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Integration of solar energy in Small-scale Industries: Application to microbreweries

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ABSTRACT

The integration of solar energy to achieve decarbonization in the industry is still incipient. The few reported cases of solar thermal and photovoltaic integration in industrial brewing processes belong to medium-sized and large breweries. Therefore, the aim of this study is to determine if solar energy integration can also be profitable for small industries under the current market conditions. A monitoring campaign was conducted to characterize the consumption profile of a microbrewery located in southern Spain, which revealed a significant difference in specific energy consumption between micro- and large breweries. In addition, performance curves of small-scale components for cold supply were adjusted under real operation conditions. Consequently, a simulation tool was created in TRNSYS to calculate energy consumption. Its results were compared with measurement data and electricity consumption bills. Furthermore, a techno-economic analysis carried out in Spain revealed that under the current market conditions a photovoltaic system would always be profitable compared to buying all energy from the grid. The cost of energy for cooling and heating supply can be reduced up to 39.9% for the best conditions of solar radiation and market prices. However, in a more moderate scenario the reduction in the cost of energy can vary between 3.63% and 11.23%. In addition, payback periods range from 4.3 to 6.6 years in the favorable scenario and from 14 to 24.9 years in the conservative scenario; depending mainly on the level of solar radiation, conventional energy prices, and the size of the photovoltaic system.

1. Introduction

To achieve the decarbonization goals to fight climate change, the development and integration of renewable energy systems are crucial, according with the European Commission [1] and the International Energy Agency [2]. Nearly 25% of the global end-use energy consumption corresponds to process heat for industries [3]. In addition, in 2019 about 67% of total final energy consumption for the industrial sector was supplied by fossil fuels (oil, gas, and coal); an additional 28.5% is accounted by electricity, the generation of which is linked to greenhouse gas (GHG) emissions in most regions of the world [4].

Within the food and beverage sector several production processes are commonly employed, e.g., pasteurization, cleaning, fermentation, freezing, etc. Therefore, it is frequent to require heat, cold, and mechanical power during the manufacturing. In addition, batch production is often used instead of continuous production, as in the case of brewing. To brew beer heat at about 110 °C and cold at 0 °C is required; moreover, electricity is needed for pumping fluids, grinding grains, and packing lines. Producing beer is a highly energy-intensive process accounting for up to 8%−9% of total production costs [5].

Furthermore, small and medium-sized enterprises (SMEs) are diverse and usually require customized solutions targeting their specific needs. Regarding energy consumption, three main features are worth mentioning:

- Small industries cannot afford large, efficient centralized boilers and chillers that run continuously.
- Heat recovery strategies are difficult to apply in a batch process, e.g., additional energy storage costs.
- As small energy consumers, their energy contracts are often offered as regulated users, which increases the cost of energy compared to large industries, which negotiate more competitive prices.

The number of microbreweries (annual production under 5,000 hL) has steadily increased in the past two decades and the trend reveals that the market will continue to grow [6]. The main reason for this expansion is the demand for higher quality products from customers, who are

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Nomenclature

ACHP	Air Conditioner and Heat Pump
COP	Coefficient Of Performance
DPP	Discounted Payback Period
EER	Energy Efficiency Ratio
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, And Air Conditioning
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Heat
LCOHC	Levelized Cost of Heat and Cold
LGP	Liquefied Petroleum Gas
O&M	Operation And Maintenance
PV	Photovoltaic
SHIP	Solar Heat for Industrial Processes
SME	Small And Medium-Sized Enterprise
TMY	Typical Meteorological Year
TOU	Time-Of-Use
VAT	Value Added Tax

willing to buy craft beers despite being more expensive due to the use of high-quality ingredients and having a smaller production and lower energy efficiency than beers from large companies. In the US the number of microbreweries expanded from 1,596 in 2009 [7] to 8,895 in 2021 [8]. Similarly, in Europe the number increased from 3,020 in 2011 to 8,937 in 2020 [9]. Particularly in Spain, a traditionally wine producing country, the number of registered microbreweries has increased from 70 in 2011 to 347 in 2020. Comparable trends are observed in Chile [10] and Portugal [11].

The size of the brewery is relevant in this study since small breweries are far less energy-efficient than larger ones. The energy efficiency of a brewery is commonly measured as energy consumed to produce a unit of beer, commonly in megajoule per hectoliter of beer (MJ/hL). This parameter works as a benchmark to assess the improvement over time based on the sustainability roadmap of a brewing company. The outcome of a study that we conducted at two breweries of different sizes revealed that the specific energy consumption of a microbrewery is 4.7 times higher than that of a large brewery: 369 MJ/hL versus 78.7 MJ/hL. Both are located in Andalusia, Spain, almost 80 km apart; hence, the climatic conditions are similar. Table 1 lists the specific energy consumption reported by various brewing companies. It exposed that the specific energy consumption increases when the brewery size decreases.

Combining the facts that brewing is an energy-intensive process; that small industries consume more specific energy; and that smaller consumers pay higher prices for energy, it can be hypothesized that small breweries and microbreweries are promising candidates for cost-effective integration of solar energy. Hence, an economic benefit in energy consumption and GHG emissions reduction could be achieved.

1.1. Literature review

Studies on the energy use and efficiency of microbreweries and other small industries are underrepresented in the literature. During the 2010 s, numerous studies were conducted on the application of heat recovery strategies and the integration of solar thermal energy in the brewing process.

Indirect heat recovery has a substantial advantage over direct heat recovery to reduce the energy demand for the brewing process; however, it requires the use of thermal storage, which increases the investment [22].

These outcomes represent a valuable insight about the brewing process and potential for improvement. Nevertheless, these studies are focused on medium-sized and large breweries. The Green Brewery Concept is a tool developed after a comprehensive study of thermal energy needs of three real breweries [23]. This methodology could only be partially applied to microbreweries, since it does not cover their unique characteristics, such as the lack of a boiler for steam generation and a condensate circuit. An important cause of the poor energy performance for small breweries is the non-continuous production, utilization of old second-hand equipment, and lack of knowledge about energy efficiency strategies [19]. A proper characterization of water and energy flows in small breweries could provide a quantitative basis for decision-making that ultimately impacts economic competitiveness, being more important for small brewers since they do not benefit from the same economies of scale as large brewers [20]. The modernization of small and medium-sized breweries will ensue when policies and regulations demand it [5].

About 15 plants of solar heat for industrial processes (SHIP) have been built to supply heat to breweries and cider makers [24]. They are mainly located in Central Europe (i.e., Germany [25] and Austria [26]), and were partially subsidized. However, high investment and high maintenance discourage the clients to install solar thermal solutions without subsidies.

On the other hand, the lower investment and simpler maintenance requirements of photovoltaic (PV) systems have caused a greater deployment of PV in breweries. More than 100 breweries have reported the installation of photovoltaic systems [27], including microbreweries [28]. Although this is still a low figure compared to the number of breweries, it is likely that the actual number of PV systems in breweries is higher due to underreporting.

Furthermore, a possible alternative to fossil fuel is the anaerobic fermentation of wastewater and biogas production [29], even in small and medium-sized breweries [30].

The few available studies identified that directly addressed energy consumption in microbreweries are recent. One study conducted an

Table 1
Specific thermal energy and electricity consumption in breweries.

Brewery	Thermal energy, MJ/hL	Electricity, MJ/hL	Total energy, MJ/hL	Year of data	Reference
AB InBev group breweries	–	–	97.7	2021	[12]
Large brewery in Seville, Spain (+4,200,000 hL/year)	52.6	26.1	78.7	2019	Direct contact
Carlsberg group breweries	60.5	25.6	86	2021	[13]
Large German breweries	85–120	27–41.4	100–160	2011	[14]
Breweries of all sizes in the US	117–135	37–68	154–203	2018	[15]
Breweries associated to the British Beer and Pub Association (average)	–	–	160	2018	[16]
	–	–	270	1990	
Medium-size brewery in the UK (250,000 hL/year)	160–180	45 – 60	205–240	2012	[5]
Sai Gon Beer, Vietnam (200,000 hL/year)	144	64.8	208.8	2011	[17]
Polish breweries (average)	97–194.4	29–43.2	126–238	2015	[18]
Small brewery in Latvia (17,000 hL/year)	219.2	81.2	300.4	2013	[19]
Microbrewery in California (12,000 hL/year)	160	420	580	2018	[20]
Microbrewery in Andalusia, Spain (200 hL/year)	–	–	369	2019	Direct contact
Microbrewery in Bloemfontein, South Africa (424 hL/year)	–	–	234	2019	[21]

experimental evaluation of a waste-heat recovery applied to a microbrewery, but it lacks the economic feasibility analysis [31]. Moreover, certain studies are focused on price-based electricity management, optimization and PV integration in South Africa [32] and others on the techno-economic feasibility of solar thermal and PV integration in Brazil [33], Chile [34], and Spain [35]. The common conclusion is that solar energy could be profitable in microbreweries under specific solar radiation conditions and conventional energy prices. Therefore, a tool that could be customized for a microbrewery's specification, as batch size and annual production, and for the local solar radiation and climate is essential.

1.2. Scope and outline

This study presents the methodology developed to assess the energy consumption of a microbrewery employing simulations and to calculate the economic feasibility of integrating a renewable energy system in a microbrewery. Accordingly, on-site measurements of the process operation were collected; the performance models of the small-scale heat and cold supply components were adjusted to the actual performance; and a validated simulation tool was developed to perform calculations of the energy demand of a microbrewery.

In addition, the required investment and the conventional energy prices allow to calculate the Levelized Cost of Heat and Cold (LCOHC) and payback period. A full-electric microbrewery with a rooftop PV system is employed as a case study. The results are presented for the 52 provinces of Spain to consider diverse climatic conditions to assess their impact in the heat and cold demand, and in the electricity generation.

The main contribution of this study is to present economically viable alternatives to the use of conventional energy in microbreweries, which are usually not taken into account in energy analyses due to their small size and batch operation since they represent a challenge for the integration of renewable energies. The tool used for the energy simulation has been validated with measurements performed in a real microbrewery.

This article is divided in 4 sections: the current introductory section; the methodology and the development of the simulation tool explanation; the results obtained and the discussion of them; and finally, the main conclusions of the study.

2. Methodology

2.1. The brewing process

The production of beer is carried out in various standard steps. Although there are differences between breweries, the common objective is to transform the ingredients, i.e., water, malt, hops, and yeast, into beer. Fig. 1 depicts the stages of the brewing process, including the type of energy required and the raw materials employed. The process begins with the barley malting stage. In the brewhouse, the process begins with barley milling, followed by mashing, sparging, boiling, whirlpooling, and cooling. The fermentation and maturation are not usually part of the brewhouse activities; however, in the case of small breweries and microbreweries they could share the spaces. The packaging stage can be divided into sub-stages, depending on the optional use of filtration and/or pasteurization, and whether bottles, cans or kegs are used.

2.2. Case study

No consumption profiles of microbreweries were identified during the literature review. Hence, it was decided to contact a microbrewery to obtain real data for the creation of a detailed consumption profile, to identify opportunities for improvement, and to adjust the performance model of the simulation tool components. In this regard, the brewery Destraperlo, located in Spain, was selected. The microbrewery runs only on electricity and has a production between 200 and 300 hL/year. The batch size commonly varies from 550 to 650 L. In 2019 the total production was 198 hL. For this same year, the total electric bill accounted for €4,570 (VAT not included), representing about 5.7% of total production costs. The process flow diagram is displayed in Fig. 2. The flows between the different tanks and equipment used in the brewing stages are indicated from left to right direction. Black lines indicate product flow, orange lines indicate heat supply, and light blue lines indicate cold supply. Pumps are designated with the letter P. Certain pumps are indicated as different pumps for an easier understanding but correspond

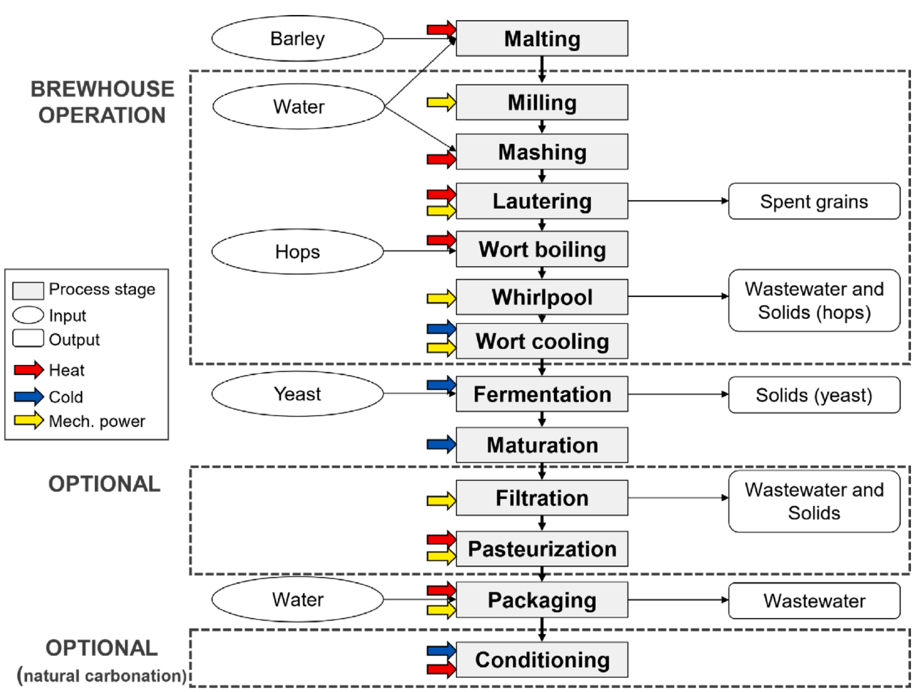

Fig. 1. Beer production process. Based on [21].

to one pump for different purposes, e.g., pump 1 (P1), same as pump 2 (P2).

Unfortunately, the brewery lacks a monitoring system and a centralized control device. Most of the components are manually controlled by the brewer. The electric heaters are controlled by independent timers and thermostats for the mash tun and the boiling kettle. Pumps and valves are manually operated.

The cooling system has more automation. The chiller has an internal thermostat (manually set) and operates autonomously depending on the temperature of the chilled water tank. The fermenters are set to "operation mode" when they are filled with beer. A thermostat on each fermenter controls the pump that distributes the chilled water (P7 in Fig. 2) and an individual solenoid valve for each fermenter to supply cold independently. Hence, the set temperature for each fermenter can be different.

In addition, since there is no monitoring system, no historic registry of variables of interest to detail the process is available. Therefore, a monitoring campaign was carried out to assess these variables of interest.

2.3. Monitoring campaign

A general prerequisite of any energy audit is that the implemented procedures should not compromise beer quality. Therefore, non-invasive temperature sensors and energy monitors were installed. Two different setups for the sensors have been employed. First, the sensors were placed to measure the electric consumption and temperature of the conditioning room's ACHP system (air conditioner and heat pump). The second setup is focused on the consumption of the brewhouse, where the total energy and the energy and temperatures of the water chiller that produces chilled water were measured. The data were recorded in 1-minute resolution. The information regarding sensors installation is presented in Figures S1, S2, and S3 of the Supporting Information, whilst the sensors' accuracy and period of data acquisition are listed in Table S1 and Table S2 of the Supporting Information, respectively. Due to the COVID-19 confinement restrictions, the brewery was not operating between March and June of 2020; hence, the data of these periods were partially lost and not representative.

2.4. Components' performance models

Data from the monitoring campaign were employed to adjust an off-design performance model for the chiller; to select a suitable performance model for the conditioning room's ACHP system; and to establish the boundary conditions for the heat transfer models of tanks and kettles.

First, for the air-to-water chiller, to calculate the ratio between real and nominal cooling capacity (equation (1)) a correction factor is estimated employing a second order polynomial regression (equation (2)) [36]. The capacity correction factor and the calculated model parameters are presented in equation (3).

$$\dot{Q}_{e,chiller} = f_{C,\,chiller} \times \dot{Q}_{e,chiller,nominal} \tag{1}$$

$$f_{C,chiller} = a_0 + a_1 \times T_{wi} + a_2 \times T_{wi}^2 + a_3 \times T_{ci} + a_4 \times T_{ci}^2 + a_5 \times T_{wi} \times T_{ci} \tag{2}$$

$$f_{c,chiller} = -124.3715 - 0.20525 \times T_{wi} + 0.0006501 \times T_{wi}^2 + 1.041228 \times T_{ci} - 0.0015771 \times T_{ci}^2 - 0.00046456 \times T_{wi} \times T_{ci} \tag{3}$$

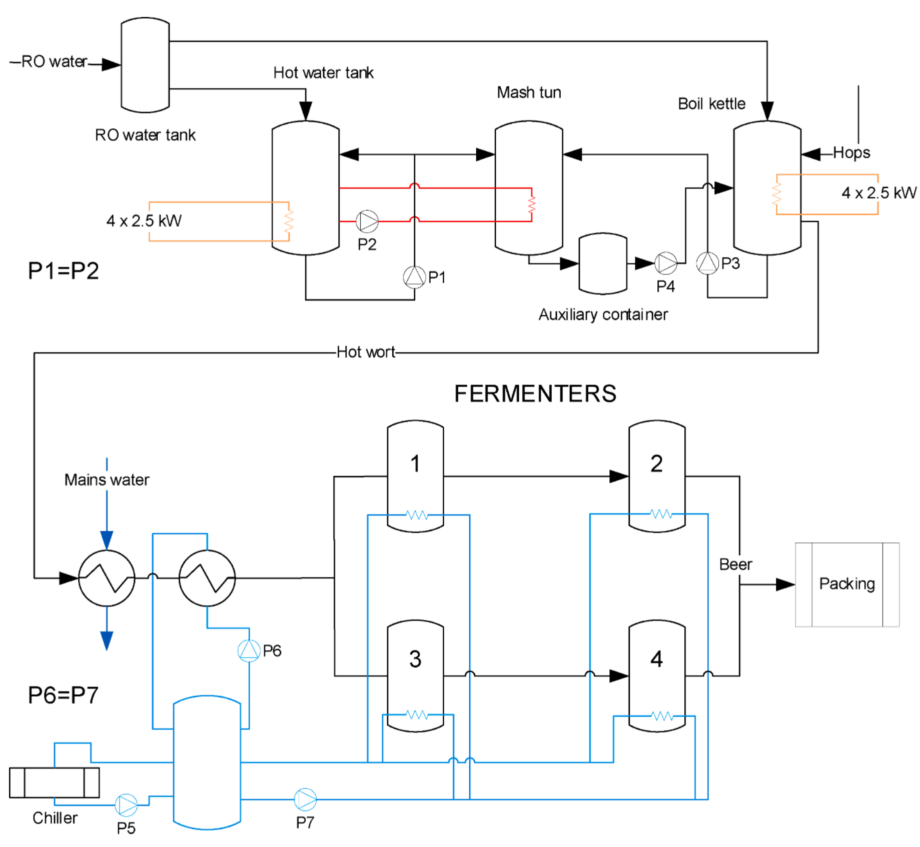

Fig. 2. Block diagram of the brewing process. RO means reverse osmosis.

$$\frac{EER = .Q_{e,chiller}}{\frac{P_{e,chiller} = .m_w \times c_p \times (T_{wi} - T_{wo})}{P_{e,chiller}}} \quad (4)$$

$$\frac{1}{EER_{ch}} = -1 + \frac{T_{ci}}{T_{wo}} + \frac{1}{.Q_{e,chiller}} \times \left(-0.03055 + 11.54 \times T_{ci} - 698.98 \times \frac{T_{ci}}{T_{wo}} \right) \quad (5)$$

Where,

$\dot{Q}_{e,chiller}$ [kW] is the cooling capacity at the evaporator,
$f_{c,\ chiller}$ is the cooling capacity correction factor,
$\dot{m}_w$ [kg/s] is the mass of chilly water in a time interval,
c_p [kJ/kg·K] is the specific heat of chilly water,
T_{ci} [K] is the air temperature at the condenser,
T_{wi} [K] is the chilly water inlet temperature,
T_{wo} [K] is the chilly water leaving temperature, and,
$P_{e,chiller}$ [kW] is the electric power consumed by the chiller.

Moreover, to calculate the electric consumption, the chiller's energy efficiency ratio (EER) is required, which is the ratio between the chiller capacity and its electricity consumption (equation (4)). Hence, to estimate the instant EER, the simplified regression model proposed by Gordon and Ng is employed [36]. This model directly estimates the chiller's EER value of the independent variables instead of calculating a correction factor by which to multiply the nominal EER. The regression coefficients were calculated employing data from measurements, resulting in the adjusted model presented in equation (5).

Since the data are subjected to inherent uncertainty from the measurement process (sensors' uncertainty mainly) the uncertainty propagation for the regression models is calculated employing the Root Sum Squares Method [37] applied on the Engineering Equation Solver software (EES). The mode value of the sample, i.e., $EER_{ch} = 1.55$, was chosen to assess the uncertainty in the dataset, resulting in a model's overall absolute uncertainty for the mode of ± 0.466.

On the contrary, the dataset for the ACHP is too short and does not cover a broad range of operating temperatures. In addition, ACHP unit manufacturer's specifications lack the necessary information to adjust a model. Therefore, the mathematical models that describe the ACHP performance were obtained from the Spanish design manual for small buildings HVAC systems [38]. Both air conditioning and air-to-air heat pump are included, validated for the diverse Spanish climate conditions.

For the different insulated tanks and kettles, an analytical heat-transfer coefficient was calculated based on the geometry and properties of the insulation material. Commonly, the tanks are partially filled, therefore a dry section and a wet section were considered. The resulting U-value ranges from 0.19 to 0.47 $W/m^2 \cdot K$, for the different tanks. Since the actual operation presents specific conditions not represented in the analytical model, a comparison with the simulation results of the model and measurements advised to include a correction factor for each overall heat transfer coefficient.

Moreover, all the pumps of the brewery are fixed-speed pumps. The measurement campaign revealed that actual power consumption matches the nameplate rated power consumption for the three main pumps. Therefore, they are modeled as ON/OFF electric load when liquid needs to be racked or recirculated.

Finally, since the process heat is supplied with electric resistors immersed in the fluid a COP (coefficient of performance) equal to 1 is assumed.

2.5. Simulation tool

The simulation model to represent the behavior of the brewery was developed in TRNSYS 18 [39]. Fig. 3 depicts the diagram of the complete model. The different components have been grouped to better understand the different processes of the brewery. A complete list of the types employed in the model can be reviewed in the Supporting Information.

- **Main building:** represents the thermal behavior of the main building of the brewery.
- **Chiller:** calculates the performance of the chiller and energy consumption under the different conditions given by the main building internal temperature and the fluid temperature of the chill tank's.
- **Heat in tanks/cold in fermenters:** reads the heat and cold demands from the load input file (annual beer production profile) and calculates the thermal losses and energy consumption to supply the required heat and cold.
- **Room ACHP:** represents the thermal behavior throughout the year of the conditioning room and the performance of the ACHP.
- **Electricity + PV:** it adds to the electric consumption from all the components of the brewery. It can be separated by different time-of-use (TOU) bands. In addition, the photovoltaic generation is calculated employing the component for PV modules included TRNSYS library (type94) [39].
- **Others: "Design"** includes the definition of the main design parameters and "**Result outputs"** sort the calculations from the other components.

The model results have been compared with actual data to assess its performance representing the brewery conditions. There are three sources of actual data employed for the comparison: the indoor and outdoor temperatures of the brewhouse from the measurement campaign; the hourly production profile and the electric heater consumption; and the monthly electric bills and brewing (production) schedule for 2019.

Initially, the simulated brewery inside temperature is compared with the available outside and inside temperature measurements and the TMY ambient temperature of days with similar weather conditions. In the summer of 2020 temperatures measurements for the interior of the brewery and hourly meteorological data provided by the Spanish Meteorological Agency were employed [40]. A good agreement is achieved.

Regarding the brewhouse energy consumption, daily variations between simulations and actual data are observed, nevertheless, the monthly total is similar. For example, for February 2020 three batches were made and the actual overall brewhouse consumption was 1176 kWh, while the simulation result obtained for a similar profile in February is 1231 kWh (+4.55%).

To observe the overall annual performance, the total electricity of the brewery is calculated for the production profile of 2019. Regrettably, public meteorological data on an hourly basis for 2019 are not available, hence the Meteonorm TMY data for Jerez de la Frontera is employed instead. The real data are obtained from the electric bills. The annual deviation is −3.6%. February is the month that shows the largest deviation (-17.3%) while July shows the lowest (-0.3%). Based on the comparison results, it is concluded that the simulation model is suitable to estimate the energy consumption of the actual brewery for the purposes of this study.

2.6. Economic metrics

To assess the economic feasibility of the PV system two economic metrics commonly employed in the sector were used: the discounted payback period (DPP) and the Levelized Cost of Energy (LCOE). However, due to the interest of the study in heat and cold of industrial processes, the Levelized Cost of Heat and Cold (LCOHC) is defined in equation (6), based on the LCOH definition [41]. The variables I_0 and S_0 are investment and subsidies, respectively, it is the period of analysis, C_t are the O&M costs for the period t, r is the discount rate, and E_t is the energy supplied during the period t, which usually is an annual figure. VAT (Value Added Tax) is not included in the costs, but specific taxes for fuels or electricity are. In addition, in the case of SMEs, some business

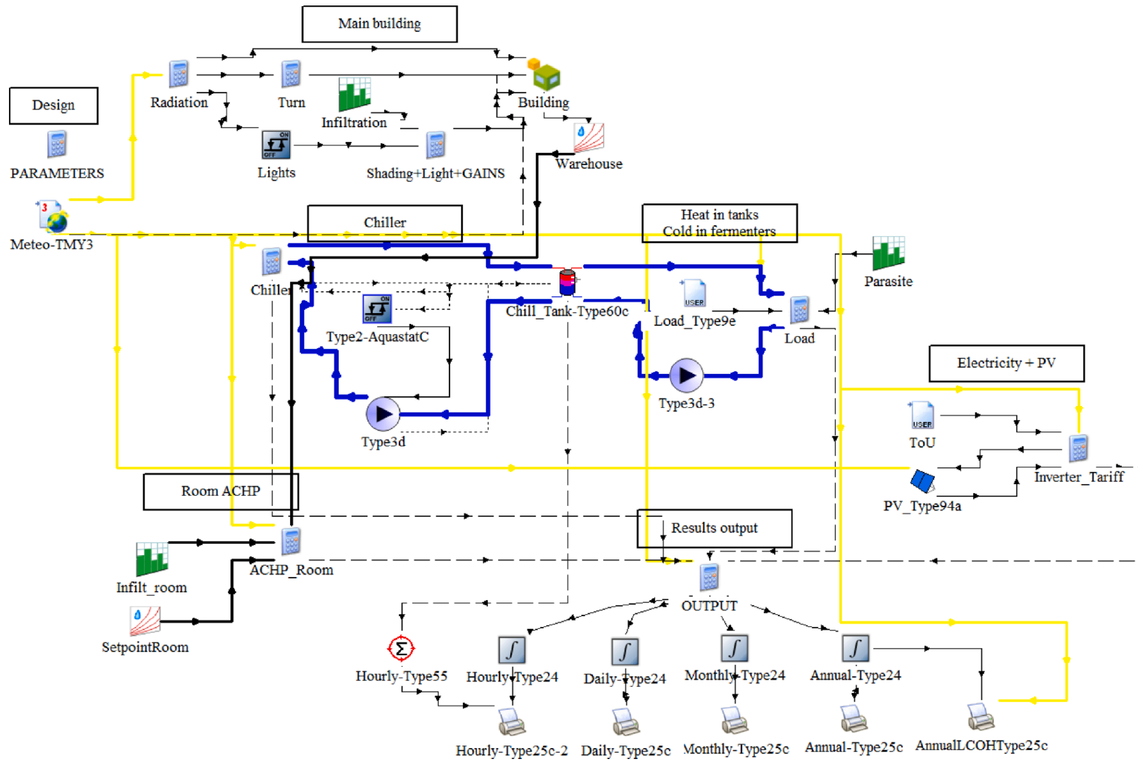

Fig. 3. Diagram of the model for the microbrewery developed on TRNSYS.

accounting terms, such as depreciation, residual value and corporate tax rate, can be ignored, as their finances are often managed more like those of residential users than those of large companies.

A tool has been developed in Microsoft Excel to automatically calculate the LCOHC and DPP from the results of the TRNSYS energy simulations. Thus, the main economic parameters can be easily modified.

2.7. Scenarios and constraints

The two factors that influence the most the viability of a renewable energy system are the prices of conventional energy sources (fuel, electricity) and the initial investment (component prices). For the latter, the price of the components to supply heat and cold and their installation are assumed known in this study, based on actual quotations received in October 2021: Heat resistors (2 × 10 kW) 1,700 €; Chiller 7.5 kW 9,000 €; Chilled water tank 1.2 m^3 2160 €; and ACHP, 3.5/3.2 kW (heat/cold) 1,100 €. Total 13,960 €. The lifespan of the components varies between 5 years for the resistors and 15 years for the water chiller and tank, and the annual O&M cost as percentage of the investment range between 0% for the resistors and to 3.5% for the chiller [42]. In addition, the photovoltaic components have reduced and standardized their prices in the last years. Therefore, for Scenario A (more conservative) a specific cost of 1.5 €/W_{DC} (euros per nominal power of installed capacity in Watts) for the entire system installed in Europe is assumed. For Scenario B (current prices, more favorable) a PV system specific cost of 1.1 €/W_{DC} is assumed [43]. In both cases a 25-year lifespan and an annual O&M cost equal to 2% of the investment are assumed. Electric storage has not been considered in the present study since the brewery requires to be connected to the main grid to ensure the electricity supply to the process, which compensates for the variability of the solar generation. In addition, the peak electrical load concentrated in a few hours of the day could lead to an accelerated reduction in battery life due to deep discharges [44].On the other hand, globally there is high volatility in the hydrocarbons and electricity price, especially between September 2021 and July 2022. Since the main source of energy for the actual brewery is electricity, the scenarios were differentiated considering the Spanish electricity price for industry and small consumers. Scenario A employs average price for the second half of 2021, and Scenario B uses the average price for the first four months of 2022.

$$LCOHC = \frac{I_0 - S_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \quad (6)$$

For industries and business with a contracted power over 15 kW, the time-of-use tariff (TOU) has 6 bands (P1 to P6) that vary every month and are defined on an hourly basis. The electricity regulated users observe in their billing receipt a fixed term and a variable term. The fix term is given by the contracted power (in euros per contracted power, €/kW), which should comply with the restriction of P1 ≥ P2 ≥ P3 ≥ P4 ≥ P5 ≥ P6 ≥ 15 kW. The actual brewery has a contracted power of 25 kW, equal for the 6 TOU periods. The variable term depends mainly on the energy price (€/kWh), that varies constantly depending on the market, and the distribution fees. The energy price is commonly different for the periods, being P1 the most expensive and P6 the cheapest. For the study, the electric rates correspond to one selected distribution company (out of 6) that presented the minimum deviation from the average price of the 6 companies for all TOU bands. The detailed electric rates employed in this study are presented in Table S3 of the Supporting Information.

An additional constraint regarding the maximum PV size is considered based on the available roof area. A maximum of 20 kW_p is established assuming a ratio of 1/2 between total PV area and total roof area (250 m^2). On the other hand, a contractual maximum PV limit of 25 kW_p could be enforced by the distribution company to avoid exceeding the contracted power.

Moreover, for the long-term analysis (25 years), an annual real discount rate of 5% is assumed. No subsidies on the investment are considered. In addition, a 3% of energy price increase is assumed per year; a rather conservative value when compared with natural gas, oil, and LPG price projections [45]. Furthermore, a net-billing scheme is proposed, where the user can inject surplus self-generated electricity to the grid and being paid for it. The price ratio between injected and purchased electricity is set in 25%. In Spain, the distribution company can offer different compensation ratios; for 2021 this ratio ranged from 20% to 83%, and in the first four months of 2022 between 35% and 49%, depending on the month and TOU.

2.8. Load profile

The load is given by the number of batches performed weekly. The brewery has intentions to threefold its production within the next years. This could be possible without upgrading most of the brewhouse hardware; however, more fermenters should be acquired. For this study three batches per week are considered; to be performed on Mondays, Wednesdays, and Fridays. Totalizing an annual beer production of 936 hL. The input load profile is given to the simulation model in liters to be processed on an hourly basis. Hence, the energy demand will depend on the instantaneous ambient conditions. The load profile is shown in Figure S5 of the Supporting Information.

3. Results and discussion

3.1. Energy demand

The results from the simulations revealed significant variations in the total energy consumption based on the location. Fig. 4 depicts the brewery's annual total electricity consumption for the capital cities of the Spanish Provinces as a heat map overlaid on a political map of Spain. The maximum electricity consumption (for Avila = 54,566 kWh) is about 22% higher than the minimum electricity consumption (for Las Palmas de Gran Canaria = 44,776 kWh). It can be observed a trend where hotter climates (south and coastal locations) require less total annual electricity than colder ones (north and inland locations). This is due to the electric heater being the highest single consumer, thus, electricity required for heating weights more in the total electricity sum. The difference could be greater due to the very different climates; however, it is contained due to the trade-off between the heating and cooling demand required for the brewing process.

3.2. LCOHC and DPP

A reference value of LCOHC is calculated when no PV system is installed. Therefore, all the electricity is bought from the grid. The reference LCOHC values for Scenario A ranges from 0.22 €/kWh in Avila, Burgos, Segovia, and Soria, up to 0.25 €/kWh in Las Palmas de Gran Canaria.

The resulting LCOHC for Scenario A of the brewery with a PV system is calculated for all the provinces and for different system sizes. Fig. 5 presents the optimum PV size (that minimizes the LCOHC) subject to the size constraints (roof space). For each location, the LCOH value is presented in euros per unit of energy (€/kWh); in parenthesis it is shown the percentage difference compared to the reference LCOHC value (when there is no PV system); and in the next line it is the PV size in kW_p linked to this LCOHC. The resulting LCOHC ranges from 0.2 to 0.222 €/kWh.

In certain regions with high solar resource, the optimum PV system sizes are between 15.6 and 20.8 kW_p. For the rest of the regions, it is common to observe 10.4 kW_p sizes to be the optimum. It is noteworthy that since climate, solar resource, hour, season of consumption and the corresponding electricity prices vary widely for the different locations; it is not possible to establish a standard behavior but to observe trends.

In addition, Fig. 5 presents the DPP values for the PV system size

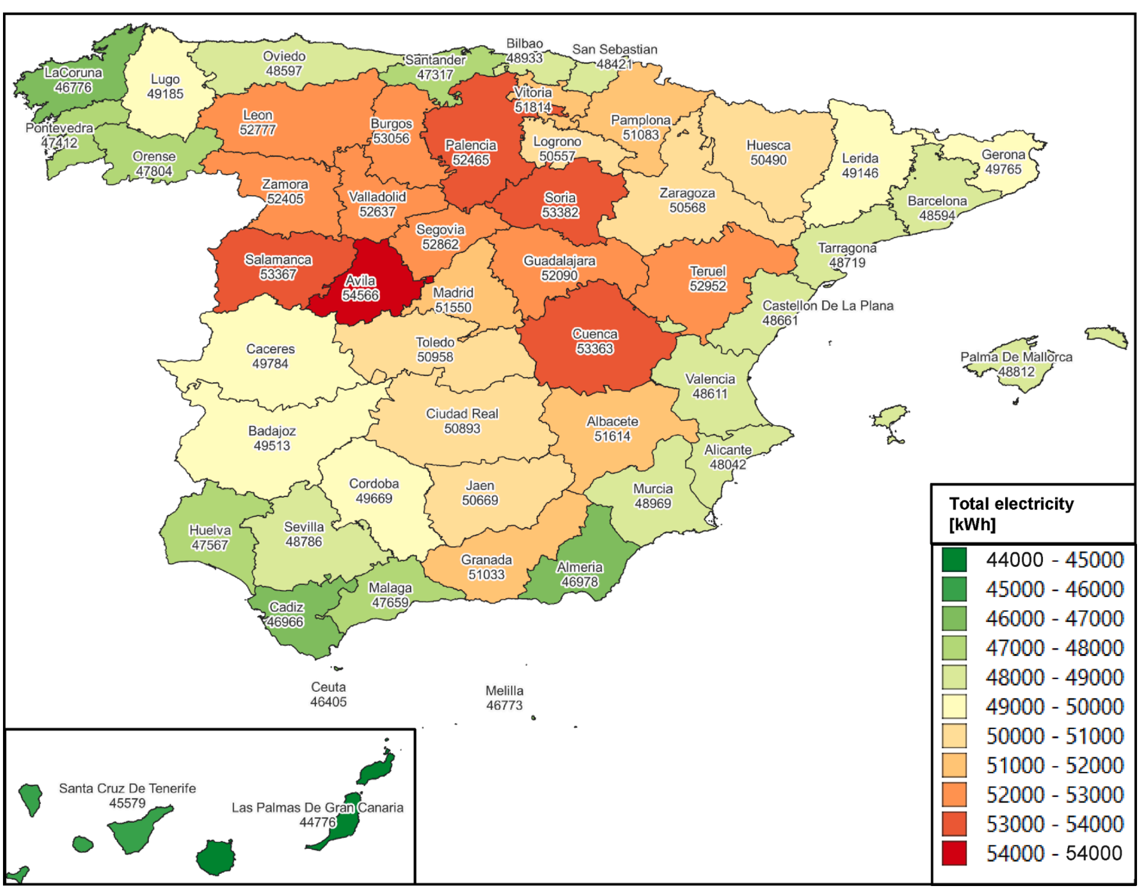

Fig. 4. Total electricity consumed by the brewery for the capital cities of the Spanish Provinces.

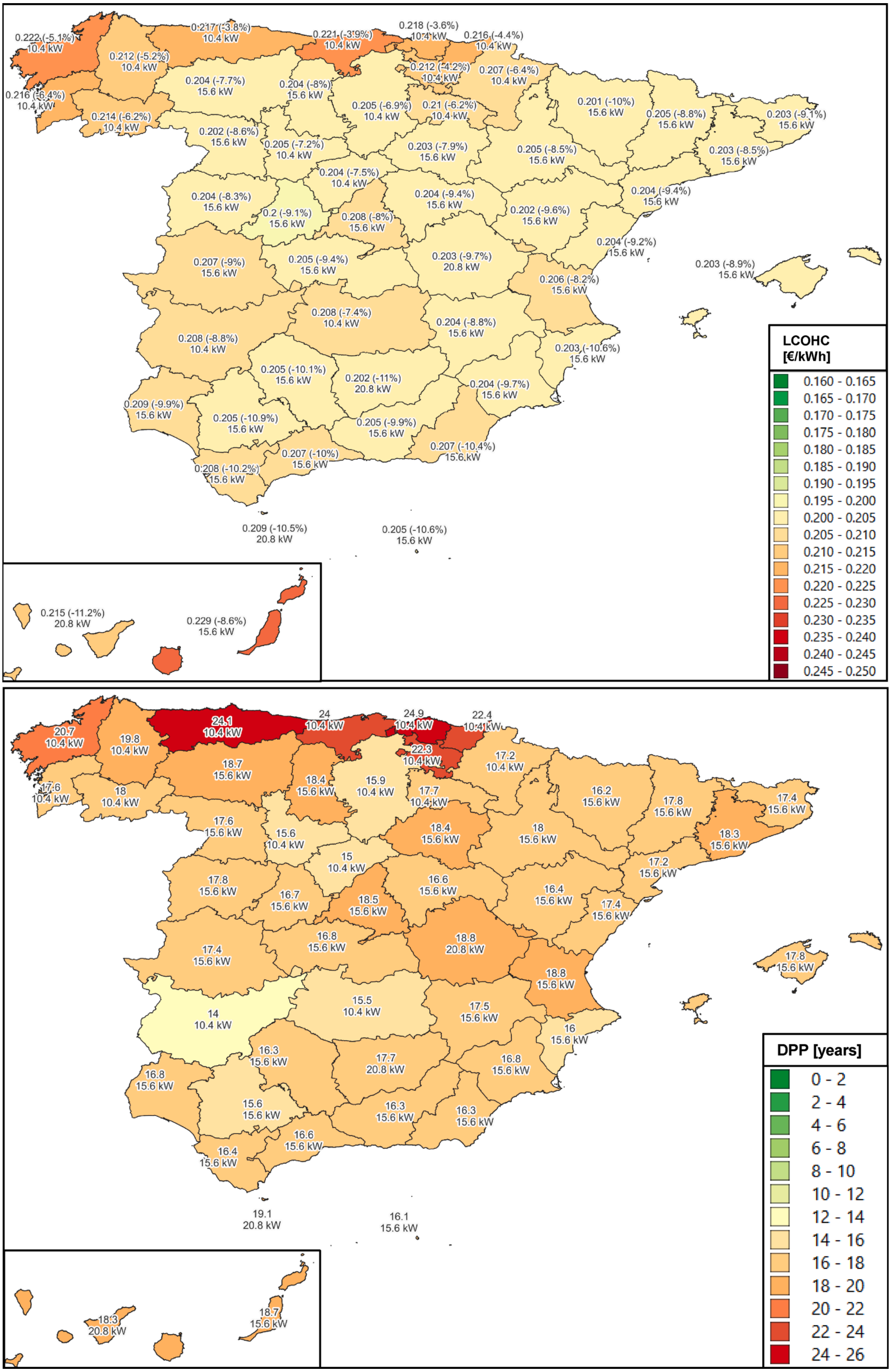

Fig. 5. Minimum LCOHC under Scenario A (top) and DPP of PV system for minimum LCOHC under Scenario A (bottom).

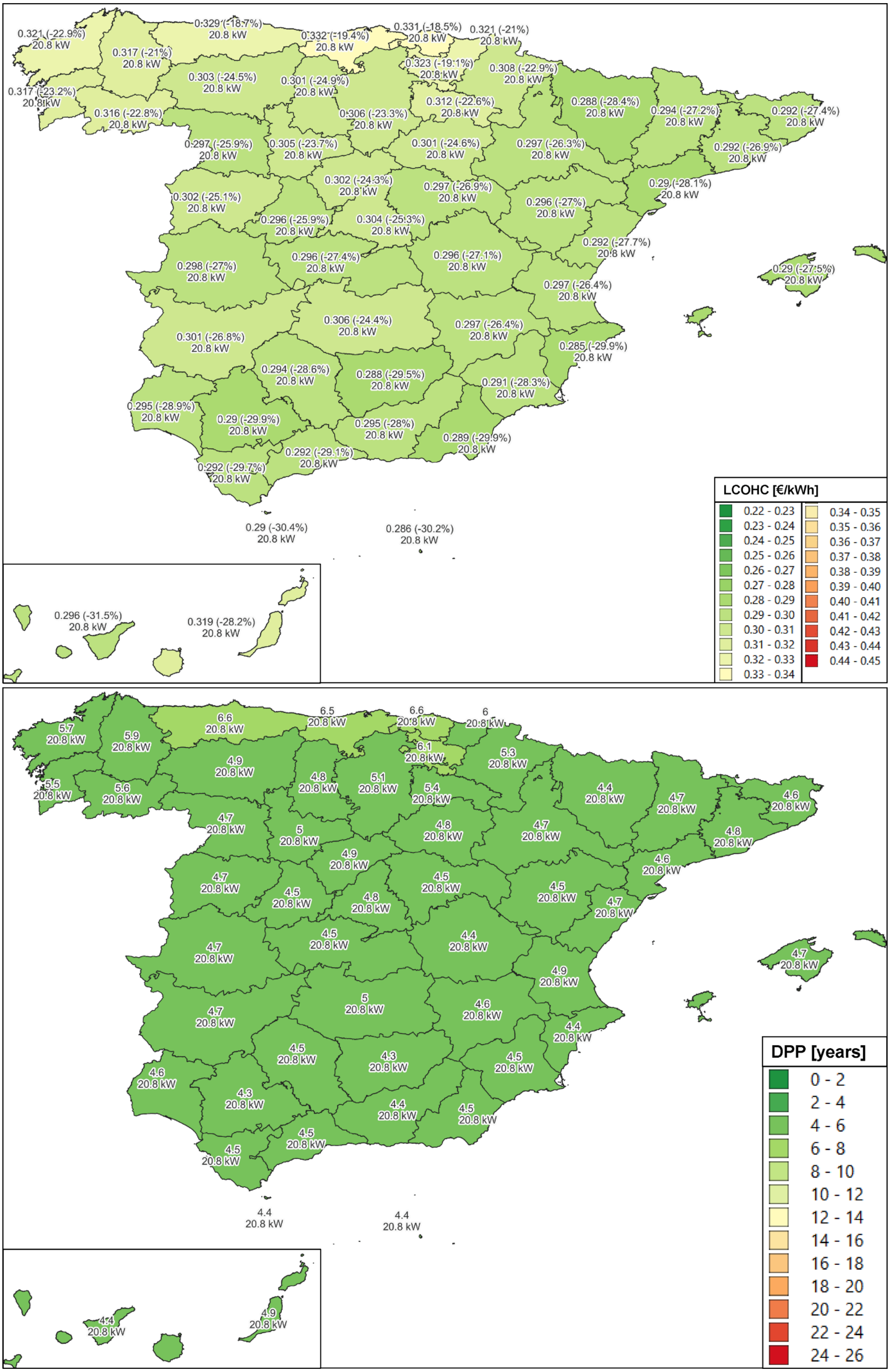

Fig. 6. Minimum LCOHC under Scenario B (top) and DPP of PV system for minimum LCOHC under Scenario B (bottom).

Table 2
Electric average prices for the selected company from June 2021 to April 2022.

Criterion	Variable	Scenario A	Scenario B
	Reference LCOHC, €/kWh	0.22 to 0.25	0.399 to 0.444
Minimize LCOHC	LCOHC, €/kWh	0.2 to 0.229	0.285 to 0.332
	LCOHC reduction, %	−11.23% to −3.63%	−31.52% to −18.53%
	DPP, years	14 to 24.9	4.3 to 6.6
	PV size, kW_p	10.4 to 20.8	20.8
Minimize DPP	DPP, years	7.8 to 15.7	2.2 to 3.7
	LCOHC, €/kWh	0.217 to 0.246	0.388 to 0.432
	LCOHC reduction, %	−1.96% to −0.8%	−3.21% to −1.81%
	PV size, kW_p	1	1

selected as the optimum, which indicates the years that takes to recover the cost of the investment of the PV system. It can be observed that DPP values range from 14 to 24.9 years.

In Scenario B, the reference LCOHC values are higher than for Scenario A since the grid electricity is more expensive. The values range from 0.399 to 0.444 €/kWh (Fig. 6).

In this case, the LCOHC with a PV system ranges from 0.256 €/kWh (in Melilla) to 0.33 €/kWh (in Bilbao). The resulting LCOHC is higher than that of Scenario A, but the percentage reduction with respect to the respective reference case is higher. The DPP of the PV system in Scenario B varies between 4.3 and 6.6 years.

Alternatively, a criterion of minimizing the DPP was applied for both Scenarios A and B. In both cases the LCOHC reduction compared to the reference is negligible. The optimum size for both cases was 1 kW_p, which corresponds to the minimum size established in the pool of simulations. For Scenario A the DPP varies from 7.8 to 15.7 years and for Scenario B it ranges from 2.2 to 3.7 years.

3.3. CO_2 emissions

Although, the core analysis of the study focuses on the economic feasibility of solar energy systems integrated in industries, the ultimate goal is to replace polluting energy sources with cleaner ones. Since the microbrewery of this study is full-electric, the power generation CO_2 emission intensity is employed. In Spain there are four independent electric systems, which electric mix varies between the Peninsula and the islands. For 2021 the average CO_2 emission intensity for the Peninsula was 0.12 tCO_2-eq/MWh, while for the Balearic Islands, the Canary Islands, and Ceuta and Melilla; it was 0.439, 0.553, and 0.8 tCO_2-eq/MWh, respectively [46].

Therefore, the manufacturing-related beer carbon footprint could vary from 6.09 to 39.64 $kgCO_2$-eq/hL for different locations. In addition, a PV system of 10 kW_p PV system can reduce these values up to a 42%, whilst a PV system of 26 kW_p can completely reduce the net CO_2 emission to zero.

3.4. Discussion

The results described in the previous sections represent the possible outcomes of the study for just one application. The tool developed, that includes both the simulation model and the economic model, can be customized to represent different conditions regarding the brewery size, location, and brewing schedule; the PV system specifications; the economic parameters, like the energy rates and components price, interest rate, taxes, and subsidies.

Moreover, it is relevant to bear in mind that there is a trade-off between the user's long-term energy bills, represented by the LCOHC improvement, and the corresponding payback period of the system. Table 2 lists the ranges of the results presented in the previous section. It is separated into the two scenarios (columns) and the 2 optimization criteria (rows).

Payback periods under 10 years can be interesting for the industries. These values are frequently achieved under conditions of Scenario B. And just for certain locations under Scenario A. The criterion of minimization the DPP results in always selecting the smallest PV system analyzed, i.e., 1 kW_p. Despite the fact that the shortest amortization periods are reached in several of them under 10 years, and in certain locations up to 2.2 years, the reduction in LCOHC is small. From an economic point of view, the main objective should be to reduce the energy bill in the long term.

Nevertheless, there are still some challenges on the PV technology that limit its widespread adoption. First, the power fluctuation due to solar radiation intermittency requires the integration of energy storage systems and flexible grid infrastructure to ensure a reliable and stable supply of electricity [47]. Currently, in Spain the distributed generation is not extensive, therefore the grid can balance the power demand of a small load like the one of the studied microbrewery. However, this could be an issue in the future. In addition, there is a limited availability of some critical materials used in PV panels, such as silver and indium. This could lead to supply chain constraints and increase the cost of PV modules, as it was observed between April and October 2022 [48]. Furthermore, the disposal of end-of-life PV panels and the environmental impact of their production and disposal are also challenges that need to be addressed.

4. Conclusions

The first relevant insight of this study is to acknowledge that small industries are less energy-efficient than large ones. A microbrewery could consume about 5 times more energy per liter of beer than a large brewery.

The results of the techno-economic analysis are promising. In the region where the case study brewery is located, the current LCOHC can be reduced by 29.7% when installing a PV system under favorable financial conditions, i.e., high electricity cost and low PV system investment. Furthermore, for the 52 Capitals of the Spanish provinces, the LCOHC under this scenario ranges from 0.285 to 0.332 €/kWh, with consequently LCOHC reduction between 39.9% and 19.4%. The payback period might be suitable for companies' investment horizon, ranging from 4.3 to 6.6 years.

From the environmental point of view, solar technologies do not emit CO_2 during their operation. Particularly, the PV systems directly displace electricity from the grid, which is linked to CO_2 emissions during its generation. A 10 kW_p PV system could lead to a 41% reduction of the annual GHG emissions.

Extremely small PV system, of about 1 kW_p, defines the shortest payback periods. Nevertheless, the improvement in the LCOHC is negligible in most cases, with reductions ranging between −0.8% and −3.21% compared to the corresponding reference LCOHC.

The overall conclusion is that, under current and expected energy price conditions, a PV system of any size installed in a microbrewery anywhere in Spain would lead to economic benefits, even when no subsidies are assumed. In addition, with the inherent benefit of leading industries toward decarbonization.

The contribution of this study to the state of the art begins by identifying gaps in the literature regarding energy consumption in small industries. Furthermore, the on-site monitoring campaign, complemented by the subsequent adjustment of the performance curves, makes it possible to identify the consumption in real conditions for this type of industry, which was not identified in the literature. Finally, the development of the simulation tool (with its components explained in detail) allows its adaptation to include storage technologies, besides being able to be used for other types of industries, which is expected to be studied in future lines of research.

CRediT authorship contribution statement

Alan Pino: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **F. Javier Pino:** Conceptualization, Methodology, Supervision, Writing – review & editing. **José Guerra:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The author declare the following financial interests/personal relationships which may be considered as potential competing interests:

Alan Pino reports financial support was provided by National Agency for Research and Development.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2023.103276.

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