Reducing Glycol Chilling Load at Ruhstaller Farm

A techno-economic analysis of low-cost,
nature-based, and growth-minded solutions

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1. Project Background

1.1. Project and client context

Ruhstaller Farm is a beer brewery and taproom located in Solano County, just north of Dixon, California [1]. Since 2012, Ruhstaller Farm has grown hops to supply the Sacramento "BSMT" taproom in the historic Ruhstaller building [1]. However, the farm became a proper taproom in 2020, with capacity to entertain hundreds of guests with live music and outdoor seating [1]. In addition to growing hops and hosting a diverse selection of beer, Ruhstaller Farm grows walnuts and fruit, and is home to a menagerie of hens, dogs, and cats [1].

Ruhstaller Farm has been a client for previous project teams from UC Davis' "A Path to Zero Net Energy" class. Previous assessments investigated the feasibility of wind turbines, rooftop solar, waste heat recovery with rainwater, biomass to biogas systems, and hop kiln efficiency projects [2], [3].

In many steps of the brewing process (boiling wort, fermentation, maturation, etc.), breweries typically require extreme cooling capacity for their beer, usually in the form of food-safe heat exchange piping systems with accompanying chillers. Ruhstaller Farm uses a propylene glycol-water solution (hereafter referred to as "glycol") as the working fluid, with a chiller and pump located just outside the brewing room.

Ruhstaller Farm values nature-based solutions, environmental and community health, and the rich history of the Sacramento region [1]. As such, the project team sought to recommend solutions that fit within these tenets to perpetuate Ruhstaller Farm's sustainable growth and unique character.

1.2. Problem statement and scope

Ruhstaller Farm (hereafter referred to as the "client") reported to the project team that on average, about 90% of their historic electricity has been used for their glycol chilling system. The project team was tasked with assessing the technological and economic feasibility of various intervention methods, with the goals of saving the client money and energy, while maintaining system operation and reliability.

This project's scope did not include detailed engineering design of intervention methods, nor did it include modeling the client's economic and business growth. While general sustainability principles were exercised in this project, life-cycle analyses were not executed.

1.3. Literature review

On April 26, 2023, the project team met with the client to obtain a basic understanding of the glycol chiller system and brainstorm potential solutions. The following literature review closely reflects the material discussed during this site visit.

1.3.1 Passive shading strategies

Improving energy efficiency is a common challenge faced by breweries [4]; however, the client's glycol chiller is located outdoors, providing significant opportunity for energy savings via passive shading. Passive shading reduces ambient air temperature and consequently increases the coefficient of performance (COP) of the chiller [5]. Observing trends in the Green Button Data [6], there's clear temperature dependence in the middle of the day, suggesting cooler temperatures may save on energy and cost (see *Appendix A*).

Theoretical studies suggest that passive shading techniques could reduce cooling loads by 50-70%, in the context of building air conditioning systems [7]. Different shading techniques may control direct, diffuse, and/or reflected solar radiation, like the strategies below [8]:

1) Externally adjustable shading prevents low-angled direct sunlight, diffuse, and reflected light.
2) Vegetation can shade whole facades and roofs, reducing conductive and radiative heat gains.

Regarding (2), shading and evapotranspiration from trees can reduce ambient air temperature by up to 5°C, which as stated before, may reduce the energy demand of the chiller system [7]. Patterns of vegetation canopy and height of shading vegetation or other built structures can be optimized to the specific footprint of the desired area to be shaded, too. Importantly, shading of the chiller may provide 1-39% improvement in the COP of condensers, at least in the context of air conditioning units [9]. A wide range of approaches can be used to meet the desired energy savings goal; simple devices or planting trees, when correctly designed, are often as effective as more expensive and complex solutions.

Shading must conform to aesthetic preferences of the client too; site-specific shading strategies may include continuation of burlap covers on the open face of the fermentation room, as well as utilization of the existing tarp on top of the chiller. Using on-site resources may decrease cost of these interventions, potentially down to simple labor and time.

1.3.2 Vertical ground-source heat exchange (GSHX) loops

In the detailed site tour on 26 April 2023, the client included an unused pumping well (due to sand intrusion) adjacent to the fermentation room and associated glycol piping. After a quick discussion, JE Paino, manager of Ruhstaller Farm, grew fond of investigating the efficacy of a ground-source glycol loop to dispose of excess heat.

According to the client, the well is 100 ft deep, with the water table around 40 ft below ground level. Water provides more efficient convective heat transfer than dry soil, so a GSHX loop with groundwater, if it can tolerate corrosion, would be much more effective than a "dry" system.

GSHX systems, glycol- or water-based, are appealing for their stability; the USGS measurement well closest to Ruhstaller reports ground temperatures of 63.3 ± 0.7°F, which may provide effective cooling even during the hottest days of the year [10]. Vertical GSHX systems have been proven to work in many applications, too; a large school in South Korea report energy savings and COP increases from reducing inlet water temperatures via GSHX [11]. Another study from Türkiye, on the other hand, warns of increase frictional loads on the pump, which may greatly increase installation cost [12].

Fluid-tight, corrosion-resistant, prefabricated loops may be easily ordered from various manufacturers on the order of hundreds of dollars [13]. Great care must be taken to match the combined cross-sectional area of a GSHX loop system with the rest of the piping network, as to not cause a bottleneck or unintended friction.

2. Methods

2.1. Considerations, constraints, assumptions, and metrics

Important design considerations were mostly handled verbally with the client; the client must be interested in the intervention idea for it to be worth analyzing. Other basic considerations also applied: it was out of scope to suggest changes that required operation-scale or impractical changes (i.e., replacing propylene glycol with another working fluid, altering brewing steps, or requiring complete thermal envelope redesign). Ultimately, the suggested interventions were meant to increase energy efficiency; therefore, onsite electricity generation was not considered.

The design team was contained to the project scope in *Section 1.2*, among other factors. The project was to be completed within Spring Quarter 2022, with the first final deliverable due date of 7 June 2023 as the effective final day of analysis.

Many assumptions were made in the project team's analysis, including averaging values that may vary diurnally, annually, by beer type, or by other factors on which the project team had little influence or information. More limitations and assumptions of this study can be found in *Section 3.2*, but overall, it's vitally important to recognize this study was based entirely on averages.

The metrics for success used in this analysis were ones that are most applicable to the client: payback time, electricity savings, energy savings, and total cost. These can be found in *Table 2* or *Appendix D*.

2.2. Site measurements

2.2.1 Quantitative measurements

On 26 April and 16 May 2023, the project team assessed various parameters of the glycol chilling system at Ruhstaller Farm, with great help from Head Brewer, Jarred Sorci.

An infrared temperature probe was used to measure many temperatures: glycol inlet, glycol outlet, fermentation tank surfaces, and chiller surfaces. As detailed measurements of tanks were not recorded in detail, it was assumed that the initial average fermentation tank temperature was ~87°F, or 2°F hotter than the coolest tank. It was observed on-site that the hottest (~100°F) tank quickly dropped off "exponentially," with the following at about 90°F, and subsequent tanks cooler still. Outdoor ambient temperature was simply recorded from online weather services as 85°F.

A laser distance device was used to measure applicable lengths of the fermentation tanks, west-facing brewing room wall, and dimensions of the chiller. In the event of a measurement being impossible with a laser measurer, various opaque objects and project team members served as stops.

Glycol flow rate was measured by timing the filling of half of a standard 5-gallon hardware bucket. Dividing 2.5 gallons by the measured time, 3 seconds, yielded a volumetric flow rate. Any variable that was not measured on site was obtained via brewing records, manufacturer specifications, or estimations from outside sources.

2.2.2 Qualitative system description

The glycol chiller unit consists of an ambient air-source chiller, a pump, and a 200-gallon reservoir kept at 26°F. The piping system is composed of two "halves": a cold side and a warm side. All cold inputs into various components of the system (plate heat exchanger and individual fermentation tanks) are controlled by solenoid valves, which can be actuated both manually and with temperature setpoints. "Used," warm glycol is sent through the warm side of the system and into the chiller, where it's cooled and recirculated. Notably, this configuration, typical of other breweries and wineries, does not "reuse" glycol, reducing cooling efficiency losses on units toward the "end" of the loop. A simple diagram of this system can be found in *Appendix E*.

2.3. Data analysis

2.3.1 Baseline analysis

Analysis was first done on Green Button Data obtained from one of the client's PG&E accounts [6]. Notably, as mentioned in *Section 1.3.1* and *Appendix A* for the diurnal case, and seen in *Appendix B* for the annual case, strong temperature dependency of electricity demand reinforces the client's need for efficiency improvements to the chilling system. The account (or "meter") included only electricity from the chiller and glycol pump; however, these needed to be separated to provide an accurate analysis of the system.

To estimate monthly electricity demand for the glycol pump, assumed power draw was multiplied by the operation time per month. A provided power draw of 5 hp was assumed based on the pump class [14], as well as constant operation (i.e., 24 hours per day, every day). This energy, about 2500 kWh/month, was subtracted from the total average monthly energy usage to find the monthly energy usage of the glycol chiller *(Appendix B)*. Because most other data was not available in daily or seasonal resolution, the project team averaged chiller energy usage over its entire lifetime – resulting in 8384 kWh/month.

Some proposed interventions (shading or replacing the chiller) were expressed as a percent increase in chiller COP, so calculating a baseline COP was necessary. As average electricity use was already estimated, the cooling load provided by the chiller was necessary to calculate average COP. Average cooling load was divided into six components:

a) Energy extracted through the plate heat exchanger to cool down boiled wort
b) Energy needed to "throttle" the beer down to a starting temperature, after being transferred to a fermentation tank
c) Energy produced by yeast during fermentation
d) Energy absorbed by beer vis a vis increased temperature (from fermentation)
e) Energy needed to "crash" the beer down to 34°F after fermentation
f) Energy radiated through fermentation tank walls during maturation

Many of these components were calculated with the constant specific heat equation *(Equation 1)*, where Q is thermal energy transfer [kBTU], m is mass [lb], c is the assumed constant specific heat [BTU/lb·°F], and ΔT is the temperature differential [°F]. Note that the time rate form of this equation, used for time rate calculations, uses $\dot{Q}$ [kBTU/hr] and $\dot{m}$ [lb/hr] instead.

$$Q = m * c * \Delta T$$

(Equation 1)

(a) was found by assuming all thermal energy from cooling 30 b of wort from boiling (212°F) to 67°F was removed by the glycol system. (b), (d), and (e) were found similarly, with baseline ΔT values of 7°F, -10°F, and 36°F.

(c) was estimated via a constant heat production value obtained from a presentation by Scheer [15]. Sugar content was estimated with starting and ending gravities of a typical beer: 15°P and 4°P respectively. Then, *Equation 2* was applied to calculate (c), with Q as thermal energy produced, e as the heat produced per mass of sugar [BTU/lb], s as the starting sugar content (gravity, with different units) of the wort [lb/lb], m as the mass of the wort [lb], and f as the fermentation completion [%].

$$Q = e * s * m * f$$

(Equation 2)

(f) was calculated via similar means to Scheer [15], using the same values for convective heat transfer coefficients of beer and air. Tank dimensions were provided by the manufacturer, EGISA [16], and these were used to calculate bulk thermal conductivity of the tank walls with known material thermal conductivities. Application of an average ΔT of 53°F (87°F – 34°F) yielded (f).

The average cooling load was calculated as the sum of (a) – (f), multiplied by the monthly average number of active 30-b batches. The average number of active batches was calculated simply by dividing the total beer production from 2022 by 30 b/batch and 12 months/year – about 3.2 batches/month. Note that (d) was negative, as beer absorbing thermal energy effectively decreases the load from (c). The baseline case yielded an average cooling load of 94,673 kBTU/month.

To calculate average COP of the chiller, the monthly cooling load was divided by the monthly electricity use, accounting for unit changes. This yielded 3.31; on average, 3.31 kWh of useful cooling energy was generated per kWh of electricity put into the chiller.

2.3.2 Intervention analysis

The project team considered four interventions, with brainstorming help from JE and Jarred. The project team did not initiate conversation with any interventions in mind and let the client staff guide initial feelings of feasibility. Each intervention was analyzed independently to find useful results, like monthly electricity savings, cost savings, and simple payback time. The four interventions considered in analysis were:

a) Shading fermentation tanks to reduce ΔT, and ultimately heat exchange through tank walls
b) Shading the entire chiller to reduce intake air temperature, and ultimately increase COP of the system [5]
c) Replacing the entire chiller with a more modern and efficient one, again to ultimately increase COP of the system
d) Installation of a ground-source heat exchange (GSHX) loop for warm glycol, to outright reduce heating load on the chiller system by cooling passively.

Outcomes of (a) were estimated by assuming all fermentation tanks would revert to the same temperature as the easternmost (least exposed to the west-facing open wall) one, for an average tank temperature 2°F cooler than the baseline case. Heat exchange through fermentation tank walls was calculated as in *Section 2.3.1*, and all other analysis remained the same.

Outcomes of (b) were estimated by a constant increase in average COP, with no change on the cooling load of the system – effectively reducing electricity consumption. ElSherbini and Maheshwari found a minimum 1% increase in COP from shading the compressor of an air-conditioning unit, so this 1% was applied to the current system COP [9].

Outcomes of (c) were estimated similarly to (b), with an improved COP. However, this new COP was obtained from laboratory test data by Thermal Care [17]. Thermal Care tested four chillers under standard procedures, but only one, a 10-ton, water-cooled, variable-speed compressor system, yielded a COP higher than the baseline case.

Outcomes of (d) were not calculated, as this solution was immediately deemed infeasible. See *Section 3.1*.

2.4. Equity and justice considerations

In parallel to the technical approach, the project team aimed to integrate equity into the design process and outcome. The project team considered four frames of environmental equity: procedural, distributive, restorative, and recognition. As detailed in Jenkins et al. (2016), distributive equity considers righting the unequal distribution of energy benefits and burdens; procedural equity considers the strategies for remediating impacts; restorative justice focuses on restoring affected communities to original conditions before damages; and recognition justice targets the most in-need communities [18]. Using this framework, the project team identified several equity elements to implement and consider during the project. *Table 1* describes each component and consideration in further detail.

Table 1: Equity and justice considerations

Element	Considerations
Procedural	Consult both management and brewing staff about potential solutions
Distributive	Cost savings benefits will Ruhstaller Farm, and recommendations should increase ergonomics of the work environment
Restorative	When does the client use most of their electricity? In California, peak times have more CO_2e-intense electricity.
Recognition	Project is local in scope; therefore, the project solution may only directly benefit the staff on-site

3. Results and Discussion

3.1. Main results

As detailed previously, four energy efficiency or conversation measures were analyzed:

a) Shading fermentation tanks
b) Shading the chiller
c) Replacing/modernizing the chiller
d) Ground-source heat exchange (GSHX) glycol loop

Detailed intermediary calculations can be seen in *Appendix C*. (a), (b), and (c) generated decreases in energy use and subsequent monthly energy savings. Installing a GSHX system (d) was deemed infeasible within the current operating parameters; anecdotal evidence suggests a peak glycol temperature of about 55°F, which is (i) less than typical groundwater temperatures of 63°F [10], and (b) significantly less than the temperature required for effective heat exchange (63°F + ~15°F ≈ ~78°F, as a general rule of thumb).

Table 2: Summary of important results

	Baseline	Tank shade	Chiller shade	Chiller swap
Cooling load [kBTU]	94,673	93,983	94,673	94,673
El. power [kW]	12.5	12.4	12.4	8.3
El. use [kWh/mo.]	8384	8323	8301	5562
El. cost [$/mo.]	$1,592.96	$1,581.35	$1,577.19	$1,057.00
El. savings [$/mo.]	--	$11.61	$15.77	$536.00
Intervention cost [$]	--	$258.75	$172.50	$21,340
Simple payback [mo.]	**--**	**22.3**	**10.9**	**39.8**

As seen in *Table 2* (and more extended in *Appendix D),* our projections estimate tank shading will save $11.61/month, shading the chiller will save $15.77/month, and upgrading the chiller to a water-cooled unit with a variable speed compressor will save $536/month. Shading the chiller has the quickest simple payback period (10.9 months) followed by shading the tanks (22.3 months) and upgrading the chiller (39.8 months). While both shading options deliver roughly similar monthly savings, shading the tanks has a longer simple payback period due to the higher intervention cost. For both options, intervention costs bill-of-materials (BOM) were estimated using material prices from local hardware stores. It is likely that the client may realize a lower intervention cost depending on the availability of existing materials onsite and installation approach.

Importantly, the monthly savings calculated for the chiller swap only include the direct savings from decreasing electricity use and do not include additional operating costs incurred by cooling water to use in the chiller. The project team suspects there are other operating costs associated with the water-cooled system that may decrease the monthly savings and extend the simple payback period. However, the client already operates a cold-water loop for the heat exchanger to lower the temperature of the boiled wort. Integrating that system with a water-cooled chiller may help to reduce operating costs. Moreover, while a glycol GSHX system was deemed infeasible, it is possible it may be feasible to cool chiller water underground to reduce operating costs. Additional study is required to evaluate this opportunity. Furthermore, the estimated COP of the new chiller was done in a controlled, standardized test; realized COP of the new system is dependent on factors like ambient temperatures and total cooling load.

3.2. Sources of uncertainty

There are multiple areas of uncertainty in the analysis conducted, which may have subsequently propagated to the results.

First, pump power was modeled without knowing the impeller size. The impeller size is a key piece of information necessary to accurately interpret a pump curve chart, which outlines the pump efficiency and power output for a given impeller size based on the flow rate and head. Without knowing the impeller size, the project team assumed the largest pump power displayed for the class: 5 hp.

Second, the average COP of chiller for baseline, shading, and replacement scenario was used. COP varies over time dramatically with temperature and load conditions; thus, using an average COP does not accurately characterize everyday conditions. To refine the analysis and results, detailed measurements taken over a longer period with varying temperatures to capture the widest operating parameters are necessary. Consequently, the project team calculated an “average” monthly electricity bill and other “average” results like glycol temperature increase – which have similar dependencies and inaccuracies as COP.

Third, the average outside temperature of tanks was used to represent all operating scenarios. As outlined in *Section 2.2*, tank measurements were taken on a single day at a single point in time. Naturally, temperature fluctuates diurnally and seasonally. Measuring tank temperature in a more systematic, detailed manner would generate a more robust dataset to refine the analysis.

Fourth, there exist variable fermentation completions, maturation times, starting and ending gravities, and temperature setpoints for different types of beer. This variation would impose different demands on the glycol system, and subsequently alter electricity use. The study only captured glycol temperature measurements on a single day when there was low cooling demand from the fermentation tanks. Additional measurement over time would be necessary to refine the analysis.

Fifth, several constants were assumed in the thermodynamic calculations performed, such as yeast heat production, electricity cost, ambient temperature, simple tank geometries, and conductive heat transfer coefficients. Many of these parameters are measurable to varying degrees, but the project team was limited by instrumentation and time. The analysis performed in this study functionally represents an average snapshot in time, as averages and assumptions were used to minimize complexity of the calculations. Furthermore, some possible sources of heat transfer, like from the wort boiler and glycol pipes, were ignored in this analysis.

3.3. Successes and challenges in environmental equity

The project team sought to integrate procedural, distributive, restorative, and recognition equity. Throughout the project cycle, the team strived to adhere to each tenant as closely as possible to the stated intent in *Section 2.4*. Upon project completion, the project team retrospectively assessed how successful the identified equity elements were implemented. *Table 3* further describes how each equity element was integrated into the project process and solution design:

Table 3: Equity and justice results

Element	Considerations
Procedural	Engaged both management and Head Brewer on solutions to assess optimal approach from each perspective
Distributive	Shading fermentation tanks improves working conditions by lowering temperatures near tanks
Restorative	Reducing electricity usage during peak times can reduce the client's marginal effect on the grid and carbon intensity of electricity. However, a significant portion of the client's cooling load takes place during non-peak times.

Notably, recognition justice was omitted from the final assessment. While it is important to consider equity from each lens, the project team felt that it is also equally important to critically evaluate how relevant an equity element is, whether it is authentically addressed, and if it was merely included without further thought. After consideration, the project team deemed that recognition justice could not be adequately addressed in the scope of this project, and thus did not include it in the final assessment.

4. Recommendations and Conclusions

The project team recommends that the client pursue three interventions: shading the fermentation tanks, shading the glycol chiller, and upgrade the Pro Refrigeration, Inc. air-cooled chiller to a Thermal Care, Inc. water-cooled chiller. Through the combination of these measures, the project team estimates the client will save about $563 per month (see *Table 4*). While these savings may not be additive, the estimated margins of error for these figures may far outweigh error from simple addition of savings. Overall, this represents 27% monthly savings (mean monthly electricity bill, $2,074).

In addition to the recommendations examined within the scope of the study, the project team further recommends that the client consider evaluating their electric rate schedule to identify additional opportunities for savings. On the client's PG&E account, there are energy and costs savings recommendations provided by PG&E based on analysis of the client's load. PG&E's "Rate Analysis" tool suggests that the client switch form their current rate plan, "Bus Low Use (B1) Community Choice Aggregation" to "Bus Med Use (B10S) Community Choice Aggregation," which would save an additional $2,145 per year, or $178.75

per month. This rate plan is designed for medium businesses with moderate energy demand. The B10S rate plan leverages a time-of-use structure in which the price of electricity changes according to time of day (TOU), with slightly higher prices during peak times but slightly lower prices during partial and off-peak times [19]. The rate also includes a Demand Charge, in exchange for lower overall energy charges [19]. The TOU structure and demand charge gives the client the ability to respond the energy prices more actively and presents an arbitrage opportunity to shift load (e.g., fermentation schedules) to different times of the day in to leverage lower energy costs.

Table 4: Cost savings of suggested interventions

Interventions	Monthly Savings	% of Total Monthly Savings
Tank shade	$11.61	0.56%
Chiller Shade	$15.77	0.76%
Chiller Swap	$536.00	25.84%
Total Monthly Savings	**$563.39**	**27.16%**

Furthermore, the project team recommends the client use the calculations from this analysis as a tool to estimate continued energy intensity, while changing parameters like temperature setpoints and brewing capacity. This tool, available as a Microsoft Excel file (.xlsx), was distributed to the client with submission of this report.

4.1. Future work

To build upon the recommendations and explore further opportunities, the project team recommends the client explore several areas:

- Intervention implementation: The project team recommended several interventions, but it is up to the client to implement those changes. The client team should internally evaluate in-house capabilities to pursue both shading interventions and conduct a more detailed financial analysis of a new glycol chiller.
- Rate plan: Conduct a thorough analysis of the rate plan suggested by PG&E, including investigating alternative rate schedules used by breweries or other distilleries with similar operating parameters as the client.
- Demand response: If the client opts to upgrade their chiller to the recommended model or different model, the new chiller will have a variable speed compressor, which may allow the client to participate in demand response programs or more tightly schedule their fermentation schedule with energy price to further minimize costs. A variable speed compressor affords the client significantly greater operational flexibility and control that may enable additional savings.

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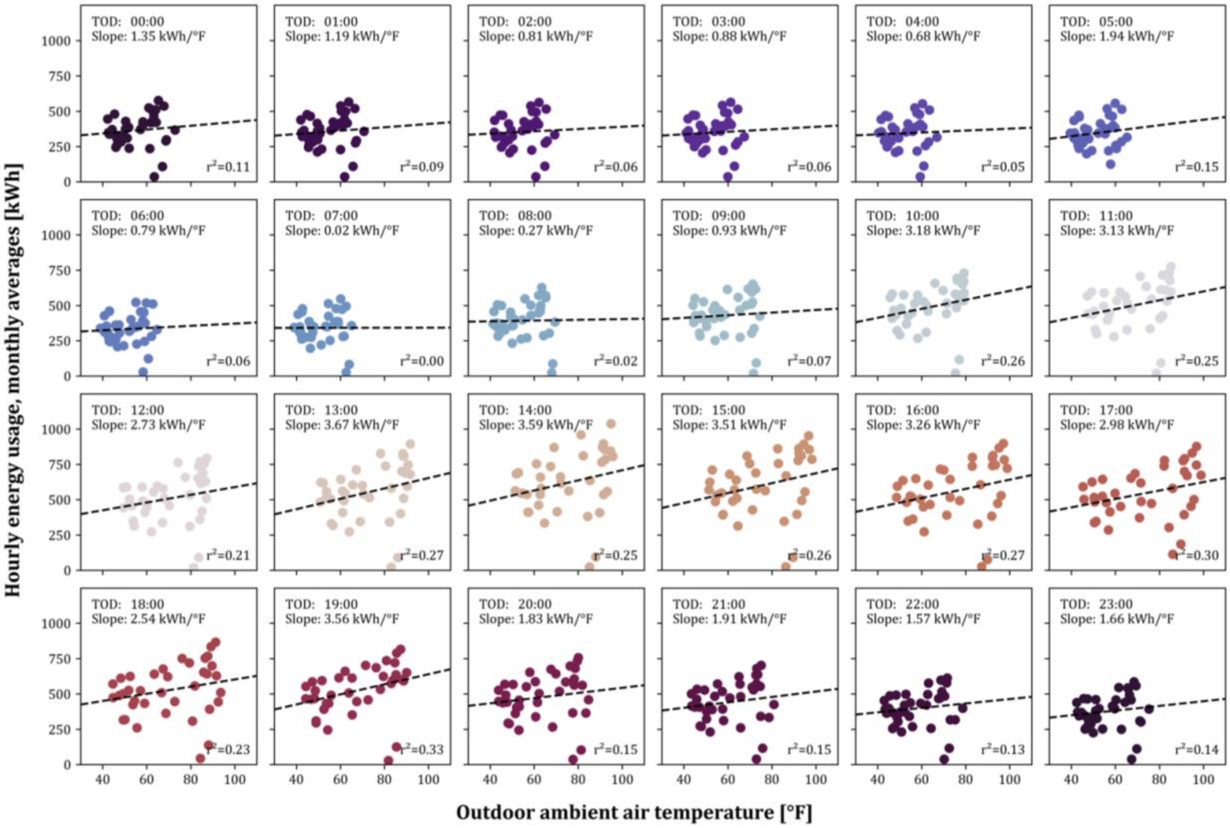
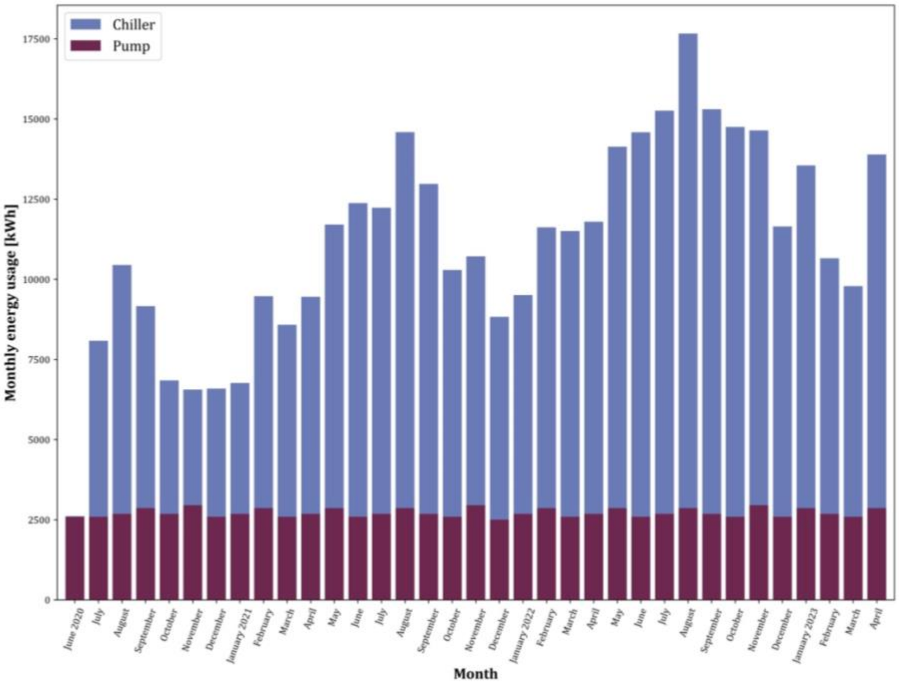
Appendix

Appendix A: Green Button data



Appendix B: Chiller and pump demand, June 2020 – April 2023



Appendix C: Inputs and intermediary calculations

Parameter	Value	Units	Source	Assumptions
Cooled beer temperature *(after wort boiling)*	67	°F	--	Mutable input
Throttled beer temperature	60	°F	--	Mutable input
Ending beer temperature/setpoint	70	°F	--	Mutable input
Maturation time at 34°F	14	days	--	Mutable input
Starting beer gravity/sugar content	15	°P	--	Mutable input
Ending beer gravity/sugar content	4	°P	--	Mutable input
Average tank outside temperature	87	°F	--	Mutable input
Time taken for everything up to maturation	14	days	--	Mutable input
Average active batches/fermenters	3.2	count	--	Mutable input
Average tank outside temperature *after shading*	85	°F	--	Mutable input
Specific heat, wort/beer	0.967	Btu/lb·°F	[15]	Doesn't change between beer types
ΔT of wort through HX	145	°F	Calc.	Boiled at 212°F
Density, wort	0.037	lb/in^3	[20]	Doesn't change much with respect to temperature
Batch volume	940	gal	Jarred	
Mass, wort/beer	8079.99	lb	Calc.	
Heat produced by yeast per mass sugar	252.9	Btu/lb	[15]	Constant through process, same for all beer/yeast
Sucrose mass ratio	0.15	lb/lb	Calc.	Assume all mash is sucrose, °Bx≈°P
Sucrose volume ratio	1.29	lb/gal	Calc.	
ΔT of beer, throttling to final	10	°F	Calc.	
ΔT of beer, cooled to throttled	7	°F	Calc.	
Stainless steel thickness (each side)	2.5	mm	[16]	

Parameter	Value	Units	Source	Assumptions
EPU thickness (in the middle)	60	mm	[16]	
Convection coefficient of beer	300	$W/m^2 \cdot K$	[15]	Constant, predictable (see [21])
Convection coefficient of air	13	$W/m^2 \cdot K$	[15]	Constant, predictable
Thermal conductivity of steel	16.2	W/m·K	[22]	
Thermal conductivity of EPU	0.025	W/m·K	[23]	Some error here
Heat transfer rate through wall	2.2	$Btu/hr/ft^2/°F$	Calc.	
Fermentation tank outer diameter	1.55	m	[16]	
Conic funnel slope	70	°	[16]	
Conic funnel height	0.95	m	Calc.	
Height ratio of cone to cylinder	1.5	m/m	Site photo	Loose estimation
Height of cylinder	1.42	m	Calc.	
Total surface area of fermentation tank	147.1	ft^2	Calc.	
ΔT between tank surface and beer, maturation	53	°F	Calc.	
ΔT between tank surface and beer, maturation, *shaded*	51	°F	Calc.	
Glycol specific gravity	1.03	m/m	[20]	At 60°F, 35% solution; relatively constant
Density of water	62.4	lb/ft^3	--	Relatively constant
Glycol density	0.037	lb/in^3	Calc.	
Glycol mass flow rate	7.2	lb/sec	Calc.	Assume measured vol. flow rate stays relatively constant
Glycol specific heat	0.915	Btu/lb·°F	[20]	35% solution, constant specific heat value
Average COP of chiller	3.31	kW/kW	Calc.	
Average COP of chiller *after shading*	3.3422	kW/kW	[9]	

Parameter	Value	Units	Source	Assumptions
Average cost of electricity	0.19	$/kWh	Calc.	
COP of new chiller	4.99	kW/kW	[17]	
Cost of building chiller shade structure	116.44	$	[24]	Four 4x4x10, Two 2x4x6, Two 2x4x12 pressure treated lumber
Cost of burlap for tank shading	187.05	$	[25]	Assume burlap dimensions fit window size

Appendix D: Full analysis results

Parameter	Baseline	Tank shade	Chiller shade	Chiller replacement	Units
Energy extracted through boiler HX	1133	1133	1133	1133	kBTU/batch
Fermentation completion	73.3	73.3	73.3	73.3	%
Energy produced by yeast	22479	22479	22479	22479	kBTU/batch
Energy absorbed by beer	-78	-78	-78	-78	kBTU/batch
Throttling cooling load	55	55	55	55	kBTU/batch
Crashing cooling load	281	281	281	281	kBTU/batch
Heat transfer rate through tank walls	17	16	17	17	kBTU/hr/batch
Total load from wall radiation	5716	5500	5716	5716	kBTU/batch
Total glycol cooling load	94673	93982	94673	94673	kBTU
Average heat removal rate from glycol	141	140	141	141	kBTU/hr
Average glycol ΔT from outlet to inlet	6.0	5.9	6.0	6.0	°F
Average chiller electrical load	12.5	12.4	12.4	8.3	kW
Average monthly electricity use	8384	8323	8301	5562	kWh
Average monthly electricity cost	1592.96	1581.35	1577.19	1056.80	$
Average monthly cost savings	--	11.61	15.77	536.16	$

Parameter	Baseline	Tank shade	Chiller shade	Chiller replacement	Units
Intervention cost	--	258.75	172.50	21340.00	$
Simple payback	--	22.3	10.9	39.8	months

Appendix E: Simple system diagram, adapted from poster presentation