UBC Social Ecological Economic Development Studies (SEEDS) Student Report

An Investigation into Waste Heat Recovery Methods for the UBC Microbrewery

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An Investigation into Waste Heat Recovery Methods for the UBC Microbrewery

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Abstract

Any chemical process, including that of UBC's Microbrewery, will inevitably release, along with its desired products, unused heat energy that is dissipated into the surrounding environment "waste heat." This report investigates two powerful strategies, namely that of Heat Integration and Flue Gas Recovery and Separation. These strategies will achieve a three-fold purpose: to recover as much waste heat as possible, hence drastically reducing the economic costs of the brewery, to further minimize the environmental footprint of the brewery, and to show that this practice of sustainability can be extended to other buildings on the UBC campus.

Due to the lack of information available about the UBC Microbrewery, results have been analyzed and presented on a per m^3 beer produced basis. According to literature findings, 1.09 GJ of energy and $10.15 CAD are required to produce every m^3 of beer. Heat integration can recover 25% of this energy, reduce the cost of beer production by $3.31/$m^3$, and remove approximately 25% of the Greenhouse Gas (GHG) and particulate emissions of the original brewery. Flue gas recovery and separation can recover 26% of the total heat energy, and can reduce the GHG and particulate emissions by another 64%, but will increase the cost of beer slightly by $0.37/$m^3$. The social benefits of the project include the creation of job opportunities for lower-skilled operators and maintenance crews, the relative ease in making the Brewery a showcase for sustainability (due to the Brewery already being a popular place for social activities), and the promotion of similar waste heat recovery concepts in other UBC buildings.

In summary, the two strategies presented in this report (Heat Integration and Flue Gas Recovery) will result in substantial energy recoveries as well as dramatic reductions in environmental footprints and economic costs. The implementation of these strategies also shows a large potential in general social awareness of sustainability, due to the innate social nature of the Brewery itself. Although the Brewery itself and the design concepts outlined in this report are in rudimentary stages, it is highly recommended that UBC continue these efforts in order so that the Brewery, once built, will truly be a place for future students to learn and discuss sustainability.

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1.0 Introduction

A "brewery" is a public drinking and social location, where the beer is produced and consumed on site. In summary, the production process involves the transformation of cereal grains into malt, by soaking the grains in water and allowing them to germinate over a specified period of time. The malt is then boiled to release its inner polysaccharide (sugar) molecules which will undergo chemical reaction to produce alcohol, the basic chemical component of beer.

The UBC Microbrewery is an extension of the new Student Union Building (SUB), with the aim of generating minor revenues for other SUB operations by the minor-scale sale of beer to students. It is also used as a "green process" display to the rest of the university, since the waste materials and energy generated by the Microbrewery will be recycled or reused to other existing processes. One example of an adjacent process was the SUB Greenhouse, and the original plan was to recover as much waste heat energy as possible from the Microbrewery and use it to power the Greenhouse operations. However, as the Microbrewery building location has been recently moved to the UBC farm, it will no longer be able to supply power for the SUB Greenhouse (whose location did not change). Despite the sudden change, the students in this group had already set the project scope as "Waste heat recovery from the UBC Microbrewery," and therefore the report will still treat this as the primary objective. This does not in any way make the goal of the report irrelevant to the original problem statement, because waste heat extraction methods are still being considered and explored. These strategies can be applied to any process that generates waste heat in order to achieve a three-fold objective: to save substantial energy costs incurred by the use of traditional fuels and utilities, to drastically reduce environmental footprints in the forms of greenhouse emissions and waste heat, and to increase social interaction and awareness of UBC's move towards more sustainable alternatives.

2.0 Overview of Waste Heat Recovery Strategies

2.1 Strategy 1: Heat Exchanger Network (HEN) and Pinch Analysis

In traditional chemical production processes such as a brewery (we can consider beer to be similar to any other commodity being produced on a large scale), substantial economic and environmental costs are incurred in order to achieve the energy demands. These demands usually arise due to the requirement of heating or cooling of various fluid streams in the process. In a typical brewery, the largest energy costs occur in the heating of mashed malt material in the wort separation and heating (18% total energy), wort boiling/vapour condensation (18% total energy), and wort cooling processes (35% total energy). These energy-intensive processes are highlighted in the following Process Flow Diagram (PFD), as well as the following energy breakdown table, both provided by Slawitsch et al (2011):

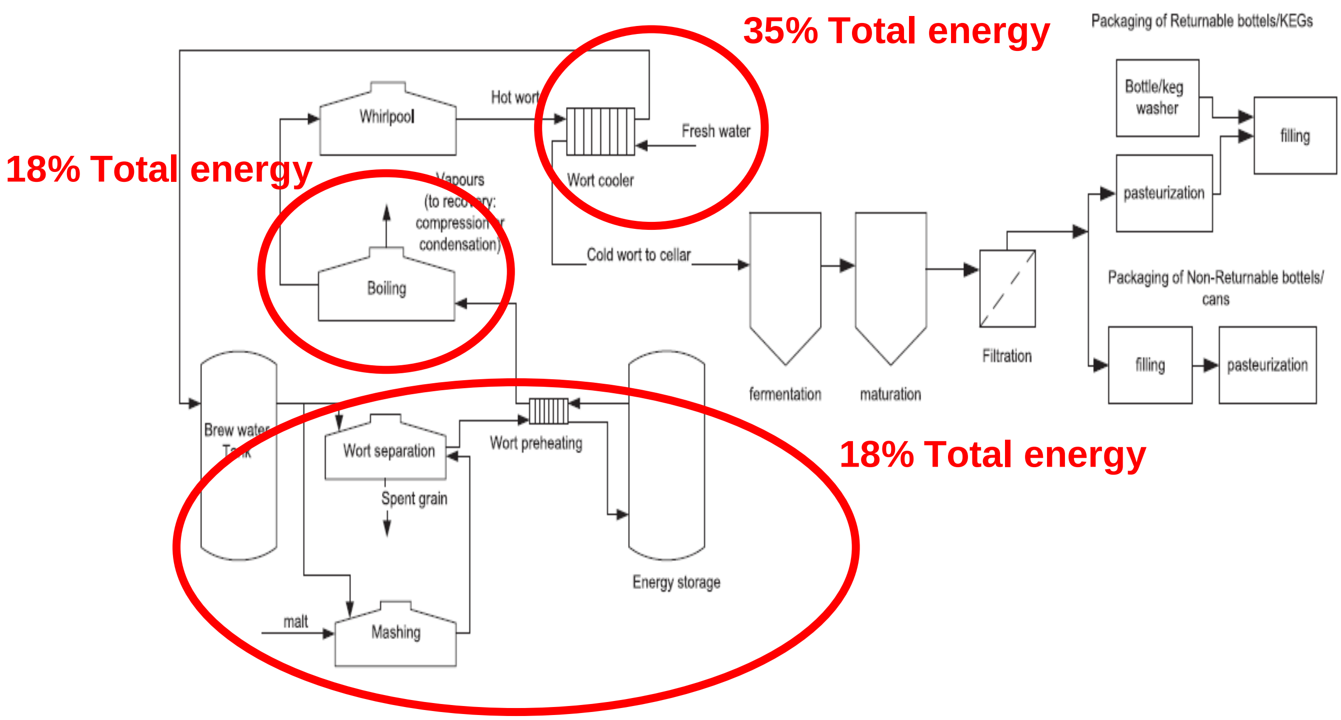


Figure 1: Process Flow Diagram (PFD) of a Typical Brewery (Slawitsch et al, 2011)

Table 1: Energy Consumption of Various Processes in a Typical Brewery (Slawitsch et al, 2011)

Brewery Unit Operation/Process	Process Fluid Temperature (C)	Energy Consumption				
		kWh/week	GJ/week	GJ/year	GJ/m3 beer	%
Waste heat in spent grain	75	26,315.00	94.73	4,926.17	0.05	4.99
Boiler start-up vapour losses	100	13,196.00	47.51	2,470.29	0.03	2.50
Vapour condensation	100	97,890.00	352.40	18,325.01	0.20	18.56
Vapour condensate recovery	95	14,759.00	53.13	2,762.88	0.03	2.80
Wort Cooling	95	182,139.00	655.70	34,096.42	0.38	34.53
Brew House Cleaning	70	9,164.00	32.99	1,715.50	0.02	1.74
Keg bottle washer	30	10,475.00	37.71	1,960.92	0.02	1.99
Pasteurizer	N/A	0.00	0.00	0.00	0.00	0.00
Packager	70	3,259.00	11.73	610.08	0.01	0.62
Bottle rinser	70	385.00	1.39	72.07	0.00	0.07
Crate Washer	40	1,862.00	6.70	348.57	0.00	0.35
Keg cleaning (outsides)	30	663.00	2.39	124.11	0.00	0.13
Keg washing (insides)	70	21,672.00	78.02	4,057.00	0.05	4.11
Keg piping losses	75	436.00	1.57	81.62	0.00	0.08
Keg steaming vapours	70	2,854.00	10.27	534.27	0.01	0.54
Waste heat cooling compressors (cooling)	110	17,676.00	63.63	3,308.95	0.04	3.35
Wort separation and Heating	30	92,626.00	333.45	17,339.59	0.19	17.56
Waste heat pressurized air compressors	70	16,657.00	59.97	3,118.19	0.03	3.16
Boiler flue gas	130	15,519.00	55.87	2,905.16	0.03	2.94
Grand Total		527,547.00	1,899.17	98,756.80	1.10	100.00

The values stated in the table are for a brewery with an annual beer production capacity of 90,000 m^3/yr. Therefore, the energy values were normalized by dividing by this annual capacity, in order to obtain a unit energy cost (GJ/m^3 beer) that can be applied to any brewery regardless of scale. Note that the item “Waste heat in spent grains” refers to the heat energy available from the hot grains as they are cooled, and not the heat content of the grains when digested to produce Biogas (See Section 2.2 Strategy 2: Biogas Production). Obviously the underlying assumption is that all operating and maintenance costs of said brewery are scaled up, or down in this case, by an identical, equivalent factor. To keep this treatment simple, this assumption is considered to be valid.

Slawitsch's analysis shows that each approximately 1.09 GJ of energy is required per m^3 (1000 litres) of beer produced. However, as Table 1 shows, many process streams are at high temperatures (>70^oC) and low temperatures (<40^oC). This proposed strategy involves the physical contact between hot and cold streams using Heat Exchangers (HEXs). HEXs are mechanical devices that provide excellent heat transfer area through heat-conductive materials such as iron or steel. As the following diagram shows, the hot process stream which requires cooling passes its heat to the cold process stream which requires heating. The amount of heat transferred is primarily influenced by the temperature difference between the two streams (refer to the heat transfer equations in Appendix 1). The two streams may pass through the heat exchanger in the shell side (large, open metal casing) or tube side (fine, hollow tubes) depending on fluid pressure, corrosiveness, and other factors.

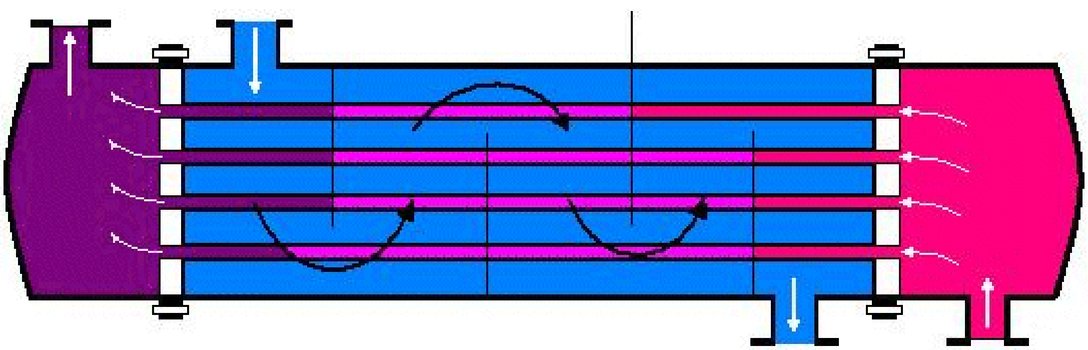


Figure 2: Insides of a shell-and-tube heat exchanger.

Although the energy-saving incentive leads designers to maximize temperature difference (ΔT) between the hot and cold streams, a trade-off exists in that high-ΔT HEXs incur high utility costs (in form of superheated steam and water), and low-ΔT HEXs incur high capital costs (costs for materials of construction and installation costs) since the heat exchange area needs to be extremely large. The figure below illustrates this trade-off.

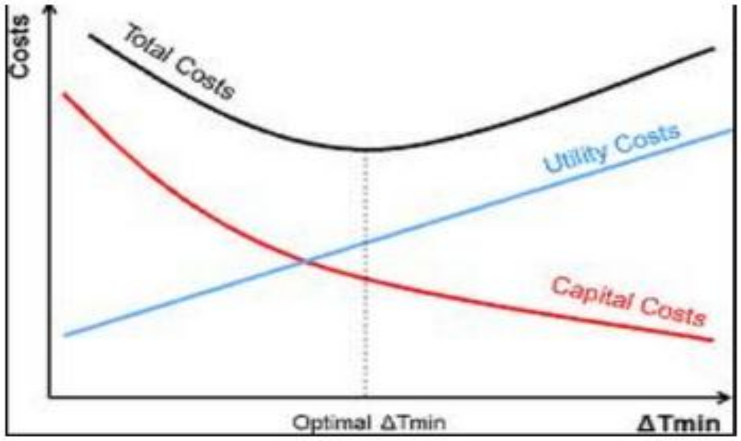
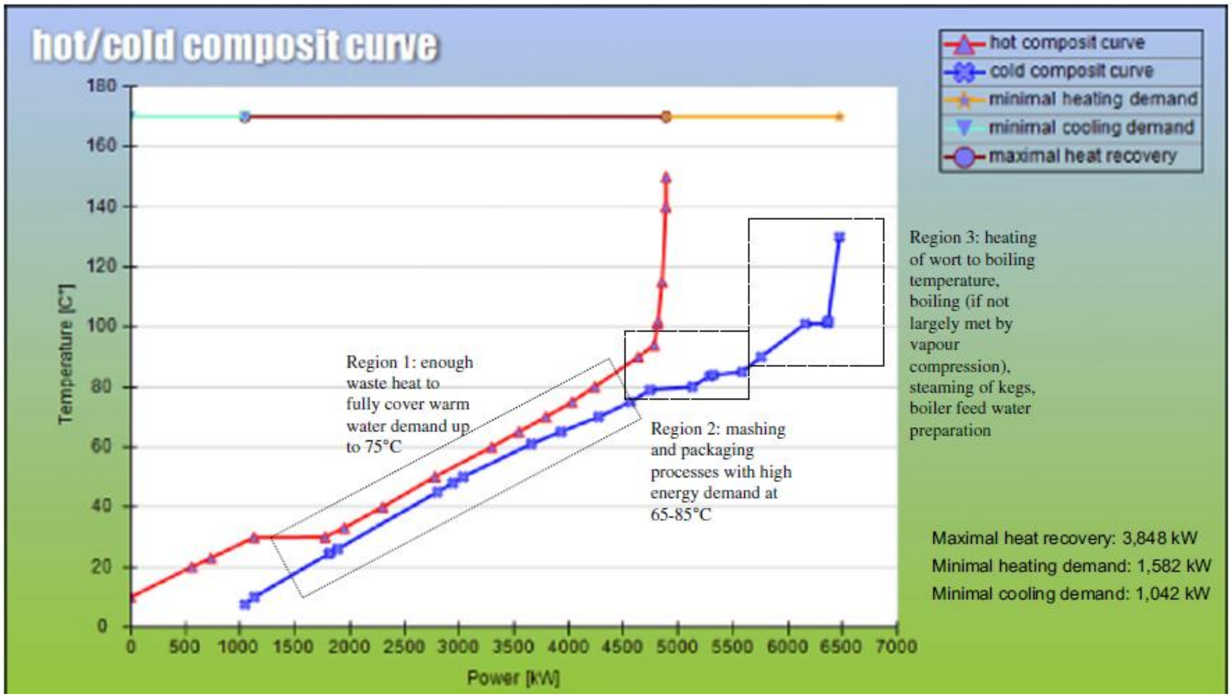


Figure 3: Trade-off between capital and utility costs, based on ΔT

Obviously a compromise must be struck in light of this trade-off. In the chemical engineering industry, this is accomplished by the use of the ***Pinch Analysis***, which is defined as the use of HEXs to *optimally pair-up hot and cold streams based on their respective temperatures, so that minimum total costs (capital + utility costs) are achieved*. Pinch Analysis is usually performed on sophisticated process simulators such as ASPEN Plus, since the hand calculation of heat transfer becomes impossible for a chemical process with more than 10 interacting streams. Also, precise temperature, pressure, heat capacity, and composition of process streams must be known. The array of heat exchangers used to accomplish this is known as a “Heat Exchanger Network” (HEN). An example of Pinch Analysis, stream and heat exchanger pairing is shown as the following:



<u>Figure 4: Hot and Cold Composite Curves for Brewery House and Packaging Operations</u>

Since the process details for the Microbrewery are completely unknown, the predicted energy savings achievable by HEN will be assumed to equal Slawitsch's expected value of 25% (0.274 GJ/m^3 beer energy savings) of the total energy for production (1.09 GJ/m^3 beer produced). Extra costs are expected due to the purchase of pipes and fittings to build this HEN; these are considered in the Economic Analysis in Section X.X.

Since this heat integration process is relatively simple, as it only involves the monitoring of various process temperatures and pressures, operators can be hired as anyone with a basic aptitude for process engineering. The operation will remain straightforward as long as SOPs (Standard Operational Procedures) are properly documented and operators are adequately informed about the safe practices in the brewery. The most challenging task will involve the maintenance and servicing of the heat exchangers. This will likely occur when the heat exchangers have undergone significant "fouling" (material has accumulated inside the heat exchanger tubes and need to be cleaned out). For this, operators will need basic hands-on experience with the assembly/disassembly of pipes and fittings, as well as basic mechanical aptitude to dismount and disassemble heat exchangers and clean them. Fortunately, plant service should only occur once every year at most, and this will not be a frequent task.

2.2 Strategy 2: Brewery Flue Gas Heat Recovery

Any brewery will undoubtedly use fuels of some sort, be it renewable (biomass) or non-renewable (coal, natural gas, etc.) to power its more energy-intensive operations (which run at or above 100^{o}C) or to provide superheated steam, such as during the process of wort boiling. The waste gases, or "flue gases" resulted from the consumption of fuels is often a hot mixture of gases containing steam (H_2O), Carbon Dioxide (CO_2), Carbon Monoxide (CO), a mixture of Nitrogen/Sulphur Oxides (NO_x/SO_x), which are all greenhouse gases. Some uncombusted hydro-carbons (molecules containing carbons single-bonded to hydrogen atoms) can also be in the flue gas, and these can be toxic or carcinogenic should they be ingested by humans. The combustion of coal can also release the extremely toxic chemical, Mercury (Hg). Obviously if the brewery owner was concerned about his/her operations both environmentally and economically, the "gift from heaven" would be a strategy which could both extract waste heat from flue gas AND clean it at the same time.

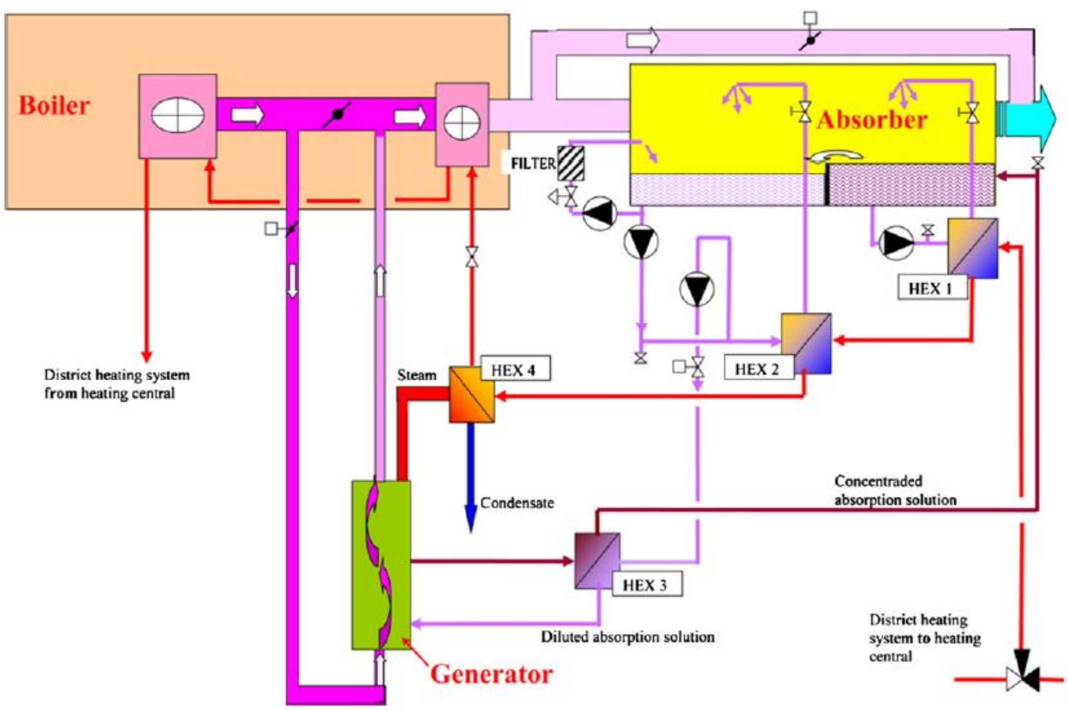


Figure 5: Proposed Biogas Production Process Flow Diagram (Westerlund et al, 2012)

In this proposed strategy, flue gas enters the boiler as fuel and is combusted. As the flue gas mixture exits the boiler, it passes through a turbine which converts mechanical energy to electrical energy via a generator. Then, the flue gas enters a scrubber, which contains a packed bed of ceramic materials which removes 38% of harmful particulates (greenhouse gases and hydrocarbon molecules) on average (Westerlund et al, 2012). An absorber removes most of the steam (H_2O) from the flue gas, where it is cooled off in heat exchangers. The heat released by the cooling flue gas as well as the latent heat released by the cooling of H_2O can be used for heat integration as detailed in Section 2.1: Strategy 1. The potential energy savings of this strategy are approximately 50% of the fuel energy required for processes such as wort boiling/cooling and wort separation/heating. This translates to an energy savings of 26% (0.284 GJ/m^3 beer) of the total energy (1.09 GJ/m^3 beer) required for the brewery.

Just like the last strategy (heat integration), any students or persons interested in process engineering and operation can be hired as operators or maintenance crew, given that they are provided the appropriate documentation. Safety requirements will be more stringent for this strategy, however, due to the more intricate nature of the process. The flue gas absorber/scrubber will require more specialized personnel to service. Chemical engineers are the suitable candidates for the daily process operation of the boiler, heat exchangers, and scrubber. Mechanical engineers will maintain the structural integrity of the plant's various pipes and instrumentation, as well as the operation of the generator. Electrical engineers will be required for the periodic calibration of various process instruments and computer interfaces. A SOP will have to be written and documented so that the operators can be trained to run and maintain the plant safely. In terms of equipment service, sensitive sections such as the packed bed absorber will have to be replaced once every couple of months. Heat exchangers will have to be serviced at most once every year. UBC engineering students or Co-op students are recommended for this task.

3.0 Economics

Table 1 shows that 0.71 GJ/m^3 of energy comes from processes operating >95^oC, and the remainder of the energy (0.28 GJ/m^3) comes from processes operating under 95^oC. According to Seider et al (2009), >95^oC processes are typically powered by non-renewable fossil fuels such as natural gas and coal, and the <95^oC processes are usually powered by electricity due to the relatively low heating requirements. Assuming that this is the case for a typical brewery, the costs of natural gas and electricity can be easily obtained from FortisBC and BC Hydro, respectively. According to FortisBC, natural gas costs $2.98/GJ, which means that $2.11 is spent per m^3 beer produced on the higher-temperature processes. BC Hydro cites its electrical costs in 2013 as $28.72/GJ, equating to $8.04 per m^3 beer produced. This means that beer production, in total, costs $10.15/$m^3$.

3.1 Economics for Strategy 1 – HEN and Pinch Analysis

Usually a HEN (Heat Exchanger Network) utilizing the pinch analysis must involve complete and accurate knowledge of all temperatures, flowrates, and heat capacities of the process streams involved in the heat integration. Since this data is not available to the students of this project, nor are approximate values of heat energy from the planned microbrewery, the heat exchangers, utilities (superheated steam and water), as well as the piping required cannot be estimated on an absolute-value basis. Rather, literature values of typical brewery waste heat production are to be extracted from Slatwitsch et al (2011) then adjusted to an "energy per volume beer produced" (GJ/m^3 beer) basis in order to provide useful scale-down to the microbrewery.

In the work of Slatwitsch et al (2011), a typical brewery with a production scale of 90,000 m^3 beer per year is estimated to release a total amount of 99,000 GJ of waste heat per year. As proposed previously, 27.4% of this waste heat, 27,000 GJ/year, can be recovered using the HEN/Pinch Analysis strategy. Although the process details are unknown, a traditional Process Engineering Handbook by Seider et al (2009) states that the amount of heat exchange area can be calculated and priced using this estimated total waste heat value. Students taking the CHBE 459 course at UBC (4th Year Chemical Engineering Process Economics) confirms that the methods stated in Seider et al (2009) match the current sizing/costing strategies, and that they approach an accuracy level of ± 50%. The equipment costs of any process equipment can be estimated according to its material of construction, pressure considerations, dimensional adjustments, and construction/installation fees. Refer to Appendix A for a more detailed breakdown of these costs.

The results from the Appendix state that a total of $60,927 CAD is required for the total heat exchanger area for a brewery producing 90,000 m^3 beer/year. Depending on the expected lifetime of the brewery, the equivalent cost/m^3 beer these heat exchangers will vary. For our case, we will expect the brewery to operate for 10 years; therefore, the heat exchangers will cost $0.67 /$m^3$ beer.

The amount of piping required will mostly depend on the brewery's plant layout (equipment, flowrates, energy rates, etc.) and plant design (accessibility of utilities, etc.). Since detailed process data is not available, we assume that the all process streams will be water-like in properties, and that the plant design of piping and instruments are "optimal." In this case, the total cost of piping can be estimated as 45.6% of the equipment cost, which in our case are the heat exchangers (Lau, 2013). This translates to an estimated piping cost of $0.31/$m^3$ beer produced. Finally, we must consider the operating costs for this strategy. According to Lau (2013), operating labor and maintenance sum up to 20% of total capital costs, as a rough estimate. The total capital cost from heat exchangers and pipes is simply ($0.67+$0.31) /m^3 beer = $0.98/$m^3$ beer. Therefore, the operating and maintenance costs are roughly $0.20/$m^3$ beer. savings achieved by heat integration.

According to Slatwitsch et al (2011), $81,100 CAD/yr can be saved if 5% of the brewery's total waste heat is integrated, for the base case brewery (with beer production rate of 90,000 m^3/yr). This is equivalent to a total energy savings of $4.29/$m^3$ beer produced. Therefore, the net value of the heat integration is simply the savings minus the extra incurred equipment costs, which are: $4.29/$m^3$ – ($0.67/$m^3$ + $0.31/$m^3$ + $0.20/$m^3$) = $3.11/$m^3$ beer produced over the base case. Therefore, heat integration should seriously considered as an energy savings alternative, from an economic point of view.

3.2 Economics for Strategy 2 – Flue Gas Recovery and Separation

Brewery wort boiling is an energy-intensive part of the brewery. The Use of fossil fuels such as methane(CH_4) in the boilers usually results in the formation of large amounts of flue gas. As detailed previously, typical flue gas compositions consist of greenhouse gases (CO_2, CO, NO_x/SO_x,) water vapour and some unburnt hydrocarbon particulates, as well as mercury. In the flue gas recovery and separation strategy, the flue gases first enter a generator, where the mechanical energy of the gas is extracted and converted to electricity. The rest of the gas is a waste stream which is rich in greenhouse gases and soot particulates. The gaseous waste stream then flows through a packed bed scrubber where the particulates and wastes get absorbed in the packing of the scrubber. Since plant data for this brewery are unavailable, the estimates shown in this paper are based on order-of-magnitude estimates and typical industrial assumptions. Considering this study as the first stage of the preliminary study, the following estimates will have an error margin of about ±50% (Lau, 2013).

A packed bed scrubber is an adsorption unit operation, where a multi-phase stream is separated into the desired products (in our case, clean air) and undesired products (GHGs and particulates). One advantage of using a packed bed scrubber is that they have low pressure drops, which mean that the fluid usually does not need to be pumped, and thus pumping costs can be ignored. Moreover, scrubber packings are typically capable of achieving high mass transfer efficiencies, therefore allowing efficient separation of pollutants from the original gaseous waste stream. Although scrubbers have low capital costs, they incur substantial maintenance costs due to the frequency of service.

The following are cost ranges associated for a typical packed bed scrubber. The information comes from a combination of typical industry numbers provided by Seider et all(2009), as well as the United States Environmental Protection Agency (US EPA).

Capital Cost: \$23,000 to \$117,000 per sm3/sec (\$11 to \$55 per scfm)

O & M Cost: \$32,000 to \$104,000 per sm3/sec (\$15 to \$49 per scfm), annually

Annualized Cost: \$36,000 to \$165,000 per sm3/sec (\$17 to \$78 per scfm), annually

Cost Effectiveness: \$110 to \$550 per metric ton (\$100 to \$500 per short ton), annualized cost per ton per year of pollutant controlled.

As stated earlier, the unavailability of plant size and data makes the calculations prone to large errors. However, the details are shown in the Appendix. After converting the numbers above to a per m^3 beer basis, it is found that \$0.49/m^3 produced is required for the capital cost, and \$0.67/m^3 beer produced is the annual operating cost (the operating cost far exceeding the capital cost, as noted earlier). Taking into account that the heat savings achievable using the flue gas strategy amounts to ~\$0.79/m^3 beer, the approximate extra cost of this strategy comes out to be \$0.37/m^3 beer.

3.3 Overall Economic Benefits and Other Economic Considerations

Considering that it takes \$10.15 to produce 1 m^3 of beer, and that the net savings achieved by the two strategies combined is \$3.31/m^3 - \$0.37/m^3 = \$2.94/m3 beer, a significant economic saving (29.3%) is achievable by these two strategies alone. Therefore, there is an extremely strong incentive for these strategies, from the economic point of view.

In these analyses, however, there was a simplifying assumption that the equipment used (heat exchangers, pipes, absorber packings, etc.) would last indefinitely and would never require replacement. In a real implementation of these strategies, extra costs would have to be incurred for equipment replacement, but it is extremely difficult to measure them accurately due to varying plant lifetimes, future inflation rates, as well as the advance of technology which may make these strategies obsolete (better strategies may emerge in the future).

4.0 Environmental Considerations

The heat integration strategy involves the use of numerous heat exchangers, pipes, and fittings, in order to integrate hot process streams with cold process streams. If no heat integration were present, much more fossil fuels and electricity would be consumed in order to meet the heating requirements of the process. Although electricity in BC is produced mainly by hydro-electric dams, a small portion of it is produced outside of BC using less sustainable means, such as the combustion of fossil fuels. Hence, the biggest environmental benefit to be reaped from the incorporation of these strategies is the significant reductions in greenhouse gases such as Carbon Dioxide (CO_2), Carbon Monoxide, (CO), Nitrous Oxides (NO_x), and Sulphur Oxides (SO_x). A mixture of these gases is known as “flue gas” in industrial terms, and they originate from the combustion of non-renewable fossil fuels such as natural gas and coal. They all contribute to global warming, which in turn leads to anomalies in seasonal climates. Carbon monoxide is extremely deadly and toxic; a concentration as high as 50 PPM and an exposure time of 8 minutes is enough to kill a full-grown human. Nitrous and Sulfur oxides are milder in toxicity, but contribute significantly to acid rain. Uncombusted fuel particles such as hydrocarbons are also present in the flue gas, which cause offensive odours and may be carcinogenic to humans if inhaled or ingested. Finally, the extremely toxic element Mercury (Hg) may be present from coal combustion, if the quality of coal is poor. Therefore, it is imperative to quantify the extent to which the Heat Integration and Flue Gas Recovery strategies can eliminate the production of these toxic and environmentally-unfriendly gases and particulates.

According to Slawitsch et al (2011), most brewery processes operating under 95^{o}C are heated by electricity, due to the relatively lower heat demands. However, the processes operating at or above 95^{o}C are usually powered by non-renewable fossil fuels, with natural gas being the most common fuel. Below is a recount of the various brewery processes, and the ones that are likely to be fueled by natural gas are highlighted in yellow.

Table 2: Distinction of High and Low-Temperature Processes Within a Brewery

Brewery Unit Operation/Process	Process Fluid Temperature (C)	Energy Consumption				
		kWh/week	**GJ/week**	**GJ/year**	**GJ/m3 beer**	**%**
Waste heat in spent grain	75	26,315.00	94.73	4,926.17	0.05	4.99
Boiler start-up vapour losses	100	13,196.00	47.51	2,470.29	0.03	2.50
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Grand Total		527,547.00	1,899.17	98,756.80	1.10	100.00

4.1 Heat Integration – Environmental Benefits

4.1.1 Fuel and Pollutant Reductions - Heat Integration

The heat requirements for the highlighted processes in Table 2 add up to a total of 0.71 GJ/m^3 beer. According to FortisBC's site, natural gas has an average energy content of 1,000 Btu/ft^3, or 37.3 MJ/m^3. Therefore, 18.1 m^3 natural gas is required to produce every m^3 of beer. According to NaturalGas.org, the possible pollutants released by the fuel consist of the following:

Table 3: Pollutants Generated per m3 Natural Gas Burned:

Pollutant	Output (kg pollutant/m^3 NG)
Carbon Dioxide (CO_2)	1.87
Carbon Monoxide (CO)	$6.41x10^{-4}$
Nitrogen Oxides (NO_x)	$1.47x10^{-3}$
Sulfur Oxides (SO_x)	$1.60x10^{-5}$
Hydrocarbon Particulates	$1.12x10^{-4}$

Hence, the amount of pollutant generated per m^3 beer produced can be approximated as:

Table 4: Pollutants Generated per m^3 Beer Produced

Pollutant	Output (kg pollutant/m^3 beer)
Carbon Dioxide (CO_2)	33.8
Carbon Monoxide (CO)	$1.16x10^{-2}$
Nitrogen Oxides (NO_x)	$2.66x10^{-2}$
Sulfur Oxides (SO_x)	$2.90x10^{-4}$
Hydrocarbon Particulates	$2.03x10^{-3}$

The total heat savings achievable across the entire brewery using Strategy 1 (Heat Integration) is approximately 25%, as detailed in Section 2.1. Assuming that this reflects a 25% reduction of natural gas requirements for the brewery processes that require temperatures of >100^oC, the associated pollutants (CO_2, CO, NO_x/SO_x and particulates) will also be reduced by 25%. Therefore, the following pollutant reductions are achievable:

Table 5: Pollutant Reductions per m^3 Beer Produced for Natural Gas, by Heat Integration

Pollutant	Output Reduction (kg pollutant/m^3 beer)
Carbon Dioxide (CO_2)	8.45
Carbon Monoxide (CO)	2.90×10^{-3}
Nitrogen Oxides (NO_x)	6.67×10^{-3}
Sulfur Oxides (SO_x)	7.27×10^{-5}
Hydrocarbon Particulates	5.10×10^{-4}

Other environmental considerations for the Heat Integration strategy include the concrete, metals (stainless steel), and other materials used in heat exchangers, pipes, and fittings. Although it is possible to estimate the amount of such materials required to produce these items, the environmental effects are indirect and difficult to quantify. For example, the processes that produce concrete or stainless steel may be sustainable or unsustainable, depending on the company's ethical and environmental policies. Therefore, the possible indirect environmental impacts of procuring these materials are pointed out, but not explored, in this report.

4.1.2 Electricity Reductions – Heat Integration

According to Table 2, 0.38GJ/m^3 beer is required for the lower-temperature processes (<95^{o}C), and is typically supplied by electricity. Typically, 80% of electricity in produced BC is supplied by hydroelectric dams, with the remaining 20% supplied by fossil fuels from powerplants outside of BC. The 20% of the electricity will be assumed as generated by coal. Applying the same proportions to the brewery, it can be assumed that 0.304 GJ/m^3 is generated by hydro-electric means, and 0.076 GJ/m^3 is generated by coal.

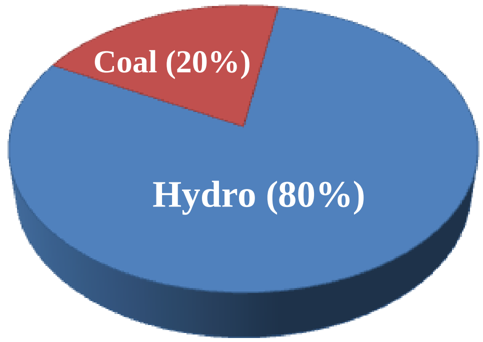

Figure 6: Breakdown of Electricity Generation in BC

According to a study performed by the University of Washington, the energy content of coal is 16.5 MJ/kg. This means that 4.61 kg coal is required to produce every m^3 of beer. NaturalGas.org also provides a table of pollutants generated by the combustion of coal:

Table 6: Pollutants Generated per kg Coal Burned:

Pollutant	Output (kg pollutant/kg coal)
Carbon Dioxide (CO_2)	1.48
Carbon Monoxide (CO)	1.48×10^{-3}
Nitrogen Oxides (NO_x)	3.24×10^{-3}
Sulfur Oxides (SO_x)	1.84×10^{-2}
Hydrocarbon Particulates	1.95×10^{-2}
Mercury	1.13×10^{-7}

Hence, the amount of pollutant generated per m^3 beer produced can be approximated as:

Table 7: Pollutants Generated per m^3 Beer Produced

Pollutant	Output (kg pollutant/m^3 beer)
Carbon Dioxide (CO_2)	6.82
Carbon Monoxide (CO)	6.82×10^{-3}
Nitrogen Oxides (NO_x)	1.49×10^{-2}
Sulfur Oxides (SO_x)	8.48×10^{-2}
Hydrocarbon Particulates	8.99×10^{-2}
Mercury	5.21×10^{-7}

Assuming that up to 25% of the heat requirements in the lower-temperature processes (<95°C) can be saved by heat integration, 25% of the total electricity requirement can be saved, and hence 25% of the pollutants from the combustion of coal can be avoided, resulting in the following pollutant reductions:

Table 8: Pollutants Eliminated from Electricity Generation, by Heat Integration Strategy

Pollutant	Output Reduction (kg pollutant/m^3 beer)
Carbon Dioxide (CO_2)	1.71
Carbon Monoxide (CO)	1.71×10^{-3}
Nitrogen Oxides (NO_x)	3.73×10^{-3}
Sulfur Oxides (SO_x)	2.12×10^{-2}
Hydrocarbon Particulates	2.25×10^{-2}
Mercury	1.30×10^{-7}

4.2 Pollutant Reductions for Flue Gas Heat Recovery and Separation

According to Section 2.2, the flue gas recovery and absorption system will recover 26% of the total waste heat from the brewery. Assuming that this proportional constant is equal to the savings achieved on the natural gas and electricity consumptions for the brewery, and accounting for the fact that the flue gas scrubber removes 38% of the greenhouse gases and carbon particulates generated by the boilers, the pollutant reductions achieved by this heat recovery strategy can be simply calculated as:

Table 9: Pollutant Reductions per m^3 Beer for Natural Gas, by Flue Gas Recovery

Pollutant	Output (kg pollutant/m^3 beer)
Carbon Dioxide (CO_2)	21.6
Carbon Monoxide (CO)	7.42×10^{-3}
Nitrogen Oxides (NO_x)	1.70×10^{-2}
Sulfur Oxides (SO_x)	1.86×10^{-4}
Hydrocarbon Particulates	1.30×10^{-3}

Table 10: Pollutant Reductions per m^3 Beer for Electricity, by Flue Gas Recovery

Pollutant	**Output (kg pollutant/m^3 beer)**
Carbon Dioxide (CO_2)	4.36
Carbon Monoxide (CO)	4.36×10^{-3}
Nitrogen Oxides (NO_x)	9.54×10^{-3}
Sulfur Oxides (SO_x)	5.43×10^{-2}
Hydrocarbon Particulates	5.75×10^{-2}
Mercury	3.33×10^{-7}

Hence, the flue gas recovery strategy achieves the following combined pollutant reductions:

Table 11: Total Pollutant Reductions per m^3 Beer Produced, by Flue Gas Strategy

Pollutant	**Output (kg pollutant/m^3 beer)**
Carbon Dioxide (CO_2)	25.96
Carbon Monoxide (CO)	1.18×10^{-2}
Nitrogen Oxides (NO_x)	2.65×10^{-2}
Sulfur Oxides (SO_x)	5.45×10^{-2}
Hydrocarbon Particulates	5.77×10^{-2}
Mercury	3.33×10^{-7}

4.3 Summary of Environmental Benefits (Pollution Reductions)

To summarize the results detailed in Sections 4.1 and 4.2, the following pollutants are generated by a typical brewery, on a per m^3 beer produced basis:

Table 12: Total Pollutants Generated per m^3 Beer Produced

Pollutant	Output (kg pollutant/m^3 beer)
Carbon Dioxide (CO_2)	40.62
Carbon Monoxide (CO)	$1.84x10^{-2}$
Nitrogen Oxides (NO_x)	$4.15x10^{-2}$
Sulfur Oxides (SO_x)	$8.51x10^{-2}$
Hydrocarbon Particulates	$9.19x10^{-2}$
Mercury	$5.21x10^{-7}$

The total pollutant reductions are summed from each strategy, and combined to arrive at the following numbers:

Table 13: Total Pollutants Reduction Achieved by Heat Integration and Flue Gas Recovery

Pollutant	Output (kg pollutant/m^3 beer)
Carbon Dioxide (CO_2)	36.12
Carbon Monoxide (CO)	$1.64x10^{-2}$
Nitrogen Oxides (NO_x)	$3.69x10^{-2}$
Sulfur Oxides (SO_x)	$7.58x10^{-2}$
Hydrocarbon Particulates	$8.18x10^{-2}$
Mercury	$4.63x10^{-7}$

This is approximately an 89% reduction in every greenhouse gas, as well as hydrocarbon particulates and mercury. Although the estimates here are magnitude-of-order (i.e. an accuracy of ±50%), these results illustrate the huge environmental incentives of the heat integration and flue gas recovery strategies.

4.4 Other environmental impacts

Deposition of organic matter is frequently encountered in equipment such as water coolers, condensers, and cooling towers. The most widespread mitigation strategy during online operation as well as offline cleaning of heat exchangers is the use of chemical agents containing substances that are potentially harmful to the environment. For example, anti-scalants, and anti-fouling agents are broadly used in desalination and chemical plants. They usually contain additives include chemicals like polyphosphate, chlorine, hypochlorite, coagulants, etc. The use of anti-scaling chemicals must be justified in the plant by the frequency and severity of the fouling. For example, if fouling occurs infrequently and not significantly, as it would in a typical brewery, the use of these chemicals may be reduced or replaced entirely by mechanical means (such as simply cleaning by hand). The final decision on whether these chemicals are used will depend on the final plant design, as well as the adequacy of chemical disposal methods available at the site.

5.0 Social Implications

In order to assess the social impact of the aforementioned heat recovery strategies, we focused on several factors. These include: the possibility of job creation, promotion of student learning, and their viability for setting an example for sustainable design. At first the reaction of the local community does seem to be a valid fourth factor for assessing the social implication of the waste heat recovery strategies. It was decided, however, that the implementation of these strategies will not be apparent to the general public, thus the social impact in that regard will be minimal.

5.1 Job creation

The implementation of both the Heat Integration and Flue Gas Het Recovery strategies will require the installation of new machinery into the brewery. Since the brewery will be in operation almost all the time, regular maintenance checks are required to ensure the machines stay in an operable state. While the brewery on its own already requires regular maintenance to keep it running, it is advisable to hire new members for the existing maintenance crew to maintain machines needed to implement the aforementioned waste heat recovery strategies. Hiring more people is the optimal solution to ensure efficiency and accuracy in the regular maintenance checks for the new machines. At the same time, energy savings generated by the implementation of the aforementioned waste heat recovery strategies will help make hiring new maintenance crew members for the brewery affordable. Thus it is safe to say that the implementation of the aforementioned waste heat recovery strategies will create some job opportunities in the operation of the brewery.

Should the implementation of the HEN and/or Flue Gas heat recovery method prove to produce positive effects for UBC, this might encourage similar designs to be implemented in future construction projects both within and outside of UBC. This will lead to an increase in the demand for the machinery needed for the implementation of these strategies. Faced with the increased demand, existing manufacturers of will need to expand their scope of operation. At the same time new companies might be created in an attempt to “cash in” on the increased demand for these machines. The various competitors then, in an attempt to produce more revenue for their companies, will attempt to develop new products or perhaps new manufacturing methods. In any case, as long as there is an increased demand for the machinery used in the implementation of the aforementioned waste heat In both cases, new job opportunities will be created.

5.2 Student Learning

With UBC acting as a pioneer by trying out different methods to achieve a sustainable lifestyle, it is important to encourage students to be mindful of the effects their actions can have on the world around them. As stated before, the implementation of waste heat recovery strategies is not immediately obvious to the public. However, the implementation of such strategy can help promote the idea of sustainable design to students in certain areas of study, such as mechanical engineering. By offering educational tours, where students are given an overview of the waste heat recovery system, students can gain an understanding of what it means by sustainable design. This can also spark interests in some students to learn more on sustainability, and perhaps pursue a career in the application of sustainable design in the future. There is no reason to limit the target audience for the aforementioned tours to just students in UBC. The tours should also be offered outside of UBC, to spread the idea of sustainable design. The ideas presented are perhaps a little unrealistic to be put into practice. It is to be noted, however, that there is an educational value in show casing the waste heat recovery system of the brewery. After all, it is much better to give an actual example of a working application of sustainable design. It will be much easier for student to understand the system and provide a much stronger view point on the benefits in a sustainable design.

5.3 Possible Case Study

By implementing the HEN and/or Flue Gas heat recovery strategy in the brewery, the facility can act as a testing ground for the viability to apply similar waste heat recovery systems for future construction projects. If results are favorable, new buildings around the campus should be equipped with heat recovery systems based off the design used in the brewery. This can aid in UBC’s goal to become more sustainable in running the campus. At the same time, energy savings can help bring total operational cost of the campus down to some extent.

The presented waste heat recovery strategies are more suited for production facilities similar to a brewery. While this might cause problems for the implementation of the system to normal buildings, there are production facilities out there that can benefit from the implementation of such system. UBC can publish some sort of an annual report concerning the operation of the brewery. This report should include the operational cost, and perhaps a calculated value on the energy savings achieved by the waste heat recovery system. This can give those in charge of production facilities similar to a brewery outside the campus a rough idea of whether or not the implementation of such a system can be beneficial them. Once again, if the results are largely positive, production facilities outside the campus may start implemented their own waste heat recovery system.

5.4 Social Impacts: Conclusions

Once implemented, the waste heat recovery system will not be apparent to the local populace. To give people an understanding on the design and benefits on implementing the system, it is advisable for UBC to offer showcasing tours and/or release annual reports on the operation of the brewery. If the waste heat recovery system is highly beneficial to the operation of the brewery, students and those outside of campus will become interested in the system. This newfound interest can lead to an expansion of the manufacturing on the machinery used in the system. This situation can create numerous job opportunities. At the same time, it will encourage the implementation of similar systems for future construction projects within and outside of the UBC campus.

6.0 Conclusions and Recommendations

UBC's Microbrewery inevitable releases waste heat along with its desired product, beer for UBC students. According to theory stated in literature, 1 m^3 of beer costs 1.09 GJ of energy and $10.15 to produce. The two strategies investigated in this report, namely Heat Integration and Flue Gas Recovery and Separation have successfully achieved a significant economic reduction ($2.94/$m^3$ beer) of beer production costs, as well as lower the detrimental environmental effects of the brewery (89% potential reductions in emissions), namely in the form of greenhouse gases and carcinogenic/toxic particulates such as hydrocarbon particulates and mercury. The last item of the triple-bottom-line analysis, social effects, is not apparently realized, since these strategies are mostly technical in nature.

In order to make the efforts of sustainability more visible to students, an array of publicity efforts are recommended. For example, some type of logo could be made and stuck on the heat integration equipment in the brewery, so that students and workers who visit the brewery on a regular basis can be constantly reminded of the effort in sustainability. The Brewery can also be advertised on the UBC website for volunteers who wish to help continue these sustainable efforts. Finally, the brewery as a popular location for social gatherings will inevitably draw large crowds of students, who will recognize these sustainable efforts and apply them in other UBC buildings.

A final recommendation is the investigation of a biogas production plant, which utilizes the waste heat from the spent grains in the brewery. The more detailed analysis in Appendix 3 shows that 58% of the total waste heat from the brewery can be recovered simply by considering the waste grains as a "waste heat" source, since the grains themselves have an extremely high heat content (1 kg of waste grains produces 10.6 L of biogas with ~70% methane, which has a corresponding energy content of 3.82 MJ). However, the CO_2 emissions from the anaerobic digestors would have to be evaluated, and balanced with the natural gas/coal fuel savings achieved in the brewery to confirm whether a net GHG emission reduction is achievable. Nevertheless, it is an extremely promising strategy worth pursuing, should the implementation of waste heat recovery strategies come to life in the UBC Microbrewery.

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Appendices

Appendix A: Heat Transfer and Heat Exchanger Sizing Calculations

**Note: Since accurate plant data is not available, this analysis is done purely on ballpark estimates and averages provided by reliable process engineering sources. Considering this to be the equivalent stage of a preliminary process plant estimate (where initial estimates are known but no design/process details are known), the gross estimate will have an error margin of ±50% (Lau, 2013).

1. Heat Exchanger Area Sizing

For heat exchangers, $Q = UA\Delta T_{LM}$, where:

U = Overall heat transfer coefficient; we assume all heat transfer interfaces to be water→steel→ water. Therefore U = 370 $W/m^2{*}K$ on average (Seider et al, 2009).

A = Surface area for heat transfer; the most important parameter used to size heat exchangers. This will be the unknown in our calculations.

ΔT_{LM} = Log-mean temperature difference between hot and cold streams. Since we do not possess accurate process data, but know that the pinch temperature differences are approximately 10^oC between all streams (Slatwitsch et al, 2011), then we assume ΔT_{LM} to be equal to 10^oC.

We can then combine the U and ΔT_{LM} estimates and the estimate of total integrated heat energy of 27,000 GJ/year = 856.2 kW to calculate the total amount of heat exchanger area required. Therefore:

$$A = Q/(U{*}\Delta T_{LM}) = 231.4 \text{ m}^2 = 2{,}491 \text{ ft}^2$$

Cost correlations (Seider et al, 2009) can be used for sizing process equipment. Various equations describe the material, pressure, tube-length correction factor, and bare-module cost; all these factors are then multiplied together to obtain a final cost for the equipment.

Material Factor F_M

This factor accounts for the material(s) of construction of the associated process equipment. Assuming heat exchangers to be of the floating head, shell-and-tube type (stainless steel on both shell and tubes):

$$F_M = a + b\ (A/100) = 2.70 + 0.07(2{,}491/100) = 4.4437$$

Pressure Factor F_P

This factor accounts for the extra costs incurred in order to design the process equipment to withstand its typical operating pressures. Assuming the shell-side pressure of the heat exchangers to be 2 atm absolute (14.7 PSIG):

$$F_P = 0.9803 + 0.018\ (P/100) + 0.0017\ (P/100)^2 = 0.9803 + 0.018\ (14.7/100) + 0.0017\ (14.7/100)^2 = 0.9834$$

Tube-Length Correction Factor F_L

This factor corrects for any expansions (or contractions) in the heat exchanger's tube length, compared to a standard length (20 ft). Assuming the heat exchangers used in the brewery contain 20-ft tubes, F_L=1.

Bare-Module Cost C_B

The bare-module cost corresponds to the raw material costs of the process equipment, construction costs, contractor fees and installation fees. The costs are stated as USD at year 2006. For a floating-head heat exchanger:

$$C_B = \exp[a_1 + a_2 \ln(A) + a_3 \ln^2(A)] = \exp[11.2927 - 0.9228\ln(2491) + 0.09861\ln^2(2491)] = \$24{,}512 \text{ USD}$$

Material Factor F_M

The material factor covers the main material of construction used for the process equipment. In our case it is assumed to be Stainless Steel-316. Therefore, F_M = 2.1 according to Seider et al (2009).

Equipment Purchase Cost C_P

Finally, C_P is the equipment purchase cost. It is the product of all the previous discussed factors, as such:

$$C_P = F_M F_P F_L C_B$$

$$= (2.1)(0.9834)(1)(\$24{,}512 \text{ USD})$$

$$= \$50{,}621 \text{ USD } (2006)$$

$$= \$51{,}633 \text{ CAD } (2006)$$

The Chemical Engineering plant index of 2006 is 500. Assuming the CE plant index of 2013 is 590:

$$C_{P,2013} = C_{P,2006} * (590/500) = (\$51{,}633 \text{ CAD})(590/500) = \$60{,}927$$

Therefore a rough cost of the total heat exchanger transfer area is \$60,927 CAD, for a total beer production rate of 90,000 m^3/year. This is a capital cost and will be cheaper, i.e. "spread out more," the greater the expected lifetime of the brewery. For example, for an expected brewery lifetime of 10 or 20 years:

Lifetime of 10 years: HEX Cost/year = (\$60,927/10 years)/(90,000 m^3/year) = \$0.677/m^3 beer

Lifetime of 20 years: HEX Cost/year = (\$60,927/20 years)/(90,000 m^3/year) = \$0.338/m^3 beer

Appendix B: Flue Gas Absorber Cost Calculations

Using information Seider et al (2009) and US EPA, \$23,000 per standard m^3 /sec is the raw capital cost of the packed bed scrubber. We use the formula $Q=C*A*(2*g*H*(T_i-T_o/T_i))^{1/2}$ to find the volumetric flow rate of Flue gas entering the scrubber, where:

Q-Flue Gas flowrate
A-Cross sectional area of the scrubber(chimney) – Assumed to be 5 m^2 for an industrial brewery
C-Discharge coefficient (0.65-0.70)
g- gravitational acceleration (9.8m/s^2)
H-height of the scrubber – Assumed to be 3m for an industrial brewery
T_i-average temperature of the flue gas – Assumed to be 500K
T_o-average outside temperature in Vancouver

Substituting in the appropriate numbers lead to operating and maintenance costs of \$0.67/m^3 of beer produced and a capital cost of \$0.49/m^3 beer produced. Assuming that natural gas costs has an energy content of 37.26 MJ/m^3, a BC cost of \$0.105 m^3/GJ, and that 0.28 GJ/m^3 beer is the energy savings achieved by the flue gas recovery strategy, \$0.79/m^3 beer is the savings. Therefore, the net cost of the flue gas scrubber system is \$0.37/m^3 beer produced.

The results:

- **Capital cost**:\$0.49/m^3 beer produced
- **Operating/maintenance costs**: \$0.67/m^3 of beer produced
- **Extra Cost compared to Normal brewery**: \$0.37/ m^3 beer produced

Appendix C: Potential Biogas Production from Waste Grain

Breweries produce massive amounts of waste cereal grain, after all sugars are extracted from the wort for fermentation. This waste grain was traditionally dumped into landfills, but a more sustainable alternative has been developed to convert these grains to livestock feed for farms. An even more sustainable alternative is proposed here, where the "heat content" of grains is extracted by converting the waste grains into biogas, a mixture comprised of mostly Methane (CH_4) gas, along with CO_2, N_2, and O_2.

In the biogas production process, the sludge-like waste grain mixture undergoes an elaborate screening and filtering process where large particles (such as debris) are removed. The remaining biomass enters a large anaerobic digester, where the sludge is fermented for a period of 35~70 days (Babel et al, 2009), killing off most pathogens and fecal coliforms. An industrially-sized digester is usually in the order of 4m-diameter by 11m-height, as shown in the following picture; obviously, the digestor for the Microbrewery will be much smaller than this. Typically 1 kg of brewery sludge can produce 10.6L of biogas mixture (with 69% CH4, 26% CO_2, 1% O_2, and 4% N_2) with an energy content of 360 MJ/m^3. The final stage of the biogas production involves the separation of gas from remaining solid wastes in a decanter. Anaerobic digestors offer the advantage of well-sealed vessel, which means that very little gaseous emission will leak out and cause a toxic/offensive odour to the surrounding environment. Also, the sludge recycle ratio is high (40~50%), meaning that waste grains can be "re-used" multiple times before they are completely stripped of their biogas potential.

Figure 7: Typical Industrial Anaerobic Digestor

The amount of brewery sludge heavily depends on many variables of the brewery, such as production efficiency, energy use, and plant design. According to the work of Slawitsch et al (2011), a brewery producing 90,000 m^3 beer/yr wastes on average 15,000 tonnes of grain per year. This is equivalent to saying that 58% of the total waste heat (0.63 GJ/m^3 beer produced) can be recovered by producing and burning biogas alone, and so it the most efficient energy recovery strategy.