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Techno-economic analysis and life cycle assessment for the rapid carbonation of beer

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Micro-breweries seeking greater environmental and economic sustainability must consider each stage of the brewing process for opportunities to improve. Intensifying beer carbonation may offer environmental and economic benefits in addition to process improvements. A bulk gas-to-atomized liquid (BGAL) approach to carbonation has been proposed as a method to provide a 40-fold increase in the rate of carbonation while maintaining the aromatic characteristics of the beer. The presented work examines the possible economic and environmental benefits of BGAL carbonation compared to traditional bright tank carbonation. The techno-economic analysis shows a 40% reduction in operating costs by utilizing the BGAL approach. Furthermore, the life cycle assessment shows a 99% reduction in cumulative energy demand and a 98% reduction in global warming potential. While the magnitude of these improvements is highly sensitive to the energy demand of the cooling system and the required residence time of the beer in the bright tanks, the results of this study indicate that using BGAL carbonation offers economic and environmental benefits to breweries in addition to the associated process intensification.

Sustainability spotlight

The Brewer's Association reports that microbreweries produce over four million hectoliters of beer annually, which is largely carbonated through traditional forced carbonation in a bright tank. This work assesses the economic and environmental advantages offered by implementing a new method to rapidly carbonate beer in place of the traditional configuration. The results show a 99% reduction in energy demand and a 98% reduction in global warming potential while also reducing operating costs to small-scale brewers by 40%. By reducing the environmental impacts of the carbonation step in the brewing process and improving the profitability of small-scale breweries, this work supports SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Introduction

Strengthening environmental and economic sustainability is one of the six core values of the Brewers Association.[1] In pursuit of this goal, it is important to examine each step in the brewing process and seek to optimize investment of both financial and environmental resources. Although frequently overlooked, the carbonation process is an ideal candidate for examination due to its lengthy time requirements and sometimes substantial energy inputs.

Presently, many micro-breweries rely on bright tanks for carbonation, wherein beer is transferred from the fermenter to a bright tank, and small bubbles of CO_2 are sparged into the beer through a carbonation stone over the course of approximately three days until the beer reaches the target carbonation level. Most beers require carbonation to 2.2 to 2.6 volumes of CO_2 per volume of beer (vol/vol), where one vol/vol of CO_2 is equivalent to a concentration of 1.95 g L^{-1},[2,3] although carbonation levels range from 1.5 vol/vol in some dark beer styles up to 4.0 vol/vol in some highly carbonated wheat beers.

Because beer absorbs CO_2 more efficiently at a lower temperature, the bright tank is continuously supplied with coolant to maintain a temperature near freezing. Because each batch of beer must be cooled continuously for upwards of three days, the associated energy inputs can be substantial depending on the size and efficiency of the cooling system. Furthermore, because the beer must reside in the bright tank for a substantial amount of time, individual brews must be carefully scheduled such that a bright tank is available when fermentation is complete. Thus, the overall production capacity of the brewery may be limited by the number of bright tanks available.

Recently, Jean *et al.*[4] reported the results of an approach to rapidly carbonate beer using a bulk gas-to-atomized liquid (BGAL) system. The proposed system, shown in Fig. 1, utilized a standard bright tank that had been retrofitted with a nozzle to spray the fermented beer into a pressurized atmosphere of CO_2 in the bright tank. Because of the preferential surface area-to-volume ratio of the droplets, the pilot system successfully carbonated the beer at a rate of 3 L min^{-1}, a 40-fold rate

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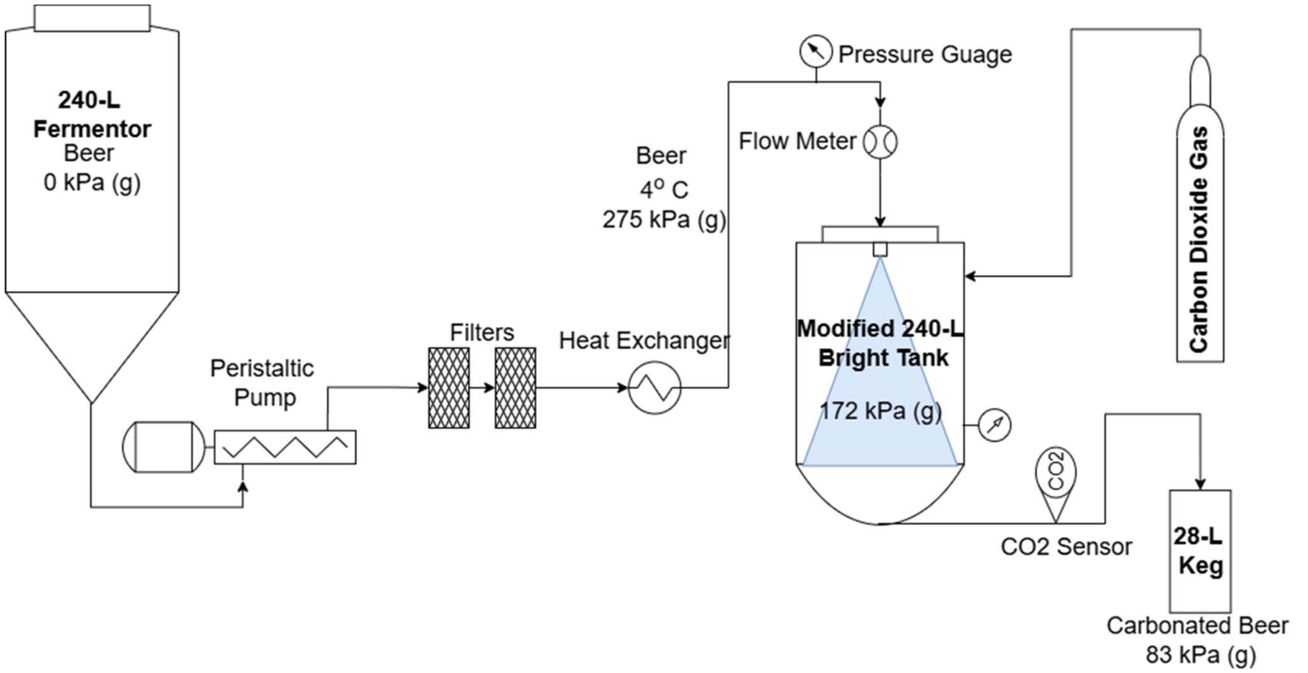

Fig. 1 BGAL system configuration reported by Jean *et al.*[4] (patent pending).

improvement compared to traditional bright tank carbonation in a comparable 240 L system.[4] Furthermore, they reported that the aromatic characteristics were consistent across the different carbonation approaches following qualitative GC-MS analysis of the beer and targeted HS-SPME-GC-MS analysis hop compounds, including myrcene, linalool, and geraniol.[4]

Although the findings of Jean *et al.*[4] indicate that BGAL carbonation offers an opportunity to intensify the carbonation step of beer brewing, it is important to understand the economic and environmental implications. Thus, we present a techno-economic analysis and life cycle assessment of the proposed approach to compare the economic and environmental effects of both carbonation approaches. These results should offer a more comprehensive picture of how BGAL carbonation can help small-scale brewers intensify their carbonation process while striving towards their missions for long-term environmental and economic sustainability.

Materials and methods

A techno-economic analysis (TEA) and a life cycle assessment (LCA) were each performed to compare the costs and benefits of traditional and BGAL carbonation, offering insights into additional benefits provided by the BGAL carbonation. The LCA was conducted according to the ISO 14040 guidelines and ISO 14044 standard framework.[5,6]

Goal and scope

The presented TEA and LCA aim to compare the proposed BGAL carbonation approach to traditional carbonation in a bright tank. Because all processes upstream and downstream of this carbonation step are not impacted, a gate-to-gate approach was selected, comparing the processes from the outlet of the fermentation vessel to the inlet of the kegging or bottling operations.[6] This boundary is specified in Fig. 2, which also shows a brief comparison of the equipment necessary for each process. The TEA specifically presents the capital costs associated with retrofitting an existing carbonation train to operate in the BGAL configuration and the associated operational savings and corresponding payback period.

The LCA quantifies three key performance indicators (KPIs) to identify potential environmental savings offered by BGAL carbonation: carbon dioxide utilization (CDU), global warming potential (GWP), and cumulative energy demand (CED). The inventory assessment only considers the mass and energy flows, excluding environmental effects from the manufacture or installation of the equipment. Although the omission of equipment manufacture from the scope of the analysis will reduce the absolute value of the impact results, the effect of this omission on the comparative results and any percent improvements offered by the BGAL system is relatively minor due to the similarity between the major equipment in the two systems. All baseline assessments utilize a functional unit of a single 240 L batch of carbonated beer, and all CO_2 or energy utilized as well as emissions generated during the carbonation step may be allocated to the final carbonated beverage product.

Inventory assessment

The uncarbonated beverage flowing into the system is assumed to have zero CO_2 intensity as the LCA only aims to determine the environmental impact of the carbonation step. The mass flows of CO_2 are quantified utilizing known operating parameters

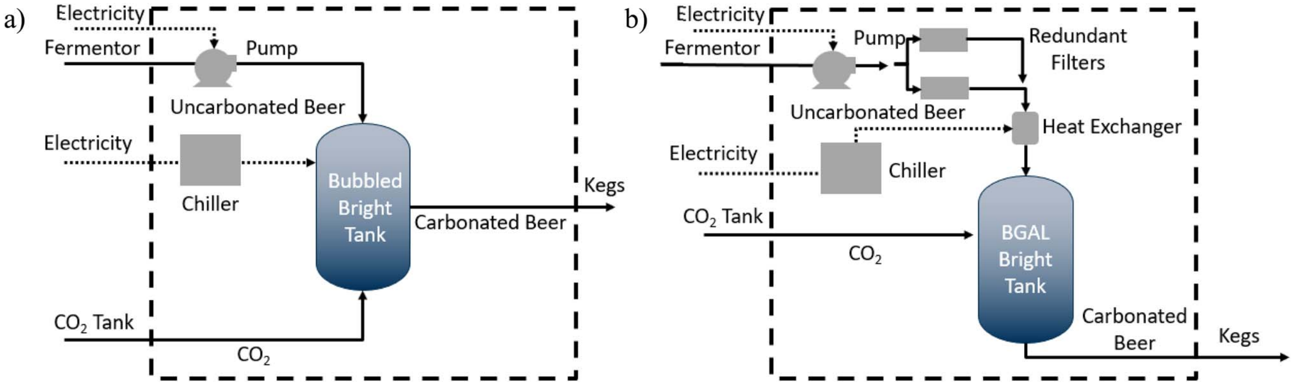

Fig. 2 TEA and LCA boundaries for (a) traditional carbonation; (b) BGAL carbonation.

such as system pressure, CO_2 concentration change, and purge conditions. The beer is assumed to have a starting concentration of CO_2, approximately 0.88 vol/vol, when it exits the fermentor, produced as a byproduct of fermentation at a temperature near 20 °C and atmospheric pressure.[7] The beer is then carbonated to approximately 2.5 vol/vol in the bright tank, requiring an additional 1.6 vol/vol CO_2 to be dissolved into the beer.

The pump and chiller are assumed to be the only power inputs within the system boundary. The energy consumed by the pump is quantified by calculating the required pumping head resulting from changes in pressure, changes in height, and friction effects associated with the required pumping flowrate within each system. The energy consumed by the chiller is quantified by assuming a 2400 W single stage chiller (GD-1.5H) operates at 100% capacity for the entire carbonation process, offering a conservative value. Both motors are assumed to operate at 70% efficiency.

Traditional carbonation inventory assessment. The traditional carbonation approach is carried out in five steps, detailed in Table 1. During the purge step the CO_2 gas is turned on and allowed to run for a specified amount of time, flowing in from the bottom of the bright tank and pushing the air of the top. For this analysis, CO_2 is assumed to flow at 19 L min^{-1} for 15 min, enough time to fill the bright tank with CO_2 and minimize excess CO_2. During the filling step, uncarbonated beer is pumped at 7.6 L min^{-1} from the fermenter to the bright tank, CO_2 gradually exiting the vessel as the headspace is reduced from 276 to 42 L while maintaining constant pressure. During the carbonation step, CO_2 bubbles are sparged into the beer through a carbonation stone at the base of the bright tank, gradually dissolving into the beer over approximately 72 hours until it reaches the final target CO_2 concentration. The analysis assumes that the chiller operates for the entire duration of the carbonation step. During the transfer step, the bright tank is topped with CO_2 at 71 kilopascal gauge (kPa (g)) to provide driving pressure as the beer is transferred to long-term storage. In the final depressurization, the bright tank is opened, releasing the remaining CO_2 to the atmosphere.

BGAL carbonation inventory assessment. BGAL carbonation is carried out in 3 steps, summarized in Table 2. The purge step is carried out identically to that of the traditional approach, although the final bright tank pressure is set to 172 kPa (g). During the carbonation step, the beer is pumped from the fermenter at a rate of 3.7 L min^{-1}. The beer flows through 5-micron and 1-micron filters to remove the suspended solids,

Table 1 Mass and energy flows for traditional carbonation

Carbon dioxide			
	Input (kg/batch)	Loss (kg/batch)	Absorbed (kg/batch)
Step 1 – purge	0.86	0.01	0.00
Step 2 – transferring	0.00	0.72	0.00
Step 3 – carbonation	0.75	0.00	0.75
Step 4 – kegging	0.72	0.00	0.00
Step 5 – depressurization	0.00	0.85	0.00
Total	2.33	1.58	0.75
Energy (kWh/batch)			
Step 2 – pumping			0.006
Step 3 – chilling			247
Total			247

Table 2 Mass and energy flows for BGAL carbonation

Carbon dioxide	Input (kg/batch)	Loss (kg/batch)	Absorbed (kg/batch)
Step 1 – purge	1.37	0.01	0.00
Step 2 – carbonation	0.75	0.00	0.75
Step 3 – depressurization	0.00	1.36	0.00
Total	2.12	1.37	0.75

Energy (kWh/batch)	
Step 2 – pumping	0.08
Step 2 – chilling	3.54
Total	3.62

then is chilled in a plate heat exchanger connected to the glycol chiller. The cooled beer then flows to the top of the bright tank where it is sprayed through a nozzle into the bright tank and immediately flows out of the base of the bright tank into its final storage vessel. Once all 240 L of beer are carbonated, the bright tank is depressurized to the atmosphere.

Impact assessment

As previously stated, the KPIs for this LCA are CDU, GWP, and CED attributed to the carbonation step of a 240 L batch of beer. The CDU and CED are computed utilizing only the mass and energy balances shown in the previous section. Alternatively, the GWP includes both the CO_2 released per batch and the GWP of the electricity used in the process. This impact assessment was conducted utilizing openLCA 2.4.0 (2024) with the databases available from LCA Commons data repository and quantifying impacts utilizing the Traci 2.1 LCA method. The average at-grid electricity consumption mix in the US from the US Electricity Baseline repository was used to quantify emissions for energy requirements.[8] These three impacts are summarized for each approach in Table 3.

From Tables 1 and 2, the CED of each system is largely reliant on the energy requirements of the chiller, determined in this baseline scenario using conservative estimates, as previously noted. Given the relatively small absolute difference in CDU between the two systems, shown in Table 3, it is clear that the difference in GWP between the two systems is equally reliant on CED. Thus, sensitivity analyses surrounding chiller energy demand and operating time will be included in the discussion section to give a more detained view of possible improvements offered by the BGAL system under alternative operating assumptions.

Techno-economic analysis

The TEA examines the cost to retrofit an existing carbonation train and the associated operational savings, offering a payback period that reveals the number of beer batches that must be carbonated to recoup the initial investment. With a single bright tank, the brewery is assumed to produce 113 240 L batches of beer in 340 operating days per year. Using traditional carbonation, each batch of beer is carbonated in approximately 3 days, which includes 72 hours in the bright tank plus 1 hour for beer transfer and vessel cleaning. To equalize all additional costs outside of the boundary and allow for a more direct comparison of both systems, 113 batches are assumed for both systems, despite the process intensification offered by BGAL carbonation.

Capital costs. The total capital investment (TCI) is composed of the fixed capital investment (FCI), working capital (WC) and land cost. Because this system is intended to retrofit an existing brewery, there are no additional land requirements. The FCI includes the installed equipment cost. The delivered equipment costs were supplied by vendors, and a factor of 45% is used to calculate the cost of instillation.[9] The baseline equipment for both systems, including the pump, chiller, and bright tank, is identical and, thus, is not included in the cost to retrofit the system. Additional equipment required for BGAL carbonation includes piping, a heat exchanger, valves, filter housing, flowmeters, nozzles, and a 4-way kegging manifold to facilitate the high flowrate. The WC, assumed to be 15% of the FCI, accounts for downtime during installation and stockpiling resources and raw materials. The capital costs to retrofit the system are summarized in Table 4.

Operating costs. The variable operating costs for both systems include CO_2 gas cylinders and electricity. The rapid

Table 3 Summary of impacts for each carbonation approach

	Traditional	BGAL
Cumulative energy demand (CED) (kWh/batch)	247	3.62
Carbon dioxide utilization (CDU) (kg/batch)	2.33	2.12
Global warming potential (GWP) (kg CO_2-eq./batch)	137.7	3.36

Table 4 Itemized capital cost to retrofit an existing carbonation train for BGAL operation

Equipment – total installed cost	
Valves	\$1020
Filter housing	\$300
Heat exchanger	\$1080
Nozzles	\$200
Kegging manifold	\$920
Flowmeter	\$450
Capital costs	
Fixed capital investment (FCI)	\$3970
Working capital (15% FCI)	\$600
Total capital investment (TCI)	\$4570

Table 5 Itemized operating costs for carbonation systems

Variable costs (\$/batch)	Traditional	BGAL
Raw materials		
CO_2	\$45.62	\$41.51
5-Micron filters	—	\$0.66
1-Micron filters	—	\$0.67
Additional maintenance (2% retrofit FCI)	—	\$0.70
Utilities		
Electricity	\$28.36	\$0.42
Fixed costs (\$/batch)	Traditional	BGAL
Additional local taxes (1.5% retrofit FCI)	—	\$0.53
Additional insurance (0.6% retrofit FCI)	—	\$0.21
Total operating costs per batch	\$73.98	\$44.69

carbonation scheme also requires 5-micron and 1-micron filter cartridges which are assumed to have a lifespan of 10 240 L batches of beer before replacement. While this estimate is intended to offer a baseline cost for the filters, actual costs and replacement time may vary depending upon upstream operational practices, such as cold crashing in the fermenter to promote solids sedimentation and removal of the sediment cone prior to the start of vessel transfer. Moreover, pumping requirements may increase as the filters become saturated with solid materials, and a different change frequency may be preferred to mitigate this operational challenge. Additionally, it is assumed that 90% of a 23-kg CO_2 gas cylinder is utilized before replacement, although many breweries may utilize much larger CO_2 storage vessels with regular refill from a service provider. 2% of the retrofit FCI is assumed to account for additional maintenance costs. Variable costs also typically include labor costs; however, the analysis assumes the carbonation step does not require any additional personnel over those already employed for other brewery operations. While this assumption may be valid for smaller scale micro-breweries with lower turnover or smaller batches that would only require one or two hours for carbonation every few days, a brewery that intends to carbonate frequently or produces larger batches of beer requiring up to eight hours for carbonation may require additional personnel to actively operate the system.

Fixed costs include overhead, taxes, and insurance. Because no additional overhead is necessary for the carbonation step over that required for other brewery operations, it has been excluded from the analysis. The additional taxes are estimated as 1.5% of the retrofit FCI annually, and the additional insurance is estimated as 0.6% of the retrofit FCI annually. These two parameters are allocated per batch using the number of batches per year. The operating costs are summarized in Table 5, indicating operational savings of \$25/batch when retrofitting a 240 L system.

Case study. In addition to considering the costs to retrofit an existing carbonation train, it is important to understand the operational benefits offered by BGAL carbonation and the corresponding economic advantages. To this end, a case study was conducted to examine the costs of building a new 18 000 hL per year micro-brewery, the maximum capacity to be considered a micro-brewery by the Brewers Association,[10] using either traditional carbonation in bright tanks or BGAL carbonation in retrofitted bright tanks. This brewery is assumed to utilize several 24 hL bright tanks and operate 340 days per year to produce 750 24 hL batches of beer per year. Under the assumption that each bright tank can carbonate 113 batches of beer per year in the traditional configuration, 7 total carbonation trains are required for this scenario. Alternatively, the BGAL system is assumed to carbonate the beer at 3.7 L min^{-1}, requiring 10.3 hours to carbonate each 24 hL batch. Assuming the same 1 hour to clean and turnover the system, 1 batch of beer can be carbonated per day in each BGAL carbonation system, requiring 3 total carbonation trains. These capital costs are summarized in Table 6. Here, the TCI has additionally been

Table 6 Itemized capital costs for 18 000 hL per year carbonation trains

	Traditional		BGAL	
Equipment – total installed cost	Units	Cost	Units	Cost
24 hL bright tank	7	\$139 600	3	\$59 800
Pump	7	\$38 700	3	\$16 600
Pressure regulator	7	\$7300	3	\$3100
Valves	—	—	6	\$5200
Filter housing	—	—	12	\$5300
Heat exchanger	—	—	3	\$3700
Nozzles	—	—	6	\$2700
Kegging manifold	—	—	3	\$3200
Flowmeter	—	—	6	\$3500

Capital costs	Traditional	BGAL
Fixed capital investment (FCI)	\$186 000	\$103 000
Working capital (15% FCI)	\$27 800	\$15 400
Total capital investment (TCI)	\$213 800	\$118 400
Annual depreciation (\$/yr)	\$21 380	\$11 840

Table 7 Itemized operating costs for 18 000 hL per year carbonation systems

Variable costs ($/batch)	Traditional	BGAL
Raw materials		
CO_2	$463.04	$414.88
5-Micron filters	—	$6.59
1-Micron filters	—	$6.66
Maintenance (2% FCI)	$4.95	$2.75
Utilities		
Electricity	$28.38	$4.16
Fixed costs ($/batch)	Traditional	BGAL
Local taxes (1.5% FCI)	$3.71	$2.06
Insurance (0.6% FCI)	$1.48	$0.82
Total operating costs per batch	$501.57	$437.92
Annual operating costs ($/yr)	$376 000	$328 000
Annual depreciation ($/yr)	$18 600	$11 800

expressed in terms of $/yr using a straight-line depreciation over 10 years.

The operating cost advantages for this case study are similar to those presented in the retrofit TEA, shown in Table 7. In addition to batch operating costs, the annual operating costs have been provided to allow for a comparison of annual costs per year by the two methods.

Results and discussion

The impact assessment findings, shown in Table 3, indicate substantial environmental benefits offered by the BGAL approach. Specifically, the BGAL approach is predicted to reduce CED by 99%, CDU by 1.7%, and GWP by 98%. Additionally, the operating cost per batch is estimated to fall by $30 per 240 L batch, a 40% reduction, using the BGAL approach. These savings would allow the capital costs of retrofitting the 240 L carbonation train to be recouped in approximately 150 batches, or 1.3 years assuming the production rate of 113 batches per year per carbonation train remains constant after the retrofit.

Although this system has been evaluated experimentally at the 240 L pilot scale, practical operational parameters may vary widely across different brewery settings with different equipment or practices. Thus, sensitivity analyses were conducted to understand how these environmental and economic benefits may vary under different circumstances. These analyses included altering the system size, energy demand, and operational time.

To understand how the proposed system would compare to a traditional carbonation scheme at different scales, environmental and economic models were built for the 240 L (baseline), 600 L, 12 hL, and 24 hL scale. In these analyses, the purge conditions were selected to minimize the amount of released CO_2. The time to carbonation for the traditional approach was maintained at 72 hours for all scales, and the operational rate for the BGAL approach for pumping and chilling energy computations was maintained at 3.7 L min^{-1}. Because the BGAL system has only been experimentally validated at the 240 L baseline scale, the operation rate was held constant at 3.7 L min^{-1} across all scales as a conservative assumption; in practice, larger systems would likely operate at higher flowrates, accommodated by correspondingly larger nozzles, pumps, filtrations systems, and chillers, potentially offering different results than those presented here. The LCA and TEA results of this sensitivity analysis are summarized in Fig. 3 and 4, respectively.

These results show slightly diminishing returns as the size of the system increases. The 99% reduction in CED achieved with the 240 L baseline falls to 85% reduction in the 24 hL scenario. Similarly, the 97% reduction in GWP for the 240 L baseline falls to 78% reduction in the 24 hL scenario. In the TEA, the BGAL system has 40% lower operating cost per batch in the baseline scenario compared to 12% lower operating cost in the 24 hL scenario. Despite the diminished operational savings in the 24 hL scenario compared to the baseline, the CAPEX to retrofit a 24

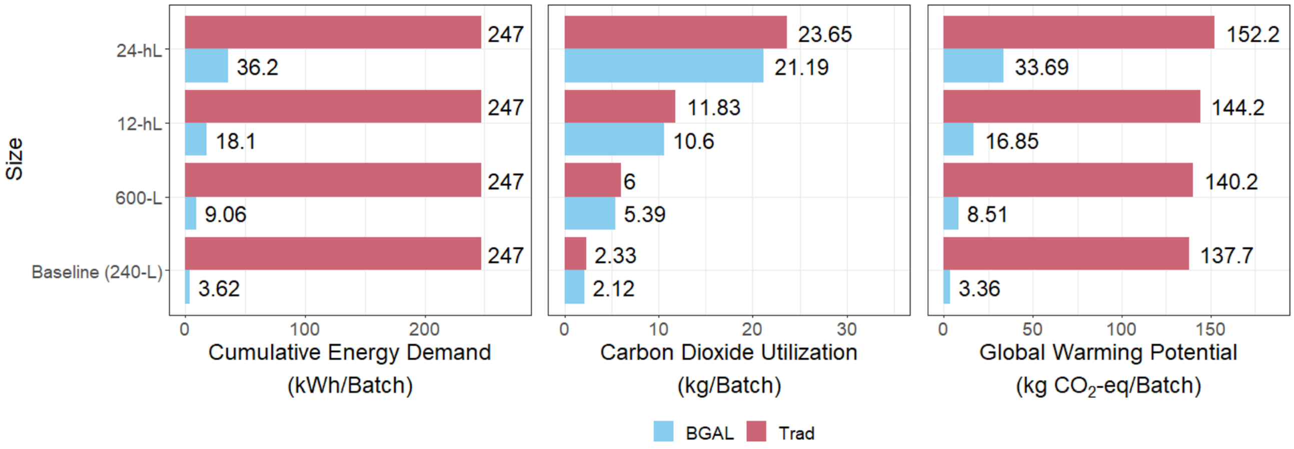

Fig. 3 LCA under different size scenarios.

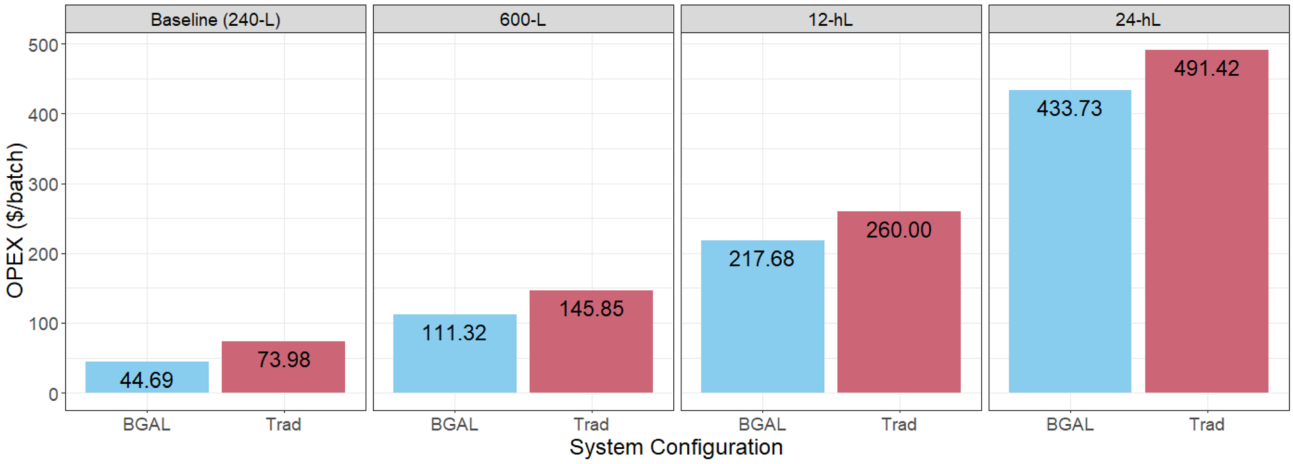

Fig. 4 TEA under different size scenarios.

hL facility is the same as that to retrofit a 240 L facility. Thus, the payback period falls from 1.5 years in the baseline scenario to 0.7 years in the 24 hL scenario due to the greater absolute magnitude of operational savings ($58/batch *versus* $30/batch) at the larger scale.

In the baseline scenario, the maximum rated energy demand of the laboratory glycol chiller (2400 W) at 70% efficiency was assumed to offer a conservative estimate. In practice, this assumption likely overestimates the amount of energy required due to changes in bulk temperature within the bright tank over time. For instance, the glycol chiller may be maximally deployed to chill the warm post-fermentation beer when it is first added to the bright tank. However, once the desired carbonation temperature is reached, the demand by the chiller may be reduced such that it only turns on intermittently to account for heat loss to the environment. Thus, four models were built, assuming an average energy demand over the entire carbonation step of 100% (baseline), 75%, 50%, and 25% of the overall chiller capacity. The LCA and TEA results of this analysis are shown in Fig. 5 and 6, respectively.

These results show diminishing returns for the BGAL system as the energy demand for the chiller is reduced. Although comparing the 25% energy demand scenario for the traditional configuration to the 100% energy demand scenario for the BGAL configuration (the best and worst cases, respectively) still shows a 94% reduction in cumulative energy demand and a 90% reduction in global warming potential, these environmental benefits are reduced compared to the baseline analysis. Similarly, because the cost of energy comprises a minor portion of the operating costs in the BGAL configuration, the operating cost savings fall from $30 per batch in the baseline scenario to $8 per batch in the 25% energy demand scenario. This reduction in savings increases the payback period of retrofitting from 150 batches to 540 batches, or 5 years. Thus, the outcome of these analyses may be very sensitive to the operational strategy for the chiller, particularly for the traditional configuration.

Because the major contributor to both operating costs and environmental impacts in the traditional system is attributed to the energy utilization of the chiller, a sensitivity analysis was performed on the residence time within the bright tank or the rate of carbonation, the closest equivalent parameter to

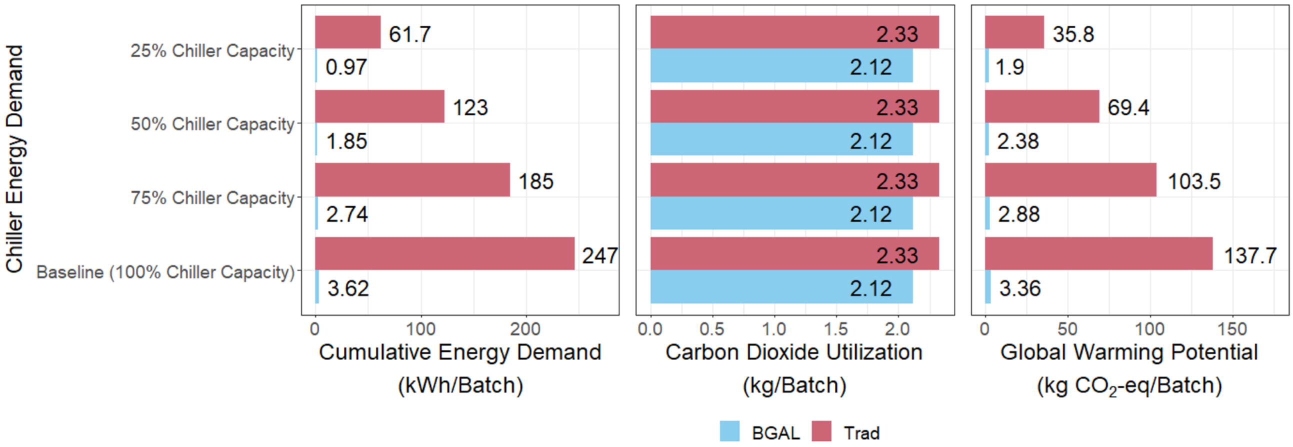

Fig. 5 LCA under different energy demand scenarios.

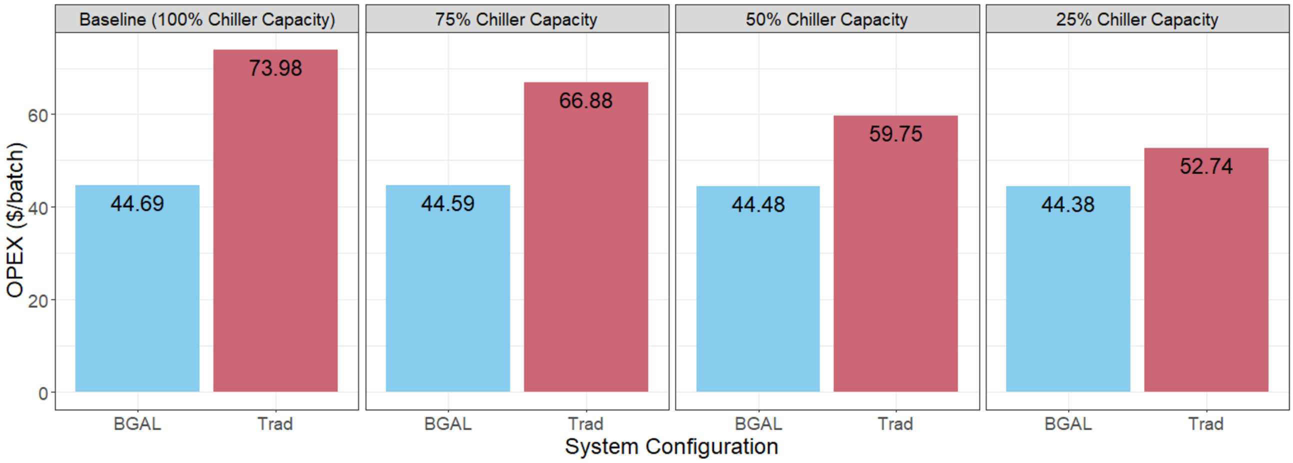

Fig. 6 TEA under different energy demand scenarios.

residence time in the BGAL configuration. The carbonation methods in micro-breweries are highly variable, dependent upon brewer preference. Some brewers prefer to bubble excess CO_2 into their bright tanks at a high flowrate that may not fully dissolve, resulting in faster carbonation but more wasted CO_2 and possible flavor stripping, foaming, or over-carbonation. Alternatively, brewers may opt to set their CO_2 flowrate very low to ensure that the gas is fully dissolved and reaches exactly the target concentration, which may require up to 5 days to reach the required carbonation levels. Thus, considering the full range of operating preferences will give a better understanding of the practical benefits of a BGAL approach.

In this sensitivity analysis, models were built for the traditional configuration by altering the residence time compared to the baseline 72 hours: half the baseline residence time (36 hours), twice the baseline residence time (144 hours), and four times the baseline residence time (288 hours). The same models were built for the BGAL configuration by altering the flowrate of the beer through the system: 3.7 L min^{-1}, 7.6 L min^{-1}, 1.9 L min^{-1}, and 0.9 L min^{-1}. These LCA and TEA results of this analysis are shown in Fig. 7 and 8, respectively.

Similarly to the sensitivity analysis involving the energy demand of the chiller, this analysis shows diminishing returns with decreased residence time and increased rate. In other words, the less time the beer must spend in the bright tank, the fewer benefits are offered by the BGAL approach. This is particularly apparent when examining the TEA results when only half the amount of time is required for carbonation. Although this scenario indicates similar environmental benefits for the BGAL configuration as in the baseline, the operating cost savings are only $15 per batch, indicating a payback period of 300 batches, approximately 2.6 years. This result indicates that the BGAL system may not be suitable in every micro-brewery setting. For breweries that regularly practice 36 hours or shorter carbonation times, the $15/batch savings may not be sufficient to justify the downtime and learning curve associated with converting to a BGAL system. Even so, these breweries may still consider the BGAL approach for its process intensification advantages rather than cost reductions alone. However, this analysis also shows the benefits of the BGAL approach if the required residence time is greater than 72 hours. At a 288 hours residence time, the BGAL approach shows a 99% reduction in

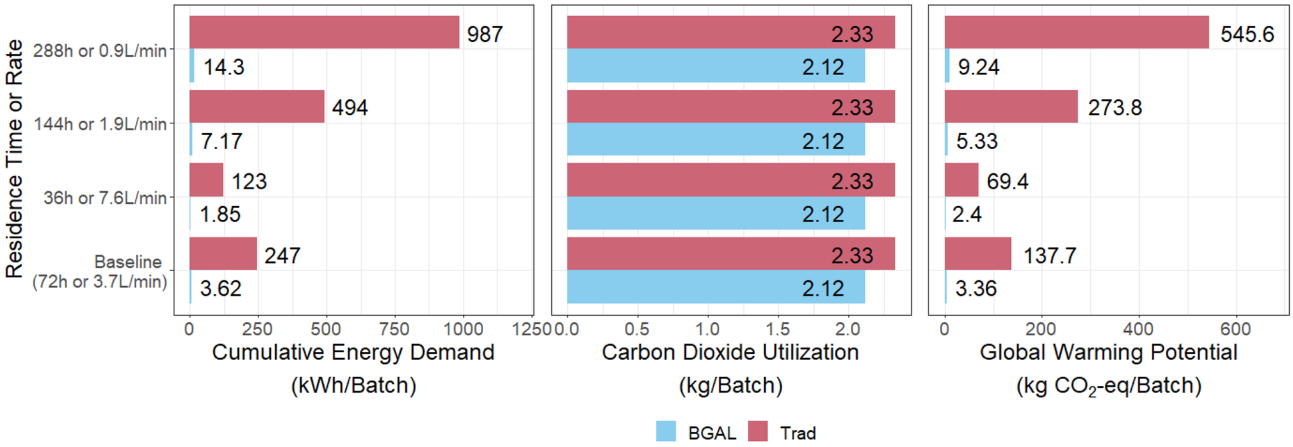

Fig. 7 LCA under different residence time and rate scenarios.

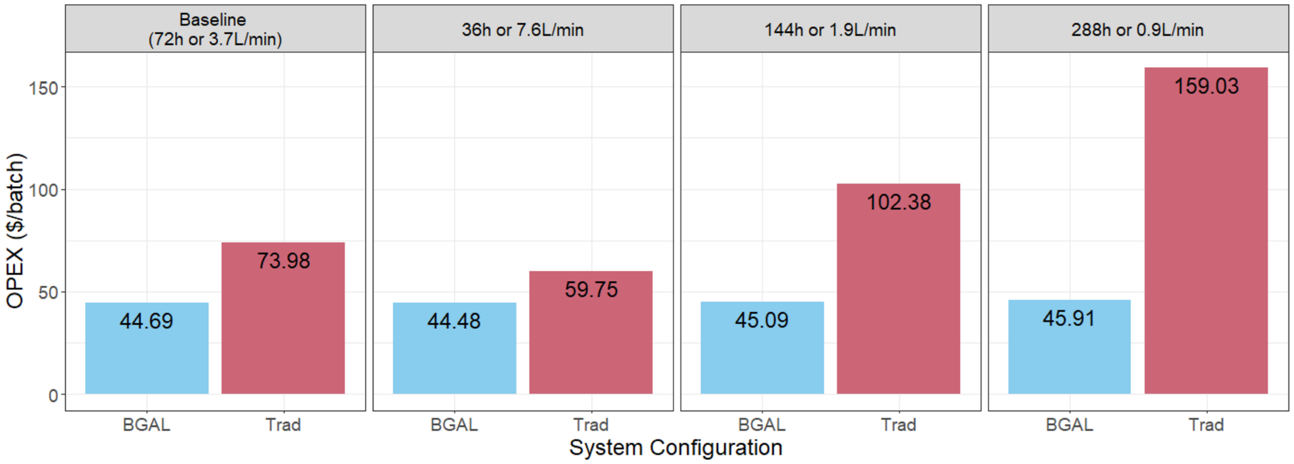

Fig. 8 TEA under different residence time and rate scenarios.

cumulative energy demand and GWP as well as a $114 reduction in operating cost per batch, indicating a payback period of 40 batches, less than 1 year.

When considering the costs of building a new 18 000 hL per year micro-brewery, Table 7 showed that the enhanced efficiency of the BGAL approach required only 3 24 hL carbonation trains whereas the traditional approach required 7 24 hL carbonation trains. This improvement resulted in a CAPEX reduction of $95 000, or 45%, by opting for the BGAL configuration. Similarly, the annual operating costs fell by $48 000, or 13%. This amounts to an annual cost reduction of 14% when distributing the capital costs of each approach over 10 years using the straight-line depreciation method. These results are shown in Fig. 9.

Although new micro-breweries may opt to gradually ramp up to an eventual capacity of 18 000 hL per year rather than building in one step as assumed, the per-batch operating cost savings reported in Table 7 would persist regardless of production rate, and the reduced upfront CAPEX requirements of the BGAL configuration would remain advantageous even at lower initial throughput. Thus, this case study indicates the substantial process improvements offered by the BGAL approach at full capacity, while the retrofit TEA provides a more conservative estimate of the economic benefits available during early-stage or lower-volume operation. Moreover, it offers insight into how brewers could scale up their operations without investing in additional carbonation trains by retrofitting their existing bright tank systems, saving both money and physical space in their brewhouse.

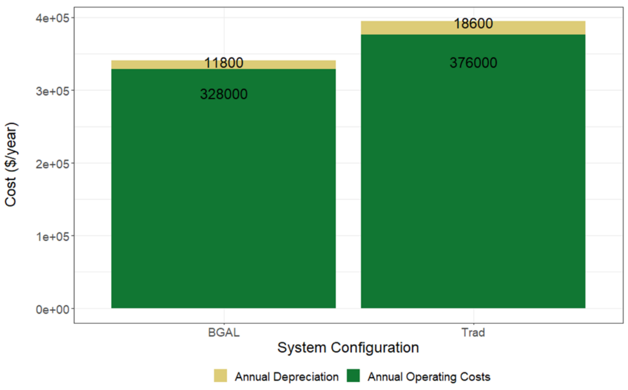

Fig. 9 Annual costs of a new 18 000 hL per year micro-brewery.

Although many of the choices made in the design of the BGAL system were intended to minimize alterations necessary to the carbonation system, practical barriers to industrial adoption may exist. While in-line filtration is often utilized in craft and larger brewery systems, filter management may be a new complexity in many micro-brewery settings, requiring new standard operating procedures.[11] Furthermore, filtration practice and schedule may require further optimization to determine pore size and replacement schedule in relation to beer style and upstream practices. Similarly, nozzle replacement and maintenance were not included in this analysis, although Jean *et al.*[4] suggested that a clean-in-place procedure could be carried out as usual in the bright tank using the installed BGAL nozzle. Transition to a BGAL system will also require unique operation and maintenance training, and operation of this system requires more active operator involvement compared to the largely passive traditional system for flowrate monitoring and keg cycling. The operational parameters such as pressure or flow rate may also need further refinement to meet specific carbonation levels and other beer style requirements. Finally, although this analysis presented TEA and LCA results for several equipment scales, operation of the BGAL system has yet to be verified at scales greater than 240 L, and different operational settings are likely necessary for different bright tank geometries.

Conclusions

Overall, the results of these analyses show that the BGAL system offers both environmental and economic benefits over the traditional approach across many different operational and system scenarios. Moreover, the payback period for the retrofit is reasonable, approximately a year in the baseline scenario, due to the 40% reduction in operating costs. However, these results clearly show that this conclusion may be sensitive to the residence time of beer within the bright tank and the energy requirements of the chiller in the traditional configuration. Thus, the BGAL approach for carbonation may be utilized to reduce the time necessary for carbonation of beer while providing additional economic and environmental incentives in support of the sustainability goals of small-scale breweries.

Author contributions

CRediT: Alexandra B. Jean: conceptualization, formal analysis, investigation, methodology, visualization, writing – original draft, writing – review and editing; Jordan Funkhouser: conceptualization, writing – review and editing; Robert C. Brown: conceptualization, writing – review and editing.

Conflicts of interest

Alexandra B. Jean, Jordan Funkhouser, and Robert C. Brown are listed as inventors on a pending patent application relating to this work (US20250325946 – Device for Rapid Carbonation of Beverages; Application No 19184904). The authors declare no other competing financial interests.

Data availability

The data supporting this article, including inventory assessments, itemized capital and operating costs, impact assessment results, the OpenLCA JSON-LD project archives are available at the GitHub repository abjean-ISU/RapidCarbonationTEALCA_2026 at https://doi.org/10.5281/zenodo.19700338. The LCAs were built in OpenLCA 2.4.0 (2024) with databases publicly available in the Federal LCA Commons Repository, available at https://www.lcacommons.gov/lca-collaboration/. Specific databases used include the Elementary Flow List v1.2024-12.0 available at https://www.lcacommons.gov/lca-collaboration/Federal_LCA_Commons/elementary_flow_list/datasets?commitId=6f84d4b90dea264b3d0a2daa7d71e6bdf4f67c66 and the US Electricity Baseline v1.2020–08.0 available at https://www.lcacommons.gov/lca-collaboration/Federal_LCA_Commons/US_electricity_baseline/datasets?commitId=feae44943f7984498ed2aad7d931b74f34f8bca4.

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