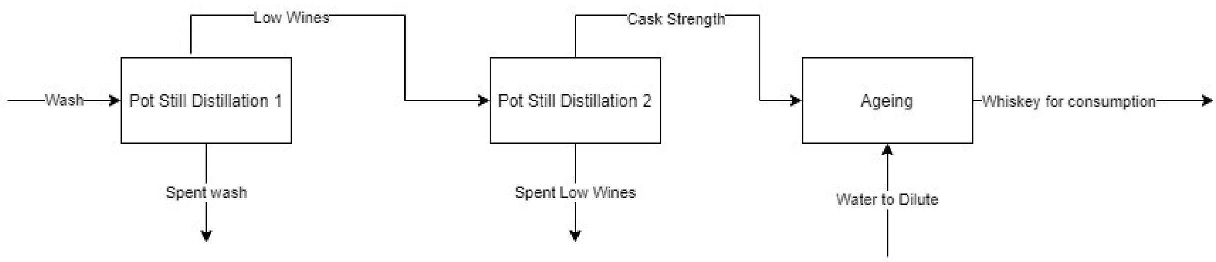

Figure 7: Simplified flow-diagram of distillation process

Utilising a simplistic model as demonstrated in Figure 7, and evaluating as a two component mixture throughout of ethanol and water for the given mass flows and fractions in Table 1, with information on ethanol volumetric fraction from Difford [8], the following table could be deduced, showing across Scotland the volumetric flows at each stage. To model the duty from shell-and-tube condensers would require perhaps overly specified systems with a vast amount of assumption upon the pressure and temperature of a vapour consisting ethanol and water of unknown composition, but a basic heat analysis can be performed for the initial preheating of the mixture into each still.

Table 1: Volumetric Flows from distillation process

	Volumetric Flowrate ($m^3\ hr^{-1}$)	**Volume fraction Ethanol**	**Volume Fraction water**
Wash	318.9	0.07	0.93
Spent Wash	22.3	0.01	0.99
Low Wines	86.7	0.255	0.745
Spent Low Wines	22.1	0.01	0.99
Cask Strength	31.3	0.7	0.3
Whisky for consumption	43.8	0.5	0.5

To evaluate the mass flow from each stream, the volumetric flows and volumetric fractions were converted to mass flows using density of each component at 50 °C. The capacity was then found using heat capacity at 50 °C and detailed in Table 2 below.

Table 2: Mass flow and corresponding capacity of streams

	Mass Flow Ethanol (Tonnes hr^{-1})	**Mass Flow Water (Tonnes hr^{-1})**	**Capacity ($kW\ K^{-1}$)**
Wash	17.0	293.0	354.6
Spent Wash	0.2	21.8	25.5
Low Wines	16.9	63.8	87.6
Spent Low Wines	0.2	21.6	25.3
Cask Strength	16.7	9.3	24.0
Whisky for consumption	16.7	21.6	38.4

Assuming between each distillation, the exiting product stream is atempered to 20 °C and preheated to 80 °C on entry to the subsequent distillation. This leads to a given heating and cooling duty across different areas of the process, and opportunities for heat capture using heat exchangers. These duties are summarised in Table 3 below.

Table 3: Duty required for each stream

	Operation	**Duty (kW)**
Wash	Heating	21273.7
Spent Wash	Cooling	1532.9
Low Wines	Heating	5257.5
Low Wines	Cooling	5257.5
Spent Low Wines	Cooling	1517.6
Cask Strength	Cooling	1441.6

Thus, the overall duties for heating and cooling of the whisky process in Scotland is given in Table 4.

Table 4: Overall duties for heating and cooling of the whisky process in Scotland

Overall Heating Duty	26531.3 kW
Overall Cooling Duty	9749.6 kW

Applying simple thermodynamic principles, there is an energy requirement assuming perfect heat recovery from hot and cold streams of 16.782 kW, which equates to a theoretical ideal minimum of 147 GWh lost across Scotland each year.

5.3.2 Analysis of heat losses by the pot still

Utilising simple heat transfer principles and making various assumptions, it is possible to evaluate the heat required to maintain the temperature of the pot-still, subject to constant conductive heat loss governed by Fourier's Law.

Equating the losses across the surface of the pot still column by using Equation 4, which considers the shellside fluid, copper and external air.

$$Q = UA\theta_{LM}$$

Equation 4: Heat transfer equation
Q = overall heat transfer, J.
U = overall heat transfer coefficient, W/(m^2.K)
A = heat transfer surface area, m^2.
θ_{LM} = logarithmic mean temperature difference, K.

The overall heat transfer coefficient, U, was found using Equation 5.

$$\frac{1}{UA} = \frac{1}{A_i h_i} + \frac{\partial}{A\,\lambda} + \frac{1}{A_o h_o}$$

Equation 5: Overall heat transfer coefficient
U = overall heat transfer coefficient, W/(m^2.K).
A = heat transfer surface area, m^2.
h_i = internal convective heat transfer coefficient, W/(m^2.K).
∂ = thickness of the copper wall, m.
λ = thermal conductivity of the copper wall, W/(m.K).
h_o = external convective heat transfer coefficient, W/(m^2.K).

Approximating the shape of a pot-still column to a spherical base with a cylindrical top, the heat loss can be found by the summation of the losses through each section. Assuming dimensions for the sphere of thickness of 16 mm, outer diameter of 2 m, and cylindrical dimensions of thickness of 10 mm, outer diameter of around 1 m, and height of 3 m with pure copper construction [38] maintained at an inner temperature of 80 °C for both distillations, and ambient air 15 °C outside the still, the heat loss was found. Assuming the spherical region is filled with an ethanol water mixture and the cylindrical region is unoccupied by the water ethanol mixture.

$$\dot{Q}_{loss,\ cylinder} = 9.05\ kJ$$
$$\dot{Q}_{loss,\ sphere} = 23.2\ kJ$$
$$\dot{Q}_{overall} = 32.2\ kJ$$

The number of distillations performed per year can be obtained using Equation 6.

$$Number\ of\ Distillations = \frac{volumetric\ flow\ of\ wash + volumetric\ flow\ of\ low\ wines}{volume\ of\ a\ single\ still}$$

Equation 6: Number of distillations per year

$$Number\ of\ Distillations\ per\ year = \frac{3552670.683\,\frac{m^3}{yr}}{6.253817297\ m^3}$$

$$Number\ of\ Distillations\ per\ year = 568081$$

The annual duty lost per year from heat losses by the still can thus be found, assuming each distillation lasts 4 hours, as 73.2 GWh per year. This correlates directly to the amount of heat required to maintain the temperature of the still in excess of heating duty to negate the heat losses to ambient surrounding. The recovery of this heat is not feasible given that the stills are not insulated to protect the aesthetic beauty, and the financial benefit of tourism likely outweighs the minimal benefit of heat capture by insulation.

The losses by ambient and heating duty equate to around 6.5% of the total energy usage of the malt whisky sector as a whole, thus does not cause for significant concern. The remainder of the total energy usage is split across maintenance and regular operation, and to obtain a figure for the waste heat lost per year in process water streams would require assuming a temperature at discharge that is not recorded by many distilleries. [9]. As such, it can only be assumed that the industry are happy with current usage for heat integration purposes, and water is dispelled at a level below around 30 °C. For an estimate of the heat loss per year, this temperature can be used in equation 3, with average ambient water temperature of 15 °C [39] and the process water volume found in Section 5.1.

$$\dot{Q}_{waste\ heat\ in\ water\ streams} = 23746142637\,\frac{kJ}{yr}$$

Given such heat loss scales to 23.7 GWh per year, equivalent to 0.7% of the total energy usage, the waste heat in water streams lost is negligible to the overall malt whisky sector. The disparity between the quoted figure for power consumption of the malt whisky distillation industry evaluated from Meadows et al. of 3.384 TWh per year, and the values of the respective losses can be attributed in part to the assumption of perfect heat recovery from hot to cold streams as well as the heat lost through the condensers which is unaccounted for due to difficulty in assessing specific conditions for the average condenser. The majority of the energy consumption of the industry is well optimised as would be expected for a global leader in such a competitive industry.

6. Conclusion

This review has shown there are various reasons for the existence of waste heat in the distillery industry, including the process' inherent cooling requirement and current technology limiting the capture of heat. Generally, distilleries employ individual techniques to exploit waste heat, primarily to preheat streams, though there exist some unique and creative solutions to waste heat such as the involvement of community heating initiatives. Traditional methods of the whisky industry are of primary focus; occasionally atypical engineering practices are prioritised to ensure the final whisky product and the image of the distillery act as a tourist attraction. The financial benefit achieved by perfect optimisation of the process is outweighed by the fiscal benefit of worldwide reputation that precedes the Scottish whisky trade, as such methods for utilisation of waste heat must inherently respect the current practices of each distillery. The GI protection status of Scottish whisky severely inhibits widespread adaptation across the industry towards alternate distillation methods. As such, the upcoming challenge for the industry is to explore mechanisms for minimisation of waste heat whilst recognising the inherent heating cost of the process.

The most likely advancements in the distillation industry would be a more coherent outlook on community-focused initiatives to utilise heat for smaller distilleries, and larger commercial entities are likely to develop and utilise developmental technologies such as heat pumps, as well as anaerobic digestion systems and combined heat and power generation systems. Existing utilisation of renewables suggests that the whisky distillery industry would be at the forefront of the rollout of such technologies.

The future outlook of the Scottish whisky trade is dependent upon maintaining worldwide demand for the product in the face of fierce international competition. The economic success of individual whisky brands and the collective industry sector is interlinked and offers a commonality through which beneficial production practices can be deployed. The implementation of nexus modelling techniques for disentanglement of the water-energy nexus would ensure favourable recognition as trade leaders in environmentally responsible practices, as well as ensure suitable foresight of water shortage in times of climate change.

The analysis of the Scottish malt whisky sector found a total energy usage of 3.384 TWh/yr and an annual process water volume of 1.135×10^8 m^3/yr utilising data from a variety of sources. There was waste heat emission analysed across various sections of the manufacturing process, including 147 GWh per year from heating and cooling duty performed, 73.2 GWh per year from convection from the still and 23.7 GWh per year carried by process water streams back to their source.

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8. Appendices

Data utilised for the calculations in Section 5.3.1 [41].
Specific heat capacity of ethanol is detailed in Table 5.

Table 5: Specific heat capacity of ethanol

at 80 C	3.2	kJ/kg.K
at 20 C	2.51	kJ/kg.K
average at 50C	2.855	kJ/kg.K

Specific heat capacity of water is detailed in Table 6 [41].

Table 6: Specific heat capacity of water

at 80 C	4.2	kJ/kg.K
at 20 C	4.18	kJ/kg.K
average at 50C	4.19	kJ/kg.K

Respective density of water and ethanol at 50 °C is detailed in Table 7 [41].

Table 7: Density of water and ethanol at 50 °C

ethanol	763.3	kg/m^3
water	988.05	kg/m^3

The dimensions of a pot-still used in Scottish distilleries is shown in Table 8.

Table 8: Dimensions of a pot-still

Spherical section	Outer diameter	2	m
	thickness	16	mm
Cylindrical section	Outer diameter	1	m
	Thickness	10	mm
	length	3	m

Heat transfer data, utilised for equation 5, is detailed in table 9. [41]

Table 9: Heat transfer data

Convective heat transfer coefficient air	50	W/(m^2.K).
Convective heat transfer coefficient water	1000	W/(m^2.K).
Convective heat transfer coefficient ethanol	1000	W/(m^2.K).
Thermal conductivity of copper	395	W/(m.K).