EVALUATION OF THE TECHNO-ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF CRAFT BEER PRODUCTION: A CASE STUDY ON MICROBREWERY

by

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ABSTRACT

Beer has been part of the civilized culture dating back to 5,000 B.C. and it is still one of the most important beverages in many countries. Beer can be produced at different scales, nowadays, craft brewery (microbrewery) has become more popular and represents 13.2% of the beer sales in the U.S. in 2018. Nonetheless, craft brewers face many challenges due to energy efficiency, resulting in low profitability margins and poor environmental performance. Therefore, there is a necessity for tools to analyze the energy efficiency profile of microbreweries and assess potential improvement strategies based on holistic modeling. This study developed an integrated Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) to (i) evaluate the economic profitability of replacing the conventional steam boiler in a microbrewery facility by a continuous water heater, and (ii) compare the environmental performance of ale and lager beer brewing at commercial and pilot scales. Labor, packaging and raw materials were the major operating costs of microbrewery. The simulation results of the average electricity and natural gas uses for craft beer production agreed well with the primary measurements. The net present value and internal rate of return obtained from the TEA indicated that the investment project of new water heating system would not be profitable. Moreover, the sensitivity analysis showed that the profit margins of the water heating system increases if the microbrewery increases its productivity. Beer processing accounted for the largest portion of the global warming, terrestrial acidification, freshwater eutrophication and water consumption of craft beer, whereby fermentation and maturation operations were the main contributors. The results obtained from this study can facilitate the decision-making process of microbrewers, technology providers and stakeholders to achieve a more sustainable beer production process.

CHAPTER 1. INTRODUCTION

1.1 Overview

Beer dates back to the year 5000 B.C. and has been a valuable product because of its entanglement with religious, culinary, and ethnic traditions throughout history (Esslinger 2009). Nowadays, beer brewing is still one of the most important food industries in various countries. "Craft beer" is defined as beer made by a brewer that is small, independent, and traditional (Brewers Association 2019a). In the U.S., 25.9 M barrels were produced by craft breweries in 2018 (Kendall 2019). Most of craft brewers operate their production based on very traditional processes and older technologies, which, however, pose challenges to energy efficiency, resulting in higher environmental footprints and lower profitability margins.

There is a necessity of tools for evaluation of energy efficiency profiles and identification of improvement opportunities of brewing systems based on holistic modeling and parametric studies under different processing conditions (Muster-Slawitsch et al. 2014). To assess the technical feasibility and economic profitability of a production process, techno-economic analysis (TEA) is a commonly used tool which can provide recommendations for process design and operation based on technical data (Zimmerman et al. 2018). Although some studies have modeled the energy efficiency of beer brewing based on general assumptions (Dumbliauskaite et al. 2009; Muster-Slawitsch et al. 2014), research on American craft brewery systems is still very limited. Furthermore, when economically feasible solutions are proposed for improving a brewing system, it is important to consider their environmental viability as well. Life Cycle Assessment (LCA) is a systematic method to analyze and compare the environmental performance of a product or process through its life cycle (ISO 2006). LCA is a powerful tool to quantify the environmental impacts of a production system and has been widely applied in beer processing (Koroneos et al. 2005; Cordella et al. 2008; De Marco et al. 2016). Nonetheless, the environmental sustainability of American craft breweries, to the author's best knowledge, has not been thoroughly studied.

1.2 Brewing process

1.2.1 Milling

The brewing process consists of multiple unit operations: milling, mashing, boiling, whirlpooling, cooling, fermentation, maturation, and packaging (Kunze 2016). Traditionally, the process starts with breaking malted barley or adjunct grains (e.g., wheat, rice, flaked corn, sorghum) down into small fragments to make their starch and other malt components available to enzymatic reaction. In general, a greater extent of grain comminution results in a larger reactive surface area to enzyme. Nonetheless, after mashing, the extract needs to be run off for which the malt husk needs to be intact to act as a filtering material. Hence over-milling of grains could impede their filtration performance. Milling can be performed in a dry or wet basis, and the use of roller mills is the most common option. Micro and pub breweries usually use simple two-roll mills.

1.2.2 Mashing

After milling, the ground grist is mashed in (mixed with) hot water (liquor) to bring the malt components into solution which are then subjected to enzymatic reaction. The main purpose of mashing is to degrade starch through gelatinization, liquefaction, and saccharification of starch granules. A series of enzyme reactions occur during the mashing process, which depend on the grains used and desired type of beer. The starch hydrolysis is controlled by α-amylase which degrades starch to dextrins, and by β-amylase which then breaks down the amylose chains into maltose molecules. Since some enzymes are very heat-sensible, the mashing temperature needs to be accurately controlled in the ranges for optimum enzyme activity. Table 1.1 summarizes the optimum temperature ranges of main mashing-related enzymes. For instance, to achieve a higher maltose content, mashing temperature should be 62−65 ºC, at which β-amylase has the highest activity. In addition to starch degradation by α- and β-amylases, other reactions occur simultaneously such as β-glucan degradation, conversion of fatty matters, and releases of phosphates, polyphenols, and zinc, which are all important for wort production. β-glucan degradation, catalyzed by β-1,4-glucanase, is needed to decrease wort viscosity and prevent filtration problems. Solubilization of phosphates and zinc is essential for ethanol formation during fermentation, zinc is directly used by yeasts for protein synthesis and cell growth. On the other hand, lipoxygenase reaction can generate free fatty acids responsible for ageing and cardboard flavors in beer, which, therefore, has to be prevented.

Mashing temperature needs to be determined together with mashing time for desired products. Generally, the maximum enzyme activity is reached after 10−20 min mashing, then decreases rapidly after 40−60 min. Longer mashing time results in higher extract and maltose contents, that in turn lead to higher attenuation level which ultimately determines the alcohol content of beer. The temperature-time combination, and thus heat use, depend on the enzyme used and the type of beer brewed. Mashing process accounts for about 20% of the energy consumption of brewhouse operations (Scheller et al. 2008), which can be decreased by optimizing the heating process of mashing water.

Table 1.1. Main enzymes associated with mashing process.

Enzyme	Optimum temperature (ºC)	Function
α-amylase	70−74	Hydrolyze amylose to smaller dextrins.
β-amylase	62 (58−65)	Cut maltose off from the reducing ends of amylose. Determine the attenuation level of beer.
Endo- β-1,4 glucanase	40−48	Degrade the β-glucan adhered to protein. Break down the soluble high molecular β-glucan in well-modified malt to soluble low molecular β-glucan.
β-glucansolubilase	62 (50−70)	Convert undesired insoluble high molecular β-glucan (causing filtration problems during mashing) into soluble high molecular β-glucan.
Proteinases	60−70	Produce high-molecular-weight protein degradation products, which are responsible for foam stability, body (palate fullness), and haze.
Peptidases	45−50	Produce low-molecular-weight protein degradation products, particularly peptides and amino acids which are essential for yeast nutrition.
Lipase	37−40	Break down lipids to fatty acids.
Lipoxygenase	35	Break down fatty acids to glycerine and hydroxy fatty acids, producing ageing carbonyls, off odors and flavors.
Phosphatases	50−53	Dissolve organically bound phosphates, which are of high importance for alcoholic fermentation.

1.2.3 Boiling and hopping

After mashing, the wort is boiled and hops are added. The bitter (hop resins) and aromatic (oil and polyphenolic compounds) components in hops are extracted into the wort, and the proteins are precipitated. Through activation by high temperature, the α-acids in hops are isomerized and solubilized to provide bitterness. Furthermore, hop oil, associated with aroma strength and pleasantness, is a desired component to retain. Therefore, hops with high-quality oils are normally added at the end of boiling or at whirlpool step. Water-soluble polyphenols dissolve immediately in the wort, which can influence the shelf life of beer due to their antioxidant properties. In addition to dissolving water-soluble hop components, boiling can cause high-molecular-weight proteins to coagulate and bond to polyphenols in hops and malt, forming water-insoluble compounds which are precipitated as break (trub).

Boiling also causes water evaporation and concentrates the wort solids, making the final wort concentration increase by 5−6%. However, evaporating a large amount of water is not economically feasible due to the high cost of energy, and thus the water evaporated should be minimized. Since boiling is the most energy-intensive unit operation of the brewhouse processing (Galitsky et al. 2003), the boiling time needs to be minimized while maintaining the beer quality. New boiling methods have been developed to avoid long boiling time, which can retain more high-molecular-weight proteins dissolved in the wort, resulting in lower energy consumption as well as better beer quality in terms of foam retention. The finished wort obtained with the new boiling methods contains approximately 1,000 mg total nitrogen per liter (Kunze 2016). For a satisfactory fermentation, 220−250 mg free amino nitrogen (FAN) per liter of wort is desired (Novozymes A/S 2013).

Wort boiling can also sterilize and destroy bacteria and molds. Besides, when all remaining enzymes are inactivated, no further degradation will occur, which helps preserve the beer. The thermal exposure of wort also accelerates Maillard reaction and production of Strecker aldehydes. To limit the formation of darker compounds, long and vigorous boiling should be avoided. The wort becomes more acidic due to the melanoidins formed and the hops added, reaching the pH of approximately 5.4−5.5. Lower pH values can prevent excessive formation of dark colors during boiling, provide a better, clean-tasting hop bitterness, and inhibit microorganism growth.

1.2.4 Whirlpool

The whirlpool tank is a vertical cylindrical vessel. Wort is tangentially pumped into the tank to create a whirlpool to move the hot break to the vicinity of tank wall by centrifugal force. When pumping is completed, the whirlpool slows down and eventually stops because of the friction caused by the wall and bottom of the tank, resulting in formation of a vigorous current drawing the solids in a spiral pattern to the center of the tank, which can then be collected in a loose heap (Kunze 2016).

It is necessary to examine the suitability of wort for whirlpool by filling an insulated Imhoff glass cone with the wort to a depth of 380 mm. A wort suitable for whirlpool can completely settle after 5−6 min. In contrast, unsuitable wort does not have satisfactory settlement even after 10 min. Possible causes of poor hot break separation include poor lautering, too high shear stress in pipe, too fast inflow, too strong secondary current in the whirlpool, too high discharge velocity, and an unfavorable matching of the height of the wort and the diameter of the whirlpool. It is very important that the inflow velocity is not greater than 3.5 m/s to prevent unnecessary shear stress.

1.2.5 Cooling

For yeast to grow and ferment, wort must be rapidly cooled by heat exchanger to the appropriate pitching temperature, which is defined by the style of the beer brewed. Cooling is also important to prevent the growth of spoilage microorganisms and to extend the shelf life of beer. During cooling process, wort is oxygenated to promote controlled yeast propagation. Oxygen is essential for the syntheses of sterols and fatty acids, the main components of yeast cell wall. Aeration, on the other hand, can deteriorate flavor by oxidation reactions, so the amount of oxygen injected needs to be optimized.

Cooling water is used to cool down the wort from 98−95 ºC to 6−8 ºC using plate heat exchangers. It is desired to maximize the heat transfer to recover the heat to regenerate hot water, which can be stored in an energy storage system or reused for other processes. The cooling process can be performed in single- or two-stage operation. In two-stage operation, cooling water is used first to pre-cool the wort from 95−98 ºC to about 3−4 ºC above the initial water temperature, while the water is heated to 90−95 ºC. Then, in the second stage, the wort is cooled down to the desired pitching temperature by iced water, of 1−2 ºC. While two-stage operation is more energy-efficient, it requires more water. Hence the single-stage operation is more commonly used nowadays, in which cooling water is heated in plate heat exchangers to 90−95 ºC while hot wort is cooled to the pitching temperature.

1.2.6 Fermentation

To produce beer, cooled wort needs to be fermented first by yeasts that convert wort sugars to alcohol and carbon dioxide. Yeast metabolizes wort components into simpler by-products, and synthetizes energy required for its metabolism and reproduction through anaerobic alcoholic fermentation. For instance, proteins in wort are essential for the cell wall production of new yeast cells. Furthermore, fatty substances form the cell membrane around the interior organelles of yeast cell. Yeast sequentially ferments monosaccharides, disaccharides, and trisaccharides in wort. Normally 98% of the sugars are fermented and the rest are metabolized through glycolysis process.

Fermentation is an exothermic reaction producing approximately 587 kJ/kg of extract (Kunze 2016), which is usually removed by coolant circulating in the tank jacket. Fermentation temperature is determined by the type of yeast used and the type of beer to be produced. At the end of the primary fermentation, the "green beer" needs to be slowly cooled down again then transferred to the maturation tank. A conventional primary fermentation takes about 6−8 days, after which yeast is cropped from the tank.

1.2.7 Maturation

During maturation, green beer is saturated with carbon dioxide and all haze-forming components are removed. The filled beer should contain about 0.5% CO_2, the one containing less than 0.32% is considered "flat" (Kunze 2016). To remove the remaining yeast cells from beer to prevent cloudiness, beer is left for longer time to sediment the small particles. The sedimentation can be enhanced by using smaller maturation vessel with higher surface-to-volume ratio, or by adding wood or hazelnut chips. To complete the cold break and for particles to settle down, beer needs to be lagered (i.e., maturated) for at least 7 days at low temperature (−1 to 5 ºC) (Briggs et al. 2004). Then, beer can be pasteurized to extend its shelf life, a common practice in traditional large breweries; however, craft beer is usually not pasteurized.

1.2.8 Filling

After maturation, beer is filled typically into glass bottles, cans or kegs, although the use of plastic bottles is becoming more popular nowadays. This primary package protects beer from quality degradation. For example, due to the light sensibility of beer, dark bottles are preferred to prevent formation of off-flavors and aromas. Moreover, oxygen intake must be eliminated to reduce oxidation reactions in beer components.

During filling, pressure, beer volume and temperature must be controlled to secure beer quality. Additional pressure can be applied to make filling faster. The volume can be controlled either by a set height or level in the bottle. The temperature difference between beer and bottle should be minimized to prevent foaming. Furthermore, filling and storing at low temperature is very important to inhibit microbial growth.

1.3 Beer types

Beer has a wide variety of styles, which manufacturers develop to meet consumers' demand. While thousands of brands can be found on the market, beer can be classified by different criteria. For instance, in Germany, beer is classified based on its original gravity (OG) into four categories: low OG beer (up to 6.9%), draught beer (7−10.9%), full beer (11−15.9%), and strong beer (16% and above). Moreover, depending on the type of yeast used and the fermentation process, beer can be classified into two main groups: top-fermenting beer, commonly known as ale, and bottom-fermenting, known as lager. Yeasts with different physiological characteristics result in difference in their behaviors during fermentation, which are summarized in Table 1.2.

Table 1.2 Physiological characteristics of top- and bottom-fermenting yeasts

Characteristic	Top-fermenting (*Saccharomyces cerevisiae*)	Bottom-fermenting (*Saccharomyces pasteuranius*)
Raffinose fermentation	Ferment up to one-third of raffinose present	Ferment completely
Spore forming	Spores form after 48 h	Poor spore-forming ability
By-products	Produce larger amounts of by-products, including alcohols, esters, particularly ethyl acetate and isoamyl acetate	Produce smaller amounts of by-products

Top fermentation is the oldest method for beer production and was developed particularly in Germany (Weiβer, Altbier or Kölsh, and alcohol-free malt beer, etc.), U.K. (Ale, Porter or Stout), and Belgium (Lambic, Gueze, Trappist beers, White beers, etc.). The top-fermenting yeasts tend to form clumps of buds which break up after fermentation starts, so that the yeasts can be carried up by the CO_2 produced to the top of the vessel, and then be harvested. Some common top-fermenting beers and their main characteristics are summarized in Table 1.3.

Table 1.3 Types of top-fermenting beer.

Beer type	Processing features	Characteristics
Wheat beer	Low mashing-in temperature; no mash acidification; at least 40% barley malt; fermentation temperature of 20−24 ºC; one or two yeast cycles; early harvesting of yeast	Different aroma; can be yeast-containing beer (fermented in bottle) or sparkling clear with no yeast contained (filtration applied)
Weiβe	Made of 30−35% wheat malt; addition of hops during mashing; wort is not boiled, just held at 95 ºC for 25−30 min; fermented using a mixture of top-fermenting yeast and lactic acid cultures. In some cases, a secondary fermentation is performed in bottle, the acidic environment allows the beer to be stable for years and the flavor continues to mature.	Naturally cloudy and pale, with approximately 7.5% OG; contains about 2.7−2.8% vol. alcohol and 0.7% CO_2; final pH of 3.2−3.4; floral flavor, often with syrup added to lessen the acidic flavor
Altbier	Traditionally brewed with barley and wheat malt	Dark amber color; bitter taste; OG of 11.5−12%; 4.8−5% vol. alcohol
Kölsch	Traditionally only brewed in Cologne, Germany; brewed using Vienna malt with up to 20% wheat malt; infusion or single mashing; primary fermentation at 14−18 ºC for 3 or 4 days; lagering at 4−5 ºC for 40−60 days, then at 0−1 ºC for 14−40 days	Dry and pale; 11.2−11.5% OG; 4.6−5.1% vol. alcohol
Ale	Using raw grains; infusion mashing; adjuncts such as honey or orange peel used for seasonal themed beers	Alcohol content varying from 3 to 10%; wide variety of flavors from fruity to honey; various types like pale ale, bitter ale, mild ale, Scotch ale, depending on the adjuncts used

Table 1.3 continued

Stout	Brewed with a mixture of pale malt and 10−20% of very highly colored malt. Guinness is the largest stout producer who uses 10% roasted barley.	Very dark color, up to 200 European Brewery Convention (EBC) units; strong burnt taste; harsh bitterness; with very fine and persistent foam (because of nitrogen gas used for dispensing
Porter	Secondary fermentation applied to achieve high alcohol levels; using *Brettanomyces* yeast strains that can live after many years and continue to ferment the beer in bottle	Dark and bitter; OG of 13−14%, containing up to 9% vol. alcohol
Belgian beer	Brewed using 10−15% caramel malt; infusion mashing; using whole hops; adding liquid candy sugar to wort; performing secondary maturation at 0−5 ºC; adding sugar and yeast to bottle before filling	High to very high alcohol content; variety of flavors

Bottom-fermentation was first applied in the end of the 15th century and gained more attention in the late 19th century. Its development was closely associated with the inventions of refrigeration system by Linde (1871), mechanical glass blowing which reduced the cost of bottle manufacturing, and beer filtration using metal sieves by Lorenz Enzinger in 1878. Some examples of major bottom-fermenting beers are described in Table 1.4. In contrast to top-fermenting beer, bottom-fermentation uses the yeasts which tend to remain suspended in wort instead of rising to the surface (Bokulich and Bamforth 2013).

Table 1.4 Types of bottom-fermenting beer.

Beer type	Processing features	Characteristics
Pilsner	Using high-quality hops; intensive three-mash method before 2-h boiling applied for desired darker color	Average OG of 11.3−12.2%; 5.07% vol. alcohol; varying colors from pale to very dark; low bitterness
Lager	Low fermentation (7−15 ºC) and maturation (−1−5 ºC) temperatures	Accounting for 80−90% of bottom-fermentating beer; OG of 10.5−12.5%; alcohol content of 4.7−5.3% vol.; moderate bitterness
Export beer	Brewed with high grain:water ratio to achieve high OG	Pale; OG of 12.5−13.5%; alcohol content of 5.38% vol.; stronger than Pilsner; more bitter than pale beers; aromatic flavor
Black beer	Original wort content of 11.5−11.8%; using roasted malts for pleasant flavor	Dark color (100−150 EBC); alcohol content of 4.8−5.0% vol.

1.4 Techno-economic analysis

Since the brewing process is very energy-intensive, it is important to identify the unit operations which are the energy hotspots in order to improve its energy efficiency. Techno-economic analysis (TEA) is a systematic and holistic tool to analyze the technical and economic performance of a process (Zimmerman et al. 2018), which can support decision-making based on the objective and quantitative indicators. TEA methodology has been used for: a) performance comparison among technologies for research purposes, b) comparisons among technologies for business purposes, c) modeling grid systems to calculate the impacts of different technologies on the delivery cost of power, and d) modeling national and international energy systems to correctly allocate resources among different sectors (Gurba and Lowe 2009).

Different from life cycle cost (LCC) analysis, which analyzes the economic performance of a product over its entire life cycle (Reidy et al. 2005), TEA mainly focuses on the production stage from manufacturer's or investor's perspective, and integrates cost, revenue and technical criteria (Zimmerman et al. 2018). The standardized TEA methodology includes four main phases: goal and scope definition, inventory, calculation of indicators, and result interpretation (Zimmerman et al., 2018), which are described in detail below.

1.4.1 Goal and scope definition

The first step of TEA is to identify its goal, and subsequently set the scope of the analysis accordingly, describing what aspects of target process or product will be assessed. The goal needs to clearly address the techno-economic questions to answer, for example, the cost or profitability of a new technology, product, plant or project. Moreover, specific audience has to be identified (e.g., funding agencies, industry managers, policy makers), which will define the type of data needed for the analysis and the adequate indicators to present the results. TEA can be conducted through process- or product-oriented approach, depending on the problem to solve. Process-oriented approach evaluates different processes to produce a set of products using a specific raw material, which can answer to the questions about product portfolio selection. On the other hand, Product-oriented approach aims to evaluate several paths for producing a single product (Gargalo et al. 2016).

A TEA needs to have a plausible goal and a realistic scope according to the project scale and time available. The project's perspective will be defined by the stakeholders involved, for instance, the results of a project need to answer plant manager's questions about the feasibility of new technologies and potential improvements required. However, because the scope of a single study is limited, the results should also document the remaining data gaps or unanswered questions.

Because a production system can have one or multiple output flows including co-products or by-products, the basis of comparison, i.e., functional unit (FU), has to be defined. Depending of the nature of the system, the FU can be defined as product volume, mass, energy, or others. The FU describes the basis which all the inputs and output flows are set into relation with.

In order to set the limit of the data to be collected and structure the data inventory, system boundaries should be defined, which is also required for result interpretation and reporting. Furthermore, well defined boundaries can help identify the allocation of the results and process hotspots.

1.4.2 Inventory

The inventory collection consists of documentation of all inputs and outputs associated with the processes included in the defined system boundaries based on one FU. The data is collected according to the temporal, geographic, and economic context of the study. The technical conditions and assumptions made for material and energy flows as well as equipment should be documented, which are important for replicating the analysis. For instance, to analyze the performance of a process, some processing parameters are closely related to the thermodynamic limits of chemical conversions, which should hence be addressed and documented (Gargalo et al. 2016). This is particularly important for new technology implementation and optimization of processing parameters to prevent overestimation of efficiency. Moreover, the quality of the data collected must be defined, which has to be as consistent as possible. To analyze a brewing process, different types of data need to be collected, including process-specific data (i.e., primary data directly from a process), average data, and generic data calculated to reflect a typical scenario based on similar processes or experts' assumptions.

1.4.3 Calculation of indicators

Technical and economic indicators are selected to answer the questions determined in the goal and scope phase and can be easily understood by the target audience. The results can quantitatively reflect the technical performance or economic impacts of the process. All the data collected and the associated assumptions are clearly linked to the indicators and the repeatability of the calculation procedure is ensured. Some of the indicators that are commonly used are capital expenditure (CapEx) and operational expenditure (OpEx) which can be directly interpreted, compared to other aggregated indicators which are obtained with further calculations.

Other TEA methods include static cost benefit assessment, annuity method, net cash flow table, net present value, and internal rate or return (Lauer [accessed 2019]), summarized in table 1.5.

Table 1.5 TEA methods.

Indicator	Output	Advantages	Limitations
Static cost benefit method	Estimate of the profitability of a project without considering interest rates.	It offers an easy and quick preliminary assessment of a project.	May overestimate the benefits by neglecting interest and inflation rates.

Table 1.5 continued

Annuity method	Calculates a fixed and constant annual payment over the lifetime of the investment.	It is a simple method and easy to compare between projects.	It is not possible to distinguish variations in cost and benefits from one year to another (i.e. the same net benefit is applied to every year).
Net cash flow table	Predicts the payback period of the project (i.e. the time required to achieve a positive cash flow).	Provides an overview on the timeline of incomes and payments over the project period. A simple and visual representation of the overall situation of a project.	It requires very good information on all benefit and cost issues available. It only provides information on the economic viability of a project; it is not recommended for comparative technology assessments.
Net present value (NPV)	Expresses the overall economic result of a project in terms of present money.	It provides useful information for long-term projects, high inflation rates and non-linear developments in prices, cost, etc. Excellent indicator for comparing between projects.	It can only be used when all information is available for a specific project.
Internal rate of return (IRR)	Represents the average return rate on the initial investment. It considers all costs and benefits over the given project period.	Is particularly useful when comparing the profitability of more than one potential projects, providing information about the efficacy of the investment. Important in decision making when investing in new technologies. Allows the comparison between projects.	It should be coupled with the NPV to provide a complete information about the profitability of the project (Mellichamp 2017).

1.4.4 TEA: Interpretation

After calculating the indicators, it is necessary to examine whether the goals are met, and all questions are answered by verifying the consistency, completeness, and reliability of the TEA model at all stages. It is also important to check if the assumptions made and the data collected are reasonable and appropriate by comparing with other TEA studies on similar systems. Furthermore, a sensitivity analysis can be carried out to analyze the uncertainty of the model and the collected data, which can validate the robustness of the model and increase the reliability of the results obtained. In a TEA study, the uncertainty and sensitivity can be determined by identifying the calculated profitability indicator following the procedures below:

a) Uncertainty characterization: This is to characterize the data quality and how well the built model fits the system studied. All the sources of uncertainty are analyzed simultaneously by considering a range of outcomes or confidence intervals rather than a single value. The uncertainties can be classified into error of measurement or estimation, uncertainty of model structure and process; variation in context and scenario due to methodological choices in the goal and scope phase. However, uncertainty resulting from the ignorance of practitioner is not assessable by the existing methods.

b) Uncertainty quanitification: This is to quantify the inherent uncertainties of the inputs of a model and present them as interval, variance, probability distribution, and possibility distribution. A complementary qualitative analysis can be conducted along with quantification to more effectively identify the sources of variation, especially at early stages,

c) Sensitivity analysis: This is to identify the key variables contributing the most to the overall uncertainty, which is done by apportioning the variance in the output among multiple input variables, and evaluating the contribution of each variable to the output uncertainty.

d) Iterative approach for data quality improvement: as a result of uncertainty and sensitivity analyses, the key variables are identified and the quality of their data should be improved depending on the priority. The high-priority variable has the highest impacts on the overall uncertainty. If the quality of its data cannot be improved, the result will inevitably have higher overall uncertainty, which should be documented in the model. On the other hand, it is recommended not to focus on improving the data with low sensitivity demonstrated.

1.5 Life Cycle Assessment

According to the International Organization for Standardization (ISO) 14044: Environmental management – Life Cycle Assessment – Requirements and guidelines (ISO 2006), Life cycle assessment (LCA) is defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system". LCA is a powerful tool to systematically and comprehensively analyze a product's life cycle from multidisciplinary perspectives, including environment, human health, and resources (ISO 2006). The LCA method was at a developing and improving stage in the 1990s, and has become more important and more widely used since 2006 when it was standardized by the ISO and complemented by guidelines. Nowadays, LCA methods are still under continuous revisions and development, which constantly increase its maturity and robustness (Finnveden et al. 2009).

Similar to TEA, LCA methods consist of four phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and result interpretation, as shown in Figure 1.1. TEA and LCA methods are also similar in terms of the type of data required. Their difference is that TEA aims to examine the technical feasibility and economic profitability of a project, while LCA is to evaluate and compare the environmental impacts associated with one or multiple products or technologies (Zimmerman et al. 2018). Furthermore, to be able to integrate TEA and LCA results, it is necessary to define consistent goal and scope for the system to be analyzed.

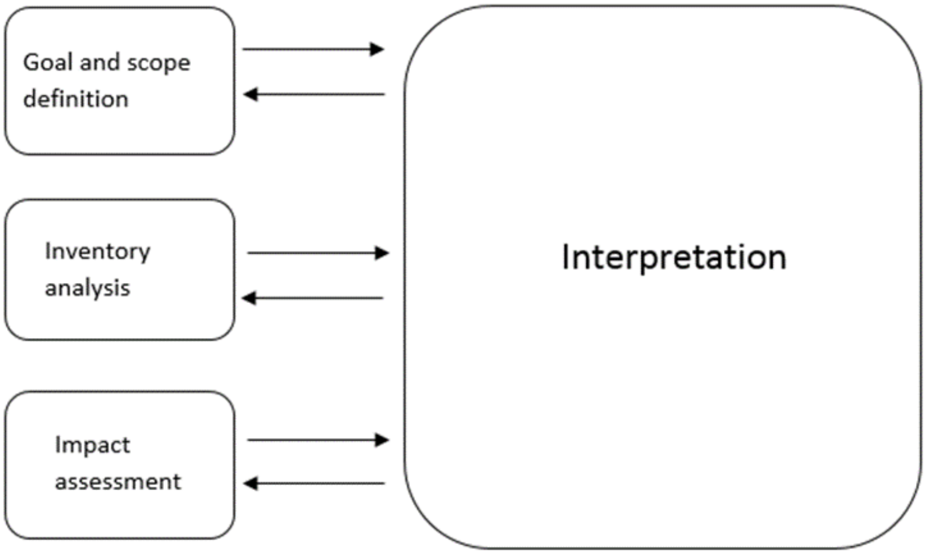


Figure 1.1 LCA framework (ISO 2006)

1.5.1 Goal and scope

The goal of the study must include the intended applications and their significance, the importance of carrying out the study and the impacts of the results. The goal is set according to the specific needs of the intended audience, which will consequently determine the LCIA methodology and the types of impacts of relevance. Moreover, the scope of the study defines the system boundaries and the unit processes to be included. The scope also determines the level of detail these unit processes should be studied, as well as the corresponding inventory data to be collected. Some unit processes could be omitted if they have proved not to have significant impacts on the overall results of the study. In this case, the cut-off criteria which the omission is decided based on should be described and recorded. The cut-off criteria are determined based on the relevance of the inputs to the study, in terms of mass, energy and environmental impacts, and avoid excluding important inputs.

It is recommended to describe every unit process in the system boundaries in order to avoid the risk of misinterpretations, and also make sure that all the relevant aspects to achieve the goal are included. Therefore, a process flow diagram is helpful to visualize the unit processes and their interrelationships, e.g., where each process begins and its raw materials, the type of the process, and where the unit process ends in terms of destination and intermediate or final products. Like TEA, a LCA study is conducted based on FU, which serves as a reference to which the input and output data are normalized. The FU should be defined consistently with the goal and scope. Furthermore, comparative studies between multiple systems should be performed based on the same FU.

The data quality required for the LCA is also specified in this phase and can be summarized into the following aspects:

- Temporary coverage: data age and time frame of its collection
- Geographical coverage: region/location where the data represents
- Precision: data variability
- Technology: specific technology or technology mix
- Completeness: percentage of the process flows included
- Representativeness: the degree to that the data set reflects the real population of interest (i.e., geographical area, time and technology).
- Consistency: whether the methodology is applied consistently over the whole study
- Reproducibility: the extent to that the results can be reproduced
- Sources of data: primary, secondary, and tertiary data.
- Uncertainty of information: use of assumption, model and approximation

1.5.2 Life cycle inventory analysis

The input and output data collected for the inventory can be classified into: a) energy inputs, raw materials, ancillary, and other physical inputs; b) products, co-products and waste; c) emissions to air, water, and soil, and d) other environmental aspects. For the unit process with more than one product (i.e., multifunctional process) and cannot be divided into multiple sub-unit processes, it is necessary to appropriately allocate the inputs, outputs and associated impacts to the different products, which can consequently help more accurately identify the hotspots in the system. The allocation shall be representative of the system and FU, and conducted on the basis of mass, volume, energy, economic value, nutrition, etc.

It is important to validate the data quality to ensure that the intended applications are fulfilled. Data validation may include mass balance, energy balance, and/or comparative analysis. Furthermore, for reproducibility purposes, it is recommended to describe the data collection and calculation procedures, and provide clear instructions for any special cases, irregularities or others.

1.5.3 Life cycle impact assessment

According to the ISO 14044, life cycle impact assessment (LCIA) is mandatory to include the selection of impact categories and characterization models, assignment of LCI results to the selected impact categories (i.e., classification), and calculation of the results of category indicators (i.e., characterization). The impact categories selected should represent the aggregated impacts of the inputs and outputs of the product system, and be environmentally relevant to the nature of the product. The selection of impact categories should avoid double counting unless required by the goal and scope (e.g., aiming to study both human health and carcinogenicity). The environmental relevance of an impact category is defined by its ability to reflect the consequences of the LCI results.

The calculation of impact category indicators using the characterization models is to convert LCI data to environmental impacts and aggregate the results within the same impact category in equivalent units. For example, the electricity and natural gas used for malt and wort production can cause emissions of carbon dioxide, hydrofluorocarbons, methane, and other greenhouse gases, which should be converted using respective conversion factors to a single unit equivalent to the amount of carbon dioxide, i.e., kg CO_2 eq. The characterization models and conversion factors to be used should be internationally accepted

The characterized environmental impacts can be further normalized to some reference values like local average, world average, etc. to provide a better understanding of the relative significance of each impact category. Normalization is especially helpful when the target audience is not LCA expert because it makes the environmental impacts of a product easier to understand and communicate when the impacts can be compared with those generated by, for example, one person over a full year (Aymard and Botta-Genoulaz 2016).

1.5.4 Interpretation

The interpretation phase comprises identification of significant issues based on the LCI and LCIA results, evaluation of the completeness and sensitivity of the study, which can help draw conclusions, identify limitations, and provide recommendations. The interpretation has to be aligned with the goal and scope in terms of definition of system function, FU, and system boundaries. Similar to TEA, sensitivity analysis can be performed to determine the influence of variations in assumptions, methods, and data on the results, some examples include system definition and boundary setting, data-related assumptions, data quality, cut-off criteria, allocation basis, selection of impact category, and reference for result normalization.

1.5.5 LCA on beer processing

Beer is a very popular alcoholic beverage worldwide and its environmental impacts have been assessed through LCA (Talve 2001; Koroneos et al. 2005; Cordella et al. 2008). Table 5 summarizes some LCA studies on brewing process and their findings.

Table 1.6 LCA studies on beer

Author	Geographic region	FU	Key features and findings
Amienyo and Azapagic (2016)	U.K.	i) Production and consumption of 1 L of beer at home; ii) annual production and consumption of beer in the U.K.	Integrated life cycle cost analysis, giving important information about the total contribution of beer to the economy and environmental impacts of the U.K.
Cordella et al. (2008)	Italy	1 L of packaged beer	Kegged beer was more sustainable than bottled beer for both system boundaries: i) from cradle to plant-gate, and ii) from cradle to consumption.
De Marco et al. (2016)	Italy	One 0.33 L-bottle of beer	Complete unit operations in ale and lager brewing systems were analyzed. Boiling and fermentation were identified as the unit operations contributing the major difference in the environmental impacts of ale and lager. Ale was more sustainable than lager.
Koroneos et al. (2005)	Greece	One bottle of beer (combined of beer, 0.52 l, and glass, 0.546 kg, for a total of 1.066 kg)	The bottle production was identified as the greatest energy consumer (85%). Normalized results were presented and identified as hotspots the bottle production, followed by packaging and beer production operations.
Sipperly et al. [accessed 2019]	Thailand	10 hL of lager beer	A cradle-to-gate study on the Singha Brewing, including a detail assessment on each unit operation from malting to recycling and waste disposal at plant
Talve (2001)	Different enterprises in Europe and U.S.	505 6-packs of 12 oz-bottled beer (total of 10 hL)	One of the first LCA studies on beer production, including agricultural production of raw materials and beer processing in system boundaries; identifying cooling as the most energy-intensive unit operation in brewhouse

1.6 TEA and LCA integration

As described in the previous sections, TEA aims to examine technical feasibility and economic profitability of a project, while LCA aims to assess and compare the environmental performance of a system. Hence, integration of TEA with LCA can provide more insights to balance economic and environmental factors of a process or production system in order to facilitate decision-making (Zimmerman et al. 2018). TEA and LCA methodologies share many similarities and require very similar data inputs, but are performed differently, as shown in Figure 1.2. Thereby, the goal and scope, as well as the FU, must be aligned in order to secure accurate interpretation of the results and avoid unreliable conclusions.

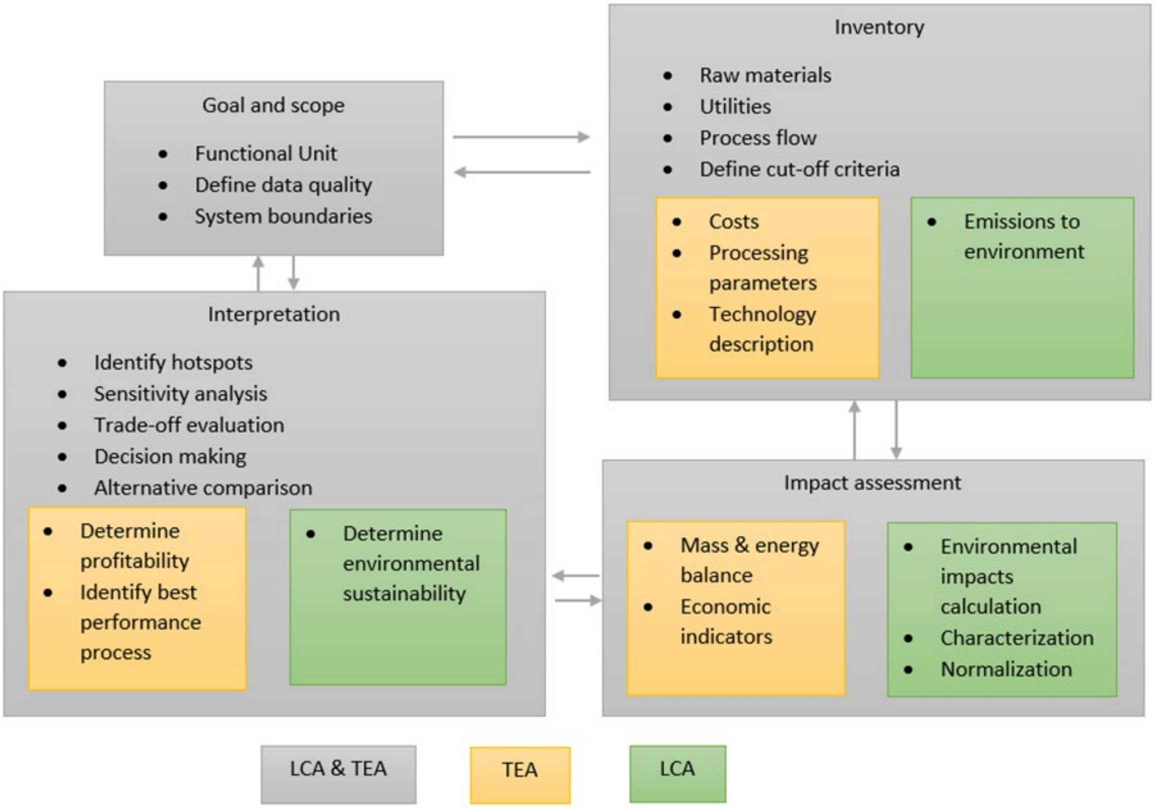


Figure 1.2 Comparison between TEA and LCA methodologies.

There are three approaches to integrate TEA with LCA: a) qualitative integration, b) partial integration, and c) full integration (Zimmerman et al. 2018). Partial integration was conducted in this study, which aligns and combines TEA and LCA studies with respective inventories, and results in separate and combined indicators. The TEA and LCA studies can be aligned by first defining the same goal and scope including FU, system boundaries, allocation methods for solving multi-functionality, and time frame and region of the studies. The unit processes and data inventory analyzed also need to be aligned. For example, if the decision about implementation of a new technology in brewery needs to be made considering all sustainability aspects, the scopes of the TEA and LCA should both be from gate-to-gate and their FU should be defined as one barrel of beer produced in a specific brewery, e.g., located in the state of Indiana.

The final results can be expressed as combined indicators for better understanding and decision-making. For example, the abatement cost (C_{abated}) is commonly used to analyze economic and environmental efficiencies, which is defined as the ratio of the change in production cost to the change in specific environmental impacts (Equation 1.1). In other words, the abatement cost measures the environmental cost required for reducing the production cost by implementing new technologies.

$$C_{abated} = \frac{C_s - C_{ref}}{ei_{ref} - ei_s} \qquad \text{Equation 1.1}$$

where

C_s = costs of studied system

C_{ref} = costs of reference system

ei_s = environmental impacts of studied system

ei_{ref} = environmental impacts of reference system

1.7 Objective and structure of the thesis

Although the environmental impacts associated with beer production in other countries have been evaluated, to the author’s best knowledge, no study has been conducted on the U.S. scenario. Furthermore, only Amienyo and Azapagic (2016) has incorporated economic aspects into LCA through a life cycle cost analysis and no effort has been made to integrate TEA with LCA for beer processing. Therefore, the objective of this thesis is to assess the economic profitability and environmental performance of American craft brewery through TEA and LCA approaches. An integrated TEA and LCA model was developed to evaluate and compare different scenarios, including: i) the implementation of a continuous water heater system to replace a traditional steam boiler in the processing plant of a craft brewery, and ii) production of ale and lager beer at commercial and pilot scales, in order to facilitate decision-making for on-site operation. Figure 1.3 summarizes the scope of this study. The results from this work will be used to identify current operation hotspots and provide recommendations to improve the energy efficiency and environmental sustainability of U.S. craft beer production while reducing or maintaining its production costs.

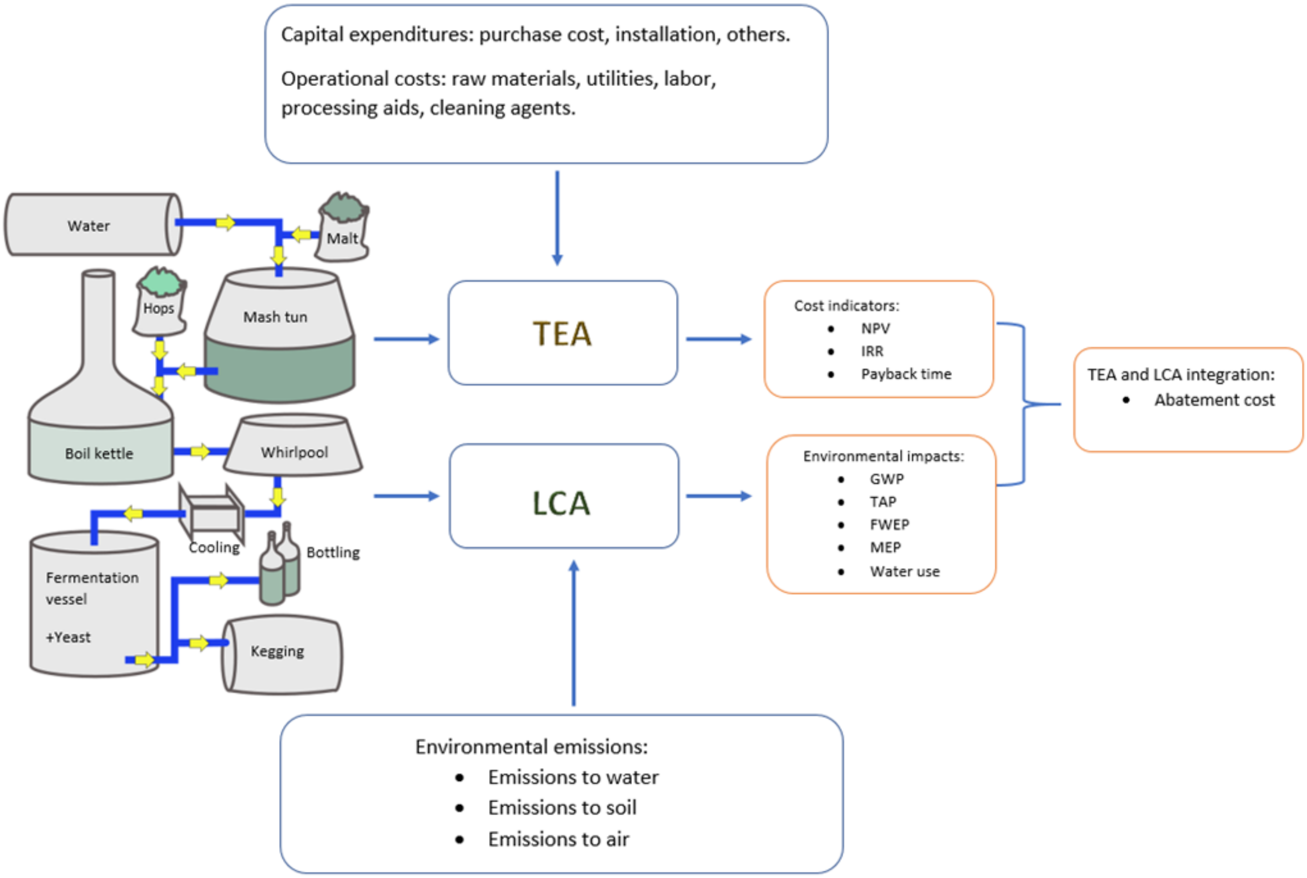


Figure 1.3 Overview of integrated TEA and LCA on craft beer production.

In the rest of the thesis, the LCA and TEA methodologies used for the craft beer production are described in Chapter 2. The energy efficiency, economic and environmental performance of different brewing scenarios, and the corresponding abatement costs are reported and discussed in Chapter 3. The main findings of this work and recommendations for future studies are presented in Chapter 4.

CHAPTER 2. METHODS

2.1 Brewing process

This section describes the unit operations included in the brewing process of craft beer and their parameters, the differences between ales and lagers are stated in the corresponding stages. The production of one batch of beer (Figure 2.1) started from heating the mashing water (995−1404 L) in the hot liquor tank (HLT) from room temperature to 75 ºC using saturated steam at 6 psi generated by a 32 hp boiler. Then, the mashing water, malts and adjuncts (all the commercial recipes are confidential information) were mixed in the mash tun (MT) under agitation by an internal rake, to ensure a homogeneous mixture of grains and water and prevent filtration problems. The grain-to-water ratio was determined according to the type of beer and the brewing recipe, of approximately 1:3 for ales and 1:4−5 for lagers. The grains and water mixture, i.e., "mash", underwent a saccharification step at 65 ºC for 30 min before the "vourlauf" step at which the mash was recirculated through the grain bed for 15 min to clarify the extract. The sweet wort was then transferred to the boil kettle (BK) (i.e., "lautering") and the grains were sparged using hot water (76 ºC) in order to maximize the recovery of fermentable sugars from the grains. The flow rate of sparge water followed the recommendation (Kunze 2016) to maintain the water level approximately 5 cm above the grain bed.

The lautering finished when the "run-off" volume (i.e., target wort volume) was achieved and the wort was brought to boiling temperature using saturated steam (6 psi) in the BK jacket for boiling for 90 min. The hops were added during the boiling step, the high temperature can facilitate the extraction of bitter compounds, which are important depending on the beer type and recipe. Then, the wort was pumped into the whirlpool (WP) tank where it rested for 60 min for the hot-break ("trub") separation step, at which all the larger particles and proteins coagulated during boiling sedimented to the bottom of the tank. The clear wort was then cooled-down from 92−94 ºC to 18−20 ºC by chilled water through a plate heat exchanger before being transferred to the fermentation vessel (FV). In the FV, the wort was further cooled down by glycol recirculating in the FV jacket to the fermentation temperature, of 18−19 ºC or 14−15 ºC for ale and lager yeast strains, respectively. The yeast was pitched in and the wort was fermented for approximately

19−20 days until the desired alcohol content was reached. Then the “green beer” was transferred to the maturation tanks and kept at 1−5 ºC for 4−7 days to obtain the final beer product.

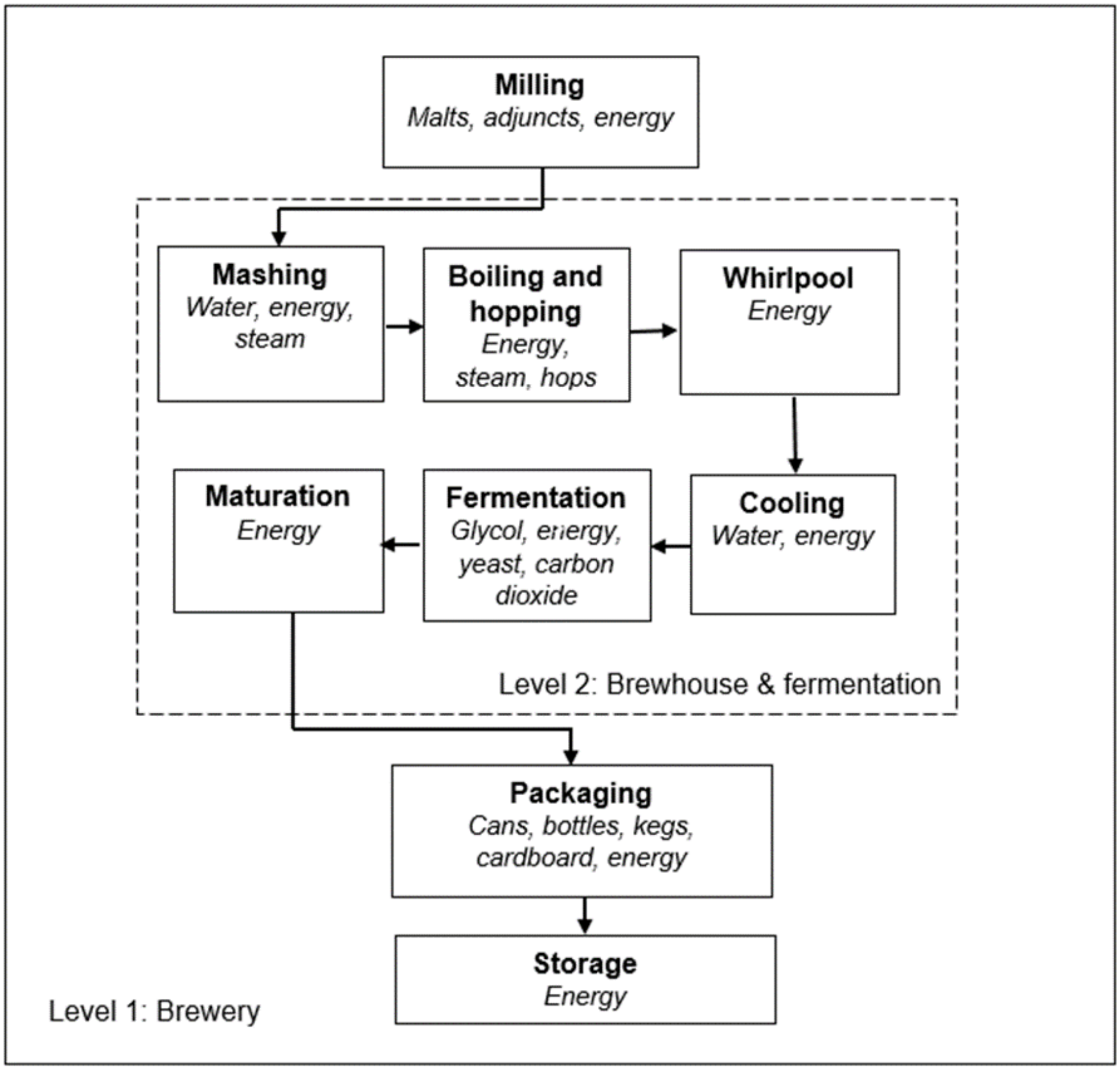


Figure 2.1 Process flow diagram of craft beer brewing.

2.2 Techno-economic analysis

A techno-economic analysis was performed on a microbrewery with an annual production of approximately 3000 bbl beer in the state of Indiana, USA, to evaluate its energy efficiency and the net cost-benefit value associated with the production of one barrel of beer. The scope of the study was from-gate-to-gate of the brewing facility, including brewhouse, fermentation, packaging, and business office operation. Moreover, the brewhouse (i.e., mashing, boiling and hoping, whirlpool, and cooling) and fermentation sections were evaluated in depth through process simulation to identify the unit operations contributing the most to the energy expenditure and consequently the costs, and to provide recommendations about how the energy efficiency of the current processing line could be improved.

As described above, the microbrewery currently heats the water through a jacketed tank (i.e., HLT) with steam generated by a gas boiler. The economic feasibility of the use of a new water heating system was evaluated in this study. The new water heating system can continuously provide hot water at 82 ºC for the mashing step and for cleaning the brewery facility. Based on the current operation, approximately 22% (56.4 m^3) of the monthly water use is for beer production at 76−77 ºC, and 78% (202.43 m^3) is for cleaning at 71 ºC. The water used for restrooms was considered negligible.

The TEA was performed at two levels, as shown in Figure 2.1. Level 1 focused on the monthly energy and water uses, as well as the total cost associated with the production of one barrel of beer in the microbrewery. Level 2 calculated the theoretical energy efficiency and operating cost of each unit operation in brewhouse and fermentation. The major potential energy saving due to the continuous water heater was estimated based on the steam use reduction in the HLT, which was obtained from process simulations within the system boundary of Level 2 (Figure 2.1). Moreover, the saving was also reflected on the reduction in the labor hours needed for brewing and cleaning operations, which was also calculated in this study.

2.2.1 Process simulation

A brewery model was built using SuperPro Designer v9.0 (Intelligen Inc., Scotch Plains, NJ, USA) to simulate the brewhouse operations described in Section 2.1. The model assumed that all the investment costs were paid-off and the brewery operated at a maturity level, therefore, only the costs associated with raw materials, labor, water, and energy were considered for the production of one 21.5-bbl batch of beer in the microbrewery.

Due to the difference between the brewing processes of ale and lager beers (Section 2.1), including grain-to-water ratio, temperature and time required for fermentation and maturation, the energy uses in both scenarios were simulated using the model developed for comparison. The data on the processing parameters of all the unit operations of ale and lager brewing were collected through primary measurements, summarized in Table 2.1, except for the data on heating and cooling agents, which was obtained from the database of SuperPro Designer. Saturated steam at 152 ºC was used for water heating and wort boiling at a fixed mass rate of 57.79 kg/h. Chilled water at 5 ºC was used to cool down the wort in the plate heat exchanger. The mass and energy balance in each unit operation, amounts of heat transfer agents required, and power demand were calculated using SuperPro Designer.

Table 2.1 Parameters for process simulation of ale and lager beer brewing at microbrewery scale

Unit operation	**Ale**	**Lager**
Heating	Mash water† of 3.63 m^3 at 75−76 ºC	Mash water† of 3.45 m^3 at 75−76 ºC
Mashing	Grains of 628.23 kg; mashing at 65 ºC for 30 min	Grains of 480.81 kg; mashing at 65 ºC for 30 min
Boiling	Wort of 2.76 m^3 for 60 min by saturated steam (152 ºC)	Wort of 2.82 m^3 for 60 min by saturated steam (152 ºC)
Whirlpool	Boiled wort of 2.60 m^3 for 20 min	Boiled wort of 2.75 m^3 for 20 min
Cooling	To target temperature of 18 ºC by water at 5 ºC	
Primary fermentation	18.9 ºC for 19 days	14.4 ºC for 9 days
Secondary fermentation	N/A	7.2−15.6 ºC for 11 days
Maturation	4.4 ºC for 14 days	4.4 ºC for 24 days

†Including sparge water

The simulated values of the total energy use for the two scenarios studied were compared with the average monthly utility bills of the microbrewery to validate our TEA model. Moreover, a separate test was conducted using a pilot-scale brewing equipment (1 bbl capacity) for validating the simulated natural gas use. The pilot-scale brewing process consisted of the same unit operations described in Section 2.1, with some modifications due to the scale and heat transfer agents available, which are described in Table 2.2.

Table 2.2 Parameters for process simulation of ale and lager beer brewing at 1-bbl pilot scale

Unit operation	Ale	Lager
Hot liquor tank	Mash water of 0.075 m^3 at 71.1 ºC; sparge water of 0.099 m^3 at 76.7 ºC	Mash water of 0.12 m^3 at 71.1 ºC; sparge water of 0.045 m^3 at 76.7 ºC
Mashing	Grains of 25.36 kg; mashing at 65.6 ºC for 60 min	Grains of 26.99 kg; mashing at 65.6 °C for 60 min
Boiling	Wort of 0.14 m^3 for 90 min by saturated steam (152 ºC)	
Whirlpool	Boiled wort of 0.11 m^3 for 5 min	Boiled wort of 0.12 m^3 for 5 min
Cooling	To target temperature of 22.2 ºC by water at 5 °C	

2.2.2 Economic analysis

The economic performance of the production of one barrel of beer was assessed by estimating the total operation cost of the microbrewery (i.e., including all the unit operations in Levels 1 and 2). Furthermore, the investment cost of the continuous water heater was considered to evaluate the economic feasibility of this technological upgrade.

The total operating cost was estimated including the costs of raw materials (depending on beer type) and packaging, utilities, and fixed cost (i.e., cost not directly resulting from brewing process). The costs related to Level 1 were estimated based on the primary data on the monthly bills of the microbrewery over 1 year, and the costs related to Level 2 were estimated based on the raw materials used for the production a single batch of beer as well as the associated utilities. The utilities were obtained from the simulation results by SuperPro Designer based on the rates of the state of Indiana, USA. The costs of wastewater treatment and sewage were considered as the fixed cost (Level 1) at the local rates.

The total investment cost of the water heating system consisted of the equipment and its installation costs. The new system included a boiler with energy ranging from 27.8 to 555 kWh and thermal efficiency of 95%, a water tank, a Taco pump, and an expansion. Moreover, the installation cost included the electric work and labor.

The revenue per barrel of beer was estimated based on the beer sales. The beer was available in three different forms of packaging: aluminum can (34.78% of total production), glass bottle (2.92%), and stainless steel keg (62.3%), with different prices per unit. The wholesale price varied with the type of beer, here, the average price per unit was \$26.9 per case of canned or bottled beer, and \$122.1 per half-barrel (58.5 L) keg.

The profitability was calculated using the static cost benefit assessment and net cash flow (NCF) method. As shown in Eq. 2.1, the cost benefit assessment determined the net profit of the sales of one barrel of beer based the collected data on operational costs and revenue. The NCF was used to estimate how long it would take for the microbrewery to pay off the investment in the continuous water heater. The investment cost was assumed to be covered by the brewery's own capital, and hence no interest rate was applied.

$$Net\ profit = Total\ benefit - Total\ cost \qquad \text{Equation 2.1}$$

2.3 Life cycle assessment

2.3.1 Goal and scope

The goal of the life cycle assessment (LCA) was to evaluate and compare the environmental performance of beer production (ale and lager) in a microbrewing facility (annual production of 3000 bbl) and a pilot plant in the state of Indiana, USA, as well as to analyze the effect of replacement of a continuous water heater for the gas boiler. The functional unit (FU) was defined as 1 bbl of packaged beer. The system boundaries of the LCA were aligned with those of the TEA for comparison purposes and also to facilitate further integration of the resulting indicators. Therefore, two LCA studies were conducted with different system boundaries: (i) gate-to-gate (i.e., Level 1 in Figure 2.1), from raw material reception to storage of final product for transportation to market, and (ii) brewhouse and fermentation operations (i.e., Level 2) to characterize the environmental performance of single unit operation. The environmental impacts associated with the co-products, i.e., spent grains, were calculated using the "cut-off" approach, by which all the impacts generated beyond the brewery gate (i.e., system boundary) were not considered. Furthermore, for the microbrewery studied here, the spent grains were not further utilized and thus had negligible value, hence, an economic allocation basis for the spent grains was applied to better determine the environmental performance of the beer products. The intended applications of this LCA study were to identify the most energy- and resource-intensive unit operations in craft beer brewing as well as the opportunities to reduce the environmental footprint of the beer produced. The intended audience included microbrewers in the U.S. and stakeholders interested in applying new technologies to improve the environmental performance of beer production, as well as consumers who want to purchase more sustainable beer products.

2.3.2 Life cycle inventory

The inventory data included the resources required for producing one barrel of beer (Level 1 LCA), such as raw materials, packaging materials and cleaning agents, as well as the utilities for brewing, cleaning, refrigerated storage and business office operation. The data on barley malting process was collected from Hedal J et al. (2009), which included the water, electricity, and natural gas uses for production of 1 ton of malt. Packaging data was based on the average beer sales, i.e., 34.78% in can (0.35 L), 2.92% in bottle (0.35 L), and 62.3% in keg (58.5 L). To fulfill the functional unit (i.e., packaging 1 bbl of beer), 129.78 cans, 9.61 bottles, and 1.27 kegs were required, respectively. Moreover, the weights of the empty containers, of 13.5 g/can, 265 g/ bottle and 13.5 kg/keg, were used to determine the total packaging materials needed. All the other foreground data was collected in an aggregate form from primary measurements in the brewing facility over 1 year and averaged. Unless specified otherwise, the background inventory data including productions of grains (barley and wheat), heat transfer agents, and packaging materials were adapted from the ecoinvent database v3.0 database developed by Wernet et al. (2016), because they were beyond the scope of this study. End-of-pipe wastewater emissions were also considered, which were estimated according to the typical ranges of the U.S. breweries (Brewers Association 2016). For the Level 2 LCA, the utilities for brewhouse and fermentation operations were obtained with process simulations using SuperPro Designer (Section 2.2.1). All the brewing equipment was not included in this study because it is rigid and considered as long-term infrastructure.

The inventory of pilot-scale brewing comprised primary and simulation data, which was obtained by similar methods to the data of microbrewery. The steam used for water heating, mashing and wort boiling were directly measured by collecting the condensate from the jacket of each tank. Furthermore, the wastewater generated by mashing and trub was collected and analyzed separately.

2.3.3 Impact assessment

The environmental impacts of one barrel of beer produced in the microbrewery and pilot plant were determined using the ReCiPe 2016 Midpoint (E) v1.02 method. The results were expressed in terms of global warming potential (GWP; kg CO_2 eq), freshwater eutrophication potential (FWEP; kg P eq), and water use (m^3), which were selected because they were found the most significant environmental impacts associated with beer production (Talve 2001; Hospido et al. 2005; Koroneos et al. 2005). All the data was analyzed using SimaPro 8.5.2 software.

CHAPTER 3. RESULTS

3.1 Beer brewing inventory

3.1.1 Level 1: Brewery

Table 3.1 summarizes the data on the resources and their costs required for the production of one barrel of beer in a microbrewery, which were used for the TEA and Level 1 LCA studies. The processing aids, as defined by the U.S. Code of Federal Regulations (21 C.F.R. 101.100, 2019), consist of "substances that are added to a food for their technical or functional effect on the processing but are present in the finished food at insignificant levels and do not have any technical or functional effect on that food". Due to their relatively negligible contributions to the final beer products, the processing aids were not included in the LCA study.

The total production cost per barrel of beer, including the operating cost (raw materials, process aids, packaging materials, utilities, cleaning supplies, and labor) and fixed cost (rent, administrative staff), was $273.57 (Table 3.1). The production cost highly depends on the brewery scale, Larger breweries facilities have lower production cost per unit of beer (Brewers Association 2018). For example, raw materials accounted for 20% of the total cost in this study. Breweries with lower productivity have less buying power, so they pay a higher rate per unit of malts or hops. In contrast, larger breweries can afford to place large orders in bulk with a cheaper price. Additionally, smaller breweries might have lower mashing efficiencies, which require more ingredients to achieve the required extract concentration in the wort (Sturm et al. 2013).

The utilities, including electricity, gas, and water, only accounted for approximately 4% of the total production cost. The relatively low contribution was because the average rate of electricity in the state of Indiana (9.77 cents/kWh) is below the national average of 10.48 cents/kWh in 2016 (EIA 2018, 2018). Moreover, the U.S. electricity rate is considerably lower than other developed countries, where ranks 17th according to the worldwide statistics in 2018 (Wang 2019).

To improve the energy efficiency of brewing, energy intensity (total kWh used/total barrel produced) should be monitored on a month-to-month basis. Energy intensity is one of the suggested key performance indicators for brewers to set efficiency goals and reduce cost and environmental footprint (Brewers Association 2019a). Figure 3.1 shows in the monthly beer production and electricity use of the microbrewery over the research period, as well as the electricity intensity of the beer produced. As shown in Figure 3.1a, the monthly electricity use was fairly stable over time, however, the monthly beer production varied greatly over the year because of the market demand, ranging from more than 400 bbl to as low as 150 bbl. The electricity used for one barrel of beer was closely related to the beer productivity, a higher monthly barrelage resulted in a lower electricity intensity (Figure 3.1b), and thus a lower utility cost. With the average value of 106.59 kWh, the electricity use per barrel of beer largely varied from 69 to 143 kWh depending on the time of the year, These values were higher than those reported by previous studies that ale and lager brewing accounted for approximately 14.16 (Amienyo and Azapagic 2016) and 2.44−2.74 kWh (De Marco et al. 2016) per barrel, respectively. This difference can be attributed to the temperature and time of fermentation and maturation, which had the higher electricity demands among all the unit operations. The fermentation and maturation periods applied by the microbrewery, as described in Table 2.1, were longer than Amienyo and Azapagic (2016) and De Marco et al. (2016), which ranged from 2−14 days for fermentation, and 28 days for maturation. The natural gas intensity was 2.25 ± 0.88 kWh/bbl. Nonetheless, as shown in Figure 3.1a, the natural gas use over the research period had a larger variation than electricity, because of the weather condition throughout the year, for instance, low temperatures during winter months.

The scale of brewery influences its energy efficiency, larger production is generally associated with lower energy expense per unit of beer produced (Brewers Association 2018). Although Amienyo and Azapagic (2016) reported the results based on the national average of the U.K., and De Marco et al. (2016) studied a “small brewery” in Italy, the data on their annual barrelage was not reported. The production of a “small brewery” can range from 500 to 8,500 bbl/year (Kunze 2016), which may thus also explain the difference between the electricity intensities obtained with the present study and those reported in literature.

Table 3.1 Gate-to-gate inventory of one barrel of beer produced by microbrewery

Item	Unit cost (USD)	Quantity (1 bbl beer)	Unit	Total cost (USD)
Raw materials				
Base malts	1.16	28.49	kg	33.07
Flaked grains	1.46	2.07	kg	3.02
Specialty malt	1.48	5.50	kg	8.12
Hops	21.91	0.44	kg	9.72
Yeast	121.84	0.02	kg	2.27
Total raw materials				**56.19**
Process aids				
Flavorings	38.00	0.05	l	1.90
Silicic acid	11.55	0.07	l	0.76
Phosphoric acid	5.55	0.08	l	0.45
Anti-foam agent	27.66	0.01	kg	0.15
Clearing agent	62.10	0.003	l	0.21
Total process aids				**3.47**
Packaging				
Bottle	0.50	6.52	unit	3.26
Can	0.45	129.29	unit	58.18
Keg	0.62	1.34	unit	0.84
Total packaging				**62.28**
Utilities				
Electricity	0.08	106.59	kWh	9.04
Gas	0.08	2.25	kWh	0.19
Water	0.66	0.94	m^3	0.62
Total utilities				**9.85**
Cleaning supplies				
Detergents	0.49	1.42	l	0.70
Disinfectants	7.68	0.02	l	0.15
Total cleaning supplies				**0.85**
Labor				
Brewing	12.00		labor-h	33.53
Packaging	12.00		labor-h	1.78
External packaging	12.00		labor-h	48.11
Total labor				**83.42**
Total operating cost				**216.06**
Fixed costs				
Facility rent	10277.00		month	40.70
Business staff	25.00		labor-h	17.16
Total fixed costs				**57.86**

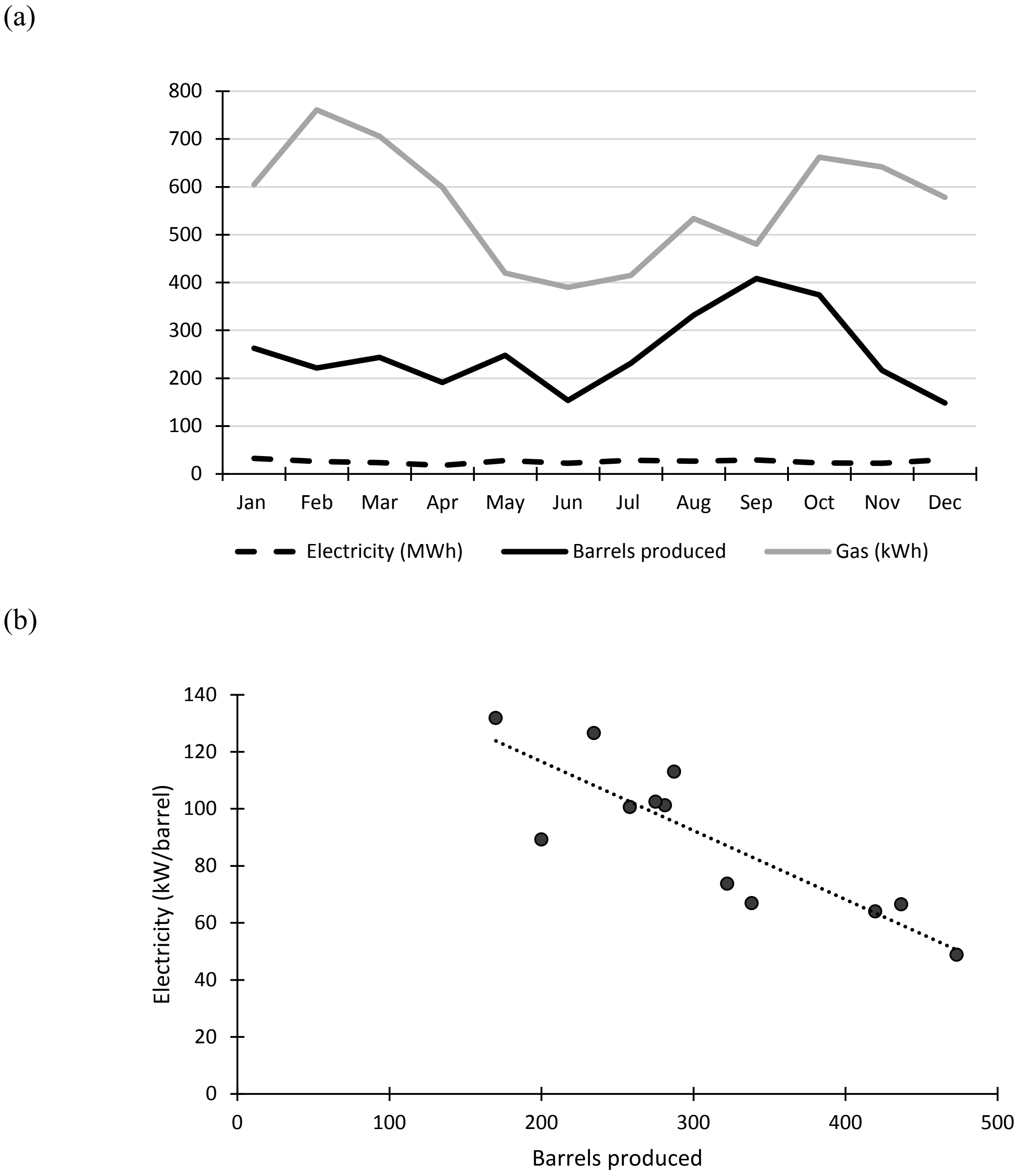


Figure 3.1(a) Evolution of barrelage, electricity and natural gas uses, and (b) electric intensity of the beer produced of the microbrewery.

3.1.2 Level 2: Brewhouse and fermentation

Accurately monitoring and predicting resource usage is important for management of production operation. Process simulation is a useful tool when primary measurements are not available, especially, to estimate the utility demand of each unit operation included in a process. Figure 3.2 depicts the flows of the brewing process modeled.

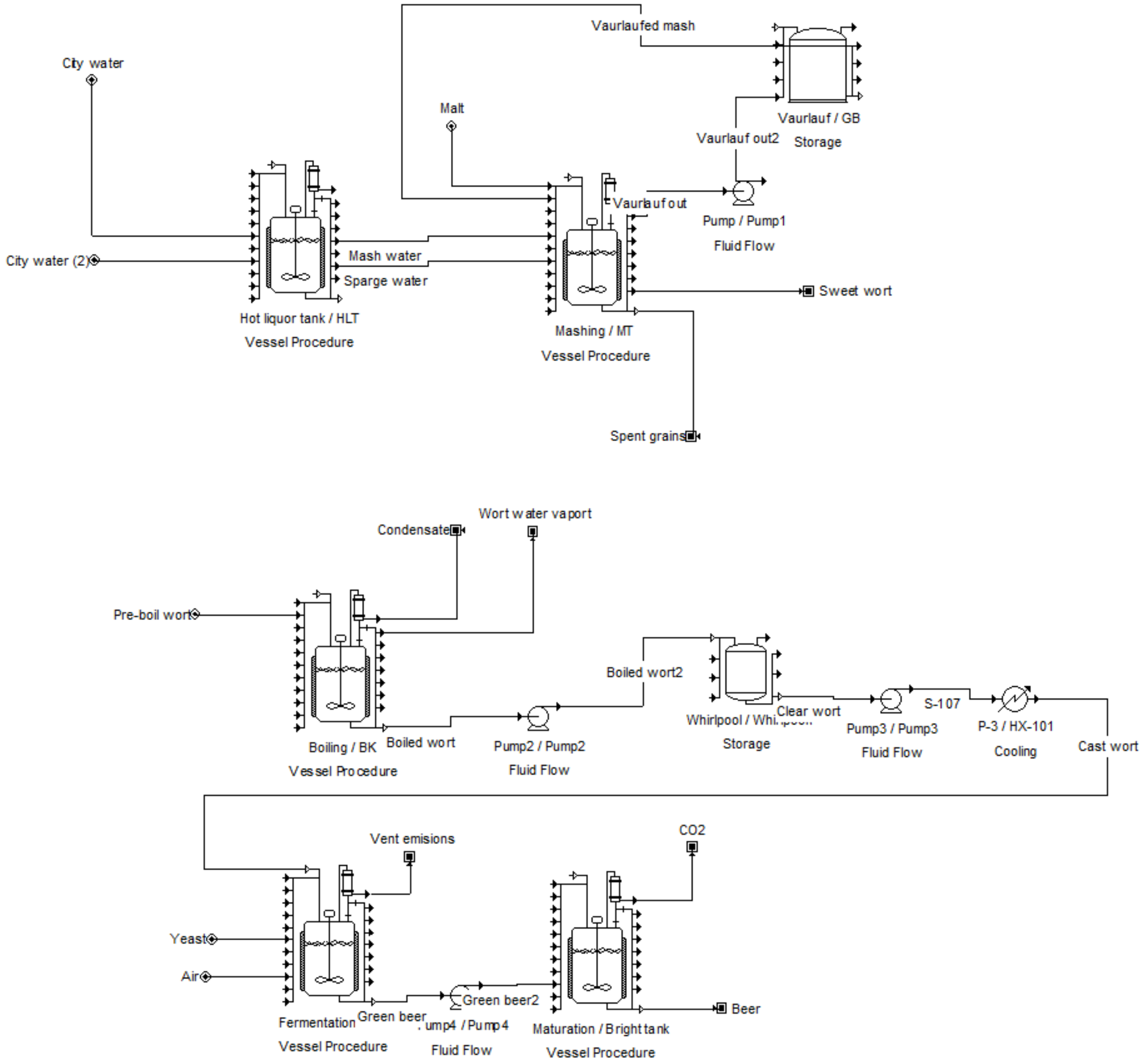


Figure 3.2 Process flow diagram of brewhouse and fermentation operations

Table 3.2 presents the inventory of the brewhouse and fermentation operations for ale and lager brewing at both the microbrewery and pilot scales for Level 2 LCA. Here, the data on the gas and electricity uses was obtained through simulations using SuperPro Designer v9.0, while all the other data reported was collected by primary measurements. As expected, the ale needed a larger ratio of grains to water to produce the same volume of beer than the lager due to a higher final extract concentration (SG = 1.0539) required. Consequently, the ale required approximately 27% more energy during boiling. The fermentation and maturation stages accounted for the highest electricity uses, of approximately 61% and 39%, respectively, for the ale, and 49.7% and 50.2% for the lager from their respective net total emissions. Due to the difference between the physiological requirements of ale and lager yeast strains, the lower temperatures and prolonged periods required for the fermentation and maturation of the lager resulted in 24% higher total electricity use compared to the ale. Similarly, De Marco et al. (2016) reported that lager beer consumed 36% more electricity than ale. The sugar assimilation efficiency of a yeast strain during fermentation is determined by the expression of its specific genes that transport α-glucosides (e.g., maltose and maltrotriose) across the yeast cell plasma, which can be delimited by the temperature of the environment (Rautio and Londesborough 2003; Stambuk et al. 2006). For instance, lager yeast strains have been reported to show a five-fold difference in reaction rate at 0 ºC than 20 ºC (Vidgren et al. 2010). However, lower fermentation temperature consumes more energy. Therefore, from the cost perspective, in order to minimize the energy use for fermentation, it is necessary to determine the optimal combination of fermentation temperature and time for the specific yeast strain used.

Table 3.2 Inventory of brewhouse and fermentation operations for one barrel of ale and lager beers produced in microbrewery and pilot scale

Unit operation	**Item**	**Unit**	**Microbrewery**		**Pilot scale**	
			Ale	**Lager**	**Ale**	**Lager**
Heating	Water	kg	173.73	169.70	214.52	216.31
	Natural gas	kWh	1.21	1.26	1.50	1.41
	Output					
	Hot water	kg	173.73	169.70	214.52	216.31
Mashing	Malt	kg	30.13	24.02	28.00	28.04
	Electricity	kWh	0.05	0.04	1.24	1.16
	Output					
	Pre-boil wort	m^3	0.13	0.13	0.15	0.15
	Spent grains	kg	61.56	49.07	57.20	57.28
	Wastewater	m^3	0.01	0.01	0.03	0.04
Boiling	Natural gas	kWh	0.93	0.68	2.64	2.45
	Hops	kg	0.24	0.01	0.22	
	Output					
	Boiled wort	m^3	0.12	0.12	0.12	0.12
	Trub	kg	1.45	1.91		
Whirlpool	Electricity	kWh	0.005	0.005	0.00	0.00
	Output					
	Wort	m^3	0.12	0.12	0.12	0.12
	Wastewater	m^3	0.03	0.02	2.10×10^{-3}	1.97×10^{-3}
Cooling	Electricity	kWh	0.005	0.005	0.00	0.00
	Water	m^3	1.60	1.58		
	Output					
	Cooled wort	m^3	0.117	0.117	0.117	0.117
Fermentation	Glycol	g	0.02	0.02	0.02	0.02
	Electricity	kWh	44.48	47.16	926.03	1220.07
	Output					
	Green beer	m^3	0.117	0.117	0.117	0.117
Maturation	Electricity	kWh	28.00	47.66		
	Output					
	Beer	bbl	1.00	1.00	1.00	1.00
Emissions to water	BOD	kg	2.62	2.62	2.62	2.62
	COD	kg	3.42	3.42	3.42	3.42
	Total N$_2$	kg	0.06	0.06	0.06	0.06
	Total P	kg	0.06	0.06	0.06	0.06

To validate the developed model, the simulated results of the steam use for the pilot-scale brewing (1 bbl) were compared with the total amount of the steam condensate collected from both the hot liquor tank and boil kettle after the experiments of ale and lager brewing. As shown in Table 3.3, the simulation results agreed well with the experimental measurements regardless of the beer type, indicating that the model can accurately estimate the natural gas use for beer brewing at pilot scale. Furthermore, the estimated electricity use per barrel of beer produced was validated by comparing with the monthly electricity bill of the microbrewery over a 1-year production (Figure 3.1). The simulation results of the electricity intensities of ale and lager brewing were 72.54 and 94.87 kWh/bbl, respectively, which corresponded to the yearly average value of the microbrewery, of 106.59 ± 36.87 kWh/bbl. Furthermore, the model estimated the natural gas intensities of ale and lager brewing to be 2.13 and 1.95 kWh/bbl, respectively, which were consistent with the microbrewery data (2.25 ± 0.88 kWh/bbl). The slight difference can be attributed to the gas use for heating the facility during the winter season and heating the cleaning water. Hence, the developed model was reliable for predicting the energy use, in terms of electricity and natural gas, at microbrewery scale as well.

Table 3.3 Steam use for production of one barrel of beer in pilot-scale brewery

Unit operation	Ale		Lager	
	Simulation (kg)	Measurement (kg)	Simulation (kg)	Measurement (kg)
Heating	22.10	23.56 ± 2.34	22.10	21.14 ± 1.54
Boiling	38.91	36.82 ± 2.71	38.41	33.91 ± 6.41

3.2 Techno-economic Analysis

3.2.1 Cost-benefit analysis

Table 3.4 presents the results of the cost-benefit analysis. The estimated total production cost per barrel of beer was $273.92, which included the operating cost of $216.06 and the fixed cost of $57.86. The total revenue, calculated based on the average sale prices per case and keg of beer, was $307.55. The excise state and federal taxes for beer in the U.S. were considered for the calculation of the net profit. In Indiana, beer vendors pay a state excise tax of $3.72/bbl of beer, plus the federal excise tax of $3.5/bbl for domestic breweries producing under six million barrelage per year (US Congress 2017). With all the costs, revenue and taxes considered, the net profit per barrel of beer was $26.67.

Table 3.4 Cost-benefit analysis on one barrel of beer produced by a microbrewery

Item	One barrel (USD)	Annual (USD)
Operating cost		
Raw materials	56.19	170,254.99
Process aids	3.47	10,503.29
Packaging	62.28	188,706.64
Utilities	9.85	29,832.44
Cleaning supplies	0.85	2,589.52
Labor	83.42	252,754.22
Total	**216.06**	**654,641.10**
Fixed cost		
Rent	40.70	123,324.00
Administrative staff	17.16	51,985.94
Total	**57.86**	**175,309.94**
Revenue		
Sales (can/bottle)	145.79	441,739.28
Sales (keg)	161.76	490,124.32
Total	**307.55**	**931,863.60**
Gross profit	**33.89**	**101,912.56**
State alcohol excise tax	3.72	11,271.34
Federal alcohol excise tax	3.50	10,604.76
Total	**7.22**	**943,134.94**
Net profit	**26.67**	**80,036.46**

Table 3.5 shows the net cash flow (NCF) table. The investment in the continuous water heater was made in the beginning of the project (year zero) with the total cost of $77,927, which included $54,028 for the equipment, and $23,899 for the installation. Moreover, the annual net profit was used to estimate the profitability of the continuous water heater over the project expected lifetime (approximately 15 years, specified by the vendor). This study used three profitability indices to determine whether this investment project is profitable or not: the net present value

(NPV), the internal rate of return (IRR), and the payback time, which were summarized in Table 3.4. “Hurdle criterion” is an approach to evaluate an investment project in plant design/costing (Turton 2009; Ross 2015), which imposes a significantly high hurdle rate before accepting a project. For example, a potential investment can set a minimum value of IRR as its rate of return (r) (Mellichamp 2017). Here, for a more conservative evaluation, the r value for the calculation of the NPV was determined based on the average rate of investing in the stock market collected from the historical data over 10 years, which was 13% (The Wall Street Journal 2019). This investment project was accepted under the criteria of NPV > 1 and IRR > r.

Because of the higher thermal efficiency of the new heating system, of approximately 95% (specified by the vendor), the potential savings were expected to be reflected in the labor time and natural gas bill. The results of the process simulation indicated that the new heating system can reduce the total time for water heating for brewing and cleaning by around 65%. Therefore, approximately 1 labor hour per batch of brewing can be saved, and 2 labor hours can be saved per cleaning cycle. In total, approximately \$3,420 per year can be saved from the labor cost. In contrast, because of the low natural gas rate in Indiana, a reduction in the gas use would have an insignificant impact on the gas bill, and thus the total cost. However, during the research period, not enough data on the brewing with the new heating system was collected after its commission for validation, hence, its projection is not reported in this study. Other potential benefits resulting from the investment include increase in the productivity of the microbrewery.

The NCF table was used to calculate the NPV, IRR and payback period assuming a 4% growth of annual sales, which was based on the average growth rate of the craft beer industry in the U.S. in 2018 (Brewers Association 2019b). The negative NPV (\$ −45,017) obtained indicated that the project is not profitable by depreciating the future cash flows to the present value. The IRR was 2.37%, which represents the discount rate that makes the NPV zero. The payback period based on the marginal profits of the water heater, represents the time when the brewery will be able to pay off the investment, was 16.53 years and longer than the lifetime of the water heater (15 years). Therefore, under the current production scale and operation, this investment is not profitable to the microbrewery based on the acceptance criteria of NPV > 1 and IRR > r, and thus should be rejected. Sensitivity analyses were performed in the following section to examine the effects of discount rate, annual beer production and investment cost on the project profitability. Further research is also needed to identify alternative options to invest the capital and increase the net profit of the microbrewery. For example, investing in additional fermentation vessels or can fillers for packaging to increase the production capacity.

Table 3.5 Net cash flow table over 15 years for microbrewery

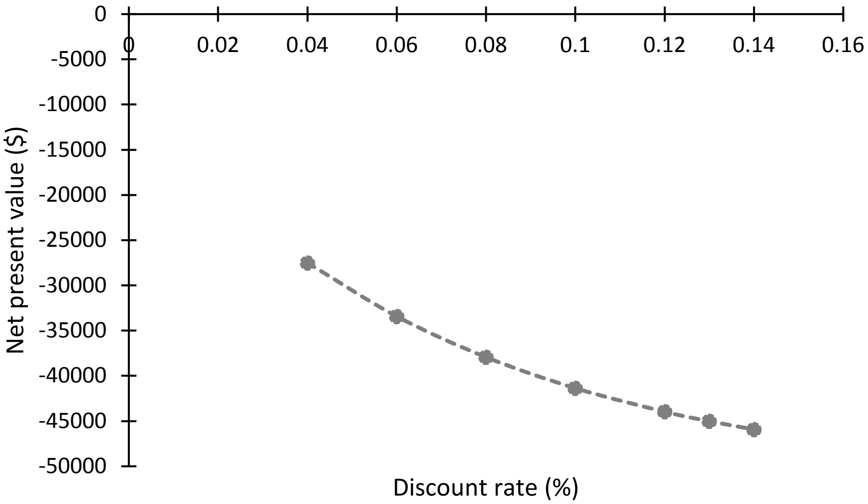
Year	Cash flow (USD)
0	−77,927
1	3,420
2	3,557
3	3,699
4	3,847
5	4,001
6	4,161
7	4,327
8	4,500
9	4,681
10	4,868
11	5,062
12	5,265
13	5,476
14	5,695
15	5,922
NPV	**$ −45,017**
IRR	**-1.45%**
Payback period (years)	**16.53**

3.2.2 Sensitivity analysis

Although the investment project on the continuous water heater was not profitable and thus not recommended for the microbrewery based on its current production, further cost-benefit analyses were performed to identify the sensitive parameters and measure the feasibility of the investment under different scenarios. The parameters related to the net profit of the investment included (i) the discount rate used to calculate the NPV, (ii) the income from the investment, which was associated to annual beer production, and (iii) the investment cost of the heater. Since the discount rate has been identified as the most important parameter due to its effects on the cost and allocation (Mallah and Bansal 2011), the lower boundary of the discount rate was set at 4% to represent a more conservative scenario. The 4% rate was determined also based on the annual growth rate of the brewery, lower rates were not considered since it would represent losses to the brewery. Craft brewery varies greatly in size, which can produce up to 6 million barrels per year (Brewers Association 2019b). Since a larger and more stable production can increase the net profit of the investment, the boundaries were set at 3,029 bbl (current production) and 10,000 bbl per year (within the capacity of the heater invested). The investment cost largely varies with the equipment capacity, provider, and installation cost. A heater with a smaller capacity (output rate of 22.3−445 kW and 95% thermal efficiency) than the current one (27.8−555 kW, same efficiency) was compared. Moreover, the installation cost was minimized, resulting in total savings of $32,927, hence, the lower boundary was set at $45,000. The profitability of each investment scenario was indicated by the resulting NPV. For the analyses on annual production and heater cost, a 4% discount rate was applied to calculate the NPV.

Figure 3.3 shows the effects of different sensitivity parameters on the NPV. Figure 3.3a shows that increasing the discount rate decreased the NPV, which agreed with the hurdle criteria described by Ross (2015), and the decrease became gradual at higher discount rate. However, the NPV remained negative over the range analyzed, indicating that this project is considered not profitable despite under the most conservative scenario (i.e., discount rate of 4%). The NPV increased linearly with the annual beer production (Figure 3.3b), with the breakeven point of 5,796 bbl/year to justify the investment. Furthermore, lower investment cost resulted in higher NPV, as expected. At the current production level, decreasing the cost to lower than $49,326 will make the investment profitable which is feasible according to the estimate of the heater provider. Overall, the profitability of the investment project was the most sensitive to discount rate, in terms of the NPV change induced by 1% of change in the test parameter, which was followed by annual production and heater cost. Discount rate was also found to be one of the most sensitive parameters in previous studies (Mallah and Bansal 2011) which examined the variations in the most relevant technical and economic parameters that affect the energy policy in India.

a)

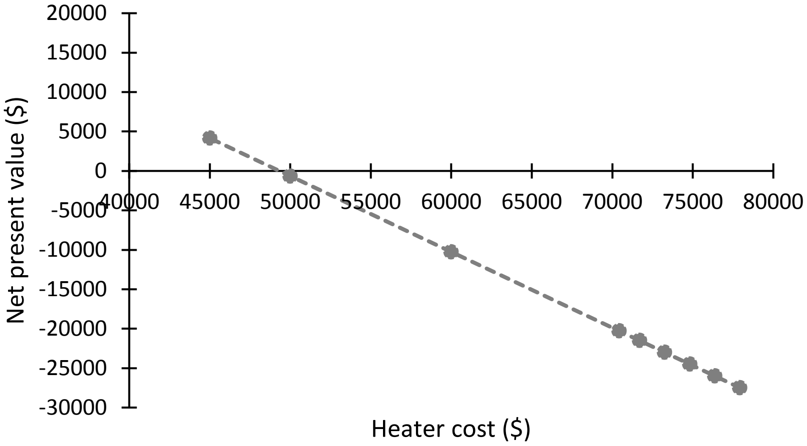


b)

Figure 3.3 Effects of (a) discount rate, (b) annual beer production, and (c) investment cost on the net present value of continuous water heater investment for microbrewery.

Figure 3.3 continued

c)



3.3 Life Cycle Assessment

3.3.1 Level 1: Microbrewery

Table 3.6 presents the overall environmental impacts of the gate-to-gate production of one barrel of beer in the microbrewery, i.e., Level 1. As shown in Figure 3.3, the processing (brewing) stage predominated in the freshwater eutrophication (FWEP; 89.26%) and water consumption (95.99%), and accounted for 95.99% of the global warming potential (GWP). The high GWP contributed by the processing stage can be attributed to the electricity use. The U.S. electricity mix is mainly composed of fossil fuels. In 2018, natural gas and coal accounted for about 35% and 27%, respectively, of the electricity sources, resulting in a higher greenhouse gas (GHG) emissions than the countries with higher renewable energy proportions in their electricity mixes (EIA 2019). For one barrel of beer (i.e., FU), 2.25 kWh of energy was generated by natural gas (Table 3.1), which only represented 4% of the GWP. Nonetheless, since the GWP per unit of natural gas is approximately 79% higher than that of electricity, potential reduction in its use can have a significant effect on the total carbon footprint of beer production. In addition to the GWP, electricity use (106.59 kWh/bbl) was the major contributor (95.65%) to the water consumption. The nitrogen emissions due to brewing wastewater were the most significant contributor to the FWEP. The wastewater effluent was mainly generated at the mashing, boiling and whirlpool stages. During mashing, the wastewater consisted of the residual water that grains did not absorb and was not transferred to boiling. The organic components in the brewing wastewater are mainly cellulose, sugars, and amino acids (Brewers Association 2016), which are generally easily biodegradable (Inyang UE et al. 2012), with the COD and BOD values of 1,800−5,500 and 600−5,000 ppm, respectively (Brewers Association 2016, 2016).

Raw material production was found to be the environmental hotspot of marine eutrophication (MEP; 99.4%), which could result from the emissions generated by agricultural activities. In this study, barley production included productions of seeds, fertilizers and pesticides, operation of on-farm equipment, and emissions from the soil, which also had a high contribution to the TAP (70.63%). Raw material production accounted for 3.67% of the water consumption because of the water required for agriculture and malting stages. Malting process involves pre-germination of barley grains by steeping in warm water, in order to modify the grain structure and make contained carbohydrates more susceptible to enzymatic reaction during brewing (MacLeod and Evans 2016). Hedal J et al. (2009) reported that malting process required 2.04 m^3 of water per ton of malt. Raw material production accounted for 49.4% of the GWP because the agricultural and malting stages of raw materials are highly resource-intensive. The Climate Conservancy (2008) reported that agricultural production and malting process were responsible for 66% and 28%, respectively, of the GHG emissions of the raw materials of beer.

Table 3.6 Life cycle impacts of one barrel of beer produced in microbrewery

Impact category	Unit	1 bbl beer
Global warming	kg CO_2 eq	39.58
Terrestrial acidification	kg SO_2 eq	0.30
Freshwater eutrophication	kg P eq	0.08
Marine eutrophication	kg N eq	0.11
Water consumption	m^3	1059.62

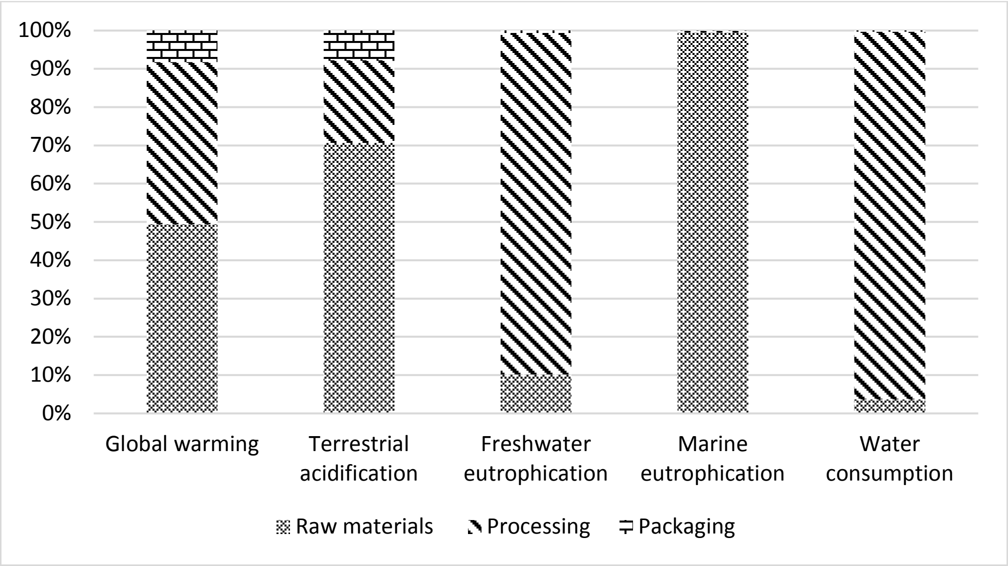


Figure 3.4 Environmental profile of beer production in microbrewery

Table 3.7 summarizes previous LCA studies on beer. While all the three studies had similar system boundaries, i.e., from cradle to grave, only De Marco et al. (2016) performed a detailed analysis on the environmental performance of each unit operation in the processing stage. Amienyo and Azapagic (2016) and Koroneos et al. (2005) found that packaging materials were the environmental hotspot of beer production. However, it should be noted that the results differ greatly among each other, which can be due to the variation in agricultural practices of raw materials in different geographical regions. For example, the U.K. study reported that 71 kg CO_2 eq was produced by the raw materials production for one barrel of beer, and the GWP associated with its raw material production was almost 4 times lower than the current study. Although both works collected the data from the ecoinvent database, the U.K. study adapted the average European data and this study used the average U.S. data. Moreover, the grain bill required for beer can vary with brewing style and facility. The beer produced in the U.K. only required 8.5 kg of barley, which can be associated with the higher mashing efficiency due to a larger scale brewing plant.

Table 3.7 Environmental impacts of one barrel of beer reported in literature

Geographic region	Reference	Scope	GWP (kg CO_2 eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)
U.K.	Amienyo and Azapagic 2016	Cradle-to-grave	298.53	1.23	0.94
Italy	De Marco et al. 2016	Gate-to-grave	12.76	0.18	3449.73
Greece	Koroneos et al. 2005	Gate-to-grave	17,660.2	6.75×10^{-4}	18.41

GWP: global warming potential
AP: acidification potential
EP: eutrophication potential

3.3.2 Level 2: Brewhouse and fermentation

This section focuses on each unit operation within the system boundary on Level 2. Table 3.8 compares the environmental performance of two types of beers, ale and lager, as well as two brewing scales, a commercial microbrewery and a pilot-scale brewery. Similar to De Marco et al. (2016), the lager beer produced higher environmental impacts, regardless of the impact category and production scale. The difference in GWP can be mainly attributed to the 22.34 kWh/bbl more electricity use for fermentation and maturation of lager at lower temperatures than ale, as previously mentioned in Section 3.2.1. Figure 3.4 shows the contributions of all the unit operations to different environmental impacts, in which fermentation and maturation were one of the GWP hotspots, contributing 28.07% and 28.37% for the lager, and 22.5% and 14.17% for the ale, respectively, to their total GWP. The electricity generation, required for fermentation and maturation, accounted for the largest share of water consumption, with relative contributions of 48.69 and 49.2% for the lager, and 58.78% and 37.0% for the ale, respectively.

The mashing stage also played an important role due to the environmental impacts associated with malt production. Since ale is featured by 8.5−14% higher original gravity than lager (Kunze 2016), its production requires a higher grain bill. In this study, the ale required 6 kg more malt than the lager for producing one barrel of beer. Therefore, the mashing step including the malt use represented 50.48% of the GWP of the ale, and 39.55% of the lager. As to the TAP, mashing had a similar contribution to fermentation and maturation. In contrast, due to the malts used, mashing predominated the total MEP, by 99.57% and 99.15% for ale and lager, respectively. The boiling step only had a significant contribution to the FWEP, which can be associated with the protein precipitated at high temperature during boiling that is then released as "trub" into the wastewater, as mentioned in Section 1.2.3.

As to the effect of production scale, the beer produced at 1-bbl pilot scale caused 1−13-fold higher environmental burdens than at the 21-bbl microbrewery, regardless of the type and impact category (Table 3.10). As explained by Sturm et al. (2013), larger brewery scales result in lower costs and environmental impacts due to economies of scales. Furthermore, energy and water consumption can be reduced by keeping evaporation rates during boiling at the minimum possible, recovering energy from vapors, installing energy storage systems, using process automation systems, equipping tanks, pipelines and the buildings with proper insulations, using variable speed drives, and minimizing losses of wort and beer. At smaller scales, these techniques become a challenge due to the technology available. Moreover, similar to the profile of the microbrewery, fermentation and maturation were identified as the environmental hotspots of the pilot-scale production (data not reported).

Table 3.8 Comparisons between the environmental impacts of ale and lager produced at different scales

Impact category	Unit	Microbrewery		Pilot scale	
		Ale	Lager	Ale	Lager
Global warming	kg CO_2 eq	3.08×10^{1}	2.62×10^{1}	1.68×10^{2}	2.09×10^{2}
Terrestrial acidification	kg SO_2 eq	2.18×10^{-1}	7.97×10^{-1}	7.97×10^{-1}	2.63×10^{-1}
Freshwater eutrophication	kg P eq	7.34×10^{-2}	7.29×10^{-2}	1.50×10^{-1}	7.31×10^{-2}
Marine eutrophication	kg N eq	8.94×10^{-2}	5.82×10^{-2}	6.61×10^{-2}	1.22×10^{-2}
Water consumption	m^3	7.26×10^{2}	8.91×10^{2}	8.91×10^{3}	1.14×10^{4}

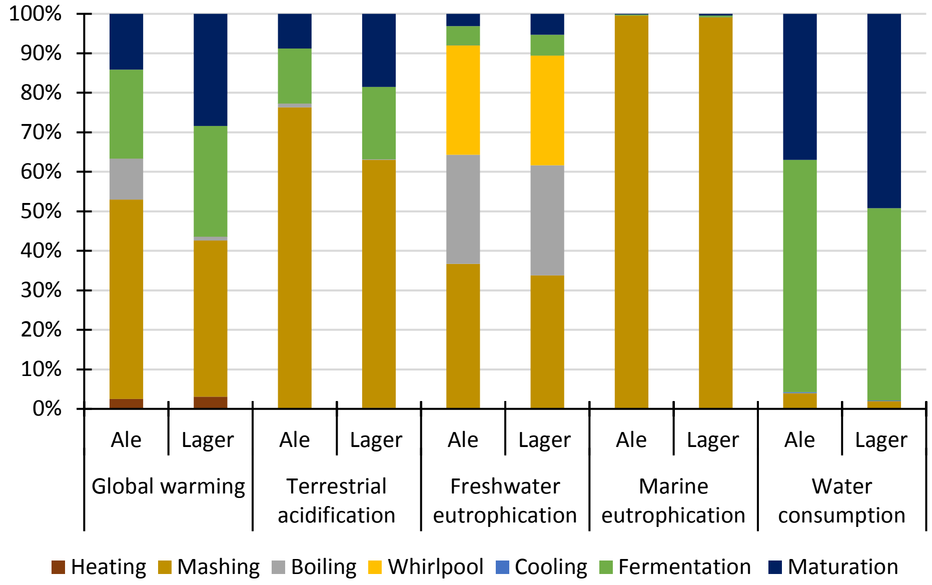


Figure 3.5 Environmental profiles of ale and lager production in microbrewery

CHAPTER 4. CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS

4.1 Conclusions

This study performed the first gate-to-gate analysis combining techno-economic analysis with life cycle assessment on the craft beer production in the U.S, in which the economic profitability and environmental performance were assessed for different scenarios: (i) investment in a continuous water heater system to replace the existing steam boiler used in a commercial microbrewery, and (ii) comparison between ale and lager brewing at industrial and pilot scales.

The production cost per barrel of beer and the energy intensity highly depended on the monthly beer production, which varied with the season. The main operating costs for craft beer production included labor, packaging and raw materials. A simulation model was developed to simulate the utilities required for each unit operation of brewing process in the microbrewery facility, which can accurately estimate the average monthly electricity and natural gas uses. Although the new water heating system was expected to save the annual labor cost, based on the results of the net present value and internal rate of return, the investment project was not recommended for the microbrewery under its current productivity and operation. Increasing beer productivity with lower heater cost can increase the net profit of the investment. Beer processing was the main contributor to the global warming, terrestrial acidification, freshwater eutrophication and water consumption associated with beer production, in which fermentation and maturation were the hotspots of global warming and mashing predominated the marine eutrophication. Furthermore, production at microbrewery scale was more environment-friendly than at pilot scale.

This TEA-LCA-integrated study on craft brewery provides important information for microbrewers, technology providers, stakeholders and researchers. The results obtained are expected to facilitate their decision-making toward a more economically and environmentally sustainable brewing process. Considering the key findings summarized above, the following points can be recommended for U.S. microbrewers:

- The goals of reduction in energy and water usage should be established by the brewery, and continuously recording the key performance indicators, such as energy intensity, resource use per barrel produced, etc. All the on-site operators should be trained to monitor the performance indicators and identify potential problems when necessary.

- Installing additional meters/sensors on brewing equipment to collect more accurate data (e.g., thermometers at the heat exchanger's inlet and outlet) on its operation, which can improve the quality of the developed model. With further integration, the energy performance of the process can be monitored and assessed in-line.
- To reduce the energy consumption of brewing, the highest applicable fermentation temperature to the yeast used should be considered. Moreover, better insulation of fermentation vessels can prevent temperature variation and reduce electricity use.
- Increase the production capacity by expanding new market or incentivizing sales, which can decrease the cost and environmental burden per unit of product, as well as justify the investment in the new water heating system.

4.2 Recommendations for future work

Since fermentation and maturation were the most energy-intensive unit operations of the brewing process due to the low temperatures required, future work should focus on selection of alternative yeast strains which can ferment at higher temperatures without compromising the yield and quality. Moreover, a sensitivity analysis can be performed using the developed model to study the effects of fermentation temperature and time on the beer yield and electricity use, which can serve as a guide to determine the optimum combination that minimizes the electricity intensity of fermentation.

Economic and environmental performance should be evaluated when implementing new technologies. While TEA has been widely used for biofuels and energy sources, it can be combined with LCA as a powerful tool to assess more food-related processes and improve their sustainability. The simulation model developed in this study should be applied to other U.S. microbreweries to compare and validate the results. Moreover, breweries at different scales can be studied to refine the model.

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