Techno-economic Analysis of Solar Photovoltaics and Solar Thermal Energy Integration in a Chilean Brewery

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Abstract

The brewery industry has an extensive energy consumption which is mainly supplied by fossil fuels (heating) and electricity (cooling). The unique solar resource available in Chile offers the opportunity to supply the brewery demand with solar technologies. The present study assesses the integration of both solar thermal and solar photovoltaic technologies into a Chilean brewery (Cervecera Guayacán), which will be relocated in order to increase five times its current production. Three different scenarios of solar heat integration with flat plate collectors were techno-economically studied. The best scenario presented a compound payback of seven years and a LCOH of 0.104 USD/kWh$_t$ to supply 79 % of the hot process water.

The brewery currently has a 20 kWp photovoltaic (PV) plant that supplies partially the electricity needed by the brew hours. In this study, five different scenarios, which consider moving (to the new location) and/or increasing the area of the PV system have been assessed. The results show that the best economic option would be the movement of the current PV plant which has a payback of almost 4 years and a LCOE of 0.022 USD/kWh$_e$, it would supply 38.5% of the total electricity consumption. If more PV integration wants to be achieved, LCOE values around 0.043 USD/kWh$_e$ and paybacks of 7 to 12 years are obtained.

Keywords: Solar heat and PV integration, brewery, techno-economic study

1. Introduction

The industrial demand around the world consumes around 32% of the final energy (Solar Heat for Industry, 2017), which is mostly supplied with fossil fuels. In the Chilean manufacturing industry, beverages production represents nearly a 2 % of the total annual thermal energy consumption, from which an 85 % is used for heating purposes and 15 % for cooling generation (which is generated by electricity in its totality) as was presented by Castillo et al. (2018). In the breweries, a high thermal and cooling demand is required for the beer production process. Thermal energy is required for water heating, maceration and beer boiling. Cooling demand is required for the fermentation process and for wort and beer cooling. Due to the high solar irradiation in Chile, solar energy integration into industrial processes, especially in the north of Chile, stands as a good candidate to reduce costs and CO_2 emissions.

Many breweries around the world have PV installations to supply their electrical consumption (van der Linden, 2016). The integration of PV in industrial processes is straightforward and doesn´t required a great understanding of the thermal industrial process. On the other hand, the integration of solar thermal energy is not straightforward and requires a deep understanding of the process and the identification of the best integration point from a techno-economic point of view. Hence, fewer integrations of solar heat in breweries compared to PV integrations have been performed. Nevertheless, some reports as the Task 49 (Hassine et al, 2015) present a guideline with different solar system configurations to help solar planers and engineers to integrate solar heat in industries. Lately some studies about solar heat integration have been published. Lauterbach et al. (2014) presented the integration of solar heat (155 m^2 flat plate collector) into a German brewery, which was methodically analyzed based on monitoring and simulations with a validated model. Design and operation of the integration of the solar thermal field was explained, as well as faults of the systems were identified. Joubert et al. (2016) presented a study to evaluate the integration of solar heat into a South African brewery. A total of 120.7 m^2 of flat plat collector were installed with a LCOH of 7.9 EURc/kWh$_t$ and a

doi:10.18086/swc.2019.12.02 Available at http://proceedings.ises.org

payback of 9.3 years. Although different breweries facilities which consider solar energy integration have been installed, usually just one technology, solar thermal or solar PV, is considered. In this work, a techno-economic study of both solar thermal and PV integration in the brew house of Cervecera Guayacán has been performed. Solar thermal energy is used to supply a fraction of the heat demand of the plant and solar PV will supply electricity to be used mainly in the refrigeration process.

Cervecera Guayacán is a brew house located in Diaguitas, in a Region called Coquimbo, in the north of Chile, where the global annual irradiation for an inclined plane of 30° of 2,460 kWh/m^2 ("Explorador solar de Chile"). Currently this brew house produces around 550 m^3 of beer per year. The company is in an expansion phase and wants to increase in five time its current production reaching almost 3,000 m^3 of beer per year. The current brew plant has already a photovoltaic plant of 130 m^2 (20 kWp) that supplies more than 30 % of the electricity demand. The new brew plant will be relocated a couple of kilometers away from the current plant. Since the company wants to decrease its carbon footprint, a techno-economic analysis to increase the PV integration (considering also the current PV panels) to supply their electricity consume has been performed. In parallel, a study to integrate solar process heat to their production process has also been performed. The best integration point of solar heat consists of heating up process water up to 80 °C, which allows to work at low temperatures and to avoid high system pressure and high cost produced by high working temperatures or water steam.

The present study will contain: In Section 2 the thermal processes of the brewery and their energy demands are presented. In Section 3, the integration of solar heat into the brewery processes is explained, along with the techno-economic analysis and the results of the solar thermal integration. Section 4 contains the analysis and results of PV integration in the brewery plant. Finally, the conclusions of the study are presented.

2. Brewery process and energy demands

2.1. Thermal processes of the brewery

The production of beer from a thermal point of view starts by heating up process water in the "Brewing Liquor Tank" (BLT) up to 80 °C (see Fig.1). The BLT is the tank where process water is prepared before starting the process of beer making. This process water consists of a mixture of osmosis water, tap water and additives, whose proportions depend on the type of bier to be produced. Osmosis water is stored in storage tank 1 (ST1) before being introduced in the BLT and tap water is obtained from storage tank 2 (ST2). Once the process water in the BLT is at 80 °C, it is introduced together with malt into the mashing/lautering tank where the mashing process occurs. During this process additional heat is required to keep the wort around 75 °C. This heat is generally supplied by direct flame (small brewery) or by a tank with a water steam jacket (medium or big size brewery). Once the lautering is finished, the wort at a temperature around 75 °C is introduced in the boiling kettle where it is boiled during approximately one hour. After boiling, the wort at around 100 °C must be cooled down to be introduced in the fermentation tanks. For this purpose, filtered water at 15 °C exchanges heat with the hot wort, resulting in heat recovery in the form of filtered water at 50 °C, which is stored in a tank (ST2) to be used in the next batch process. To start the next batch process, the required process water must be at 80 °C in the BLT. To heat up the process water in the BLT from 50 to 80 °C extra-heat is provided through the steam jacket of the BLT.

After the heat recovery, the wort is not yet at 20 °C, required temperature in the fermentation tanks. Hence, extra-cooling generated by a conventional chiller is necessary. A cold mixer of water-glycol stored in ST3 will cool down the wort to temperatures suitable for the fermentation process. In addition, cooling is also required in two more processes. The fermentation process can last between 7 to 20 days, where the bier inside the fermentation tanks must be kept at different temperatures generally bellow 25 °C. During the bottling process bier is generally kept at temperatures around 5 to 8 °C in storing tanks. For both the cooling of the fermentation tanks and the bottling tanks cooling energy coming from a chiller is also required. Since high demand of cooling energy is required in a brew house, the chiller is the first electricity consumer of the plant.

In addition to heating process water, also osmosis water is stored in ST1 and heated up to 80 °C for cleaning purposes.

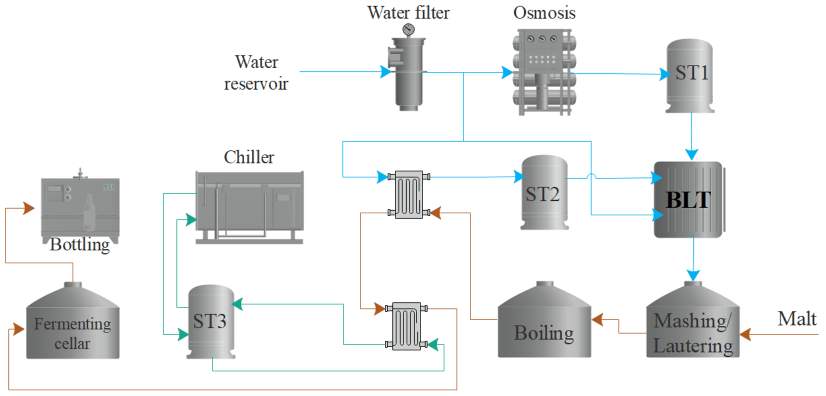

Fig. 1: Configuration of the future plant without solar heat integration (ST: storage tank)

2.2. Energy demands

The future plant is being designed to produce initially 1,375 of m^3 of beer (2.5 times its current production) between 2020 and 2025, which corresponds with 2 batch per day from Monday to Friday. At 2025 the plan is to reach a maximum production of beer of 2,750 m^3 (5 times its current production), which corresponds with 4 batch per day from Monday to Friday.

The thermal demands of the present study were defined based on information provided by the client about the future plant. The future brew house of Cervecera Guayacán will use two types of water: osmosis water for water process and/or cleaning processes and tap water for water process. Each batch process requires 9,200 liters of process water (which can be just tap water or a mixture of tap water with osmosis water), in addition to osmosis water for cleaning purposes. Both osmosis and tap water must be heated up from 18 to 80 °C. Process water is discharged to the "Brewing Liquour Tank" before a batch starts. For the study of solar heat integration was decided to design the system to supply process water for 2 batch per day.

The electricity demand was defined based on a monitoring campaigns of almost five weeks (22/02/2019 to 27/03/2019) of the electricity consumption of the current plant. A linear interpolation of the monitored electrical demand was performed to estimate the electricity consumption of the future plant. The electricity demand used for the study consists in the sum of two periods. For the period 2020-2024, a demand of 2.5 times the current electrical composition will be considered and for the period 2025-2039 a demand of 5 times the current electrical consumption. Furthermore, the demand was characterized generating a daily hourly curve representative of the period and to obtain an approximate annual profile, these results were weighted with ratios proportional to the electric accounts that the Guayacán brewery provided. The result of the annual consumption profile generated for the brewery gives a total annual consumption of 297.2 MWh.

3. Solar Thermal Integration

3.1. Description of solar thermal integration

The integration of solar thermal energy to a brew house has been based in a previous study performed by Lauterbach et.al (2014). However, several changes have been performed to adapt the integration to the present case.

The solar system considered in this study (see Fig. 2) consists in a primary loop which contains solar field of flat plate collectors, a stratified storage tank ("Solar tank") and a cooling system (to avoid overheating). In the secondary loop, heat from the solar field is transfer trough a heat exchanger and stored in a "variable volume tank" (see Fig. 2) until it is required by the production process. The proposed configuration of solar system requires of control strategies for its good performance. The pump of the solar field is activated when the collector outlet temperature is 7 °C higher that the upper temperature of the solar tank. The secondary loop, which sends feed water to the variable volume tank after absorbing heat from the solar field, is activated when the outlet temperature of the solar tank is higher than 40 °C and the volume of the variable volume tank is below 55 %. The pump will stop when the volume in the variable volume tank reaches 60 % of its maximum level. In order to protect the solar field from overheating, a cooling system exists, which is activated when the bottom temperature of the solar tank is above 60 °C.

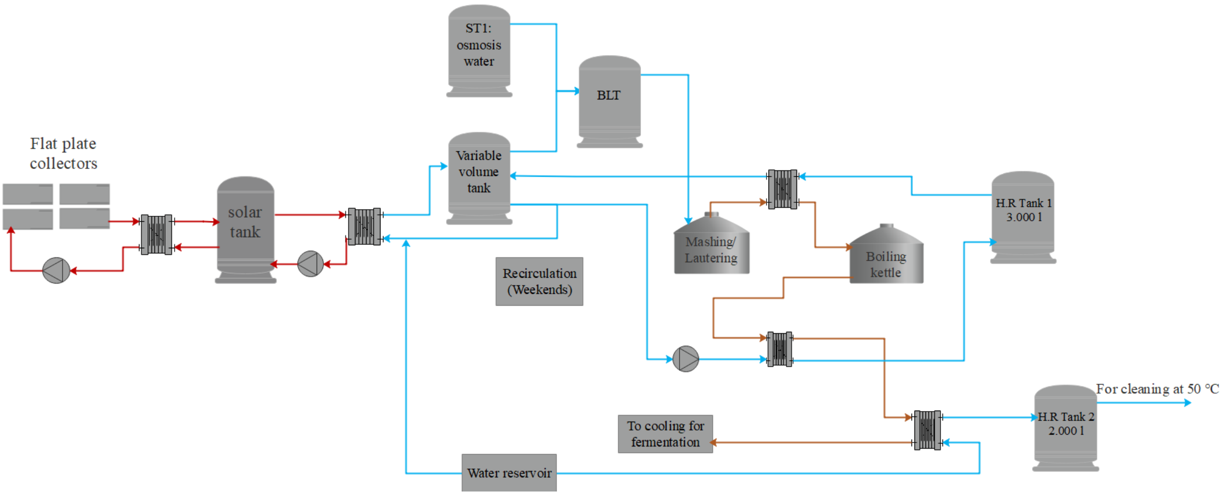

Fig. 2: Proposed configuration for solar heat integration

As it was mentioned in section 2.1, a heat recovery (H.R) is often used in breweries, between the wort leaving the boiling kettle at around 100 °C and the feed water at around 18 °C (see Fig.1). Nevertheless, this heat recovery occurs in the same range of temperature in which is ideal to integrate solar heat at a low temperature level. Hence, it is proposed a change in the heat recovery of the hot wort to integrate easily solar thermal heat at low temperatures. The feed cold water required for process water will be heated up by the solar field and stored in a "variable volume tank". The "variable volume tank" will be discharged every time that process water is required (twice per day) to the BLT. In the BLT the process water will be heated up to 80 °C with a steam jacket in case that the water is not hot enough. Additionally, a heat recovery between the wort at 100 °C and water coming from the "variable volume tank" will occur in order to store hot water at around 95 °C in "H.R Tank 1 – 3,000 l" for the next batch process. This hot water in the next batch process will heat up the wort leaving the Mashing/Lautering tank before entering the Boiling kettle. This heat recovery will save water steam in the boiling kettle to heat up the wort to temperatures near 100 °C. The new proposed configuration needs a new tank ("variable volume tank") and the relocation of the tank ST2 (see Fig.1) to be the "H.R. tank 1 – 3,000 l". The variable volume tank is needed due to the discontinuity in the charging of the tank and process demand.

Since in the new configuration the wort at 100 °C will exchange heat with a process stream at higher temperatures (around 75-80 °C) versus 18 °C, the wort will need more cooling energy to reach the desired temperature around 20 °C before entering the fermentation tanks.

3.2 Studied scenarios for solar thermal integration

Using the solar thermal integration described in section 3.1, three different scenarios were analyzed and simulated in TRNSYS 18. The main TRNSYS types (models) used in the simulation are Type 1:"Solar Collector- Quadratic Efficiency – Flat Plate Solar Collector" for the flat plate collector, Type 534: "Cylindrical Storage Tank" for the constant volume stratified solar tank and Type 39:"Variable Volume Tank" for the variable volume tank. The properties of the considered collectors are shown in Tab.1. The heat losses of the solar tank were obtained also from Lauterbach et al. (2014). For the simulations, irradiation data from the "Explorador Solar de Chile" was used. Scenario 1 considers to heat up 100 % of the volume demanded of process water and scenarios 2 and 3 consider to heat up just 50 % of the volume. The three different scenarios are shown in Tab.2.

Tab. 1: Properties of collectors used in the simulations

Parameter name	**Collector 1** (Keymark 011-7S2688F, 2016)	**Collector 2** (Keymark 011-7S659F, 2016)
a0	0.812	0.76
a1 (W/m^{2}K)	2.936	3.779
a2 (W/m^{2}K^2)	0.009	0.009
Maximum temperature (°C)	225	193
Maximum pressure (bar)	10	6
Gross area (m^2)	15.9	2.12

Tab. 2: Studied scenarios for solar heat integration

Parameter name	**Scenario 1**	**Scenario 2**	**Scenario 3**
Thermal demand to heat by solar field (liters/day)	9,200	4,600	4,600
Collector model	Collector 1	Collector 1	Collector 2
Total solar collector area (m^2)	96	48	50
Solar tank size (m^3)	22	15	15
Variable volume tank size (m^3)	9	7	7

The economic indicator Levelized Cost of Heat (LCOH), shown in Eq.1 was considered in order to compare systems with and without solar thermal energy integration.

$$LCOH = \frac{I_o + \sum_{i=1}^{n} \frac{C_t}{(1+t)^i}}{\sum_{i=1}^{n} \frac{E_t}{(1+t)^i}} \qquad (\text{eq. } 1)$$

In Eq.1 I_o represents the investment costs, C_t corresponds to the operation and annual maintenance costs, E_t corresponds to the reference energy generated in the system, i symbolizes the analysis period in years and t corresponds to the discount rate to consider. A system life of 20 years was used for this study.

3.3. Results of solar thermal integration

The results of the simulations for the three studied scenarios are shown in Tab. 3. As shown the results, scenario 1 allows to supply 79 % of the process water demand (137.6 MWh$_t$/year) since it was designed to heat up 9,200 liters per day. The scenarios 2 and 3 were designed to heat up 4,600 liters/day of hot process waters, therefore their solar fraction is much lower (36 and 33 % respectively) than scenario 1. Scenario 2 allows to integrate more solar energy to process (63 MWh$_t$) than scenario 3 (58.2 MWh$_t$). This fact is due the higher efficiency of the collector of scenario 2 compared to scenario 3. This is also the reason why scenario 2 requires more cooling demand to avoid overheating for approximately the same collector area than scenario 3. In addition to solar heat supply to the variable volume tank, a part of the heat temporary stored in the variable volume tank for process heat recovery purposes is also transferred to the process water in the variable volume tank. Therefore, extra-energy coming from the heat recovery is transferred not only to the wort going to the boiling kettle, but also to the process water. This value corresponds to a value of 15.1, 11.8 and 13.5 MWh/year for each scenario. The highest solar-Heat Recovery system yield is obtained for Scenarios 1 and 2, with a value of 60 %. Therefore, scenario 1 with a high system yield and a higher solar fraction will be studied in detail.

Tab. 3: Results of the three studied scenarios

	Scenario 1	**Scenario 2**	**Scenario 3**
Required energy by process (MWh_t/year)	173	86.5	86.5
GHI on collector (MWh_t/year)	227	114	118.3
Energy generated by collector (MWh_t/year)	153	76.6	67.5
Energy supplied by solar to variable volume tank (MWh_t/year)	128	63	58.2
Energy supplied by H.R to variable volume tank (MWh_t/year)	15.1	11.8	13.5
Energy consumed for refrigeration (MWh_t/year)	14.3	4.6	2.2
Energy supplied to process (MWh_t/year)	137.6	69.1	66.6
Solar + H.R system efficiency (%)	60	60	56
Solar fraction to total process water demand (%)	79	36	33
Annual average temperature of delivered water (°C)	67.2	67.6	65.7

As the energetic results per month of scenario 1 shown in Fig.3, during summer time (November to March) the highest solar heat integration is obtained. On the other hand, during winter time (May- August) lowest solar heat integration and higher heat recovery to the variable volume tank is obtained. This fact happens since the water coming from the heat recovery system is hotter than the water in the variable volume tank.

From the three studied scenarios, Scenario 2 presents the highest annual average integration temperature to process with a value of 67.6 °C, however scenario 1 is very close with a value of 67.2 °C. In Fig. 4, the monthly average temperatures of the water delivered to process from the variable volume water tank of Scenario 1 are presented. During summer time the integration temperature is higher than during winter time, reaching values above 70 °C. The remaining heat required by the process water to reach 80 °C, will be provided by a water steam jacket in the BLT tank.

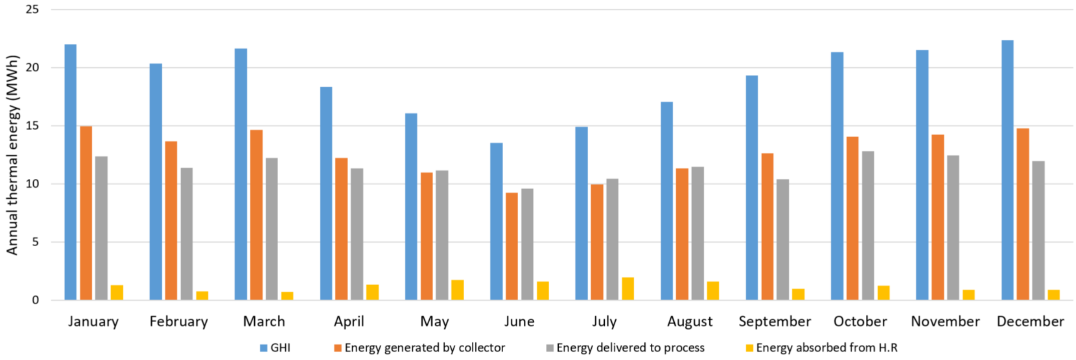

Fig. 3 Generation results for the scenario 1

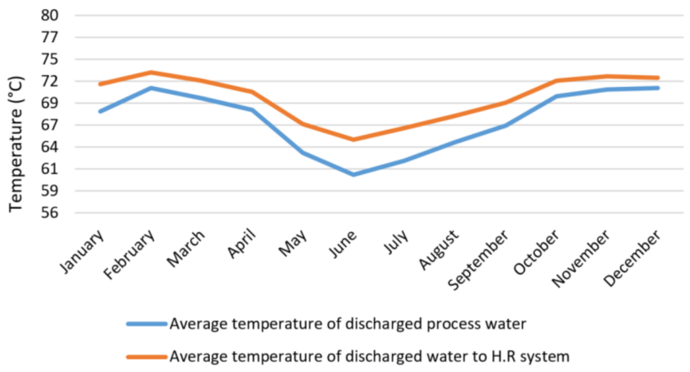

Fig. 4 Annual average temperatures for the scenario 1

The three scenarios where also studied from an economic point of view. A discount rate of 7 % was considered, as well as investment costs of the main equipment (thermal collector, storage tanks, heat exchangers, cooler) based on quotation and information provided by distributors and/or companies that install turnkey projects.

For scenarios 1 and 2 a fix price of USD per square meter of collector 1 was considered. However, this value includes not just the price of the collector, but of the whole system, including also the solar tank, heat exchangers and cooling system (turnkey case). On the other hand, scenario 3 considers quotations from different distributors, as there is no turnkey possibility. For this reason, in scenario 3, collector 2, solar tank, heat exchangers and a cooling system were quoted separately. Additionally, for each of the scenarios a variable volume tank was considered necessary for proper solar heat integration. The main values of the investment costs are shown in Table 4.

Table 4: Investment values for main equipment

Equipment	Units	Cost	Equipment	Units	Cost
Collector 1	USD/m^2	650	Heat exchanger Water – water-glycol	USD/m^2	715
Collector 2	USD/m^2	392	Heat exchanger Water - water	USD/m^2	665
Storage tanks	USD/m^3	1957			

For the economic analysis of solar heat integration the following parameters were considered: LPG price of 0.068 USD/kWh$_t$, electricity price of 0.098 USD/kWh$_e$, a boiler efficiency of 0.85, an efficiency of the heat exchanger in the water steam jacket of the tanks of 0.65 and a COP=4 for the cooling system of the solar field. O&M cost of 1% of the initial investment costs was considered. The Tab. 5 shows the main results of the economic analysis.

Table 5: Results of the techno-economic study.

Scenario	Compound payback (years)	IRR	NPV (USD)	LCOH (USD/kWht)	CO$_2$ savings (tCO$_2$ / year)
1	7	18 %	84,365	0.104	41
2	9	15 %	35,042	0.116	20
3	19	7 %	2,503	0.179	19

As shown Tab.4, scenario 1 presents the best economic indicators with a compound payback of 7 years and an IRR of 18 %. The lowest LCOH is also obtained for scenario 1 with a value of 0.104 USD/kWh$_t$, which is lower than for a scenario without solar thermal integration (0.123 USD/kWh$_t$). If a turnkey business model cannot be achieved, the following option corresponds to scenario 3, which presents the most unfavorable economic indicators for solar thermal energy, with a compound payback of 19 years and an IRR of 7 %.

4. Solar Photovoltaic Integration

4.1 Studied scenarios for the solar PV integration

In order to integrate solar PV in the Chilean industry specific regulations must be taken into account. Chilean law (Ley 21118, 2018) determines that for industries with generation systems over 20 kWp is not possible to generate profits from the sale of energy to the network, rather these injections will be discounted from the electric accounts of the installations associated with the system during the period of one year. This means that any system above those 20 kWp should have an upper limit for the annual energy production of the system, which should not exceed the expected annual energy consumption of the brewery facilities.

The demand for the PV analysis of the future plant is being designed, as mentioned before, to produce 2.5 times its current production between 2020 and 2025 and from 2025 the plan will reach 5 times its current production. Bearing in mind the just mentioned Chilean electrical regulation and future electric demands, simulations of five alternatives of different installed capacities were carried out, which have a production limit of 140 kWac (theoretical maximum production capacity). The electrical production simulations were carried out considering polycrystalline silicon modules mounted on a fixed structure at ground level, distant obstacles such as the surrounding hills were evaluated. These simulations were carried out with the PVsyst 6.63 program and irradiation data from Explorador Solar de Chile was used. The brewery currently has a 20 kWp photovoltaic system that has been operating for 4 years, which will be used in each of the options presented, since the costs of moving the system generate more benefits than the purchase of a new system under economies of scale. The five scenarios considered in the present studied are presented in Tab.6.

Tab. 6: Main electrical characteristics of the five alternatives selected for the PV systems to evaluate

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Nominal power of PV array (kWp)	20.3	41.6	72.8	104.0	151.0
Nominal power od inverter (kW_{AC})	20.0	40.0	70.0	95.0	140.0

4.2. Results of solar of PV integration

The technical results of the five PV scenarios are shown in Tab. 7. In scenarios 1 and 2 there is not electricity injection to the grid, since the PV panels generate energy just for self-consumption. As the power of the PV plant increases, the energy injected to the grid increases reaching a value of 174.7 MWh/year for scenario 5.

Tab. 7: Results of the energetic analysis of the five alternatives studied for the PV system integration

Energy (MWh/year)	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Generated by PV	41.1	84.0	149.0	210.5	302.8
Consumed from the grid	255.8	213.4	182.6	174.3	169.1
Injected to the grid	0	0.2	34.3	87.5	174.7

To analyze the scenarios from an economic point of view, it is necessary to have clarity about the income and expenses that this project will have for the user (in this case Cervecera Guayacán). For this study, it was considered that the income for the owner of the plant would not only be the self-consumption, but also the energy injections from the PV plant to the grid. These will be discounted throughout the year from the plant owner's consumption during periods when the photovoltaic plant does not produce energy. The investment costs of the main photovoltaic elements were also considered in a conservative manner, discounting the 20 kWp PV system that the brewery already had and adding the cost of moving and installing the system, which in this case is around 0.6 USD/kWp due to the proximity of the new location. The investment costs of the PV plants considered in this study are shown in Fig.5, which corresponds to values of the Chilean market (G. Neumeyer, ACESOL 2018). Operational and maintenance costs of 10 USD/kWp/year were considered. Based on this information the payback, LCOE,VPN and IRR were obtained for each alternative using discounted cash flows at a discount rate of 7 %, all the previous considering a duration of system useful life of 20 years. Furthermore, the CO_2 emissions for every alternative were also calculated.

The economic and environmental results are presented in Tab.8. As the results show, the best economic indicators are obtained for scenario 1, which consists in just moving the current PV plant. If the solar PV integration wants to be increased, the scenario which obtains a better trade-off between economic and environmental indicators is scenario 3, which obtains a compound payback of 7.7 years and a zero-emissions indicator for the period 2020-2024. The zero-emissions are obtained because the CO_2 emissions during the period 2020 to 2025 are 62.6 tCO_2/year approximately, which fits completely with the CO_2 emissions savings of scenario 3.

Tab. 8: Results of the economic and environmental studied for the different alternatives of PV solar fields

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Investment (USD)	13,571	50,050	93,038	132,477	188,327
Compound payback (years)	3.5	6.9	7.7	9.2	12.2
IRR (%)	38.0	20.2	18.5	15.5	11.6
NPV (USD)	34,957	61,274	99,223	107,211	82,306
LCOE (USD/kWh)	0.022	0.040	0.042	0.043	0.043
CO_2 savings (tCO_2/year)	17.4	35.2	62.5	88.4	127.2
CO_2 emissions percentage (2020-2024)	72%	43%	0%	-41%	-103%

In the present study, the effect of economies of scale for the studied PV plants in the economic indicators were also studied. Without considering alternative 1, which only considers the existing plant, it can be noticed that the new plant with the highest installed capacity (scenario 5 of 130 kWp aprox.) has a unit investment cost (USD/kWp) 25 % lower than the smaller new plant (scenario 2 of 20 kWp aprox.). In addition, the generation of the PV plants is directly proportional to the size of the plant. Therefore, in a 100 % self-consumption scenario, the investment-generation ratio or investment/savings should be 25 % lower for the largest plant (130 kWp) than for the smallest plant (20 kWp). Consequently, the payback for the large plant should be less than for the small plant. However, as the plant grows, not all the energy goes to self-consumption, instead a percentage goes to the power grid, and this percentage increases as the PV plant grows (see Tab.6). The fact that the percentage of self-consumption production is reduced is detrimental to the payback of the project. This is due to the fact that the Chilean electricity regulation imposes a purchase price of energy from the grid that is 23 % higher than the price applied to the injections of a regulated client photovoltaic system into the grid. For this reason, the scenario with higher kWp PV integration doesn´t obtain the best economic indicators.

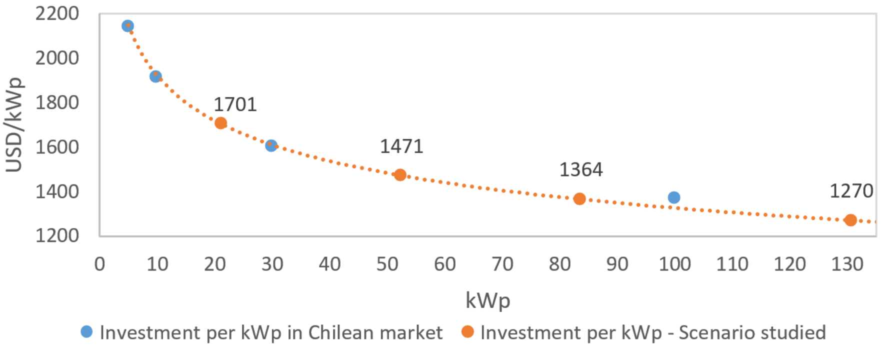

Fig. 5 Investment cost per kWp of new photovoltaic installations according to Chilean market values

In addition, it is important to note that these economic results are strongly affected by the installation and movement cost assumptions of the old PV system. For cases where the installation labor or transportation price is expensive it is highly recommended to evaluate the complete purchase of the system using economies of scale. This can be appreciated in Fig.6 where it is clearly shown that when exceeding prices of 1.5 USD/kWp the payback ceases to have attractive values for low capacity systems and the prices of economies of scale begin to have greater relevance.

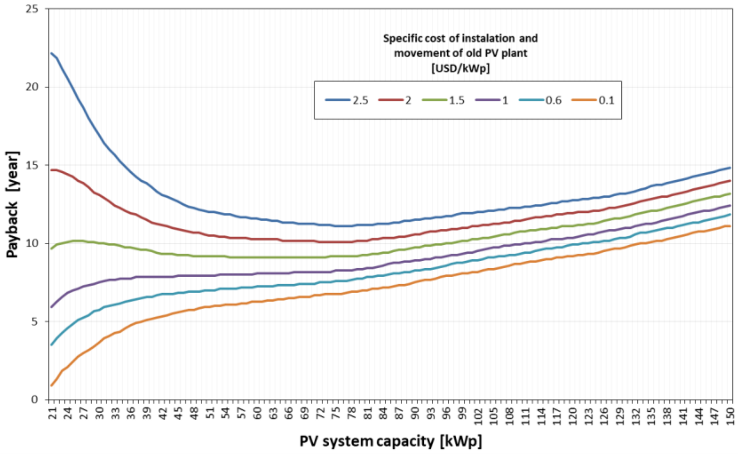

Fig. 6 Sensitivity of the payback analysis due to varying plant sizes to be installed and the costs of transport and installation of old PV equipment.

5. Conclusions

In this study a techno-economic assess of the integration of both solar thermal systems and solar PV in a Chilean brewery has been carried out. Three different scenarios of solar thermal integration were assessed. The scenario which present better economic indicators is Scenario 1, which consist in a 96 m^2 flat plate collector and 22 m^3 of solar tank to cover 79 % of the hot process water. This scenario presents a compound payback of seven years with an IRR of 18 % with a turnkey business model. The LCOH for 20 years of system life corresponds to a value of 0.104 USD/kWh, a lower value as for a system without solar thermal integration. Hence, this alternative is a very good option to substitute fossil fuels, since it is cost effective and decreases 40 ton of CO_2 emissions per year. If the turnkey business is not possible, scenario 3 must be chosen. However, this scenario presents much adverse economic results. Additionally, must be considered that for the good performance of the thermal system a good control is essential.

Regarding the integration of a PV system, the alternative that obtained the best economic indicators is scenario 1, which only consist in moving the 20 kWp PV plant. This result is due to the significant savings in CAPEX when reusing the modules and inverters, however, it should be noted that this result is strongly affected by the assumptions of costs of structures and mobilization of equipment and that these did not include risk studies due to the mobilization of itself. If PV integration wants to be increased, the option of preference should be option 3 because of the trade-off between economic and environmental indicators, which allows to obtain a good payback of 7.7 years and a zero-emissions factor during the period 2020-2024.

6. Acknowledgments

The authors acknowledge the generous financial support provided by CORFO (Corporación de Fomento de la Producción) under the project 13CEI2-21803. This study was supported by another CORFO funded project that allowed this study to take place; “Voucher de Innovación de la Región de Coquimbo, código 18VIPR-103559”. Mercedes Ibarra also acknowledges CONICYT/FONDAP/15110019 “Solar Energy Research Center” SERC-Chile.

The authors are also grateful to Cervecera Guayacán Spa for the fruitful collaboration.

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