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Research article

Heat recovery and water reuse in micro-distilleries improves eco-efficiency of alcohol production

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ABSTRACT

The number of micro-scale spirit distilleries worldwide has grown considerably over the past decade. With an onus on the distillery sector to reduce its environmental impact, such as carbon emissions, opportunities for increasing energy efficiency need to be implemented. This study explores the potential environmental benefits and financial gains achievable through heat recovery from different process and by-product streams, exemplified for a Scotch whisky distillery, but transferrable to micro-distilleries worldwide.

The eco-efficiency methodology is applied, taking into account both climate change and water scarcity impacts as well as economic performance of alcohol production with and without heat recovery. A Life Cycle Assessment, focusing on climate change and water scarcity, is combined with a financial assessment considering investment costs and the present value of the savings over the 20-year service life of the heat recovery system.

The proposed heat recovery systems allow carbon emission reductions of 8–23% and water scarcity savings of 13–55% for energy and water provision for 1 L of pure alcohol (LPA). Financial savings are comparatively smaller, at 5–13%, due to discounting of the future savings – but offer a simple payback of the investment costs in under two years. The eco-efficiency of the distillery operations can be improved through all proposed heat recovery configurations, but best results are obtained when heat is recovered from mashing, distillations and by-products altogether. A sensitivity analysis confirmed that the methodology applied here delivers robust results and can help guide other micro-distilleries on whether to invest in heat recovery systems, and/or the heat recovery configuration.

Uptake should be enhanced through increased information and planning support, and in cases where the distillery offers insufficient heat and water sinks to use all pre-warmed water, opportunities to link with a heat sink outside the distillery are encouraged. A 10% reduction in heating fuel use through heat recovery has the potential to save 47 kt of CO_2 eq. or £7.4 M per annum in United Kingdom malt whisky production alone, based on current fuel types used and current prices (2021).

1. Introduction

Reducing resource consumption and greenhouse gas (GHG) emissions has become a focus for food and drink companies targeting environmentally sustainable production. Food and beverage production are among the most water- and energy-intensive and consuming industrial subsectors (Bromley-Challenor et al., 2013; Compton et al., 2018; Griffin et al., 2013; IEA, 2021; Kowalski et al., 2011; Sanders and Webber, 2012).

Within the United Kingdom (UK) food and drink industry, the

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distillery sector is a major consumer of heating energy and water resources (EA, 2013). Scotland has a particularly successful sector, and in 2017, 70% of all licensed water abstractions from industrial and commercial users were from distilleries, of which 80% was for cooling (SEPA, 2019). Although there is a commitment for more sustainable production in the sector, with the Scottish Whisky Association (SWA) aiming at net zero carbon emissions by 2045, in 2018 about 72% of primary energy was still met by fossil resources (SWA, 2020), with a reduction of only 3% between 2008 and 2016 (Sibille, 2020). Heating demand is responsible for over 80% of the energy demand, with the remainder electricity. The main energy source was natural gas, followed by fossil oils (Sibille, 2020).

The SWA alone reports 134 operating Scotch whisky distillery members (SWA, 2021), but the number of enterprises involved in "distilling, rectifying and blending of spirits", including also gin, vodka and other spirit producers across Scotland, England, Wales and Northern Ireland amounted to 475 in 2018 (O'Connor, 2018). A year later, a new distillery opened on average every week in the UK, with an increasing number of small-scale craft spirit makers (French, 2019; O'Connor, 2018). Indeed, the great majority (90%) of distilleries in the UK can be classified as micro-distilleries, with up to nine employees (O'Connor, 2018). With these developments, the UK follows a global trend, which, in the US for instance, has led to the formation of over 1800 craft distilleries (Fortune Business Insights, 2021).

In the water-energy-food nexus – the interplay between water and energy use in food/drink production – numerous technologies and processes are available to enhance water and/or energy efficiency, depending on the specific goods produced and existing process configurations. With the combination of simultaneous heating and cooling requirements, distilleries are ideal for study of the potential for heat recovery and cooling water reuse. Site visits to UK distilleries and discussions with their distillery managers revealed that the potential of heat recovery has currently only been partially realised. Heat recovery requires changes to cooling and heating processes in a distillery and hence investment in new equipment. While the environmental benefits of a process change might be clear, financial viability must also be considered.

The eco-efficiency concept tries to facilitate decision-making where environmental and economic interests might compete, by combining environmental and economic indicators (Huppes and Ishikawa, 2007). According to ISO 14045 (ISO, 2012), which describes eco-efficiency assessment on a product level, eco-efficiency relates the "environmental performance of a product system to its product system value". An eco-efficiency assessment can serve as a measure to compare alternatives from an environmental and economic perspective, identify trade-offs between environmental and economic performance, and ultimately be a tool to enhance sustainable growth; decoupling negative anthropogenic impacts on the environment from economic development (Caiado et al., 2017; UN-ESCAP, 2009). Eco-efficiency assessments can be applied from micro to macro level (Caiado et al., 2017; Huppes and Ishikawa, 2007): for a process, a product, a service (Faragò et al., 2019), a business, a sector (Konstantas et al., 2020), a geographic region (Gómez-Calvet et al., 2016) and in the public or private sector. Similarly, a range of eco-efficiency methodologies has been developed, as the ISO norm leaves a range of methodological choices to the practitioner (see Section 2.3).

In terms of sustainable water management in businesses, previous eco-efficiency studies have looked at processes in the sugar cane industry (Ingaramo et al., 2009), desalination in oil refineries (Ronquim et al., 2020), or processes in the paper and pulp industry (Yu et al., 2016), amongst others. The EcoWater research project has developed a web-based tool for improving the eco-efficiency through innovative technologies in water use systems involving several stakeholders from water supply, use and treatment, including case studies from the dairy, automotive or textile industry (Angelis-Dimakis et al., 2016; Arampatzis et al., 2016). Skrydstrup et al. (2020) have explored eco-efficiency implications of decentralised wastewater treatment and reuse in a Danish dairy.

Despite the large and rapidly growing number of (micro-) distilleries, the authors are not aware of scientific literature covering the technical potential of heat recovery in a spirit distillery nor an assessment of the associated environmental and economic aspects.

The goals of this study were therefore to:

- showcase the life-cycle environmental benefits of heat recovery in a micro-distillery and subsequently assess climate change, water scarcity and economic benefits and/or trade-offs through heat recovery through an eco-efficiency assessment
- develop and demonstrate the application of an eco-efficiency framework suitable for decision-making focussed on heat recovery in distilleries
- offer practical guidance to distilleries in heat and water reuse aspects.

The proposed heat recovery system developed offers a straightforward design, requiring minimum process changes and investment, suitable for financially constrained micro-distilleries. The study uses Life Cycle Assessment (LCA) to explore its environmental impacts and benefits in 16 impact categories and takes climate change and water scarcity impacts forward to include in an eco-efficiency analysis. The LCA includes the manufacture of heat recovery equipment, as previous studies have detected possible environmental trade-offs through infrastructure requirements in energy or water efficiency projects (Blom et al., 2010; Schestak et al., 2020). The economic assessment looks at the costs for energy and water use for alcohol production, considering – in the case of heat recovery – capital investment and operational cost savings, the latter as present value (PV), i.e. discounted cash flows. Primary data for the case study were provided by Arbikie distillery, established in 2014, and located on the east coast of Scotland (Arbikie, 2021). The distillery was chosen due to excellent data availability and its good representativeness in terms of the specific energy consumption of malt whisky distilleries (section 2.2.1). Results are therefore relevant and recommendations applicable to the broader distillery sector. An extrapolation of the results estimates the national greenhouse gas and economic savings potential through heat recovery in UK distilleries.

2. Materials and methods

2.1. Hotspots of fuel and water consumption in the distillery

In the following, the three heat sources in a distillery suitable for heat recovery are described, based on production data from Arbikie distillery:

- Mashing: This is the first step in spirit making. In the case of single malt whisky, barley malt and hot water are mixed to produce a slurry with a temperature of 64 °C. At the end of mashing, the developed wort (approx. 3050 L per batch), is separated and cooled down to 18 °C for subsequent fermentation. The left over spent grain is discarded.
- Distillation: In the first distillation, the alcohol containing beer wash from the fermentation is heated up to 100 °C and gradually cooled in the condenser, yielding circa 780 L of low wines. In the second distillation, two batches of low wines, plus the undesirable fractions from the previous second distillation, are heated and condensed for further concentration and refinement of the alcohol fraction. This yields 500 L of "hearts" at approximately 70% alcohol by volume (ABV) raw spirit, which after dilution and maturation, becomes whisky. This raw spirit is regarded the final product in this study. In addition, the second distillation delivers "heads and tails" which are separated due to the presence of undesirable flavour and aroma compounds and re-enter the first distillation.

- By-products: Both distillations leave a hot by-product, which does not require cooling, but which poses another source of heat: 2270 L of pot ale from the first distillation, and 1060 L of spent lees from the second distillation.

Currently, all heating requirements are met by a steam boiler running on diesel, while cooling of wort and distillates is undertaken through an open loop cooling tower with a fan, requiring regular supplementing of water as a result of evaporation.

2.2. *Proposed heat recovery configurations and inventory*

The proposed heat recovery system design focusses on avoiding major process changes or significant investment in equipment. The cold incoming water from the borehole or mains water supply is used for cooling the wort, distillates or by-products (depending on the heat recovery configuration) during which it gets pre-warmed. The pre-warmed water is then temporarily stored in the warm water tank, and is finally used for all hot-water-consuming processes, depending on the amount available. Pre-warmed water use is prioritised to first meet mash water requirements, secondly, boiler water top-up and finally (only in configuration 1, schedule B, see Section 2.2.1) enters the existing cooling water system. The addition to the cooling water system is possible (as long as it enters the cooling tower first), as the pre-warmed water temperature in configuration 1 reaches only about 30 °C.

Three different heat recovery configurations are proposed, with the respective flows shown in Fig. 1:

- 1. Heat recovery from mashing only. The existing cooling water system is still necessary for distillation cooling.
- 2.Heat recovery from mashing and the distillations. No conventional cooling system required.
- 3. Heat recovery from mashing, distillations and the by-products pot ale and spent lees. No conventional cooling system required.

Retro-fitting of the heat recovery system requires in all configurations an additional water tank for intermediate storage of the pre-warmed water, as well as further pipework and a pump delivering the pre-warmed water to the existing process water tank. Configuration 3 requires an additional tubular heat exchanger to recover heat from by-products, while in the other cases, the existing heat exchangers are sufficient. Fig. 1 shows how the main equipment fits into the heat recovery configurations and Table 1 contains the inventory of all set-ups for the case study. Costs for the equipment are from 2019; price changes have been considered in sensitivity scenarios.

2.2.1. *Production schedules*

Arbikie has steadily increased its production volume over the years (Arbikie, 2021). A variety of spirits are produced, of which this analysis takes into account single malt whisky production. Extensively monitored production and consumption data from 2018 to 2021 allow our study to compare heat recovery potentials for different production schedules with varying baseline energy and water consumptions:

- Schedule A: 2 mashes/day for 5 days/week, 50 weeks
- Schedule B: 3 mashes/day for 5 days/week, 50 weeks

Table 2 shows an overview of the different heat recovery scenarios combining production schedules A and B as well as heat recovery configurations 1–3.

The production schedules greatly influence water and fuel consumption per litre of pure alcohol (LPA) produced (Table 2). Efficiency gains with an increased production from schedule A to B can be explained through a) shorter time periods during which the boiler is not used and left to cool down, and b) change in cooling water flow which influences cooling water temperature and evaporation. With a total energy consumption of 9.2 kWh (schedule A) and 8 kWh per LPA (schedule B), Arbikie is representative for the average energy consumption per LPA in Scottish malt whisky distilleries which is 8 kWh (Sibille, 2020). Energy and water consumption without heat recovery is referred to as the baseline case.

2.2.2. *Heat recovery estimation*

In order to calculate heat recovery potential, further parameters were recorded at the distillery. This included characteristics of the currently used cooling system such as flows, temperatures and cooling times with the existing heat exchanger for mash cooling and the heat exchangers in the distillation stills. The temperature of the incoming freshwater from the borehole was 11 °C (yearly average). As pre-warmed water is stored in the tank, overnight heat losses are considered.

Full details of the heat recovery estimation can be found in the Supplementary Material.

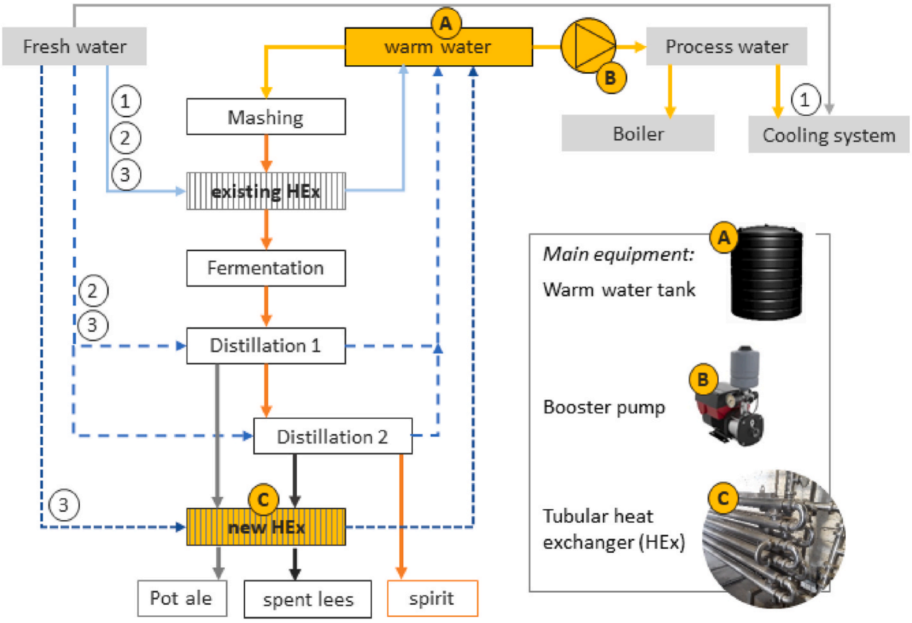

Fig. 1. Overview of process steps in the distillery and heat recovery configurations. The heat recovery configurations with the respective water flows are numbered 1 to 3. Configuration 1: Heat recovery from the wort after mashing. Configuration 2: Heat recovery from wort and both distillations. Configuration 3: Additionally, heat recovery from the by-products pot ale and spent lees. In yellow: main new equipment necessary for heat recovery. Additional pipework required not shown for simplification. Figure is not to scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Inventory of the three heat recovery configurations for the environmental and economic assessment (prices from 2019). MDPE = Mid-density polyethylene.

Configuration				1	2	3
Heat recovery				Mashing	Mashing Distillations	Mashing Distillations By-products
Equipment						
Part:	**weight**	**material**	**unit cost**	**amount**	**amount**	**amount**
water tank	430 kg	MDPE	£2490	1 piece	1 piece	1 piece
pump	28.1 kg	Various[a]	£1716	1 piece	1 piece	1 piece
pipework	4 kg/m (DN50)	Stainless steel, welded	£21/m	25 m	50 m	60 m
Tubular heat exchanger	132 kg	Stainless steel	£13,600	–	–	1 piece
Total capital costs:				£4731	£5256	£19,066

[a] See environmental assessment in Section 2.3.2 for details.

Table 2
Overview of heat recovery scenarios assessed in this study and production data in the baseline cases.

Heat recovery configuration	Production schedule A	Production schedule B
1: Mashing	A1	B1
2: Mashing and distillations	A2	B2
3: Mashing, distillations and by-products	A3	B3
Inventory for baseline cases		
Product water [L/LPA]	22	22
Boiler water [L/LPA]	27	8
Cooling water [L/LPA]	66	11
Total water [L/LPA]	115	42
Diesel [kWh/LPA]	8.0	6.8
Electricity [kWh/LPA]	1.2	1.2
Production [LPA/year]	102,000	135,000

2.3. *Eco-efficiency*

The eco-efficiency methodology is performed according to ISO 14045 (ISO, 2012), and contains the following steps: definition of goal and scope, environmental assessment, economic assessment, quantification of eco-efficiency and interpretation of results.

2.3.1. *Goal and scope*

This study aims to evaluate the climate change and water scarcity performance and economic costs of energy and water consumption – here referred to as operational footprint – in a whisky distillery, considering baseline operations and three alternative heat recovery modifications. A sensitivity analysis shows how inclusion of all 16 impact categories effects the eco-efficiency results. Additionally, the LCA results in 16 impact categories are shown for the operational footprint of alcohol production with and without heat recovery. The functional unit is the production of 1 LPA from the final distillation step. Only processes or inputs affected by heat recovery are included in the system boundaries, namely:

- Heating fuel (diesel) consumption
- Electricity consumption
- Water consumption
- In the case of heat recovery: equipment required for heat recovery, which is additional to the existing equipment of the distillery

Further inputs and outputs from whisky making such as malt are not included. Changes in electricity consumption are only considered for the fan in the cooling tower, which runs at a constant, non-adjustable speed when turned on. Pumping energy consumption in the distillery is expected not to significantly change with the introduction of heat recovery, as cooling requirements remain unchanged, too. Pumping of water from the borehole contributes less than 1% to the total distillery electricity consumption. In the case of heat recovery, the assessment includes the environmental burden of the heat recovery installations from cradle-to-grave and the investment costs. The lifetime of the heat recovery system is 20 years, which reflects the estimated service life of the equipment.

2.3.2. *Environmental assessment*

The environmental burden of energy and water use in the whisky distillery with and without heat recovery is determined via an LCA as defined in ISO 14040 (ISO, 2006) and as required by the eco-efficiency norm.

According to the eco-efficiency norm, the number and type of impact categories of the LCA to be included in the eco-efficiency assessment are defined by the practitioner. As heat recovery affects water and energy consumption, two suitable impact categories reflecting the changes in the environmental burden of the distillery operations are climate change (CC), and water scarcity. The Life cycle impact assessment follows the recommendations of the Product Environmental Footprint (PEF) Initiative by the Joint Research Centre of the European Commission (Fazio et al., 2018). According to the PEF methodology, the CC impact is calculated as Global Warming Potential (GWP100) (Fazio et al., 2018). For instance, CC characterisation factors are 34, 37 and 298 for biogenic and fossil methane and nitrous oxide, respectively (European Commission, 2019). Water use is calculated as water scarcity footprint (WSF) using the AWARE (Available WAter REmaining) methodology (Boulay et al., 2018). For the foreground water consumption, i.e. water consumed by the distillery, the annual, Arbikie watershed specific AWARE characterisation factor (CF) of 1.1 m^3 world eq./m^3 for non-agricultural water use is applied, which is available at the Water Use in Life Cycle Assessment (WULCA) group website (WULCA, 2021). Background WSF calculations use relevant annual country- and sector-average CFs as is the default procedure according to the PEF methodology and as available in the SimaPro software (Fazio et al., 2018; PRé Sustainability, 2020). The inclusion of all PEF impact categories beyond climate change and water scarcity into the eco-efficiency assessment is considered in a sensitivity analysis (see 2.4). The LCA follows the attributional approach and was modelled using SimaPro software with the EF 3.0 method (PRé Sustainability, 2020) and background datasets from Ecoinvent 3.6 database released in 2019 (Wernet et al., 2016).

2.3.2.1. *Energy and water consumption.*

Diesel serves as heating fuel in the distillery, and electricity is UK average grid electricity, from Ecoinvent 3.6. Water is mainly provided from a borehole (86%) and the remaining share (14%) from the mains supply, which is only used infrequently as a backup. The electricity for pumping water from the borehole is included in the distillery's electricity consumption. Mains water supply considers an average UK leakage rate of 17% (DEFRA, 2008), a split between ground- and surface-water of 3:7 (Water UK, 2020) and specific electricity consumption of 0.59 kWh/m^3 (Olsson, 2015). It was modelled adjusting Ecoinvent processes to UK specific conditions.

In the case of water, there is a distinction between water use and water consumption. While water *use* includes all water abstracted and entering the distillery, water *consumption* accounts for all water entering the distillery, minus the water returning to the distillery's watershed such as water used for cleaning and the water contained in spent lees. I.e. only water contained in product, evaporated during cooling or used through the boiler counts as consumption. Water in the pot ale is considered to be consumed as well as it can be further used outside the distillery. Only the water consumed contributes to the water *scarcity* impact, but all the water used needs to be considered for embedded carbon emissions and water costs paid by the distillery.

2.3.2.2. Heat recovery installations. A list of the equipment required for the three heat recovery configurations can be found in Table 1. The inventory is based on manufacturer data and literature values. All equipment was modelled from cradle-to-grave, including transport, and applying the recycled content approach which accounts for recycling benefits and burdens at the manufacturing stage, but not at End-of-Life (EoL), i.e. EoL stage only includes the fate of the non-recycled material share (Johnson et al., 2013).

Warm water tank: The required tank is a black 20,000 L drinking water tank made from MDPE (mid-density polyethylene), manufactured in the UK through rotational moulding (Enduramaxx, 2021). Energy requirements for rotational moulding were modelled according to Kent (2018) with 0.81 kWh/kg electricity and 2.5 kWh/kg natural gas, base and process loads combined. The polymer material is complemented with 2.5% black carbon for UV resistance (Gholami et al., 2020). The tank is assumed to be fully recycled at EoL.

Pipework: Steel pipes as used in the distillery are welded pipes from austenitic stainless steel, grade 304, i.e. containing 74% iron, 18% chromium and 8% nickel. Raw material type and composition were modelled as in Johnson et al. (2008) for global stainless steel, with primary chromium originating from ferrochromium, primary nickel from ferronickel and refined nickel, and pure primary iron from directly reduced iron. Total recycled content of 70% is considered from European production, according to a study on global stainless steel material flows (Reck et al., 2010). Scrap metal treatment, such as sorting and pressing is included, but no burdens applied to the scrap itself. For manufacturing welded stainless steel pipes, hot rolling and arc welding are considered, while other manufacturing steps are represented through an average metal working process (Hashmi, 2006). The EoL recycling rate for stainless steel building and infrastructure is assumed to be 92%, with the remainder going to landfill (Reck et al., 2010).

Tubular heat exchanger: The tubular heat exchanger is made from stainless steel and was modelled the same way as pipework.

Pump: The 28 kg booster pump was modelled according to a water pump production process from the Ecoinvent database (Wernet et al., 2016), which was scaled up to reflect the weight of the pump (Grundfos, 2021). Additionally, finishing of crude metal parts from aluminium, iron, copper and stainless steel to final pump parts is considered. Stainless steel was modelled as for the pipework. At EoL, the pump is sent to a dismantling facility where 90% of the parts are sent to recycling (Psomopoulos et al., 2018). Only the metal parts are assumed to undergo recycling, with PVC going to municipal incineration.

2.3.3. Financial assessment

The ISO norm does not state how economic performance has to be determined for an eco-efficiency assessment (ISO, 2012). Here, it considers the costs for water and energy provision per LPA, without or with heat recovery, while in the latter case, the installation costs of the heat recovery system are included.

The operational costs, taken from Arbikie for the year 2019, are as follows: the diesel price is 0.045 £/kWh for agricultural diesel, grid electricity is provided at a rate of 0.14 £/kWh and the costs for water are 0.85 £/m^3 for non-domestic customers and apply to the share of water from the mains supply only. As historic and recent price developments have shown great volatility, sensitivity scenarios (see section 2.4) consider yearly price increases for heating fuel and electricity (European Commission, 2020; Taal et al., 2003).

In the baseline case without heat recovery, the financial assessment includes the current operational costs ($costs_{base}$) for diesel ($costs_{diesel}$), electricity ($costs_{elec}$) and water ($costs_{water}$) per LPA produced:

$$costs_{base} = costs_{diesel} + costs_{elec} + costs_{water} \tag{1}$$

In the heat recovery cases, the new (reduced) operational costs and the investment costs are considered. The new operational costs consist of the baseline costs minus the savings. In order to take into account for the risk and uncertainty associated with the installation of the heat recovery system, the savings are discounted by calculating their present value (PV). The concept of PV is frequently used in assessing the profitability of long-term investments, including for heat recovery (e.g. as part of net present value, NPV, calculations) (Fierro et al., 2020; Kordana et al., 2014; Lim et al., 2006; Mazur, 2018; Nemet et al., 2012; Spriet and McNabola, 2019). It takes into account that the value of money (here: the savings) changes over the lifetime of the project. Savings received in the future may not be worth as much as present money e.g. because of the risk of an investment or uncertainty about the savings made in the future. The PV can also consider that different returns are achievable if the money is invested elsewhere (Department of Resources Energy and Tourism, 2013). Future cash flows (*CF*) (savings) are therefore discounted through application of a discount rate (*r*) to determine their present value. The annual discount rate is 3.5% in accordance with UK government guidance (HM Treasury, 2020). The PV of the savings ($PV_{savings}$) is calculated as follows:

$$PV_{savings} = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \tag{2}$$

With *n* being the timeframe for the savings i.e. the service life of the heat recovery system of 20 years and *t* the specific year in which the savings are made.

The costs for energy and water use with heat recovery ($costs_{HR}$) under consideration of the new operational costs ($costs_{new}$) and investment costs ($costs_{invest}$) are calculated as follows:

$$costs_{HR} = costs_{new} + costs_{invest} \tag{3}$$

$$costs_{HR} = costs_{base} - PV_{savings} + costs_{invest} \tag{4}$$

In order to obtain $costs_{HR}$ per LPA, the costs for 20 years are divided by the amount of alcohol produced during this period.

The investment costs of the three configurations are listed in Table 1 and were obtained from invoices of the distillery and respective manufacturers. Labour costs are not included due to lack of data.

Additional to the cost calculations for the eco-efficiency assessment, this study shows the NPV (PV of savings minus investment costs) and the simple payback time of each heat recovery installation. The NPV is a useful measure to understand the maximum possible financial frame for labour costs while ensuring profitability. The simple payback time is calculated by dividing the investment costs by the yearly, undiscounted financial savings. Note that NPV and payback time are not part of the eco-efficiency score.

2.3.4. Eco-efficiency score

An eco-efficiency score is calculated as a "ratio between environmental impact and economic cost or value" (Huppes and Ishikawa, 2007). Depending on whether the focus is on either environmental improvement or production value and on whether environmental or economic performance is the numerator or denominator, four types of eco-efficiency can be distinguished (Huppes and Ishikawa, 2007). This study applies the environmental intensity approach, dividing the environmental impact by the economic performance. The environmental and financial burdens are the CC, WSF or costs of energy and water use (or consumption) in the distillery per LPA. In order to derive an eco-efficiency score where the lowest value represents the most favourable solution, driven through a low environmental impact and low costs, the inverse of the costs is used. The advantage of considering the total impact and total costs for energy and water opposed to only the savings of both through heat recovery is the ability to deal with an increase in costs (instead of savings) or environmental impacts without generating negative values, and to include the baseline operations in the comparison. This enhances the transferability of the method to other distilleries and other water or energy saving investments.

First, eco-efficiency indicators $EEI_{i,a}$ are determined for each impact category i and each alternative a, i.e. the baseline case or a heat recovery option:

$$EEI_{i,a} = \frac{impact_{i,a}}{\frac{1}{costs_a}} \tag{5}$$

As eco-efficiency indicators for different impact categories have different units, they need to be normalised in some way before they can be aggregated to a final score. Multi-criteria decision analysis provides a variety of approaches which can be used for this purpose in eco-efficiency assessments (Konstantas et al., 2020; Seppälä et al., 2002). Here, an approach is applied which scales different indicators relative to the best or worst performing alternative (Seppälä et al., 2002). With the eco-efficiency indicator defined as above, the highest (here: worst) indicator of all alternatives $EEI_{i,a,max}$ is set to 1, and the remaining indicators are scaled relative to it. Note that normalisation in the eco-efficiency sense is different from normalisation in the LCA sense. A normalised indicator $EEI_{i,a,norm}$ is calculated via:

$$EEI_{i,a,norm} = \frac{EEI_{i,a}}{EEI_{i,a,max}} \tag{6}$$

In order to derive the final eco-efficiency score EE_a of an alternative, the normalised eco-efficiency indicators of different impact categories are averaged, i.e. they are weighted equally (Konstantas et al., 2020).

$$EE_a = \frac{\sum_i^I EEI_{i,a,norm}}{I} \tag{7}$$

where I is the number of environmental impact categories included in the assessment.

2.4. Sensitivity analysis

Eighteen sensitivity scenarios are run to test parameters affecting the climate change, water scarcity and economic assessment. Three sensitivity scenarios assess how a change in heating fuel would influence the results, looking at a natural gas boiler and an electric boiler running on either grid mix electricity or purely renewable electricity. One scenario regards inclusion of all 16 PEF environmental impact categories into the eco-efficiency score, thus going beyond climate change and water scarcity impacts. The remaining scenarios consider the following: no or higher discounting (7% discount rate) of the cost savings, fuel or electricity price increases over time, different costs for water, changed investment costs, different water scarcity at the location of the distillery, and a different CC or WSF burden of the equipment. The yearly fuel and electricity price increase of 4.3% and 1.1%, respectively, is based on pre-pandemic price developments for Europe (European Commission, 2020), and therefore considers a conservative scenario compared to the recently observed energy price increases (IEA, 2022, ONS, 2022).

Full descriptions are available in the Supplementary Material (Table S5).

3. Results and discussion

3.1. Changes in energy and water use through heat recovery

Table 3 shows the absolute and relative changes of fuel and electricity consumption as well as water use per year through the proposed heat recovery configurations. Heating fuel consumption can be reduced by 10–25%, and electricity use by 11–13%, the latter in configurations 2 and 3, where no cooling tower fan is required anymore. Fuel savings in schedule B, configurations 2 and 3 (B2 and B3), are lower than in schedule A, which can be explained by the lower required boiler top-up per LPA in schedule B, which in turns means that less recovered heat is re-used.

Reduction of water use (abstraction) compared with the baseline operations depends on the specific case. The reason is that under some configurations, more water is required for cooling than can be re-used for mashing or boiler top-up. This results in water overflow – water which cannot be used in the distillery, however which can be released back to the watershed and therefore does not fall under the definition of water consumed and does not add to the water scarcity footprint according to the AWARE method. Due to the temperature of the overflow however (~60–70 °C), it would have to either sit in a tower or lagoon to allow cooling before discharge or be used for hot water purposes outside the distillery (see Section 3.2.1). This issue means that in schedule B, only configuration 1 (B1) uses less water (−12%). In the heat recovery cases A3 and B1, despite generating a considerable overflow, water use is still lower than in the baseline case, due to the high amount of cooling water required in the baseline case.

The overflow issue is also the reason why fuel savings only marginally increase between configurations 2 and 3. The increase in fuel savings here is mostly due to a higher temperature of the pre-warmed water in the third configuration, as the volume of pre-warmed water, which can be used in the distillery, is limited. Additional benefits achievable through the use of the heat embedded in the overflow are discussed in Section 3.2.1.

If this heat recovery system was realised in other distilleries, electricity savings might also be observed in configuration 1 if variable speed drive cooling fans are fitted (opposed to a single speed fan considered here). Also, different cooling water savings could occur where distilleries employ other cooling systems, such as refrigerant based cooling or once-through cooling using e.g. river water.

3.2. Environmental assessment

3.2.1. Environmental benefits

Through heat recovery, the operational carbon footprint of 1 LPA can be reduced from 2.7 to 2.1 kg CO_2 eq. in schedule A, and from 2.4 to 1.9 kg CO_2 eq. in schedule B, with configuration 3 delivering the lowest footprint in both schedules. The changed footprint through heat recovery application considers the footprint of the installation (section 3.2.2).

Savings in GHG emissions per functional unit are dominated by a reduction in fuel use and range from 8 to 23% (Fig. 2). CC results take into account that more water has to be supplied in configurations B2 and B3, but as CC burden of water provision is small compared to fuel or electricity, and as the share of mains water is only 14% of total water use, this has no significant effect on the total result.

The operational WSF per LPA produced decreases from 0.14 to up to 0.064 m^3 world eq. (schedule A) and from 0.059 to up to 0.044 m^3 world eq. (schedule B) with heat recovery, equating to a 13–55% reduction, assuming that potential overflow is released into the same catchment. Again, the WSF from the installation is taken into account. Water consumption is generally lower in heat recovery configurations 2 and 3, where no cooling tower is required. Relative savings are more significant where the baseline water consumption is higher, here schedule A. As expected, water scarcity savings predominantly reflect direct water consumption, with only marginal contributions from embedded water in

Table 3

Change in heating fuel, electricity consumption, water use, and water consumption per year in case of heat recovery compared to the baseline case. Shown for production schedule A and B, and heat recovery configurations 1 to 3. Negative changes (green cells) represent a reduced use/consumption, while positive values (red cells) show an increased use or overflow. While there are energy savings for all configurations in both schedules, water use (abstraction) when applying heat recovery is increased compared to baseline operations in B2 and B3. In configurations A3, B1, B2 and B3 an overflow of pre-warmed water is created which is not needed within the distillery. Water consumption is reduced in all heat recovery cases.

Config.	Fuel consumption [MWh/yr]	[%]	Electricity consumption [MWh/yr]	[%]	Water use (abstraction) [m^3/yr]	[%]	Water overflow [m^3/yr]	Water consumption [m^3/yr]	[%]
A1	-82	-10	0	0	-3923	-33	0	-4087	-36
A2	-159	-19	-13	-11	-6727	-57	0	-6891	-61
A3	-208	-25	-13	-11	-5321	-45	1406	-6891	-61
B1	-105	-11	0	0	-662	-12	226	-888	-18
B2	-157	-17	-20	-13	+1341	+24	2863	-1522	-31
B3	-190	-21	-20	-13	+3962	+70	5484	-1522	-31

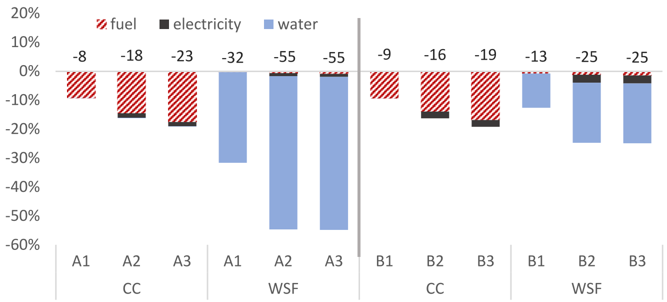

Fig. 2. Relative change in environmental impact per litre pure alcohol (1 LPA) through heat recovery compared to the baseline case, split into contributions from heating fuel, electricity and water consumption. The environmental burden of the installation is considered. Left: schedule A, right: schedule B. CC = Climate Change, WSF = Water Scarcity Footprint. Numbers above bars show total relative change of environmental impact in %.

fuel and electricity generation. Detailed results on the environmental footprint including all 16 PEF impact categories can be found in the Supplementary Material (Table S3 and Table S4) and show that the environmental footprint is reduced through heat recovery in all 16 analysed impact categories, through all heat recovery configurations and for both production schedules.

Even though this study shows that heat recovery reduces the environmental impact in all 16 analysed impact categories (Tables S3 and S4, Supplementary Material) including for cases where there is a significant overflow of pre-heated water, this issue should be the focus of future studies which explore potentials across a wider range of case studies and elaborate appropriate best practice guidelines. For a distillery which does not have underground wastewater tanks (septic tanks) such as in the case of Arbikie, and the possibility to (in the least efficient case) dispose of the water in agriculture, huge amounts of surplus water could be an issue. Table 4 shows the total yearly recoverable heat for all configurations and the share which is still embedded in the overflow, which is a considerable 62% for configuration B3. The pre-heated water could be used in a distillery's visitor centre or be fed into a district heating network for space or hot water heating in nearby businesses or homes. For example, the 62% or 213 MWh heat equal space heating requirements of almost 20 UK homes annually, considering average space heating consumption of 11 MWh (Palmer and Cooper, 2013). Carbon emission savings would amount to 42 t CO$_2$ eq. if replacing heat from a domestic gas boiler and accounting for a conservative 15% heat loss in a district heating network (Cooper et al., 2016). This would be additional to the GHG savings in the distillery which are 54 t CO$_2$ eq. in configuration B3. An expansion of the system boundaries to include overflow heat and also the water itself, could make an even stronger case for heat recovery in distilleries as it can potentially more than double the amount of useable recovered energy.

Table 4

Total heat recovered per year and share of “unused” heat in the overflow of the distillery.

	configuration	1	2	3
schedule A	total [MWh]	49	111	202
	% in overflow	*no overflow*	*no overflow*	26
schedule B	total [MWh]	76	199	344
	% in overflow	6	46	62

Not included in this study are savings from reduced chemical consumption – especially chemicals usually required for operation of the cooling tower. However, a previous study with Arbikie distillery has shown chemicals contribute only marginally to the operational footprint of alcohol production (Schestak et al., 2022).

3.2.2. *Environmental footprint of the installation*

Detailed results for CC and WSF of the heat recovery installations can be found in the Supplementary Material (Table S2). CC footprints are dominated by impacts from the MDPE tank manufacture in configurations 1 and 2, and by tank and stainless steel equipment in configuration 3. WSF results follow a similar pattern. Production of the pump, transport and disposal of the parts not going to recycling show only minor contributions.

Table 5 shows the environmental payback time for both categories, which are equal or below one year, and in the case of CC even below one

Table 5

Costs for energy and water provision for 1 L pure alcohol (LPA) with heat recovery, environmental/financial payback times in years for heat recovery configurations considering the environmental burden and financial costs of the equipment, as well as Net Present Value (NPV) for a service life of 5 and 20 years. CC = Climate Change, WSF = Water Scarcity Footprint.

Config.	Costs [£]	Payback times [years]			NPV [£]	
	per LPA	CC	WSF	Financial	5 years	20 years
A1	0.514	0.07	0.22	1.15	13,798	53,596
A2	0.475	0.04	0.14	0.54	39,052	134,216
A3	0.468	0.04	0.17	1.61	34,264	148,805
B1	0.452	0.06	0.98	1.00	16,655	62,588
B2	0.426	0.04	0.56	0.54	38,493	132,458
B3	0.425	0.04	0.65	1.76	29,895	135,051

month for all configurations. The highest observed environmental payback time of all 16 PEF impact categories was that for resource depletion of minerals and metals with about 2 years in both schedules (Supplementary Material, Table S7, Table S9).

Hence, from an environmental perspective, the adoption of heat recovery measures as proposed here should be encouraged.

3.3. Economic assessment

The baseline operational costs of £0.54/LPA (schedule A) and £0.47/LPA (schedule B) can be lowered by 5–13% through heat recovery (Table 5, Fig. 3), under consideration of the capital costs for the installations. This is predominantly due to heating fuel savings, and to a lesser extent from electricity savings. Costs for water – which are higher in schedule B2 and B3 – play a minor role, again because of the majority of water being supplied through a business owned borehole and thus incurring negligible costs. Relative financial savings are lower compared to relative energy savings, mainly due to cost savings being discounted.

Simple payback time, i.e. the number of months/years over which investment is paid back through financial savings (undiscounted), is about half a year for configuration 2, and one to two years for configurations 1 and 3, with the latter requiring another heat exchanger (Table 5). These are short payback times and in the case of Arbikie, would be suitable to a business plan favouring a payback time of under five years. As labour costs are not included in these calculations due to lack of data, the NPV is shown here as a means of estimating the financial flexibility for labour costs. As a business is likely to require a payback of much less than the 20 year service life considered here for the installations, we provide NPV results for 5 years, too (Table 5). In heat recovery configuration B3 for instance, a 5-year heat recovery project would still be financially viable even if spending additionally £30,000 on consulting or labour.

Maintenance and disposal at EoL of the heat recovery equipment are not included as there were no data available. Whether maintenance costs would change overall due to additional equipment is questionable, considering that other equipment such as the cooling tower would no longer require maintenance, at least in configurations 2 and 3. Another factor important for any retro-fit works in a distillery can be the amount of downtime required for installation, and the related loss of profit.

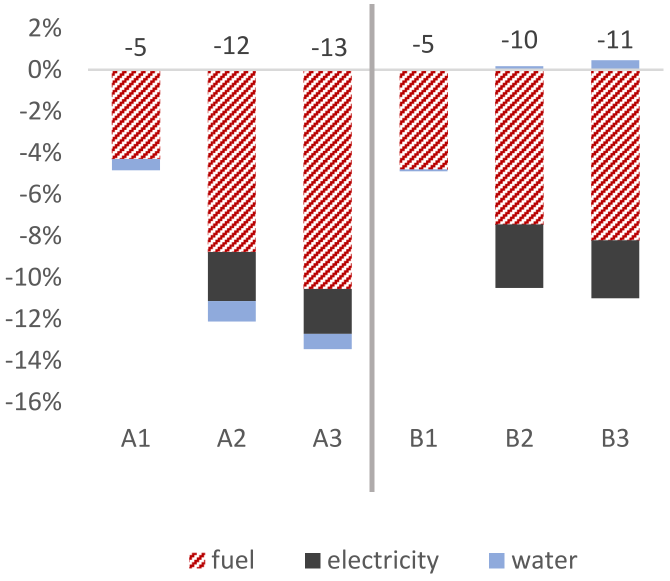

Fig. 3. Relative change in costs of fuel, electricity and water used per functional unit (1 LPA) through heat recovery (costs$_{HR}$) compared to baseline costs (costs$_{base}$). Left: Schedule A, right: schedule B. Numbers above bars show total relative change of costs in %.

If the same study was repeated across other distilleries, some differences that should be explored include:

- Change in wastewater treatment costs where distilleries dispose overflow water to a municipal wastewater treatment plant, although the water would not *require* treatment
- Change in costs due to potential additional storage of overflow water for cool down
- Changes in water supply costs where distilleries do not have their own borehole (the requirement for higher initial water abstraction could present a bottle-neck for heat recovery in distilleries with limited water availability)

3.4. Eco-efficiency

Modifications to a combination of climate change, water scarcity and economic performance through heat recovery delivers the changes in eco-efficiency indicators *EEI* presented in Fig. 4, and the overall eco-efficiency scores *EE* in Table 6. As the above results did not reveal any trade-off between environmental impacts and economic costs, it could be expected that all heat recovery related eco-efficiency indicators deliver an improvement, however, the extent differs depending on the configuration and impact categories considered. Heat recovery renders water consumption of the distillery more eco-efficient by up to 61% (schedule A) or up to 33% (schedule B) compared to baseline conditions. Eco-efficiency in CC can be improved by up to 33% (schedule A) or up to 28% (schedule B), i.e. both carbon emissions from and costs for energy use are reduced.

Eco-efficiency indicators, which are separate for each impact category, are combined to derive the final eco-efficiency score for an alternative, i.e. baseline or heat recovery configuration. As lowest eco-efficiency indicators can be obtained with heat recovery configuration 3 for both CC and WSF in both schedules, configuration 3 also achieves the best overall eco-efficiency score. Hence, under eco-efficiency considerations, heat recovery from mashing, distillation and by-product streams should be considered even if the distillery itself cannot utilise all the pre-warmed water and generates an overflow, as both water scarcity and climate change impacts are reduced along with operational expenditure. Eco-efficiency score improvements between configurations 2 and 3 are, however, marginal (1–3%) and the additional planning and installation effort might not justify this eco-efficiency improvement for a distillery from a practical perspective. As all heat recovery alternatives

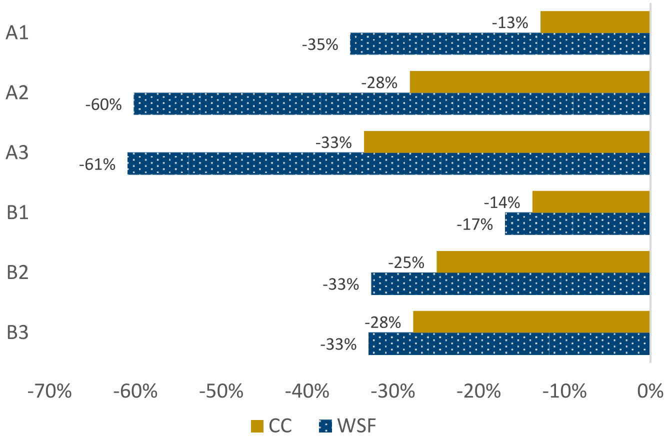

Fig. 4. Eco-efficiency indicators (EEI) for the impact categories Climate Change (CC) and Water Scarcity Footprint (WSF), calculated from the environmental impact and financial costs for energy and water use for the production of 1 LPA. EEI are shown relative to the baseline, i.e. the negative results represent an improved eco-efficiency performance where impacts and costs are reduced. Numbers on bars show the relative change of the indicators compared to baseline results.

Table 6
Eco-efficiency scores (EE) for all alternatives (baseline and heat recovery). Lowest values reflecting the best score within each schedule are marked in bold.

Configuration:	baseline	1	2	3
Schedule A	1.00	0.76	0.56	**0.53**
Schedule B	1.00	0.85	0.71	**0.70**

achieve both an improvement in environmental (considering all 16 analysed impact categories) and economic terms, recovering heat in distilleries with the proposed set-up can generally be regarded an eco-innovative practice (Levidow et al., 2016).

3.5. Sensitivity analysis

The ranking of the eco-efficiency scores remains unchanged in all sensitivity scenarios (Supplementary Material Tables S6–S9), hence the applied methodology can be regarded as delivering robust results for decision-making. Environmental and economic payback times and NPV however could be changed considerably. In the following, we describe the main changes introduced through the sensitivity cases taking schedule B as example. Generally, changes affecting the equipment result in minor changes due to the long lifetime of 20 years. If the distillery was switching to a gas boiler, CC payback time would increase, however to a maximum of a month; WSF payback would remain almost unchanged while the financial payback time would reach almost 3 years with configuration 3 due to gas being cheaper than diesel at the time of data collection for this study. This is the longest financial payback time observed amongst all sensitivity scenarios. With an electric boiler instead, financial payback would be reached after a maximum of only eight months, and the highest NPV is achieved with £200,000 to £390,000 after 20 years. Financially, no distinction is made between tariffs for the grid mix or green electricity due to unknown green electricity tariffs for business customers in the UK, and Arbikie's tariff for the green electricity scenario is adopted. However, it can be expected that financial payback would be quicker in many cases where distilleries are on green electricity tariffs. The main difference observed with the green electricity scenario is the increased CC payback time for the installation's footprint of up to four months.

If no discount rate is applied to the savings, the NPV after 20 years increases from max. £135,000 to max. 193,000 with heat recovery configuration 3. Higher discounting at a rate of 7% (Spriet and McNabola, 2019) decreases the NPV to max. £93,000.

The scenario with an increased fuel (diesel) price increases the NPV to 198,000, while an increase in electricity price changes the NPV only marginally as energy requirements are mostly met by diesel. A change in water costs does not significantly alter the financial results. A −25% change in investment costs reduces financial payback time of the most expensive configuration (3) to 1.3 years and a +25% change increases payback time to 2.2 years, respectively.

Longest WSF payback time (1.5 years) is under the assumption that water scarcity is lower than in the Arbikie watershed, as for example in the Speyside whisky production hotspot further north in Scotland, where the AWARE CF is only 0.72 instead of 1.1 m^3 eq./m^3. If the distillery was located in London with a CF of 1.8 m^3 world eq./m^3, water scarcity payback would be between 4 and 7 months. With a 25% higher WSF of the heat recovery equipment, WSF payback would increase to 1.2 years.

Consideration of all 16 PEF impact categories including additional impacts such as eutrophication, acidification, human toxicity and resource depletion, amongst others (Supplementary Material Tables S7 and S9) does not change ranking of eco-efficiency scores. Hence, focusing on climate change and water scarcity impacts for the environmental assessment has shown to be sufficient for a robust eco-efficiency assessment result in this study. However, it could pose a limitation for distilleries using different energy sources differing in their environmental impact profile from diesel and grid electricity.

3.6. Sector-wide implications

The results can be extrapolated based on figures for average energy consumption in distilleries from Sibille (2020). According to the study, a malt whisky distillery consumes on average 8 kWh per LPA, of which 83% is for heating, 76% as natural gas and the remainder as fossil oil. Assuming that a conservative estimate of 10% of heating fuel savings can be reached through heat recovery amongst malt whisky distilleries, 195 GWh of heat consumption could be saved, equating to 47 kt of CO_2 eq. per year (Wernet et al., 2016). This considers the yearly average production of malt whisky production in the UK of 294 M LPA during 2015–2019 (HMRC, 2021). Inclusion of other spirits produced yearly in the UK (382 M LPA in 2019 (HMRC, 2020)) would further increase these figures.

The savings in heating fuel would translate into yearly financial savings of £7.4 M for all malt whisky distillers in the UK. This number is based on the UK 2021 annual average prices for red diesel of 0.6564 £/L (AHDB, 2022) and for natural gas of 0.0305 £/kWh for medium-sized customers, including the climate change levy (BEIS, 2022). Considering the recently observed increase in energy prices, this is likely to be much higher in the future. The amount of heating fuel which can be saved will be greatly influenced by the current energy efficiency of a distillery which in turn will depend on the production scale, among other factors. Arbikie, with a total production capacity of 250,000 LPA/year, lies in between the distilling capacities ranging from 25,000–21 M LPA/year in Scottish malt distilleries and below the malt whisky distillery average of 2.5 M LPA/year. Therefore, extrapolated results must be interpreted with care. For this reason, we are not extrapolating results to the seven grain whisky distilleries which have a capacity of 50 M LPA/year on average (Gray, 2020). However, considering that the total number of (micro-) distilleries in the UK including all potable spirits is three times higher than the number of whisky distilleries, and in light of a growth of the spirit sector worldwide, the results of this study are highly relevant.

4. Conclusions

This is the first study to quantify the technical, climate change, water scarcity and further environmental impacts as well as economic potential for energy and water savings through heat recovery in a whisky micro-distillery, generating new insight pertinent to a growing number of such distilleries worldwide. The implications – predominantly savings – for fuel, electricity and water consumption make a strong case for installation of streamlined heat recovery systems. Heating fuel savings are estimated at 10–25%, GHG emission savings at 10–20% and water consumption savings at up to 50%. In some cases, not all pre-warmed water can be used in the distillery, generating an overflow. Use of this overflow to contribute to heat sinks outside the distillery would increase environmental savings, but was not considered here as it will be highly context specific. A trade-off of this overflow is a greater initial water abstraction requirement, though water is returned to the catchment and therefore does not contribute to water scarcity.

The environmental burden and economic costs for the heat recovery equipment do not pose a barrier to implementation, as all payback times, including those of all 16 analysed environmental impact categories as well as financial investment, are under 2 years despite considering pre-pandemic energy prices not accounting for the recently (2021–22) observed energy price rise (IEA, 2022; ONS, 2022). Similarly, the profit through heat recovery, represented through NPV, leaves enough room for consulting and/or labour costs while still allowing for financial payback.

Sensitivity analyses confirms that the eco-efficiency methodology provides a robust score to support decision-making across different heat recovery configurations. Eco-efficiency indicators in the CC and WSF category show a benefit through heat recovery in all configurations. Overall, eco-efficiency is best (lowest score) for heat recovery configuration 3, where heat is recovered from mashing, distillations and by-products. The steps and methodology of this eco-efficiency assessment can be used as a template to conduct further heat recovery assessments across micro-distilleries.

Due to a heat recovery installation being a potentially very worthwhile investment, financial incentives might not be required for the equipment. However, the data and planning effort required to obtain a robust and convincing estimate for a heat recovery project can pose a barrier to further uptake across distilleries. Funds should therefore be targeted to provide technical and administrative support to facilitate greater application of heat recovery in the sector.

Credit author statement

Isabel Schestak: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization. Jan Spriet: Methodology, Formal analysis. Kirsty Black: Investigation, Writing - review & editing. David Styles: Conceptualization, Writing - review & editing, Supervision. Maria Faragò: Methodology, Writing - review & editing. Martin Rygaard: Methodology, Writing - review & editing. A. Prysor Williams: Writing - review & editing, Supervision, Project administration, Funding acquisition.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116468.

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