

Emission Factor Determination and Application for Materials
Associated with Producing Beer

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Abstract

This thesis uses openLCA software with the ecoinvent and Agribalyse databases and the TRACI impact assessment method to determine cradle-to-gate emission factors for key materials and processes in beer production. It focuses on upstream ingredients and energy inputs, excluding brewing operations, packaging, and distribution, to create a modular toolkit (i.e., individual emission factors adaptable to brewery-specific inputs) for breweries in Northern Colorado aiming to reduce environmental impacts. Greenhouse gas emissions and eutrophication are analyzed. While not a full life cycle assessment, this study promotes more equitable access to sustainability metrics and provides a foundation for future carbon footprints, hotspot analyses, and brewery-level emissions inventories.

Introduction

Beer has been an important aspect of culture and community for thousands of years, dating back to ancient Chinese practices (around 7,000 BCE) (Mark, 2023). It has taken many forms throughout its evolution, but none have been as impactful as the recent explosion of beer production resulting from globalization. Even more recently, the craft brewing industry specifically has become a staple of local beverage markets, especially in the United States and Europe. In 2015, there were just under 5,000 registered craft breweries in the U.S., but eight years later, in 2023, that number had almost doubled (Brewers Association, 2025). However, this rate of growth is not sustainable; the market is becoming saturated, and breweries are being forced to find new ways to stay viable. Domestic production and imports to the U.S. decreased by 5% in 2023, and sales have plateaued in the past few years. Projections do not show the same upward trend that the market experienced decades previous (Billingsley, 2024).

The industry faces problems beyond just economic sustainability. Greenhouse gas emissions from the alcoholic beverage industry (including craft brewing) are significant, contributing to about 0.7% of global emissions when the entire life cycle is considered (Shin & Searcy, 2018). Some of the most successful American craft breweries have addressed issues of economic and environmental sustainability in tandem by implementing new and old techniques for impact reduction. Separating themselves further from the conglomerates that dominate a large

portion of beer sales, organizations like New Belgium Brewing have implemented sustainable practices with proportionally enormous positive implications for the environment.

To do so, New Belgium Brewing conducted a life cycle assessment (LCA) for one of its beers and used a hotspot analysis to identify the most impactful opportunities for emission reductions. While not as large as corporations like AB InBev, New Belgium had sufficient resources to support an analysis tailored to its operations (Caum et al., 2010). Many small to mid-size craft breweries lack such capacity, yet broad participation across the industry is essential to meaningfully reduce emissions. The market potential of carbon-neutral beer, such as New Belgium's Fat Tire, is also often underutilized (New Belgium Brewing, n.d.). This report offers a foundational step for smaller Northern Colorado breweries to assess environmental impacts using regionally relevant emission factors. When paired with brewery-specific data on ingredients and energy use, these findings help contextualize opportunities for emission reduction, whether by lobbying upstream providers or reducing energy use within the brewery itself. Such actions not only support climate goals but can also serve as a powerful form of ethical marketing, enhancing market presence while maintaining a high level of social responsibility.

The methods outlined below address upstream emissions from cradle to plant gate, while also incorporating emission factors for heat and electricity, the two primary energy inputs used during brewing. This report quantifies upstream carbon intensity for each key ingredient (water, yeast, barley, and hops) and common energy resources (heat and electricity) as accurately as possible. Because it is intended for use by established breweries, the report excludes equipment manufacturing and installation (i.e., embodied emissions), as well as the upkeep and cleaning of equipment. While direct brewing operations are not analyzed, heat and electricity factors are included to support future brewery-level emissions inventories. Additionally, due to the variability in packaging methods depending on the final product format (e.g., cans, bottles, kegs), that stage is excluded, along with distribution and transport to the consumer. Further notes about transportation boundaries are provided below.

This study aims to quantify the most relevant environmental impacts of beer production to inform breweries, specifically those in Northern Colorado, as they take steps towards greater levels of sustainability. While carbon intensity is emphasized, eutrophication emission factors are also included in this report because of their significant relationship to the brewing supply chain.

Wastewater from brewing processes typically contains high levels of organic matter, other nutrients like phosphorus and nitrates, and even pollutants including nickel and chromium. Some advanced water treatment systems can lessen these effects, but this takes more energy and is often expensive (Peramuna, 2024). Amienyo & Azapagic (2016) reported impacts due to eutrophication to be especially concentrated in the raw material stage of brewing—the primary focus of this report. Other impacts can be analyzed with life cycle impact assessment (LCIA) methods, but are not relevant enough to the study to include here. Water usage itself is also an important aspect of the environmental impact of beer production, but is excluded from this report to focus more specifically on the outputs of the brewing process. It should be noted that a full LCA is not completed, and to do so, one should follow International Organization for Standardization (ISO) standards (14040:2006) to ensure results are reliable and generalizable (Guinée et al., 2002).

Methods

Emission factors were calculated within the openLCA software based on life cycle analyses for each material associated with beer production. Materials (product flows) relevant to the production of beer were identified in the databases. Once a given material was found and the appropriate upstream provider identified, a product system was created for the material. The product system combines all unit processes (the smallest scope from which data can be extracted for a given process) into a larger product system (including the entire life cycle of the material within a given scope or system boundary). This workflow is more streamlined and relevant to these methods because the research aims to determine total upstream emissions. Accordingly, emissions from the full upstream process are considered to calculate impacts without stratification. An example of a simplified product flow diagram for beer's product system is shown in Figure 1, with processes included in the scope of this analysis contained within the dotted line. While it was deemed to be unnecessary for each material (at least given the capacity of this study), unit processes could have been added or removed based on more specific information about upstream data and procedures to improve final emission factor accuracy.

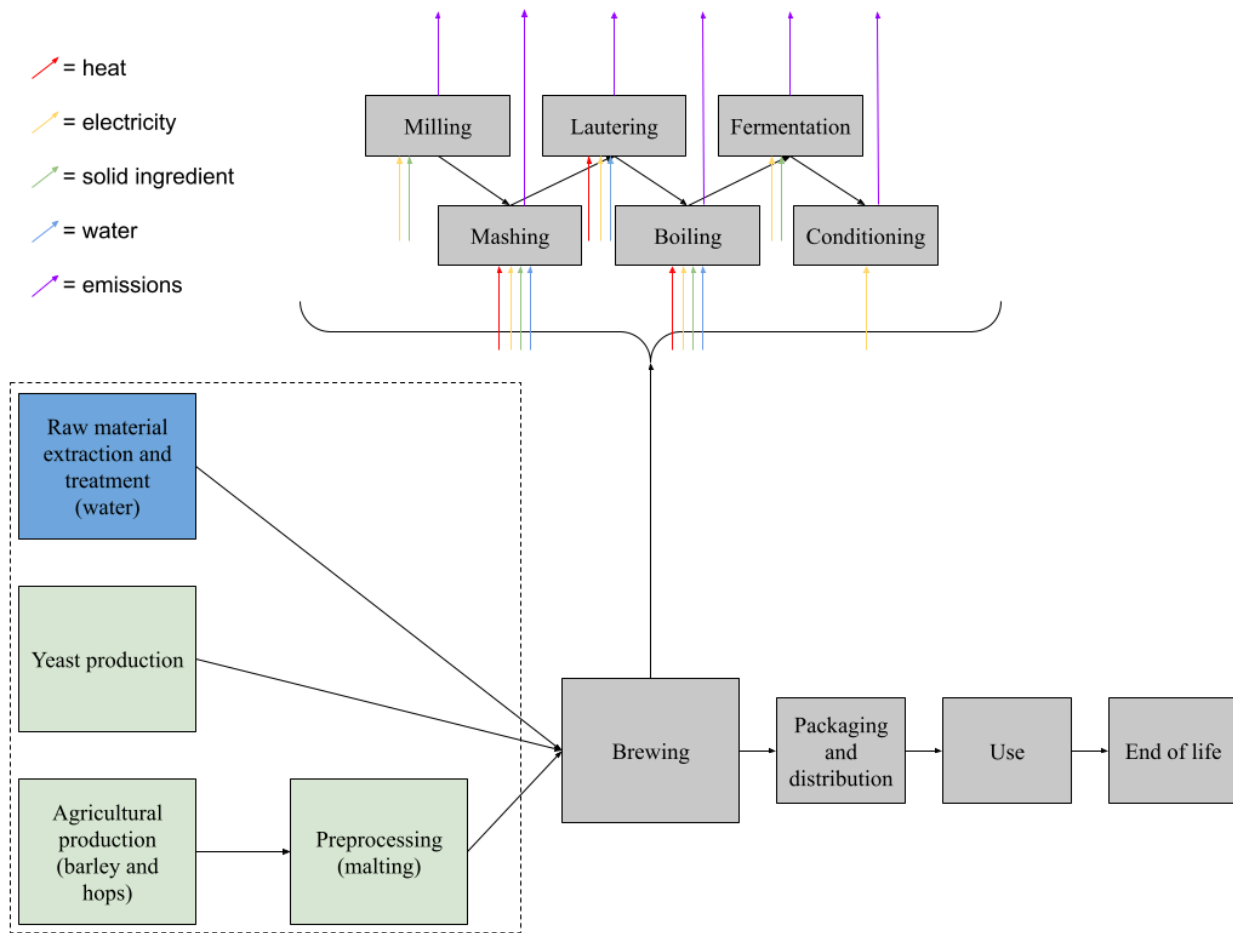


Figure 1

Generic Product Flow Diagram for Beer

After the creation of a product system, impacts were calculated within openLCA using the most recent TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) method (TRACI 2.1). This method was developed by the U.S. Environmental Protection Agency (EPA). It assesses the impacts of different stressors (such as resource use, chemical releases, etc.) on the environment and humans, including: ozone depletion, global warming (or greenhouse gas emissions), acidification, eutrophication, smog formation, ecotoxicity, human health criteria-related, cancer, and noncancer effects, fossil fuel depletion, and land use effects.

TRACI is designed to balance detail and practicality in terms of spatial resolution. Research and training for the method were completed with data from the U.S., which is one

reason why this method is more relevant to the determination of emission factors for a Northern Colorado brewery than others might be. TRACI assesses impacts at the midpoint level of the cause-effect chain so as to maintain reliability (that is, it would be very difficult to accurately model the impacts of climate change on human health, so the method stops at CO₂ equivalent emissions) (Bare, 2002).

Impacts were calculated using allocation methods defined in the upstream processes and the lazy/on-demand calculation type in openLCA. The “allocation, cut-off by classification” system model was employed, in which recyclates used in the product system are considered burden-free: wastes are the producer’s responsibility (the “polluter pays” model). Emission factors were considered as the resulting emissions value for each midpoint impact category (global warming and eutrophication) per unit of output of the material.

Databases used in openLCA (including Agribalyse 3.11 and ecoinvent 3.11), the country or region of data origin, the final life cycle stage considered, the reference flow of the material, and the results from the TRACI impact analysis (denoting greenhouse gas emission factors as well as those for eutrophication) were documented for each material. Transportation emissions relating to each ingredient are generally not accounted for. Estimations of transportation emissions vary greatly based on the source of the ingredient, so they were not attempted in these methods. The material list below is not exhaustive because decisions about ingredients are usually made based on creative or market preference and can deviate significantly.

Emission factors were determined for each required (or at least extremely common) ingredient in the brewing process: water, yeast, barley, and hops. Emission factors for water were determined with values from Quebec, Canada and should be replaced with regionally specific factors where available. The entry represents a mix of groundwater and surface water, averaging information from nine different plants; it specifies that the water comes from a tap (i.e., water utility). Though tap water can be used for brewing, breweries often treat water additionally in some way to ensure taste and consistency. In mountainous areas like Colorado, high-elevation stream water is frequently used for its naturally low mineral count, which integrates smoothly with brewing. While some treatment is necessary for water from mountain streams, it is often gravity-fed to the brewery and uses levels of energy for treatment comparable to tap water (DSEDP, 2018).

Like water, there are many different types of yeast, and a few specific to brewing. The most common include *Saccharomyces pastorianus* and *carlsbergensis*, both associated with lager beers. Another common type of yeast, used mostly for ales like India Pale Ales (IPAs), is *Saccharomyces cerevisiae*. While yeast types matter a great deal for the brewing process, the main ways in which these differences change carbon intensity are through shifts in the temperature of fermentation, which is already included elsewhere in these methods (Holl, 2024). Thus, emission factors were determined for a catch-all database entry for yeast production used for an unspecified purpose. Europe was the only available region for calculations.

The next key ingredient in brewing, grain (usually barley), could represent significant emissions due to intensive agricultural practices. Conventional spring barley is used in this analysis, and includes impacts from cultivation on the farm from harvest to harvest in France (the only country available in the database). While it is specified in the database entry that this barley is intended to be used for animal feed, it also mentions that it is of “malting quality,” and so likely has similar cultivation processes to those of barley for brewing. Malting (the process of germinating barley grain by soaking it in water and then drying it to bring out unique flavors) itself is not included in this estimation, but this stage of preparation for barley to be used for brewing is relatively significant, contributing to about 11% of its total emissions (Chow, 2025).

One study cites that the process of malting one metric ton of barley emits about the same amount of greenhouse gases as the transport of a gas-powered car for 690 miles, equal to approximately 283.59 kilograms of CO₂ equivalence on average, based on values from the U.S. EPA and the following calculations (Rochester Institute of Technology, 2020; U.S. Environmental Protection Agency [EPA], 2014):

$$\frac{8,887 \text{ g } CO_2 \text{ eq emissions per gallon}}{21.6 \text{ miles per gallon}} = 411 \text{ g } CO_2 \text{ eq emissions per mile}$$

$$411 \text{ g } CO_2 \text{ eq emissions per mile} \times 690 \text{ miles} = 283,590 \text{ g } CO_2 \text{ eq emissions}$$

Therefore, the emission factor for the process of malting barley can be estimated with this equation:

$$\frac{283,590 \text{ g } CO_2 \text{ eq emissions}}{1,000,000 \text{ g malt}} = 0.284 \text{ g } CO_2 \text{ eq emissions per g malt}$$

Converting to kilograms to maintain consistency with the rest of the emission factors does not change the value, so the final emission factor is 0.284 kilograms of CO₂-equivalent

emissions per kilogram of malted barley. Based on the methods employed to arrive at this value, high levels of uncertainty should be assumed.

Because there was no entry in the databases for hops specifically, a substitution had to be made. While another study referenced below uses hemp in place of hops due to their shared heritage, the processes of cultivation pertaining to hops and hemp are not very similar; for example, hemp often does not require the use of a trellis, especially in industrial cases. A more appropriate substitution is wine grapes, which do use trellises and have similar soil and climate preferences to most hop varieties (The Growler Guys, 2024). Therefore, French grapes were used for this analysis.

Emission factors were also determined for the use of heat and electricity throughout production. However, it is important to consider that these uses of energy can differ significantly based on a variety of factors. Most simply, electricity grids vary extensively based on location; for this purpose, the database entry regarding electricity from the Western Electricity Coordinating Council (WECC) grid in 2014 (the most recent available year) was implemented for use in Northern Colorado. Voltage also needs to be specified; most breweries use medium-voltage electricity, so that is what was used here (Carpenter & Wallner, 2023).

Additionally, it is crucial to acknowledge the type of heating a given brewery employs. Three types of heating are most common in brewing: steam heating, direct fire heating, and electric heating. Steam heating uses a steam jacket that is wrapped around a kettle and is ideal for larger breweries due to its fast, uniform heating. Direct fire heating heats a kettle from below with a physical fire, usually powered by natural gas. It has a low initial cost and is a simple system, though it is not as efficient or effective as other methods. It can be used for small to mid-size breweries, but the more common option for breweries that carefully consider sustainability is electric heating. While it can be more expensive, heat provided by electricity is ideal for energy efficiency in smaller breweries (Micet Group, 2023). Since both steam and direct fire heating use natural gas, an emission factor was calculated for natural gas heating in general (global average), relating to both district and industrial settings. Electric heating is represented by the emission factor for electricity.

Attention should be drawn to the fact that emission factors for heat and electricity are “market for” values from openLCA, which take an average of as many sources of the given resource as possible in the region at hand. This makes the factors more generalizable across

breweries, though more specific emission factors could be added to more accurately represent carbon intensity based on a brewery's heat and electricity sources. On this note, it is important to recognize that commercial breweries keep most information about their brewing processes private; not only are recipes proprietary, but the details about specific systems utilized often are not publicly available. Therefore, some information for this report was found by searching for and corroborating evidence across different homebrewing sites and online communities.

Results

Emission factors for global warming potential (GWP) ranged from 1.3E-04 kilograms of CO₂ equivalence (tap water) to 5.47 kilograms of CO₂ equivalence (yeast) per unit of material (usually 1 kilogram). For eutrophication, emission factors ranged from 2.5E-08 kilograms of CO₂ equivalence (tap water) to 0.0200 kilograms of CO₂ equivalence (yeast) with the same unit stipulations. A table including material (and reference flow), the country or region of data origin, the final life cycle stage considered, and the results from the TRACI impact analyses (denoting greenhouse gas emission factors, referred to as GWP [based on verbiage used in openLCA] as well as those for eutrophication and specifying units) is shown in Table 1.

Table 1*Emission Factors by Material for Upstream Processes Associated with Beer Production*

Material (1 kg unless otherwise specified)	Country/Region	Final Life Cycle Stage	GWP (kg CO₂ eq per unit)	Eutrophication (kg N eq per unit)
Tap water	Canada-Quebec	At treatment plant gate	1.3E-04	2.5E-08
Yeast	Europe	At plant	5.47	0.0200
Spring barley	France	At farm gate	0.29	0.0058
Grape (substitute for hops)	France	At plant	0.13	0.0031
Heat from natural gas (1 MJ)	Rest of world	Market for	0.04	1.9E-06
Medium-voltage electricity (1 kWh)	U.S.-WECC	Market for	0.50	0.0038

Though it is useful to understand the impact of barley production alone compared with the malting of such barley, it may be more useful for brewers to have an emission factor for malt and its upstream agricultural inputs as a whole. Combining the value for spring barley from the database noted in the table above and the previously defined value for malt, the final factor for 1 kilogram of malted barley is 0.58 kilograms of CO₂ equivalence.

When applying these emission factors, it is vital to bear in mind that the emissions are per unit of material (i.e., per reference flow) and that these units are not consistent. For ingredients directly added to beer, a unit of 1 kilogram is consistently used. Heat and electricity cannot be measured in terms of mass; therefore, the reference flows are in terms of energy common to each: megajoules and kilowatt-hours. When possible, kilograms of CO₂ equivalence are used to represent GWP. This unit allows for easy scalability if emissions are much larger or smaller than the magnitude typically represented by a kilogram. Similarly, eutrophication uses kilograms of nitrogen (N) equivalence wherever attainable. The discussion of units brings up an important point: these emission factors are useful for application to larger carbon footprints and corresponding hotspot analyses, but cannot be compared to one another without a more detailed understanding of the proportions of ingredients used in a particular batch of beer. To further demonstrate the use of these emission factors, a conceptual carbon footprint for 1 kilogram of

unpackaged beer is included in the following section, based on material amounts reported in a prior Agribalyse LCA.

Discussion

This section frames the practical significance of the results presented above by connecting them to existing research and sustainability initiatives in brewing, while reinforcing the original goal of improving equity in breweries' ability to identify and address significant sources of emissions. The determination of emission factors is a critical first step in this process, especially when developed in a modular format that allows adaptation to a brewery's specific circumstances. For example, a brewery that sources hops locally or uses a solar-powered heating system can substitute in more tailored values to better reflect its unique emissions profile.

To further contextualize the results, emission factors from this study are compared to those in existing literature and demonstrated in a conceptual carbon footprint for unpackaged beer. They are also applied to emerging strategies such as circular economic models, renewable energy transitions, and the real-world example of New Belgium Brewing's sustainability initiatives. Finally, this section identifies key limitations and translates them into actionable recommendations for future research.

To check results for validity and to provide an example of how these emission factors might be used, Table 2 shows calculations of total greenhouse gas (GHG) emissions and eutrophication for 1 kilogram of unpackaged, French, "regular beer" at the plant based on amounts of materials from a completed LCA in Agribalyse and the emission factors (EFs) determined in this report. This table should not replace a more accurate calculation of emissions based on actual amounts of materials used in a given brewery, but it assists conceptualization nonetheless.

Table 2*Estimated Environmental Impacts by Material for 1 Kilogram of Unpackaged Beer (at plant)*

Material	Amount from Agribalyse	Unit (per kg beer)	EF (kg CO₂ eq per unit)	EF (kg N eq per unit)	GHG Emissions (kg CO₂ eq)	Eutrophication (kg N eq)
Water	6.8890	kg	1.3E-04	2.5E-08	0.001	1.72E-07
Yeast	0.0002	kg	5.47	0.0200	0.001	4.00E-06
Barley	0.1360	kg	0.58	0.0058	0.079	7.89E-04
Grape (substitute for hops)	0.0002	kg	0.13	0.0031	2.6E-05	6.20E-07
Heat	1.9640	MJ	0.04	1.9E-06	0.079	3.73E-06
Electricity	0.5525	kWh	0.50	0.0038	0.276	2.10E-03
Totals					0.435	2.90E-03

The analysis from Agribalyse documents the total carbon footprint for 1 kilogram of beer as about 0.32 kilograms of CO₂ equivalence. While the value calculated in Table 2 with emission factors from this report, about 0.44 kilograms of CO₂ equivalence, is higher, multiple variables could explain this difference. For instance, the original analysis referenced in Table 2 contains about 20 additional, yet minor, ingredients that contribute to the final value for GHG emissions. Also, as mentioned previously, that study uses hemp as a hop substitute instead of wine grapes. Finally, this report uses location-specific emission factors (like for water and electricity) more reflective of Northern Colorado conditions, whereas the original French LCA used national or regionally averaged values for France. The value of the results in this report lies in their applicability to and ease of use in the Northern Colorado brewing industry, not necessarily in their exact consistency with previous analyses.

Not only is the GHG emission value for electricity in Table 2 extremely high compared to the others, brewery size also has a significant impact on emissions from energy use in beer production; per volume of beer, larger operations usually emit less due to economies of scale and

efficiency improvements (Cimini & Moresi, 2017). Peramuna (2024) notes that “as production scales down, the carbon footprint of beer rises by a whopping 51%.” Thermal and electrical energy are the primary drivers of this drastic difference. This underscores the importance of widespread and accessible emission factors in the case of small to mid-size breweries, especially, even if uncertainties are high. Specifically, energy use seems to have a considerable effect on total emissions (as opposed to the impacts of agricultural inputs or water). This is discoursed through discussions of renewable energy transitions below.

Importantly, due to the assumptions made to reach the final emission factors for hops and barley, these results should be put into context. Chow (2025) notes that hops can have a carbon footprint close to seven times higher than that of barley per kilogram. Results from this report’s methods do not align with these findings, and instead suggest that barley emits more than double the amount of CO₂ equivalence per kilogram of product (even without the impact of the malting process).

This suggests that the substitution of wine grapes for hops may not be sufficient for an accurate analysis of emissions. Inclusion of hop-specific emission factors (and even factors for different hop varieties) should be a primary focus of further research. Not only would the aforementioned discrepancies likely be tempered, but this would also allow for a further analysis of other processes associated with using hops for brewing, such as the energy-intensive drying that drives much of their emission profile. Fortunately, this is a less important limitation when taking into account the amounts of each ingredient used in a batch of beer; barley is used in far greater quantities than hops, even in hop-hungry beers like IPAs (Chow, 2025).

Peramuna (2024) and other studies make clear the extent of the impact of packaging and transportation on the life cycle of beer. Transportation accounts for approximately 10-14% of the total carbon footprint, and packaging represents about 60% more emissions than any other stage (except for the case of stainless-steel kegs, which drastically reduce emissions but are not practical for most scales) in the example of a Peroni Nastro Azzurro. Additionally, Amienyo and Azapagic (2016) found that the carbon footprint of 1 liter of beer is highly sensitive to packaging type. While this report does not include the impact of packaging, it is absolutely necessary to do so in a larger analysis used for the purpose of an emission inventory.

In any scenario, increasing the implementation of circular economics and emission offsets improves a brewery’s overall sustainability. Waste is a potent influence on overall impacts

in almost any LCA, but especially so regarding brewing. A primary representation of this influence lies in the rightmost column of Table 1. Water use is always important to analyze when studying the impacts of beer production (it makes up 90-95% of the product by weight, after all), and this concept is highlighted when considering eutrophication (Peramuna, 2024).

However, 85% of breweries' byproducts by mass are attributed to spent grain (Cimini & Moresi, 2017). Since spent grain is rich in protein and fiber, this example is a great one for the discussion of reuse. It can be repurposed for animal feed or even baked snacks (using flour made from spent grain) for human consumption (Brewster, 2024; Cimini & Moresi, 2021). Attention to these exciting practices complements emission factors by examining how impacts can be avoided downstream in addition to upstream. However, sensationalism is a real threat in the field of sustainability; further research is necessary to determine the scale of real positive effects as opposed to exciting or marketable ones.

As has been mentioned, energy use is a key factor in even a base-level analysis of beer production. Energy is required for every step, but especially cooling and heating processes require significant inputs (Peramuna, 2024). The substitution of renewable energy in the form of electricity is important across scales, but particularly for smaller breweries, this substitution can be made in addition to the implementation of electric heating, combining to achieve one of the quickest and simplest ways to drastically reduce emissions. These renewable energy transitions can be achieved through varied means. Breweries like Sierra Nevada Brewing in Chico, California have installed large solar arrays and fuel cell systems to accompany them (Sundance Power Systems, n.d.). Additionally, in the example of New Belgium Brewing, multiple creative strategies have been employed.

Not only has New Belgium installed solar arrays on its campuses in both Fort Collins, Colorado and Asheville, North Carolina, but it has implemented other tactics to ensure an invested pursuit of a clean brewing process. For example, it lobbied for the City of Fort Collins to adopt a 100% renewable electricity goal, impacting the Platte River Power Authority's (Fort Collins' electricity supplier) decision to shift to 100% non-carbon electricity by 2030 (Lorensson, 2024). If these goals are met, the emission factor for electricity given above would reduce to almost 0 kilograms of CO₂ equivalence per kilowatt-hour, dramatically reducing the size of the overall footprint of any product produced in Northern Colorado, but especially those that are energy-intensive, like beer. Finally, New Belgium has managed to create its own energy

systems independent of the grid on which it sits. These systems rely on the recapture and use of methane-rich biogas, creating energy from the treatment of wastewater and tackling both TRACI impact categories included in this report. A true sustainable success story in the region, New Belgium is on track to achieve its goal of carbon neutrality by 2030 (Lorensson, 2024).

As smaller breweries with fewer resources begin to implement similar sustainability strategies, the base emission factors offered here can serve as an essential foundation, providing an accessible entry point into the world of emission reductions. These factors can be built upon and adapted to fit each brewery's unique context, but the unskippable first step has been taken, focusing on the categories most directly within a brewery's control. Many craft brewers face institutional and financial barriers to conducting full LCAs, especially when the required tools and data are inaccessible or overly complex. By offering a modular, regionally relevant toolkit, this study lowers the threshold for participation and empowers small to mid-size breweries to take meaningful action. Not only can this spur climate-conscious decision-making for ethical reasons, but breweries that prioritize sustainability early may gain a competitive edge, attracting environmentally inclined consumers and aligning with future regulations or supply chain requirements. If enough breweries take part, the ripple effects could scale across the craft brewing and alcoholic beverage industries, contributing to broader climate goals and setting new standards for sustainable local production.

While this study offers a valuable set of emission factors to support sustainability efforts in beer production, it is important to acknowledge several key limitations. Most notably, the system boundary excluded brewing operations themselves (though emission factors were applied to conceptualize this stage) and most transportation, packaging, distribution, and post-consumer end-of-life stages, despite evidence that these phases, particularly packaging, can contribute emissions on par with or exceeding upstream raw-material production (Amienyo & Azapagic, 2016; Peramuna, 2024). Equipment, cleaning, specialty ingredients, and water treatment were likewise excluded due to variability and data scarcity. Although the results include global warming and eutrophication metrics using TRACI, these are midpoint indicators only, and other models like ReCiPe might yield different characterizations. Additionally, the TRACI outputs are reported in different units and cannot be compared across categories without batch-level ingredient quantities, limiting direct cross-impact evaluation. The lack of a formal carbon footprint or hotspot analysis, while outside the scope of this project, means that the emission

factors alone cannot be used to quantify the total environmental impact of a given beer product.

Data-related uncertainties also affect the results. Many inventory datasets used (such as those for barley and yeast) are derived from European sources, not from the U.S., raising concerns about representativeness, especially given possible regional differences in tillage practices, fertilizer use, and irrigation. In addition, the substitution of wine grapes as a proxy for hops likely led to underestimations in that category. In general, more specific emission factors can always be determined since all ingredients found in openLCA are not necessarily produced for the purpose of brewing in Northern CO. While the study provides a strong starting point for emission estimation, future research should refine these values using regionally specific or primary supplier data, or at least complete Monte Carlo simulations to propagate error to the final results of a carbon footprint or hotspot analysis. Temporal limitations also exist in the datasets used, such as the 2014 WECC electricity mix, highlighting the need to incorporate newer or projected emissions values as regional energy grids transition.

While this report anticipates future grid decarbonization (like Fort Collins' target of 100% renewable electricity by 2030), it does not quantify its effects. Similarly, sustainability interventions like spent grain reuse, methane recovery from wastewater, and rooftop solar installations are discussed but not assessed in terms of emissions reductions. Future work could quantify these contributions directly. Nevertheless, the modular format of the emission factor table allows breweries, especially those without the capacity for full LCAs, to incrementally assess emissions associated with their materials and energy use. As such, while not comprehensive, the work serves as a practical toolkit for environmental insight, with future research needed to extend its application across a full product life cycle. Collaborative studies with local breweries could greatly enhance the representativeness and applicability of emission factors and help inform targeted, real-world emission reduction strategies.

To conclude, an especially pivotal concept should be explicitly noted. Shin and Searcy (2018) insightfully write that many craft brewers have chosen paths of inaction for simple reasons: either they perceive the challenges to outweigh the benefits, or they have realized an inability to overcome challenges to reach any benefits at all due to an institutional, financial, or informational barrier. This study intends to return some access to breweries in this position, especially those in Northern Colorado, where implications for cascading reactions across the craft brewing industry are strong.

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