Solar Thermal and Photovoltaics to Supply Heating and Cooling Demand for a Microbrewery

Alan Pino, F. Javier Pino and José Guerra

Energy Engineering Department, University of Seville, Seville (Spain)

Abstract

Within the food industry breweries are intensive energy consumers. In order to reduce the energy cost of a microbrewery, the integration of a combination of two solar technologies is proposed. The brewing-process is presented, its energy demand profile is detailed, and a simulation model is developed accordingly. A heat recovery strategy is proposed. Furthermore, five different solar thermal systems (ST) and six photovoltaic systems (PV) are studied. The thermal performance of the ST systems is obtained in 1-hour timestep employing TRNSYS. Whereas for the PV systems System Advisor Model is utilized. In order to assess the economic benefits of each system the Net Present Value (NPV) and Discounted Payback Period (DPP) are calculated for all the alternatives. The 55 provinces in Chile are studied considering the local energy price and solar irradiation, and current electricity net-billing regulation. The NPV is positive for all the ST and PV systems, except for the largest ST system in one province where gas is subsidized. The DPP can be as low as 3.83 year for a solar thermal system that saves 40% of the annual thermal energy demand. For a PV system that covers 82% of the annual electricity consumption, a DPP of 5.2 years can be achieved in provinces with high solar irradiation and high electricity price from the grid. The favorable results obtained in this study show the potential benefits of solar energy integration in the small-scale industry with a batch process.

Keywords: brewery, heat recovery, solar-thermal, photovoltaics, SHC, SHIP

1. Introduction

Craft breweries are an innovative and continuously growing segment of the brewing industry. In Europe the number on microbreweries has doubled in the last years, from 3,020 in 2011 to 7,953 in 2017 (The Brewers of Europe, 2018). Likewise, in the United States there were 45 breweries in 1978 (only 2 of them producing craft beer), whereas in 2016 this number increased to 5301 breweries, where the craft beer share of the market was 12.6% (Ibañez, 2018). Chile has also followed this global trend, experiencing a growth in the number of micro and small breweries from 20 in 2005 to 442 in 2016 (ACECHI, 2019). The microbreweries (which generally produce craft beer) are recognized for small production and the utilization of high-quality raw material, leading to higher specific cost (USD/L) than industrial breweries. The Brewers of Europe Association (2018) defines a microbrewery as a brewery with yearly production up to 1,000 hL, whilst the US Brewers Association set the annual production 15,000 hL/year. It is reported that energy cost of a small-medium brewery constitutes up to 8% - 9% of the total production cost (Kubule, Zogla, Ikaunieks, & Rosa, 2016; Sturm, Hugenschmidt, Joyce, Hofacker, & Roskilly, 2013).

Extensive research has been conducted to increase energy efficiency of brewing equipment. Moreover, different innovative strategies to reduce waste heat, wastewater and solid waste of the brewing process have been studied. Nevertheless, these strategies have been primarily adopted by large breweries, exposing the potential for micro, small and medium breweries to improve their processes. Kubule et al. (2016) studied the thermal and electric energy consumption of a microbrewery located in Latvia. Their results were compared with similar studies in different locations, reporting that both thermal and electric specific energy can double the specific energy benchmarks available. The main cause of the poor energy performance is due to the batch process and non-continuous production, utilization of old second-hand equipment and lack of knowledge about energy efficiency strategies. Furthermore, several energy efficiency barriers were identified, for instance, management's attitude towards energy efficiency and lack of financial capacity. Sturm et al. (2013) thoroughly studied the process of a medium-size brewery (250,000 hL/year) located in the UK, in order to identify the opportunities and barriers for

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efficient energy use. The authors presented a measure to save 20% of the current energy consumption with very low investment and an estimated return of investment period of 1.27 years. Their main conclusion is that the technology for efficient brewing exists, and that the lack of energy efficiency implementation is related to managing decision and lack of knowledge of technological solutions. Moreover, the authors report that the modernization of small and medium breweries will ensue when policies and regulations demand it. Sturm et al. (2012) modelled a combined heat and power system (CHP) and a trigeneration unit (heat, cold and power) to reduce the overall energy consumption of a small brewery located in the UK. The system is proposed to be driven by biogas gathered from the own brewery's solid waste (grains) and from cattle manure of nearby farms. A biogas-fired absorption chiller is also proposed to provide cold and to be combined with the CHP system. The economic analysis includes the UK Government's subsidies that can be obtained. The trigeneration system is not feasible as the cold load is constantly required and at much lower power than the heat. The combination of CHP and absorption chiller yield to the highest additional income and lowest Payback Period. Moreover, the efficient use of the brewery's solid waste can potentially make the enterprise more sustainable. Muster-Slawitsch et al. (2011) developed the Green Brewery Concept, a thorough study to demonstrate the potential to reduce thermal energy consumption in breweries. It includes a list of measures to reduce energy requirements and opportunities for solar heat integration. However, the study is focused in breweries with a beer production over 20,000 hL per year, hence it fails to cover some of the singular features of microbreweries.

The integration of solar energy in industries can lead to an energy cost reduction, therefore increasing competitiveness, whilst reducing environmental cost, i.e. fossil fuels use and electricity consumption from the grid. Furthermore, in some countries there are tax reduction incentives and public funding to integrate energy efficiency strategies in the industries. Moreover, intrinsic benefits are obtained. For instance, reduction in greenhouse effect gas emissions (GHG) and a favorable perception from the customers due to their environment concern. Nevertheless, Small and Medium-sized Enterprises (SMEs) rarely integrate renewable energy in their processes due to the high investment cost, the unawareness of the technology, and lack of direct governmental incentives.

Breweries have a high potential for solar heat integration due to low temperature levels needed. All the thermally-driven processes require heat at temperature between 25 and 105°C (Daniels, 1996), that can be achieved with non-concentrating solar collectors. Moreover, the brewing process requires cold at different temperatures, usually above 2°C. Within the framework of IEA SHC Task 33/SolarPACES Task IV, it was shown that the pinch analysis is a strong tool for a first estimation of the energy saving potential by heat recovery, based on an optimized heat exchanger network between hot and cold streams. However, for industrial processes running in batches, as in a microbrewery, the pinch methodology represents a rough estimation of the actual load profile. Therefore, the Task have also shown that adopting heat management strategies, i.e. operating thermal storages, can help to integrate solar thermal (ST) plants more efficiently (Brunner, Slawitsch, Giannakopoulou, Schnitzer, & Research, 2008). Furthermore, within the IEA SHC Task 49/SolarPACES Annex IV, time-dependent simulation methodologies and software tools were developed to obtain insight about the performance of the heat storage management strategies for solar heat in industrial processes (Krummenacher & Muster, 2015). It must be borne in mind that some of the microbreweries' processes are not optimized, monitored or automated. Additionally, in most batches productions there are further challenges to the system sizing; the utilization rates are generally low, and some pieces of equipment are largely oversized. Eiholzer et al. (2017) studied the integration of a solar thermal system in a medium-size brewery (250,000 hL) located in Scotland employing the pinch analysis. In a first stage the direct and indirect heat recovery potential was determined. Later, the optimum integration point was chosen, and an economic analysis performed. In order to obtain UK government's economic incentives, the size of the ST must be below 200 kW, which yield to a solar fraction (SF) of only 7.7%. Numerous studies have been conducted regarding solar thermal energy integration in breweries, mainly for medium- and large size scale (Brewers Association, 2018; Lauterbach, Schmitt, & Vajen, 2014; Mauthner, Hubmann, Brunner, & Fink, 2014). Not only have positive outcomes been reported, but also improvement potential has been identified.

The aim of this study is to perform a location-dependent economic analysis for solar thermal and photovoltaic systems integration in a microbrewery located in Chile. This article is organized as follow: Section 2 presents the case study with thorough detail of process, the solar irradiation and regulations scenario, the solar systems studied, and the simulation description; Section 3 presents the main outcomes and discussion; and finally the conclusions of this study are reported in Section 4.

2. Methodology

2.1. Case study: the craft-beer brewing process

The process specifications and energy demand profile of this study are based on an actual craft-beer microbrewery located 50 km south of Santiago. An energy audit was carried out, based on electricity and gas bill data as well on information from the head brewer. The actual batch size is 500 L and it has been scaled up for the study to achieve a 1,000-L batch output, leading to a monthly production of 10,000 liters (1,220 hL per year). The key parameters to design a brewery are the batch size, number of fermenters, and duration of fermentation and maturing processes. A schematic diagram of the craft-beer brewing-process stages is shown in Fig. 1, where process temperatures and water/wort/beer volume for each stage are indicated. Moreover, it is indicated if a certain stage requires heat, cold, electricity and/or water. Day 1 of the process is named "brewing day" (duration of 6 hours), when the malted barley wort is produced before the fermentation. The brewery has 7 fermenters, the duration of the fermentation is 10 days at 20 °C (Ale beer) and maturing is 10 days at 2 °C. The last day of the process corresponds to the packaging and labeling stages (8 hours). It is considered that half of the volume (500 L) is kegged and the other half is bottled. Therefore, the complete process from raw materials to finished beer takes 21 days.

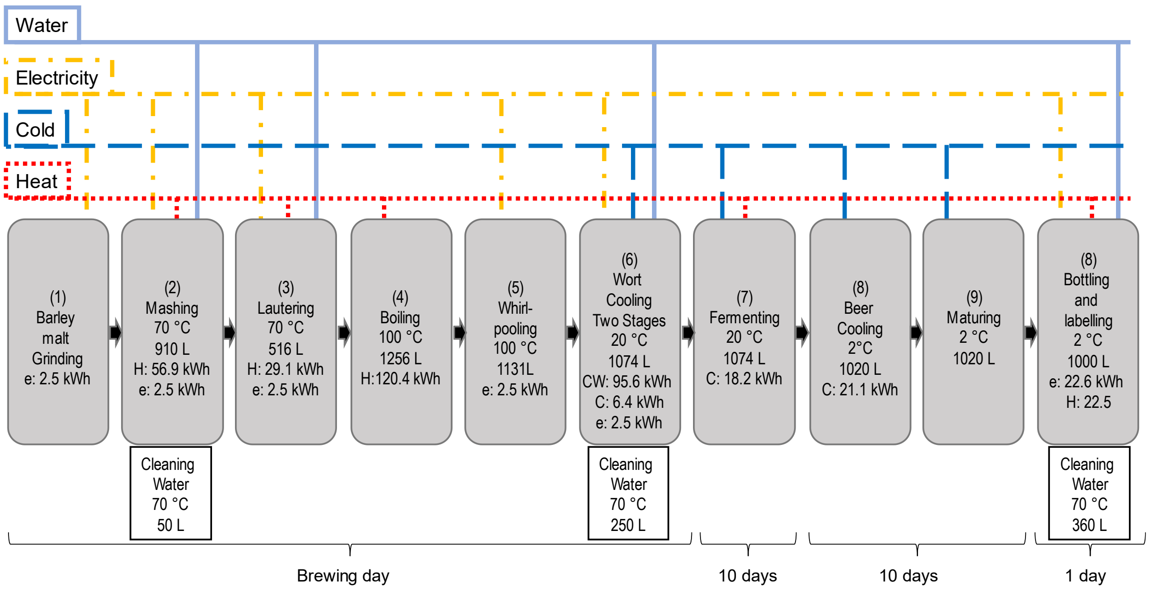


Fig. 1: Simplified scheme of the beer production process for the studied microbrewery. The liters of water/wort/beer employed are indicated together with the set temperature for each stage. *H* means heat load, *C* means cold load, *CW* means the cold load of Cooling Water and *e* means electricity. Moreover, the required cleaning water is indicated below each stage.

Although the brewing day has a total duration of 6 hours, it is the most energy-consuming day, because the beer wort is produced. The day starts grinding the malt with a 2.5 kW grinder for one hour. Meanwhile, cleaning and mashing water is heated up to 70°C in the mashing kettle employing a 120-kW LPG burner (efficiency 90%). There is no steam boiler as in larger breweries. The water is obtained at 15 °C from a private well located in the property. Mashing is the process of hydrating the malted barley to convert the grain starches into sugars. Later, during lautering, the mash is separated into the clear liquid wort and the residual grain. The grains absorbed 15% of the mashing water during hydration that is discarded. Lautering consists of 3 steps: mash out, recirculation, and spargin; therefore, additional hot water is required. The wort is transferred to the boiling kettle, where it is heated up to 100 °C employing the LPG burner to start the boiling stage. The boiling stage usually has a duration between 60 and 90 minutes, during this stage the hops are included. After the boiling stage the remaining solid particles are separated from the wort within a whirlpool. In this step the wort is pumped tangential into the whirlpool in order to push unwanted solids to the center and bottom of the brew kettle. When the wort is clear it is cooled down to fermentation temperature by two plate heat exchangers in series while it is transfer to the fermenter. One cold stream is water from the mains to decrease the wort temperature to 25 °C. The cooling water is kept in an uninsulated vessel when heated. Later, 250 L of this hot water is used for the cleaning process. The remaining water is used for other purposes (e.g. irrigation) when it reaches ambient temperature, hence its useful sensible energy is dumped. The second cold fluid is chilled water at 7 °C, obtained from the fermentation chamber's chiller. This process must be quick (less than 1 hour) to avoid contamination and production of dimethyl sulfide (DMS).

Between one stage and the next one a small share of the liquid is dumped; these losses cannot be avoided. For the mashing and boiling processes properly insulated vessels are employed, thus thermal losses to the ambient are neglected. However, during the boiling process, 10% of the volume is lost due to evaporation. The fermentation starts during the brewing day.

The fermenting and maturing processes occur subsequently in one fermenter. The fermenting stage is divided an active-yeast period, which is exothermic, and an idle period. The maturing (conditioning) stage consists in keeping the beer at low temperature to avoid undesirable flavors after fermentation and become palatable. For small breweries it is common to implement temperature-controlled chambers where the fermenters are maintained under the desired conditions. Hence, for this case two rooms are considered: a fermenting chamber at 20 °C and a maturing chamber at 2 °C. Fig. 1 indicates the internal loads for the fermenting, cooling and maturing stages. The refrigeration system needs to supply this demand plus the loads associated to the thermal losses of the chambers. On the packing and labeling day (21st day) the first fermenter is emptied and cleaned, the next day it is used for a new batch. This 21-day process is repeated for the 6 fermenters left with a time gap of 3 days. The refrigeration system is sized in order to supply the maximum refrigeration peak demand during the year. The fermentation room's chiller has a rated capacity of 5 kW, a rated Energy Efficiency Ratio (EER) of 3.5 (Eurovent conditions) and an evaporator set temperature of 7 °C. If heat is needed an electric heater is considered, with a Coefficient of Performance (COP) of 1. The maturing chamber has a wall-mounted refrigeration system with a rated capacity of 1.6 kW and rated EER = 2.8 when the outside temperature is 35 °C and the evaporator temperature is -3 °C.

The packaging and labeling day is separated in 3 stages. The first one is kegging, where CO_2 is needed to impulse and carbonate the beer. In addition, 2.5 kW of electric power is needed for one hour. Secondly, the bottling process lasts 6 hours and utilized a semiautomatic pneumatic bottling machine that requires power (450 W) and compressed air (compressor rated power: 1.8 kW). CO_2 for carbonating the beer is also needed. Furthermore, 0.9 kW of pumping power is constantly needed and 360 L of cleaning water at 70°C. The beer is not filtrated. Finally, the labeling is perform by a semi-automatic machine (2 hours, 1.2 kW rated power).

2.2. The Chilean context

Chile has a length of around 4200 km from north to south. It has several different climates, dominated by the Pacific Ocean to the west and the Andes along its eastern edge. Chile is renowned for its high solar irradiation levels (Escobar et al., 2014). The electric marked defines two types of clients, regulated and unregulated (>200 kW of installed capacity). There are 4 tariffs for regulated clients depending on the connection voltage (low or high) and the structure of cost. For this study the LV1 retail price is considered (low voltage: 240 V, tariff 1). In 2014, the technical normative of Regulated Net-Billing Law 20.517 became available. The Law regulates the economic value of the surplus electricity self-generated (PV, wind, micro hydro, etc.) injected to the grid. The maximum installed capacity of the system allowed is 100 kW. The specific energy price paid to the client for the injected electricity is about 50% of the retail price. Natural gas networks are only available in certain cities, hence Liquefied Petroleum Gas (LPG) is considered in this study. The fossil fuels wholesale price is regulated, but the retail price depends on the distributor. Nevertheless, each company should inform their prices to the Energy Commission every week and publish them online as public information for consumers. For a brewery of this size the cheapest option is to install bulk LPG tanks that are filled by trucks monthly (when natural gas network is not available). Depending on the monthly/annual energy consumption price discounts are made. However, the contract is usually tailored for each company, hence it is difficult to normalize the specific energy price. A previous research performed by the authors shows low economic attractiveness of integrating solar thermal in a microbrewery located in Spain. There were long Discounted Payback Period (DPP), over 29 years, owing to the low price of natural gas (Pino, Pino, & Guerra, 2019). Therefore, Chile presents a more favorable scenario to integrate solar energy due to the expensive energy price for regulated consumers.

In order to cover the entire country, the actual 55 continental provinces of Chile were studied. The hourly weather data have been obtained for the capital city of provinces employing Explorador Solar; a free online platform published by the Ministry of Energy. The solar radiation and weather data are satellite-image based and are validated with over 120 ground stations (Molina, Falvey, & Rondanelli, 2017). The retail LV1 electricity price is obtained from the National Energy Commission website, updated monthly (Comision Nacional de Energía, 2019). The LPG bulk energy price is obtained from a distributor website, that cover most of the districts and is updated monthly (Lipigas S.A., 2019). Fossil fuels in the southernmost region of Chile are subsidized. Both the electricity and LPG price for each province is an average of the available price for the districts that belongs to each province.

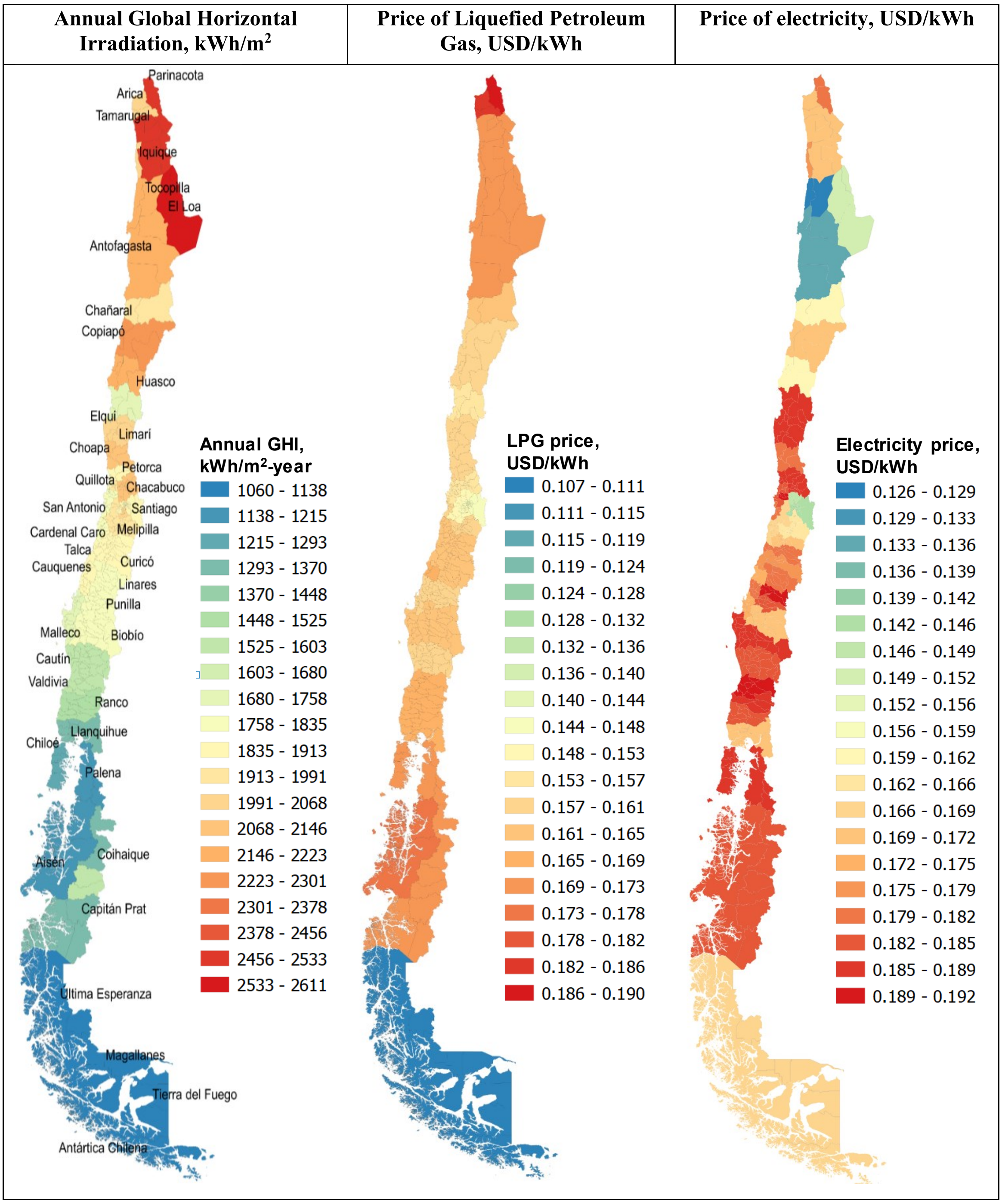


Fig. 2: Total annual GHI, price of LPG and price of electricity for different provinces in Chile. Values are calculated for the Capital of each province. Stereographic projection: EPSG:53016.

2.3. Solar thermal and photovoltaic systems

For this study, a combination of solar thermal and photovoltaic technologies has been proposed to reduce the LPG and electricity consumption, respectively, in a microbrewery. The tilt angle for both the flat-plat collectors and the PV modules is equal to the latitude, hence location-dependent.

Prior to sizing the solar thermal (ST) system, the feasibility to employ heat recovery strategies, as the proposed in the reviewed bibliography, was studied. For the actual brewery, the head brewer has planned to employ the heated cooling water for a more useful purpose, e.g. to be used in the next batch. It has not been done because water use reduction is not a priority (the brewery has its own well) and lack of financial resources. However, it can generate economic benefits and the investment should only consider the tank, piping and installation costs, as the plate heat exchanger already exists. Hence, the first measure is to size the water tank for the ST system that enables to apply this heat recovery strategy. The cooling water volume employed to cool down the wort is similar to the wort volume. Additionally, the required hot water at the beginning of the brewing day is 1,476 L (910+516+50 L). Accordingly, the water storage tank designed size is 1.5 m^3 (thermal loss coefficient 1 W/m^2K), independently of the total collector area. Therefore, the flat-plate collectors (a0 = 0.701, a1 = 2.277 W/m^2K, a2 = 0.0043 W/m^2K^2) provide heat to the storage tank in order to keep water as hot as possible for the brewing and packing days. The system has been designed to provide hot water at 70°C and not to supply energy to the boiling process. Five systems with different collector area have been studied: 1.96 m^2 (1 collector), 3.92 m^2 (2 collectors in series), 7.84 m^2 (4 collectors, 2 loops of 2 in series), 11.76 m^2 (6 collectors, 2 loops of 3 in series), and 17.64 m^2 (9 collectors, 3 loops of 3 in series).

The PV system proposed is formed by 250-Wp polycrystalline modules with matching-capacity on-grid inverters (no storage considered). Six different installed capacities are compared: 0.5 kW_{dc} (2 modules), 1 kW_{dc} (4 modules), 1.5 kW_{dc} (6 modules), 2 kW_{dc} (8 modules), 2.5 kW_{dc} (10 modules), and 3 kW_{dc} (12 modules). The PV modules' nominal efficiency is 16.24% (NOCT), open circuit voltage of 37.7 V_{dc}, Short circuit current of 8.9 A_{dc}, and a temperature coefficient of -1.025 W/°C. The inverter has a CEC weighted efficiency of 95.9%, with a nominal AC voltage of 240 Vac.

For the economic analysis, market price of the systems including VAT and excluding subsidies are considered. The investment costs are estimated for a residential system due to its size. The ST system price is obtained from an unpublished study performed by the authors for Spain and compared with the published price of local dealers in Chile. The PV system cost structure is based on updated available references (Fu, Feldman, Margolis, Woodhouse, & Ardani, 2018; IEA International Energy Agency, 2018; Jäger-Waldau, 2018), and also compared with published price of local dealers in Chile. Furthermore, annual Operation and Maintenance (O&M) costs are considered as a percentage of the initial investment. Tab. 1 presents the specific costs employed in this study for both ST and PV systems.

Tab. 1. Specific cost for solar thermal and photovoltaic systems in Chile, including VAT.

Specific Cost					
Solar Thermal			**Photovoltaic**		
Collector	USD/m^2	250	Module	USD/W_{dc}	0.6
Storage tank	USD/m^3	2200	Inverter	USD/W_{dc}	0.25
Balance of plant	USD/m^2	450	BoS equipment	USD/W_{dc}	0.35
Installation labour	USD	1200	Installation labour	USD/W_{dc}	0.5
			Overhead	USD/W_{dc}	0.1
O&M (3% of investment)	USD/year	variable	O&M (2.3% of investment)	USD/kW-yr.	38

2.4. Simulation

A simulation model has been developed in TRNSYS (Klein, Beckman, Mitchell, & Duffie, 2011). The model includes the annual schedule for the brewing process described in Section 2.1, the thermal interaction of the fermentation and maturing chambers with the environment, solar gains, and internal loads. Moreover, the electric chillers performance and the proposed solar thermal system is modeled.

The brewery is modeled employing Type 56 (TRNBuild) as an industrial building of 16 x 8 x 5 m, roof with 10% transparent cover and no windows in the walls. The longer side is oriented north-south. The fermenting and maturing room (envelope U = 0.35 W/m^2K) are placed inside the main building, with dimensions of 6 x 3 x 3 m each of them. Infiltrations are considered as 0.3 renovations/hour regularly and 2 renovations/hour when the doors are opened. The effect of the LPG burner losses (10%) is accounted as an internal load for the brewhouse. The chillers' condensers are outside the main building. Their instant performance has been calculated employing the DOE2-2 black-box model (Hydeman, Gillespie, & Dexter, 2002; Hydeman, Webb, Sreedharan, & Blanc, 2002) and the regression parameters presented in Calener-GT (Grupo de Termotecnia AICIA, 2009).

The ST system has been modelled employing TRNSYS's Flat-plate collector Type (1b), the storage tank, a pump and a temperature hysteresis controller. The required pumping power is 300 W per loop. The surplus energy, i.e.

when the energy demand is lower than the available energy, is not considered in the calculations of useful energy because it cannot be utilized, therefore it is dumped.

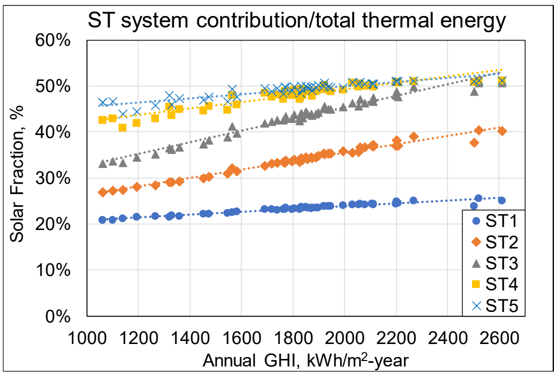
Hourly data are obtained from the TRNSYS simulation results. The total annual values of energy contribution by the ST system are employed to calculate the Net Present Value (NPV) and the partial Discounted Payback Period (DPP). The main parameters for the economic analysis are a 5% annual nominal discount rate, a 20-year period for NPV, no loan for the investment and no subsidies applied.

The PV system has been modelled in System Advisor Model (SAM) (National Renewable Energy Laboratory, 2018). The modules' and inverter's parameters are obtained from the SAM software library. The total hourly electric load input, including the electric consumption of all the equipment and the chillers is obtained from the TRNSYS simulation output for the entire year. It is employed in SAM in order to calculate the self-consumed PV power and the power injected to the grid (sold) on every timestep. SAM includes a financial model that estimate the NPV and DPP, therefore the same parameters of the ST economic analysis are utilized. Moreover, a 0.5%/year degradation rate is considered for the PV modules.

3. Results and Discussion

For the described process in Santiago (without solar), the specific thermal energy is 99 MJ/hL, and electric energy is 22.4 MJ/hL. The British Beer&Pub Association, (2014) reports a total specific energy benchmark of 173.2 MJ/hL as average for their associated breweries in 2013. Larger breweries total specific energy can be as low as 97 MJ/hL (Carlsberg, 2017), and for small breweries as high as 346 MJ/hL (Kubule et al., 2016; Sturm et al., 2013). Nevertheless, this study only accounts energy required for the brewhouse. The beer type is Ale, which ferments at higher temperatures, the process does not include filtration, and there is a major use of man labor (not automated). Moreover, lighting power, additional facilities' thermal and electric energy is not considered.

The displacement of conventional fuels and electricity has economic and environmental benefits. The savings for the different ST systems are calculated as a ratio between the LPG energy displaced and the total thermal energy without the new system. It is worth to note that the values include the contribution of storing the cooling water to employ it in the next batch. Fig. 3 presents the results comparison for the different provinces. The x-axis presents the annual total GHI. These results depend solely on the energy performance of the system under the climate of the different locations. Any of the ST systems allows to save at least 20% of the thermal energy, mainly for the heat recovery strategy. Although, the contribution of the system increases with the collector area, it can be observed that the maximum is 52%, achieved in regions with GHI over 1800 kWh/m^2-year. This is the superior limit because the total thermal energy demand includes the heat required for the boiling stage (>100°C), hence it is not provided with the solar system but with the LPG burner. For regions with GHI lower than 1800 kWh/m^2-year it is still noticeable the increment of the system's contribution by increasing the collector area from ST3 to ST4, however the size augmentation to ST5 is not worth it. For regions with GHI over 1800 kWh/m^2-year systems bigger than ST3 will cause an important amount of dumped energy that cannot be utilized. On the other hand, for the PV system the behavior is modular; for bigger systems a higher yield is obtained. The results shown include the total annual generation of the PV systems (self-consumed + injected to the grid) compared with the annual electricity consumption. Often the energy availability and demand are not coupled. The main difference with the ST system is that there is no dumped energy, because the surplus can be injected to the grid.



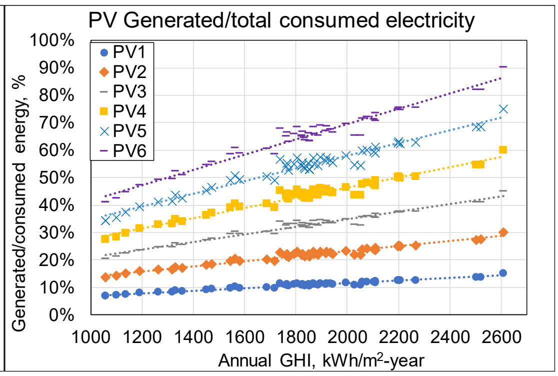


Fig. 3. Energy contribution for the solar thermal and photovoltaic systems.

The Net Present Value (NPV) for a 20-year analysis is obtained for all the ST and PV systems for each province. The positive cashflows in the analysis period correspond to the annual cost of the displaced conventional energy due to the integration of solar systems. In addition, the Discounted Payback Period (DPP) is calculated as a complementary index. Fig. 4 present the NPV and DPP results for the solar thermal systems. An increasing trend of NPV with GHI can be observed; nevertheless, all the sets of data have different slopes. The ST1 has the lowest NPV for all the locations, followed by the ST5 configuration. The rest of the data sets, i.e. ST2, ST3 and ST4, are spread depending on the province. In the bottom left corner of the NPV plot there are outliers that represent the southernmost provinces of Chile, which have low solar radiation and subsidized LPG prices, leading to low NPV (ST5 has negative NPV). Therefore, installing a solar thermal system there it is not financially attractive under the current scenario. On the plot of the right the DPP is shown. It can be observed that the ST2 configuration systematically has lower DPP, followed by the ST3, ST1 and ST2 configuration, depending on the province. These results indicate that ST5 is oversize for all the locations, since it has the highest DPP and it does not lead to the highest NPV, implying that energy is dumped. Moreover, based on the two criteria, i.e. higher NPV or lower DPP, the best alternative for each location can be ST2, ST3 or ST4.

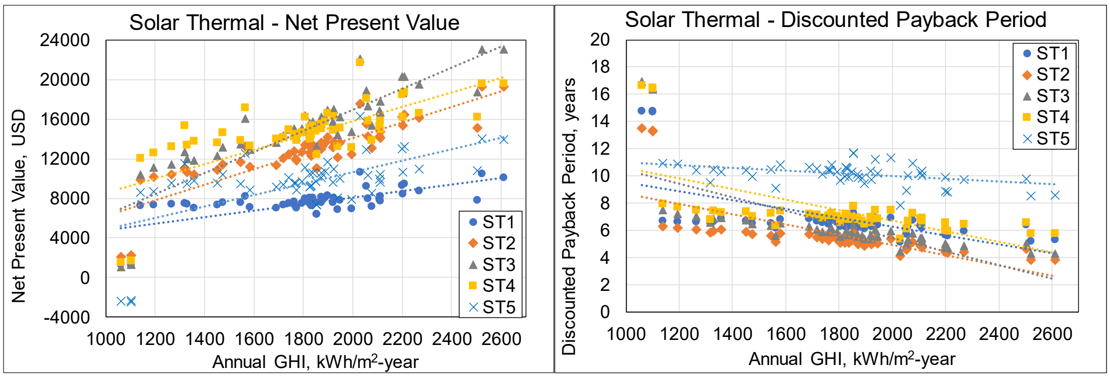


Fig. 4: Net Present Value (left) and Discounted Payback Period (right) for the 5 solar thermal systems studied. Locations are represented by their global horizontal irradiation (GHI) on the x-axis.

Similar results for the PV systems analysis are shown in Fig. 5. In this case the NPV trend is also increasing with the GHI, but it has a more linear behavior compared with the solar thermal system behavior. Although the linear trending line slope of the different data sets (PV1 to PV6) are different, their behavior is constantly increasing with the GHI. Since the electric performance of PV modules and inverters is similar regardless of the size of the system, and because of the net-billing scheme, it is possible to sell the surplus power to the grid, consequently avoiding dumping energy and penalizing oversized systems. For the DPP plot, the data sets are mixed, especially for location with GHI of 1700-1900 kWh/m^2-year (central region of Chile). There are some outliers that represent locations with low electricity price, hence reducing the NPV and increasing the DPP. For instance, Tocopilla (GHI = 2200 kWh/m^2-year and electricity price of 0.126 USD/kWh) and Santiago (GHI = 1850 kWh/m^2-year and electricity price of 0.145 USD/kWh). The ST6 configuration maximizes the NPV for all the provinces, while the PV1 minimizes the DPP.

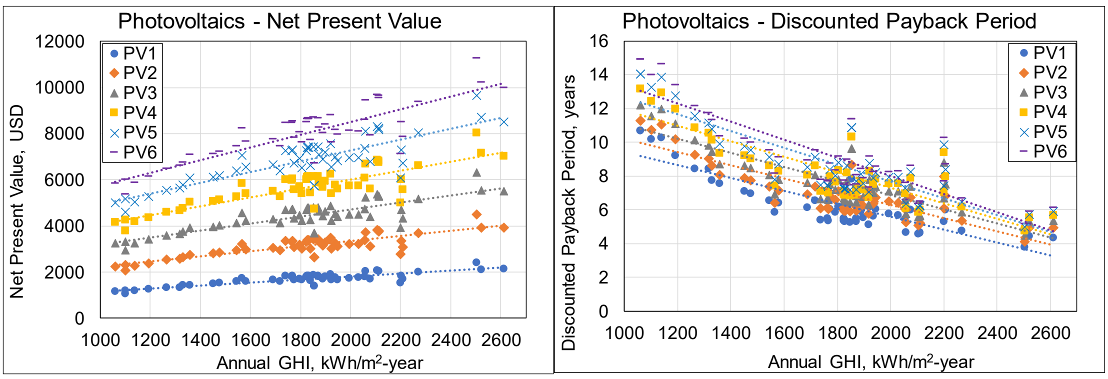


Fig. 5: Net Present Value (left) and Discounted Payback Period (right) for the 6 photovoltaic systems studied. Locations are represented by their global horizontal irradiation (GHI) on the x-axis.

Solar thermal system		Photovoltaic system	
NPV, USD	DPP, years	NPV, USD	DPP, years

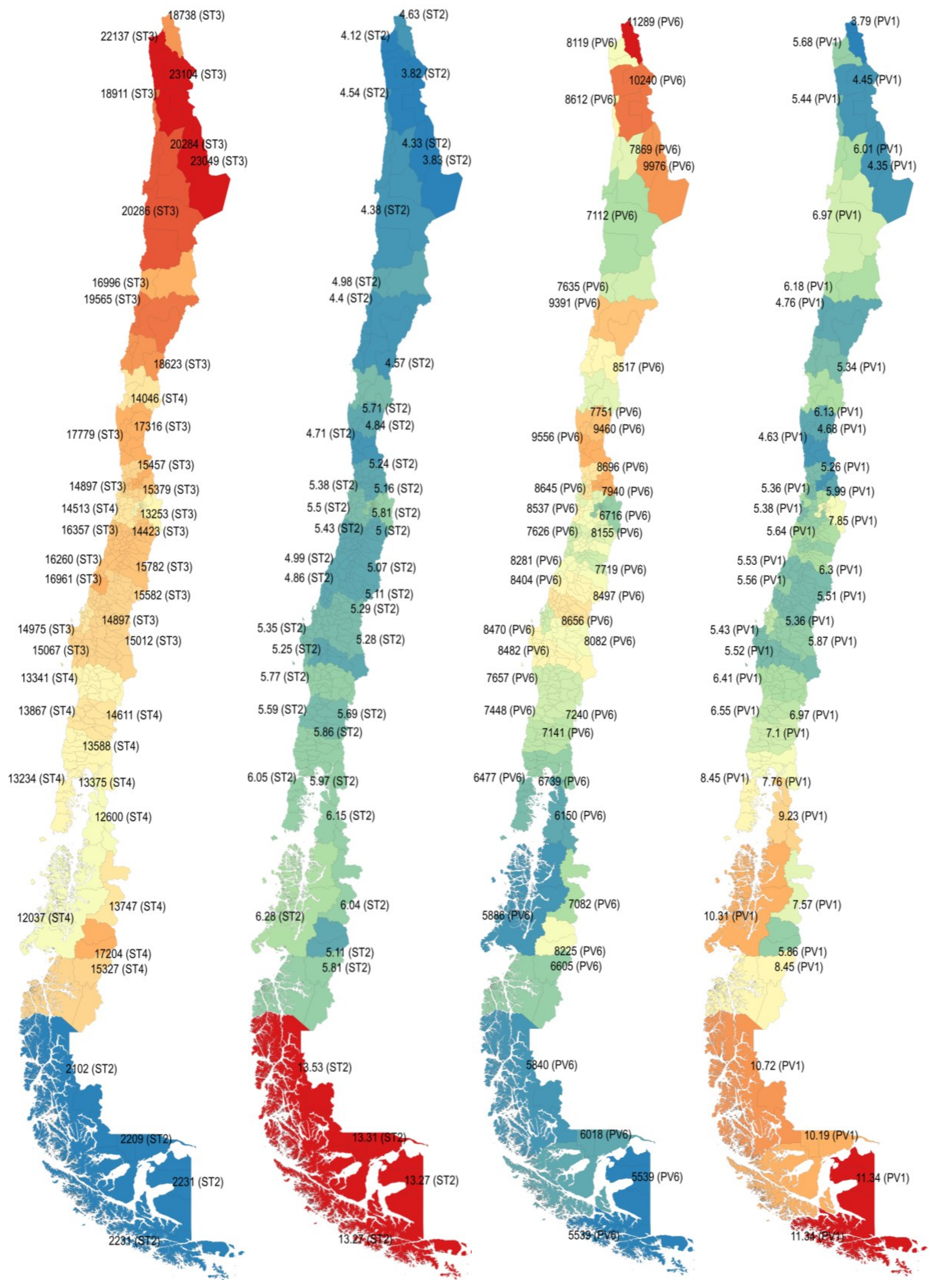


Fig. 6: Net Present Value and Discounted Payback Period with best option of system for the ST and PV systems. Stereographic projection: EPSG:53016.

The maximum NPV and minimum DPP obtained for each location are presented in Fig. 6. This Figure also indicates which system is considered the optimum according to each criterion, for both the ST and PV analysis.

In the sunniest locations of Chile (northern regions) where the LPG price is high, the 20-year NPV for the solar thermal system is over 23,000 USD, for instance in Tamarugal and El Loa (with ST3). Consequently, the smallest partial DPP that can be achieved in the region is 3.8 years for a smaller system (ST2), although saving 40% of the annual thermal energy. The main drawback of the solar energy integration is the high investment cost. Regardless of the lifespan of the solar system being 20 - 25 years, frequently, the payback period is too high compared with companies' investment strategies. This short period of payback can be attractive for the companies.

For the PV system, Tamarugal and El Loa are also the provinces with high NPV and low DPP. Nevertheless, as the electricity is more expensive in Parinacota, this province obtains the lowest DPP (3.79 years for PV1).and the highest NPV (11,289 USD) for PV6, also generating 82% of the annual electricity consumed. Moreover, it can be observed that some areas in the center, like Santiago and surrounding provinces, the NPV and DPP strongly depend on the specific electricity price, since the solar irradiation in the area is similar.

For all the cases, the installation of a PV system has positive NPV in a 20-year timeframe, therefore it is a profitable investment under the different scenarios proposed. Regarding the thermal system, the NPV is positive for all cases except for ST5 located in the Region of Magallanes, where the LPG is subsidized because it belongs to an extreme region with severe climate. In addition, it is possible to observe several regions with solar thermal and photovoltaic DPP lower than 5 years, it could be financially attractive for microbreweries to invest in solar energy, despite that the selected alternative does not maximize the NPV.

4. Conclusions

In order to become more competitive, the craft breweries need to reduce their costs without detriment of the high-quality beer they are known for. By implementing energy efficiency strategies and integration of solar energy, the total energy cost is reduced and environmental benefits are also obtained. Currently, the beermaking industry typically supplies the process-heat with fossil fuels, whilst cold is commonly supplied with electric vapor-compression refrigeration chillers. Furthermore, electric power is required by auxiliary equipment (pumping, bottling, grinding, etc.) and to provide heat to the fermentation chamber. For Small and Medium-sized Enterprises (SMEs) the application of energy efficiency strategies not only depends on the current financial situation, but also on the awareness of the technologies and their benefits, and local environmental regulation.

Currently, there is lack of solar energy utilization studies for small scale craft breweries. The aim of this study is to assess the economic impact of the solar energy integration in a microbrewery for the different provinces in Chile. The location-dependent parameters considered are weather and electricity and LPG price.

The annual thermal and electric energy demand of a microbrewery is simulated in 1-hour timestep. A 1.5 m^3 water storage tank is proposed to implement a heat recovery strategy since heating and cooling are required at different time. Five different areas of flat-plate collector are compared, whereas for PV six different installed capacities are compared. For electricity, under the current regulations the self-generated surplus energy can be sold to the grid (net-billing scheme).

The first interesting outcome, yet not surprising, is that the generated energy from the PV systems constantly increases when there is more installed capacity, whilst for the ST system there is a useful energy optimum that not necessarily coincide with the largest system. Moreover, the useful energy for both PV and ST systems increases where more solar irradiation is available. However, for the ST system in high solar irradiation locations (Annual GHI > 2400 kWh/m^2) the optimal energy option is a smaller system than for the rest of the regions.

The Net Present Value and Discounted Payback Period are calculated as economic indexes to compare the different systems' economic performance. Some general conclusions: higher irradiation levels lead to higher NPV and lower DPP; higher conventional local energy cost, either LPG or electricity, causes higher NPV and lower DPP (for the ST and PV systems). Nevertheless, only the combination of the three local parameters considered allows us to compare the economic benefits of each system. Furthermore, the results are constrained to the case study, as a different thermal and electric energy demand profile will modify the present outcome.

For the different thermal systems analyzed (heat recovery + flat-plate collectors), the Discounted Payback Period can be as low as 3.8 years in the northern regions of Chile. In the southern part, where the LPG is subsidies and there is less solar irradiation, the DPP can exceed 13.5 years. Similarly, for the PV systems, the economic indexes vary highly when comparing provinces. The NPV can be doubled, e.g. Parinacota (northernmost) versus Tierra del Fuego (southernmost) provinces with PV6 system; and DPP can be 3 times higher when comparing the same provinces.

Finally, this research study has successfully shown that the integration of solar energy can lead to economic benefits for a small-scale craft brewery without affecting the process, hence, the quality of the product. For future work, a slightly bigger microbrewery will be considered in a similar analysis, where measurements can be obtained to better define the energy profile. The case study brewery employed in this study, has a highly variable energy profile, as the batch process is performed every 3 days. The main constrains are the number of fermenters and the size of the fermenting and maturing rooms. There are microbreweries that repeat the brewing process daily and sometimes twice a day. By doing this, the utilization of the ST and PV systems proposed will likely increase, which can lead to higher economic benefits. In contrast, for higher energy consumption better rates can be obtained from the local energy distributor for both electricity and LPG.

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