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Quantifying the impact of increasing wash strength for Scotch malt whisky production: a modelling study

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Abstract

Why was the work done: High gravity fermentation (*ca* 8% ABV) is used in the production of Scotch malt whisky but the impact of increasing wash strength on fermentation and distilling has not been quantified, especially in relation to environmental and operational performance.
How was the work done: A representative scenario of a 200 hL wash at 8% ABV was used to model wash strengths of 10-14% ABV under two conditions: the same wash volume (*Condition 1*) and the same ethanol mass (*Condition 2*). All scenarios were assessed quantitatively.
What are the main findings: In *Condition 1*, increasing wash strength enhanced batch production capacity but may require a larger spirit still or multiple distillation batches. In *Condition 2*, higher wash strength reduced batch processing volumes, enabling the use of smaller vessels without compromising the capacity for ethanol production. Distilling energy dominated the total energy demand, whereas fermenter cooling energy was negligible. On the basis of a litre of pure alcohol (100% ABV) and an annual target basis, increasing wash strength from 8 to 14% ABV progressively reduced energy use and carbon footprint by 15.8-16.1%, while also reducing post-distillation discharge volumes by 55.0% in pot ale and 30.4% in spent lees.
Why is the work important: This study provides quantitative evidence of the effects of increasing wash strength (8-14% ABV) on the operational and environmental performance in Scotch malt whisky production. This supports process innovation, capacity planning, and industrial decarbonisation strategies.

Keywords

malt whisky; wash; high gravity fermentation; energy saving; water saving; cost saving; sustainability.

Introduction

Scotch whisky is a symbol of Scotland's heritage and a significant driver of its economy. In June 2025, 152 whisky distilleries were in operation across Scotland with exports in 2024 worth £5.4 billion (*https://www.scotch-whisky.org.uk/*). In line with global sustainability efforts, the industry has committed to achieving Net Zero emissions by 2045. According to the Scotch Whisky Association report on distillery sites (*https://www.scotch-whisky.org.uk/industry-insights/sustainability/climate-change/*), 88% of total emissions originated from activities at distilleries, 11% from non-distilling production sites with about 1% from offices and warehouses. However, upstream factors such as barley cultivation and transportation also need to be considered in efforts toward full decarbonisation (*https://www.fas.scot/downloads/ktif-final-report-decarbonising-scottish-malting-barley/*).

The Scotch malt whisky industry typically employs a two-pot batch distillation process, which consumes around 50-70% of total energy at a distillery and generates over 6 billion litres of liquid residues annually, including pot ale from wash distillation and spent lees from spirit distillation (White et al. 2020). Many efforts have been made towards recovering energy from the distillation process (*https://www.renewablethermal.org/piller-chivas-case-study/*), harnessing renewable energy (Kang et al. 2020), and valorising these liquid residues (Edwards et al. 2022; Duffy et al. 2023).

High gravity fermentation has shown promise in supporting sustainability targets within the brewing and distilling industry. In brewing, this involves the fermentation of stronger worts (typically 15-20°P (degrees Plato); or 1.061-1.083 (specific gravity)) to produce stronger beers (> 8% ABV (alcohol by volume)), which post fermentation are diluted to the required ABV (Stewart 2010). Although brewhouse efficiency can decrease when using a more concentrated mash (mitigated by extending with adjuncts and sugar syrups), the advantages of high gravity fermentation are to enhance productivity, reduce capital investment, and lower energy demand (Stewart 2010; Puligundla et al. 2020). It also minimises extract losses associated with the handling of weak worts. However, at the upper end of 'high gravity', there are increasing challenges to yeast stress and viability on repitching (Gibson et al. 2007), foam stability and altered flavour profile in final beers (Stewart 2010).

In the production of Scotch malt whisky, a typical wash strength of about 8% ABV is achieved through the use of high gravity fermentation. Many of the issues found in brewing are less relevant without yeast recycling and with foam stability being of little concern. Further, flavour consistency is managed through post-fermentation processing through distilling, maturation and blending. Alternatively, in a whisky context, any changes in flavour profile may be welcomed, as they can contribute to the development of novel sensory characteristics.

An increased wash strength has direct impact on fermentation and distillation. During fermentation, higher ethanol production is associated with an increased release of metabolic heat by yeast. This is up to 1065 kJ per kg of ethanol (Kelsall and Lyons 2003), and requires additional cooling capacity in fermenter to maintain optimal yeast health and activity. Moreover, increased ethanol titres have a direct implication for batch processing volumes and annual throughput, as a given production output can be achieved with fewer or smaller fermentation batches. At the distillation stage, distilling water is more energy intensive than distilling ethanol, as water has a higher specific heat capacity and latent heat of vaporisation (Smith et al. 2018). Accordingly, an increased wash strength could reduce the energy required and associated carbon footprint for distillation, including heating up, vaporisation, condensation and cooling. Further, experience from large scale fermentation plants, such as those operated by Cargill (Pothakos et al. 2018), demonstrates that operating at higher product concentrations (e.g. ethanol, or lactic acid, and 2-keto-L-gulonic acid) reduces the volume of water that must be removed downstream. This, in turn, lowers capital and operating expenditure for separation and purification which reduce overall energy demand. These principles are directly relevant to whisky production, where distillation generates large volumes of aqueous liquid residues (pot ale and spent lees). While spent lees can be treated using conventional biological effluent processes, pot ale presents a greater challenge due to its high chemical (COD) and biological oxygen demand (BOD). Accordingly, in whisky production, fermentation at elevated gravity could reduce the volume of these downstream streams, thereby reducing both the energy demand for distillation and the volume of the downstream liquid residues. This would improve the efficiency and sustainability of distillation processing, particularly for pot ale.

The impact of increasing wash strength above the usual industrial practice (about 8% ABV) on fermentation and distillation has not been quantitatively assessed. Whilst achieving more concentrated worts (> 20°P) may be subject to constraints at the mashing stage (as sugar adjuncts are not permissible), this work applies a forward looking perspective to explore the potential benefits for producers of Scotch malt whisky of increased wash strength, which will inform process innovation, capacity design and decarbonisation strategies within the industry, particularly in relation to savings of energy, water and cost.

To address this, a system boundary comprising of fermentation and two-pot distillation in Scotch malt whisky production was defined (Figure 1). An industrially representative dataset for a 200 hL wash at 8% ABV was used as a baseline, against which wash scenarios of 10-14% ABV were modelled and quantitively assessed.

Methods and materials

Industrially relelevent scenario at 8% ABV

An industrially relevant scenario was adapted from a typical Scotch malt distillery process (Buxton and Hughes 2021), where a 200 hL wash at 8% ABV was charged into a two-pot distillation system (Figure 2). This was used as a baseline for modelling scenarios at 10-14% ABV.

Modelling scenarios

Using the dataset at 8% ABV, two conditions were modelled, each with three wash strength scenarios: 10, 12 and 14% ABV.

Condition 1: The same wash volume (200 hL), representing conditions in existing distilleries where washback capacity is already defined;

Condition 2: The same ethanol mass, equivalent to 8% ABV in 200 hL, with wash volume adjusted to achieve target ethanol mass. This reflects conditions relevant to new distilleries or the expansion of distilleries.

Assumptions

a. Wash was considered as an ethanol-water mixture, with other compounds (congeners etc) having a negligible impact on the model but not negating the impact they may have on other quality parameters of new make spirit.

b. The ABV of new make spirit, pot ale and spent lees remained constant. The ABV of low wines, foreshots and feints increased by 2% for every 2% increase in the wash strength.

c. Wash or low wines were assumed to be heated from 20°C [293K] to 95°C [368K], vaporised at 95°C, and then condensed and cooled from 95°C to 20°C.

d. In the spirit still, the volume ratio of foreshots and feints to new make spirit was constant at 3.66, based on the 8% ABV dataset. The foreshots and feints recycled from the previous batch were considered equivalent to those generated in the current batch.

e. Distilling energy loss due to radiation and convection was assumed to be 3.5% of the total energy at both the wash still and spirit still.

f. Fermentation producing an 8% ABV wash does not require active cooling. Washes at 10-14% ABV require active cooling to reduce the fermentation temperature to that of the 8% ABV baseline. For every kilogram of ethanol produced, the heat released was 1,065 kj/kg (Kelsall and Lyons 2003). For wooden washbacks, active cooling is limited but may be possible using an internal cooling coil or, less effectively, through the management of fermentation hall temperature. However, with stainless steel washbacks, cooling panels/jackets can be used.

g. Cooling for both the fermenter and two-pot still condensation was from an ammonia refrigeration unit. Cooling energy demand was calculated using a system coefficient of performance (COP), which is defined as the ratio of thermal energy removed (cooling duty) to electrical energy consumed by the refrigeration system. The COP, inclusive of distribution pumps and cooling tower fan power, was assumed to be constant at 3 (Howard et al. 2020).

h. The annual production target of pure alcohol was 2,000 hL.

Figure 1. The Scotch malt whisky production process and the system boundary used in this study.

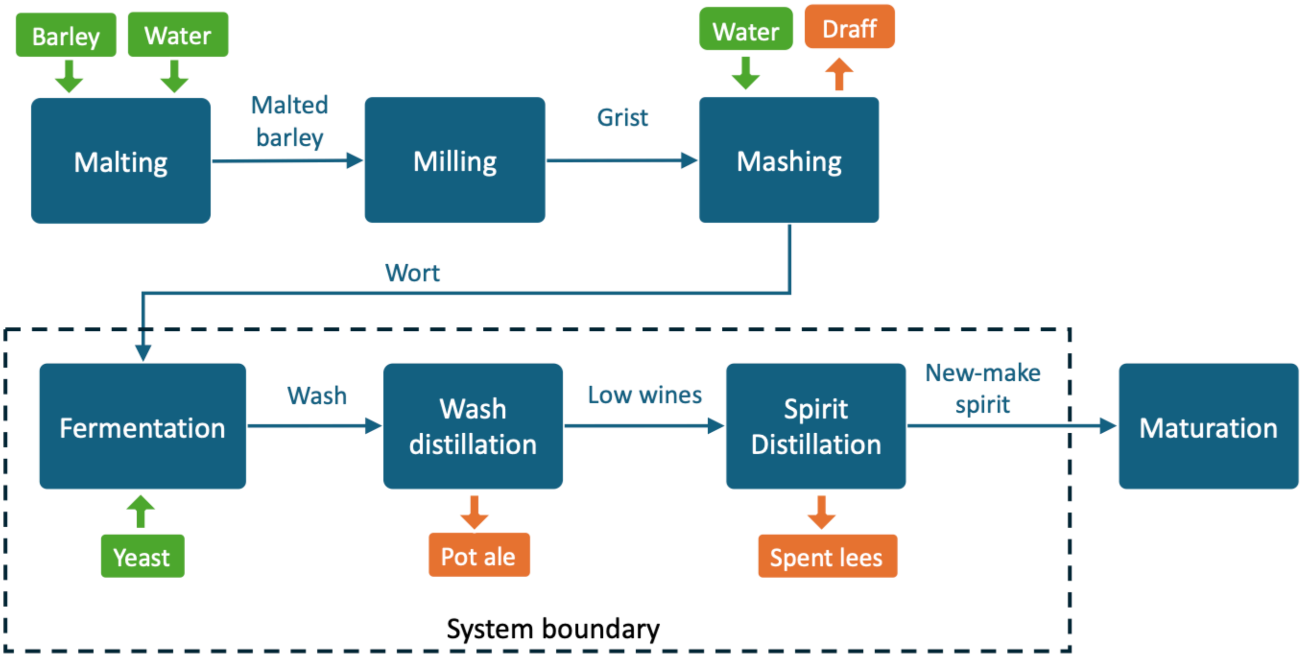
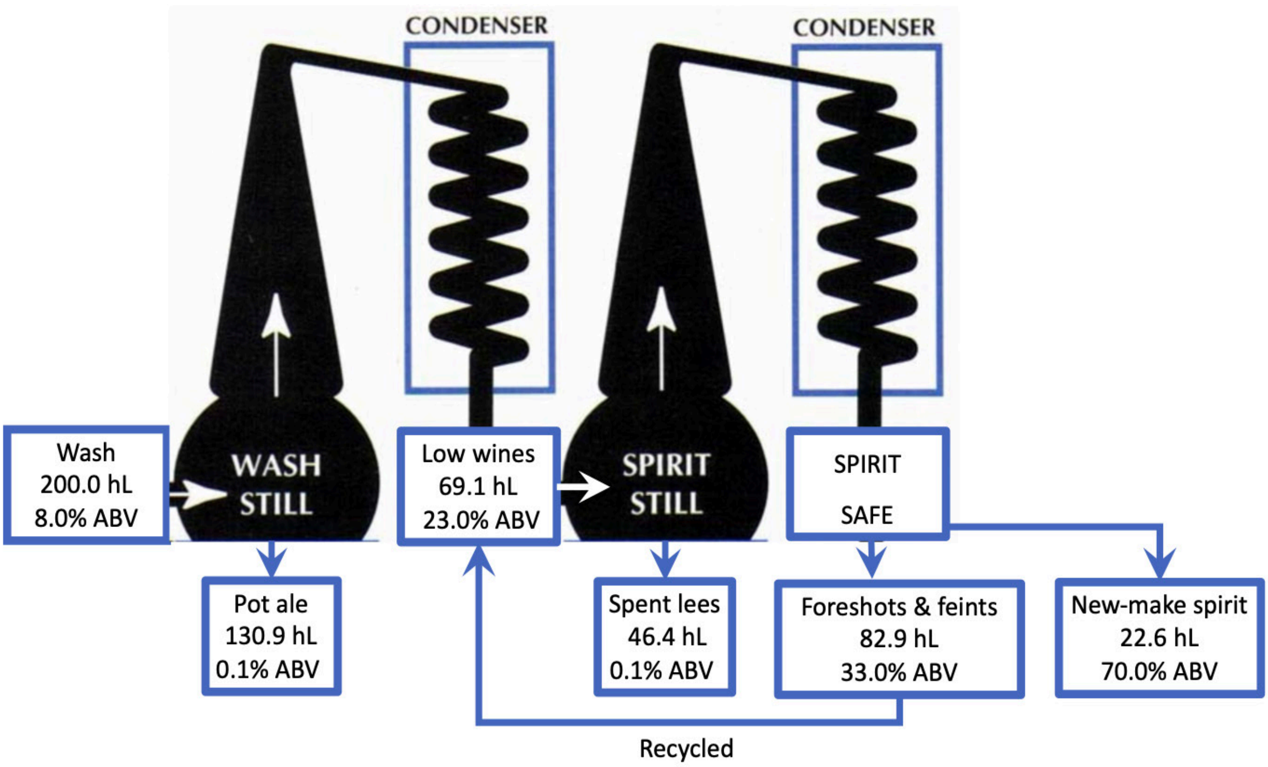


Figure 2. Process flow data starting with a 200 hL wash at 8% ABV (data adapted from Buxton and Hughes 2021), (drawings adapted from Aylott and MacKenzie 2010).



Equations

Mass balance

The overall material mass balance (Eq. 1) and ethanol mass balance (Eq. 2) were calculated according to Richardson et al (2002):

$$F = D + B \qquad \text{(Eq. 1)}$$

$$x_F \times F = x_D D \times x_B B \qquad \text{(Eq. 2)}$$

Where *F*, *D*, and *B* represent the mass (kg) of the process streams. In the wash still, these are wash (*F*), low wines (*D*), and pot ale (*B*). In the spirit still, these are low wines (*F*), new make spirit (*D*), and spent lees (*B*). x_F x_D x_B represent the ethanol mass content (% w/w) of the respective streams.

Energy consumption

Cooling during fermentation

The additional heat released during production of a 10-14% ABV wash, compared to the 8% ABV baseline, was calculated using Eq. 3:

$$Q_f = \Delta m_{EtOH} \times H_{EtOH} \qquad \text{(Eq. 3)}$$

Where Q_f (kJ) is the additional heat generated during fermentation, Δm_{EtOH} (kg) is the ethanol mass produced in 10-14% ABV wash compared to the 8% ABV, H_{EtOH} is heat released per kilogram of ethanol produced, which is 1,065 kJ/kg (Assumption f).

The energy consumption to cool the additional heat to the same temperature of 8% ABV was calculated using Eq. 4 (Howard et al. 2020):

$$E_f = \frac{Q_f}{COP} \qquad \text{(Eq. 4)}$$

Where E_f (kJ) is energy required for fermenter cooling, Q_f (kJ) is additional heat generation during fermentation (Eq. 3), and a system COP of 3 is used (Assumption g).

Heating up and vaporisation during distillation

The heat required for heating up (Eq. 5) and vaporisation (Eq. 6) was calculated from Smith et al (2018):

$$Q_{d,s} = m_{d,s} \times C_p \times \Delta T \qquad \text{(Eq. 5)}$$

Where $Q_{d,s}$ (kJ) is the heat required for heating up water or ethanol (sensible heat), $m_{d,s}$ (kg) is mass of water or ethanol and C_p (kJ/(kg·K)) is the specific heat capacity for water or ethanol.

To simplify the calculation, C_p (water) was kept constant at 4.18 kJ/(kg·K) (*https://www.engineeringtoolbox.com/specific-heat-capacity-water-d_660.html*) and C_p (ethanol) at 2.57 kJ/(kg·K) (*https://www.engineeringtoolbox.com/ethanol-ethyl-alcohol-properties-C2H6O-d_2027.html*), while acknowledging that these values exhibit small variations depending on specific conditions. ΔT is the temperature change (K) with ΔT = 368-293 = 75K for both wash still and spirit still.

$$Q_{d,l} = m_{d,l} \times \Delta H_{vap} \qquad \text{(Eq. 6)}$$

Where $Q_{d,l}$ (kJ) is the heat required for evaporation (latent heat); $m_{d,l}$ (kg) is mass of water or ethanol; ΔH_{vap} (kJ/kg) is the enthalpy of evaporation for water or ethanol. To simplify the calculation, ΔH_{vap} (water) was kept constant at 2,442 kJ/kg (*https://www.engineeringtoolbox.com/water-properties-d_1573.html?vA=25&units=C*) and ΔH_vap(ethanol) at 846 kJ/kg (*https://www.engineeringtoolbox.com/fluids-evaporation-latent-heat-d_147.html*), while acknowledging that these values exhibit small variations depending on specific conditions.

Condensation and cooling during distillation

The heat removed during condensation (Eq. 7) and cooling (Eq. 8) was calculated as:

$$Q_{c,l} = m_{c,l} \times \Delta H_{vap} \qquad \text{(Eq. 7)}$$

Where $Q_{c,l}$ (kJ) is the heat removed during condensation (latent heat); $m_{c,l}$ (kg) is mass of water or ethanol in the vapour; ΔH_{vap} (kJ/kg) is the enthalpy of evaporation for water or ethanol. To simplify the calculation, ΔH_{vap} (water) was kept constant at 2,442 kJ/kg (*https://www.engineeringtoolbox.com/water-properties-d_1573.html?vA=25&units=C*) and ΔH_{vap}(ethanol) at 846 kJ/kg (*https://www.engineeringtoolbox.com/fluids-evaporation-latent-heat-d_147.html*), while acknowledging that these values exhibit small variations depending on specific conditions.

$$Q_{c,s} = m_{c,s} \times C_p \times \Delta T \quad \text{(Eq. 8)}$$

Where $Q_{c,s}$ (kJ) is the heat required to be removed during cooling (sensible heat), $m_{c,s}$ (kg) is the mass of water or ethanol in the vapour; C_p (kJ/(kg·K)) is the specific heat capacity for water or ethanol. To simplify the calculation, C_p (water) was kept constant at 4.18 kJ/(kg·K) (*https://www.engineeringtoolbox.com/specific-heat-capacity-water-d_660.html*) and C_p (ethanol) at 2.57 kJ/(kg·K) (*https://www.engineeringtoolbox.com/ethanol-ethyl-alcohol-properties-C2H6O-d_2027.html*), while acknowledging that these values exhibit smal variations depending on specific conditions. ΔT is the temperature change (K) with ΔT = 368-293 = 75K for wash still and spirit still.

The energy consumption during condensation and cooling was calculated using Eq. 9 (Howard et al. 2020):

$$E_c = \frac{Q_{c,l} + Q_{c,s}}{COP} \quad \text{(Eq. 9)}$$

Where E_c (kJ) is energy required for condensation and cooling, $Q_{c,l}$ and $Q_{c,s}$ (kJ) the heat to be removed during condensation (Eq. 7) and cooling (Eq. 8), and a system COP of 3 was used (Assumption f).

Carbon footprint

The carbon footprint resulting from energy consumption was calculated using Eq. 10:

$$C_e = E \times C \quad \text{(Eq. 10)}$$

Where C_e (kg CO_2 e) is carbon emissions, E (kJ) is energy consumption, and C (kg CO_2 e/kJ) is carbon emission conversion factor for Scope 1-3 emissions. For natural gas, fuel oil and biomass (wood chips), the factors were obtained from the UK Department for Energy Security and Net Zero (*https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2024*); for electricity from wind, hydropower, and solar, the factors were from World Nuclear Association (*https://world-nuclear.org/Information-Library/Energy-and-the-Environment/Carbon-Dioxide-Emissions-from-Electricity*).

Unit conversion

Mass/volume conversion of the ethanol-water mixtures at 20°C used a density and concentration calculator (*https://www.handymath.com*).

Results and discussion

Table 1 presents the input and output batch volumes for the baseline wash (8% ABV) and the modelled scenarios (10, 12, and 14% ABV) across the two conditions. These data were used to assess batch production performance and were subsequently normalised to LPA (Litre of Pure Alcohol) and annual totals to evaluate energy demand, carbon footprint, and post-distillation liquid residues.

Batch production

In *Condition 1* (the same wash volume), increasing wash strength produced more new make spirit per batch (Figure 3a). This would support either fewer batches to meet an annual target or an increase in production capacity. However, it is likely that the higher wash strength would need a larger spirit still or multiple runs for the higher volume of low wines generated. Conversely, under *Condition 2* (the same ethanol mass), increasing the wash strength reduced the wash volume required per batch to produce the same ethanol output (Figure 3b). This is relevant for new build distilleries or undergoing expansion, enabling the use of smaller washbacks and stills while meeting production capacity.

Compared to fermentation, the distillation stage dominated the total energy consumption per batch (Figure 3c, d). In *Condition 1*, the fermenter cooling energy was negligible accounting for 0.16, 0.28 and 0.38% for the washes at 10, 12 and 14% ABV (*Figure 3c*). In contrast, *Condition 2* did not require additional fermenter cooling (Figure 3d) due to the same ethanol mass being produced per batch. Increasing wash strength resulted in higher per-batch energy demand in *Condition 1* (Figure 3c), but lowered energy demand in *Condition 2* (Figure 3d).

Differences were observed between the two conditions in the total volume of pot ale and spent lees produced (Figure 3e, f). Discharge of pot ale decreased with increasing wash strength, which was more pronounced in *Condition 2* (Figure 3f). Changes in the volume of spent lees were modest.

Figure 3. Impact of increasing wash strength on production volume and energy demand per batch. (a, b) volume of wash and low wines, and number of batches for an annual production of 2,000 hL of pure alcohol, (c, d) energy consumption for fermenter cooling and distillation, and (e, f) volume of pot ale and spent lees. Panels (a, c, e) show *Condition 1* (same wash volume of 200 hL across a range of wash strengths) and (b, d, f) show *Condition 2* (same ethanol mass equivalent to 200 hL wash at 8% ABV across the same range of wash strengths).

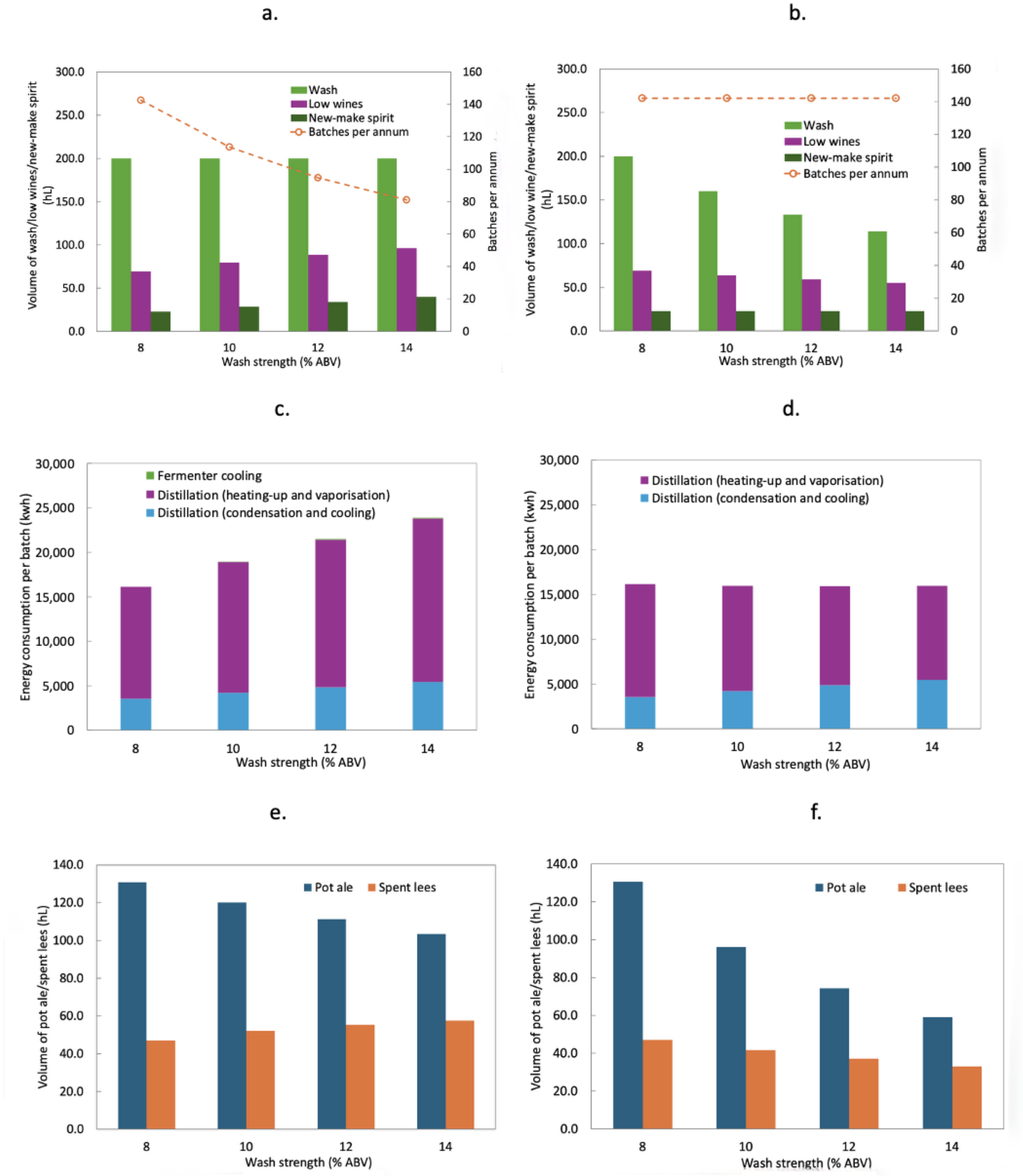


Table 1. Batch data for the two conditions, and a baseline dataset at 8% ABV against which the three scenarios (10, 12 and 14% ABV) were modelled.

Pot still	Flow direction	Materials	Unit	Baseline 8% ABV	Modelling scenarios 10% ABV	12% ABV	14% ABV
***Condition 1*: Same wash volume**							
Wash still	Input	Wash	hL [1]	200	200	200	200
	Output	Low wines	hL	69.1	79.6	88.5	96.3
		ABV of low wines	% ABV	23	25	27	29
		Pot ale	hL	130.7	120.1	111.2	103.5
Spirit still	Input	Low wines	hL	69.1	79.6	88.5	96.3
		Foreshots and feints [2]	hL	82.9	103.8	124.7	145.7
	Output	New make spirit	hL	22.6	28.4	34.1	39.8
		ABV of new make spirit	% ABV	70	70	70	70
		Spent lees	hL	47.1	52.1	55.4	57.6
		Foreshots and feints	hL	82.9	103.8	124.7	145.7
***Condition 2*: Same ethanol mass**							
Wash still	Input	Wash	hL	200	160	133.4	114.3
	Output	Low wines	hL	69.1	63.7	59	55
		ABV of low wines	% ABV	23	25	27	29
		Pot ale	hL	131	96	74	59
Spirit still	Input	Low wines	hL	69.1	63.7	59	55
		Foreshots and feints [2]	hL	82.9	83	83.2	83.3
	Output	New make spirit	hL	23	23	23	23
		ABV of new make spirit	% ABV	70	70	70	70
		Spent lees	hL	47	42	37	33
		Foreshots and feints	hL	82.9	83	83.2	83.3

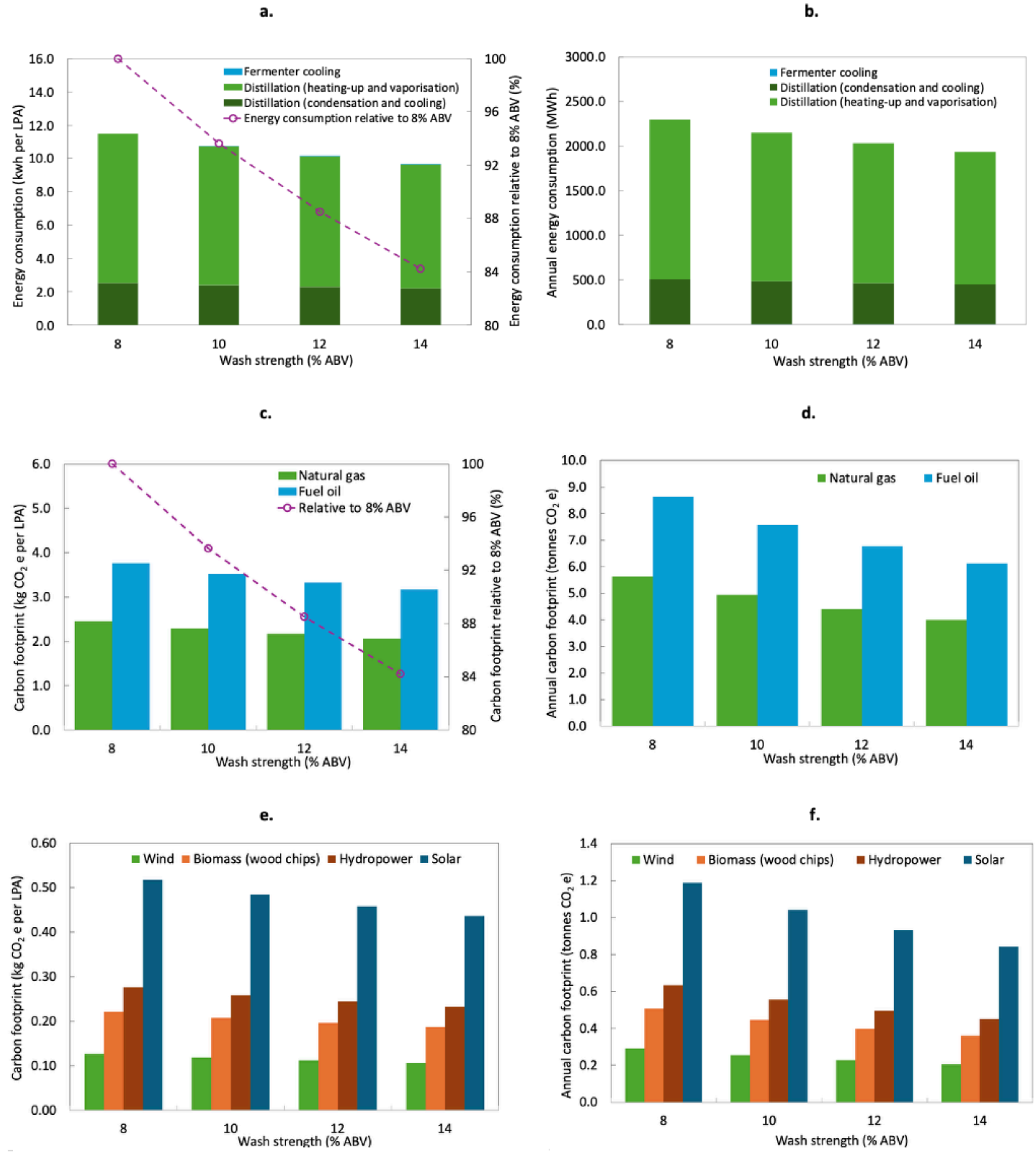
Notes: [1] Volume at 20°C and 1 atm; [2] Volume ratio of foreshots and feints to new make spirit was assumed to be constant at 3.66 for both conditions (Assumption d), obtained from the industrially representative dataset using 8% ABV wash.

Energy consumption and associated carbon emissions per litre of pure alcohol

Condition 1: the same wash volume

Figure 4a illustrates the energy requirement for fermenter cooling and distillation on the basis of per-LPA. As with batch production, distillation was the dominant consumer of energy, with fermenter cooling taking a minor share equivalent to 0.16, 0.28 and 0.38% for the washes at 10, 12 and 14% ABV. When the wash strength increased from 8 to 10%, 10 to 12%, and 12 to 14% ABV, the energy required decreased in

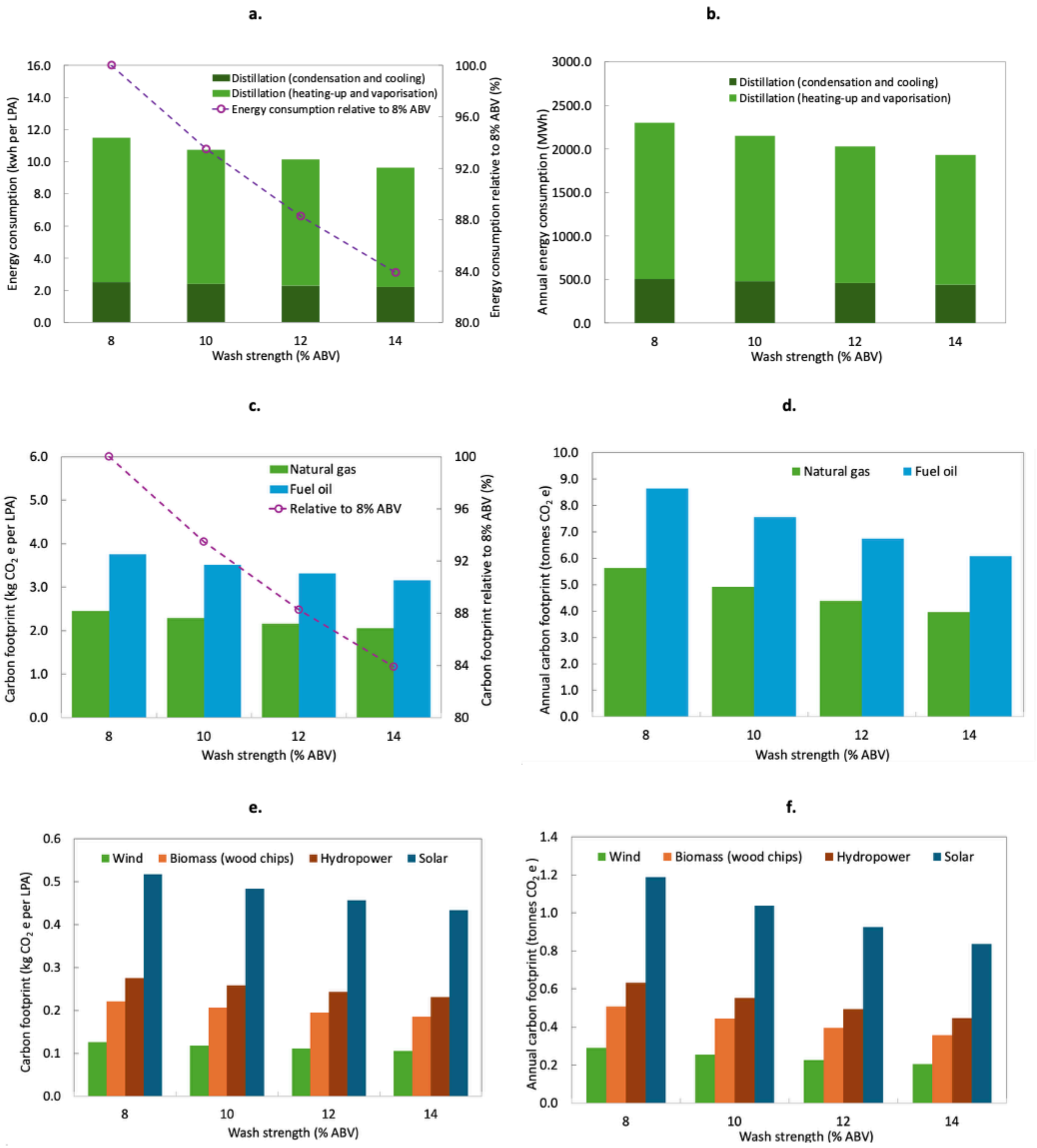
Figure 4. Impact of increasing wash strength on energy consumption and carbon emissions in Condition 1 (same wash volume of 200 hL across a range of wash strengths), (a, b) energy consumption, (c, d) carbon footprint from natural gas and fuel oils, and (e, f) carbon footprint from renewable energy. Panels (a, c, e) present results as per-LPA and (b, d, f) show annual totals corresponding to a production of 2,000 hL of pure alcohol.



a stepwise manner, with savings of approximately 6.4, 5.1, and 4.3% relative to the 8% ABV baseline. Overall, raising the wash strength from 8 to 14% ABV resulted in a total energy saving of 15.8% per LPA, equivalent to 84.2% of the energy consumption at 8% ABV. This corresponds to a reduction in total energy consumption from 2,299 to 1,936 MWh, based on an annual production of 2,000 hL of pure alcohol (Figure 4b).

This reduction in energy consumption led to a stepwise decrease in carbon footprint for distilleries powered by natural gas and fuel oil, both on a per-LPA basis (Figure 4c) and total annual emissions

Figure 5. Impact of increasing wash strength on energy consumption and associated carbon emissions in *Condition 2* (same ethanol mass equivalent to 200 hL wash at 8% ABV across a range of wash strengths). (a, b) Energy consumption, (c, d) carbon footprint from natural gas and fuel oils, and (e, f) carbon footprint from renewable energies. Panels (a, c, e) present results per-LPA and (b, d, f) show annual totals corresponding to a production of 2000 hL of pure alcohol.



(Figure 4d). Overall, increasing wash strength from 8 to 14% ABV led to a 15.8% reduction in carbon emissions from energy use. Specifically, carbon emissions from natural gas decreased from 2.45 to 2.06 kg CO_2e per-LPA, equivalent to a drop from 5.63 to 3.99 tonnes CO_2e per year. Similarly, emissions from fuel oil decreased from 3.76 to 3.17 kg CO_2e per-LPA, equating to a reduction from 8.65 to 6.13 tonnes CO_2e annually. Natural gas and fuel oil were the dominant energy sources in the 2020 emission inventory (*https://www.scotch-whisky.org.uk/media/1733/scotch-whisky-net-zero-report.pdf*), accounting for 63% and 31% of total distillery emissions.

Mindful of industry initiatives to decarbonise, four renewable energy sources were modelled: wind, biomass (wood chips), hydropower, and solar. While the baseline carbon intensities (from the highest to lowest) are solar > hydropower > biomass (wood chips) > wind, each energy source showed a stepwise decrease in carbon footprint as wash strength increased. As with natural gas and fuel oil, this led to a overall reduction of 15.8% in carbon emissions, both per-LPA (Figure 4e) and annual totals (Figure 4f). Specifically, carbon emissions decreased from 0.13 to 0.11 kg CO_2e per LPA for wind (from 0.29 to 0.21 tonnes per annum), 0.22 to 0.19 kg CO_2e per LPA for biomass (from 0.51 to 0.36 tonnes per annum), 0.28 to 0.23 kg CO_2e per LPA for hydropower (from 0.63 to 0.45 tonnes per annum), and 0.52 to 0.44 kg CO_2e per LPA for solar (from 1.19 to 0.84 tonnes per annum).

Condition 2: the same ethanol mass

As the ethanol mass per batch was maintained, *Condition 2* did not increase fermenter cooling demand compared to the 8% ABV baseline. The savings on energy use and associated carbon emissions were therefore dominated by distillation. With *Condition 2* the total reduction was 16.1% relative to the 8% ABV baseline (Figure 5), similar to the 15.8% reduction observed in *Condition 1*.

Discharge of pot ale and spent lees per LPA

Pot ale and spent lees are major liquid residues from whisky distillation. Here, the results were identical for the two conditions, in terms of per-LPA (Figure 6a, c) and annual total (Figure 6b, d). For each stepwise increase in wash strength (8 to 10%, 10 to 12%, 12 to 14% ABV) resulted in a reduction in pot ale discharge by 26.6, 16.8, and 11.5%, respectively, relative to the 8% ABV baseline. This cumulative 55% reduction corresponded to a decrease from 9.3 to 4.2 litres of pot ale per-LPA. On an annual basis, the annual discharge reduced from ca. 18,600 to 8,400 hL based on an annual production of 2,000 hL of pure alcohol.

Similarly, for each stepwise increase in wash strength, spent lees discharge was reduced by 11.7, 10.1, and 8.6%, leading to an overall 30.4% reduction at 14% ABV compared to the 8% ABV baseline. This corresponded to a decline from 3.4 to 2.3 litres per LPA, and a reduction from ca. 6,700 to 4,600 hL for the same level of annual production.

This decrease in residue volume would lower manufacturing costs related to the handling, transportation, and treatment of post-production residue materials, with the impact being significant for pot ale. Additionally, the components in pot ale (yeast, protein, carbohydrate etc) would be more concentrated in higher ABV wash residues leading to increased efficiencies for post-distillery processing and valorisation.

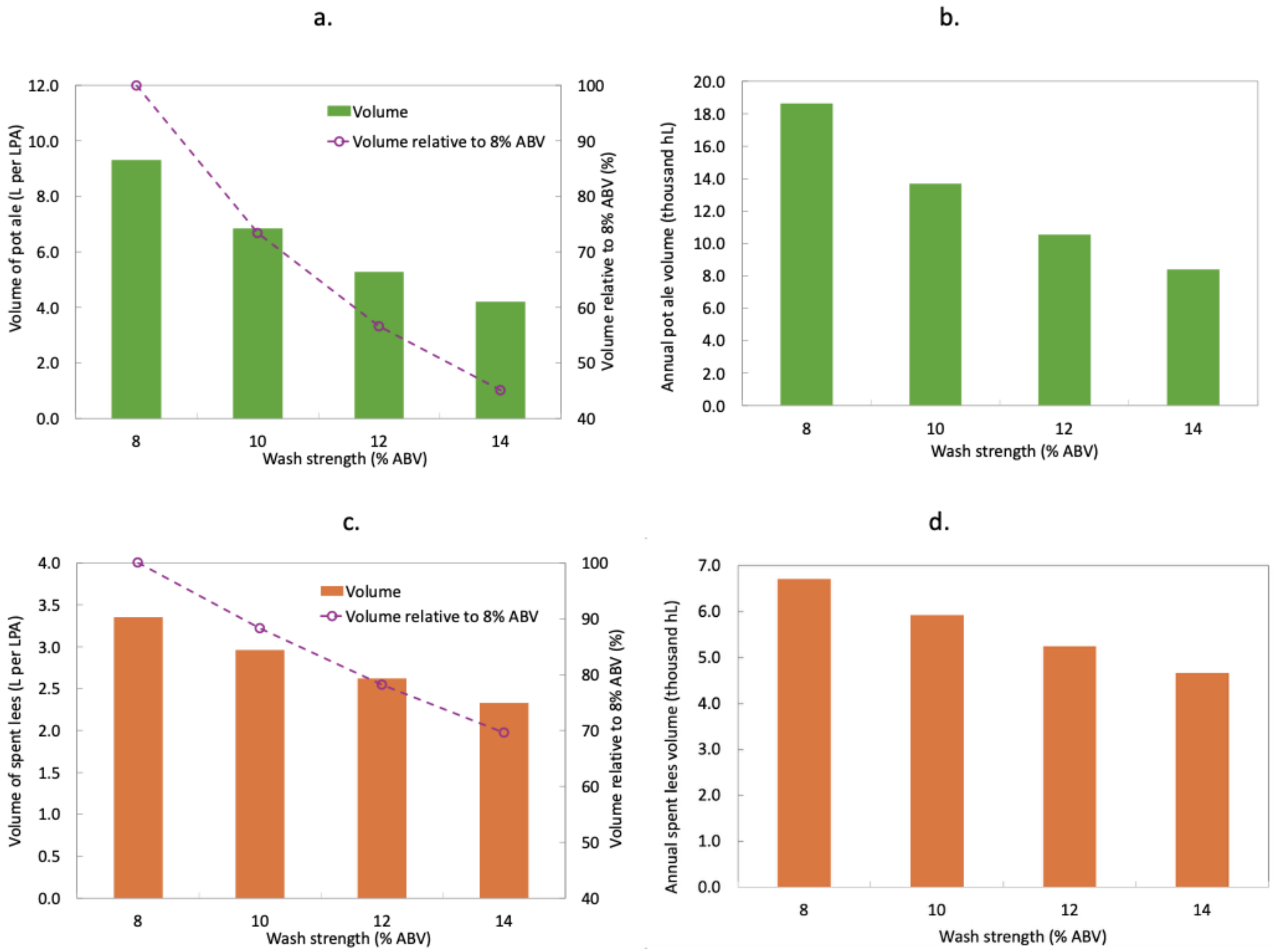
Considerations

The results suggest increasing wash strength within the defined system boundary of fermentation and distillation, would enhance operational efficiency and sustainability performance for Scotch malt whisky distilleries (Figure 1). Although the patterns of energy demand differ between the two conditions at the batch level, the normalised savings in energy use, carbon footprint, and liquid discharges per-LPA, together with the corresponding annual total, are comparable. This suggests that the potential benefits are robust across the different operational modes. The main distinction lies in production strategy: *Condition 1* enhanced batch production capacity at a given fermenter capacity, whereas *Condition 2* reduced vessel sizes for a given production target. Therefore, they offer distillers different pathways to achieve efficiency gains depending on site-specific configurations and production planning considerations. The model is based on a batch wash volume of 200 hL; however, it is noteworthy that the larger the wash size, the greater the potential savings, showing that the benefits may be especially relevant for large scale distillers.

Despite these advantages, there are several practical considerations that need to be addressed:

(1) Producing wort at 21-27°P to achieve 10-14% ABV may be a significant challenge. Achieving such gravities would likely reduce brewhouse efficiency, through limitations in extract recovery. Innovation, such as mash filters (Stewart 2010), would be required to optimise grain utilisation and achieve spirit yield.

Figure 6. Impact of increasing wash strength on (a, b) pot ale and (c, d) spent lees discharges. Panels (a, c) present results per-LPA and (b, d) show annual totals corresponding to a production of 2,000 hL of pure alcohol. The results were identical for the two *Conditions*.



(2) Concentrated worts impose environmental stresses on yeast (Gibson et al. 2007; Zhuang et al. 2017), resulting in stuck fermentations (Stewart 2010), altered yeast carbon partitioning (Zhuang et al. 2019), and changes in the fermentation cycle time and flavour profile. Mitigation requires an improved understanding of the physiology of distilling yeast under stress conditions, combined with optimal yeast handling strategies (yeast viability, pitching rate and single use regimes). In addition, development of stress tolerant yeast through adaptive laboratory evolution Gibson et al. 2020) would be useful in counteracting the additional heat stress (where temperature control is not in place) and ethanol stress during fermentation.

3) Strategies for cutting the spirit, maturation and blending may need to be adjusted to accommodate the potentially modified flavour profile from new make spirit from increased wash strength. However, increasing the wash ABV may introduce new beneficial flavour profiles.

(4) Reduced energy consumption would affect heat recovery, altering heat transfer dynamics across the process. Accordingly, an assessment of the full energy profile would be necessary to evaluate the net impact of *higher* gravity fermentation.

(5) The effect of increasing wash strength on the quality of pot ale, spent lees, and spent grains (or 'draff') (Figure 1), has yet to be investigated. An important consideration is the liquid-to-solid ratio, due to their role as ingredients for other applications (White et al. 2020; Edwards et al. 2022; Duffy et al. 2023; Stewart et al. 2024).

It should be noted that this modelling study used baseline data with a defined set of assumptions (outlined in the Methods and materials). In particular, it was assumed that an increase in wash strength leads to a corresponding increase in the ABV of low wines during the wash distillation. This is primarily due to the higher ethanol concentration in the wash, which shifts the vapour-liquid equilibrium towards a more ethanol-rich vapour phase. Under an otherwise identical still operation, this would result in a higher average ABV in the condensed distillate collected as low wines.

It is also important to note that this analysis does not account for all parameters (e.g. the capital cost of a cooling system), grain use and associated brewhouse efficiency. A full life cycle assessment that includes these factors would be necessary to comprehensively evaluate the impact on net sustainability. Consequently, the savings will vary depending on the technology, infrastructure, and operational practices used by distilleries.

Conclusions

To the best of our knowledge, this study provides the first quantitative assessment of the effect of increasing wash strength (8 to 14% ABV) on fermentation and distillation in Scotch malt whisky production, with particular regard to operational and environmental performance. When the wash volume was held the same (*Condition 1*), increased wash strength raised batch production capacity but may require larger spirit stills or multiple batches. When ethanol mass per batch was held the same (*Condition 2*), higher wash strength reduced batch processing volumes, allowing the use of smaller vessels while maintaining the same production capacity. This work also showed that distillation energy - including heating up, evaporation, condensation and cooling - was the dominant energy demand, while fermentation cooling was found to be negligible. Across both conditions, total energy use and carbon footprint decreased as wash strength increased from 8 to 14% ABV, resulting in a 15.8-16.1% reduction at 14% ABV compared to 8% ABV on per-LPA basis. Post-distillation discharge also declined with increasing wash strength, with a total reduction of 55% in pot ale and 30.4% in spent lees at 14% ABV. However, to fully realise such advantages, it is suggested that distillers tailor these practices to their specific systems, accounting for energy, water, yeast, product handling, and effeciency of grain use.

CRediT author contributions

Shiwen Zhuang: Conceptualisation, methodology, investigation, writing (original draft, reviewing and editing).
Jane White: Conceptualisation, methodology, investigation, writing (reviewing and editing).
Chris Boulton: Writing (reviewing and editing).

Conflict of interest

The authors declare there are no conflicts of interest.

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