Conference Proceedings

Solar World Congress 2015
Daegu, Korea, 08 – 12 November 2015

Combined Generation of Heat and Cooling for a Winemaking Process Using a Solar-Assisted Absorption Chiller

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Abstract

One of the key processes in winemaking is the alcoholic fermentation, an anaerobic process carried out by the metabolic action of a microorganism. During this process, temperature has an important effect on the fermentation kinetics of the process. As the fermentation is an exothermic process most of the wineries use a cooling system composed by mechanical refrigeration cycles and cooling towers in order to control the process temperature during summer and winter, when eventually additional heating might be required. Solar energy could supply both the heating and cooling demands by using an absorption chiller driven by process heat from a solar field. The aim of this study is to assess the thermal performance of the novel system composed by an absorption chiller driven by solar and biomass sources, investigating the behavior of the system in an industrial winemaking process (Miguel Torres Chile). This system consist of a lithium bromide absorption chiller, a flat plate collector solar field and a biomass-burner water heater. The results indicate that the proposed system is able to supply 48% of the cooling demand during the summer and over 90% of the heating demand during the winter

Keywords: *Winemaking industry, solar process heat, Solar cooling,*

1. Introduction

Chilean winemaking industry is worldwide renowned due to the quality of the wine and the significant annual total production. Regarding the latter, in 2013 Chile was placed as the sixth largest wine producer country and the fourth largest exporter (OIV, 2015). During this year, more than 1.3 million m^3 of wine were produced, which represents an increase of 30% with respect to 2014 (SAG, 2015). In this context, the United States and the United Kingdom are the leading importers of the Chilean wine (Vinos de Chile, 2014). As an globalized industry, the wineries needs to stay at the forefront of green technologies, reducing the carbon footprint associated to their processes, in order to maintain and/or improve the competitiveness of the industry (Christ and Burritt, 2013). In this context, during the last decade, the Chilean winemaking industry has started to adopt several sustainable solutions as an actual measure for increasing sustainability of their processes.

One of the key processes in winemaking is the alcoholic fermentation, since it is when the wine acquire its unique flavor and aroma. The fermentation occurs in the absence of oxygen (anaerobic process) and it is during the metabolic action of yeast cells, that the sugar present in the grapes is converted into ethanol, organic acids and CO_2. The yeast's life cycle and enzymatic activities are highly related to the environment conditions as sugar concentration, pH and temperature, where the latest presents higher impacts the in the process, affecting significantly the quality of the final product (Masneuf-Pomarède et al., 2006; Prusina and Herja, 2008). The optimal range of temperatures for winemaking fermentations depends on the type of wine, ranging from 15°C for white wines and up to 30°C for red wines (Sablayrolles, 2009). As the fermentation is an exothermic process, the temperature of the wine tends to rise and could surpass the aforementioned temperatures ranges by up to 10°C (Comfort, 2008). If that happens, other microorganism dominates the process (commonly bacteria) affecting the action of the yeast and changing the characteristics of the must. On the other hand, if the temperature is below the lower limit, the yeast's enzymatic activity decreases significantly and the fermentation periods can extend considerably (Calderón and Navascués, 2002). The fermentation typically occurs during the end of summer (March to April in the southern hemisphere). Therefore, wineries need to control the operating temperature of the fermentation vats by using conventional mechanical chillers (Torija et al., 2003). After the fermentation is completed, starts the maceration phase that gives the wine sensory characteristics, and specifically gives red wines its typical pigmentation. Additionally, this process gives wine some of the desire properties for human health, as antioxidants, antibiotics, antiviral, among others (Jackson, 2014). The maceration process occurs at an optimum temperature range between 25 to 30 °C, and it occurs commonly during the winter. Therefore, in order to keep the tanks at that temperature, wineries commonly use gas or diesel heaters.

In this context, aiming to introduce sustainable solutions in the process, several wineries in Europe have implemented absorption chillers in their production process, which allows using residual heat sources to drive the absorption machine and reducing the electricity consumption. For instance, in Austria a 100m^2 solar field was installed to feed a NH_3/H_2O absorption chiller in order to assist the fermentation process and to control and dehumidify the cooling chamber (Zeiler et al., 2000). This scheme has been also use in the sugarcane industry, for the same purposes (namely controlling the temperature of the fermentation) (Magazoni et al., 2010).

The annual global solar irradiation in the winemaking regions of Chile is about 1800 kWh/m^2, according the measurements and estimations reported in the literature (Escobar et al., 2015). This level of global irradiation allows the utilization of almost every solar thermal technology. Hence, the present study proposes a new configuration of an absorption chiller system, driven by solar energy that allow the utilization of the absorption machine as a chiller during the summer and as a heat pump during the winter, attending the energy demands of the production process all over the year. Additionally this system is integrated to a biomass heater were part of burned material is the biomass self-generated by the vineyard, which has high calorific power (Fernández-Puratich et al., 2015).Thus, the present study present the performance assessment of the system proposed through transient numeric simulations, considering the features of a pilot scale plant installed in Chilean central valley.

2. System description

The system considered herein is a pilot installation deployed in an actual industrial environment (Miguel Torres Winery). It considers an 80m^2 flat plate collectors solar field, a 5TR single effect Lithium Bromide absorption chiller and a 150 kW biomass boiler. Besides, the additional components required for integrating both systems to the existing cooling/heating circuits currently existing in the winery, such as pumps and heat exchangers. The original cooling/heating system considers three storage tanks, which one supply cold or heat to the vats at the temperature defined by the operators, depending on the season and the stage of the fermentation or maceration process. Each one of the tanks is kept at different temperature: one tank at low temperature for cooling purposes (7°C), one tank at medium temperature for heating the maceration process (30°C) and one high temperature tank (80°C) for supply heat to the previous one and for cleaning processes.

In order to facilitate the operation during both summer and winter seasons, the system proposed considered a pipe manifold and valves system, so it can operate on two different modes according the demands of the plant. Despite the fact of being a pilot scale (represents 3% of the current cooling capacity), the solar polygeneration system operates integrated directly to the productive process. Hence, in the summer mode (Fig. 1) the solar field supplies the thermal energy for driving the absorption chiller, while the chilling effect is used for reducing the temperature of the water returning from the fermentation vats cooling system. The cooling water for the absorption chiller is supplied from the mid temperature tank, which is kept at 30°C.

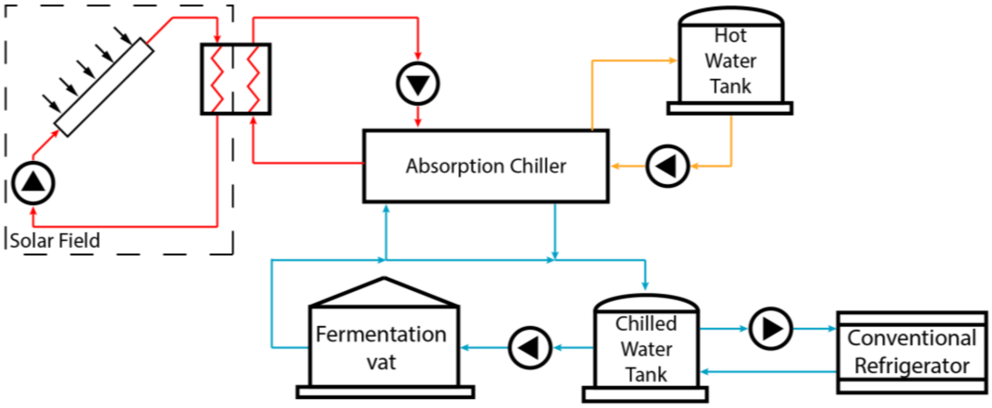


Fig. 1: System configuration in summer mode operation

In the second operation mode, during wintertime (Fig. 2), the solar radiation available is highly reduced, so the heat for driving the absorption chiller comes from the high temperature tank (80°C), which is heated by a biomass water heater. During this operation mode, the energy demanded by the process is heat at 30°C. Therefore, the returning water from the fermentation vats is used as cooling water for the absorption chiller (absorbing heat in the process) and then also absorbs the heat from the solar field. The chilling effect of the absorption machine is received by the low temperature tank, which is kept at 7°C.

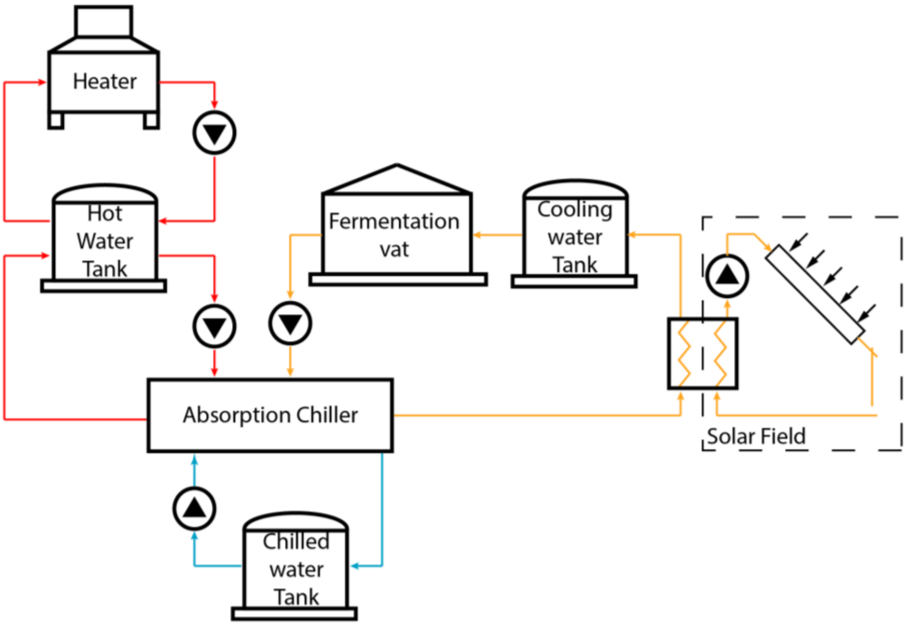


Fig. 2: System configuration in winter mode operation

3. Methodology

The methodology used in this study was adapted from the methodology developed by the Solar Energy Laboratory at the University of Wisconsin-Madison (McMahan et al., 2007). The Transient System Simulation Program (TRNSYS, 2012) was used to carry out the simulations of the complete system, where each component was simulated using a TRNSYS module (Type).

For the case of the absorption chiller, the TRNSYS Type requires the availability of a performance matrix, which can derived from catalog data. For purpose of this study, a dedicated thermodynamic model was developed using EES software (Klein and Alvarado, 2015), and that model was validated using the datasheet of the actual absorption chiller installed in the winery, manufactured by Yazaki Energy. This approach allows the evaluation of the systems using different component capacities, allowing to optimize the configuration and to analyze the performance of the device, in operating conditions, not necessary reported by the manufactured. Therefore, thermodynamic model was developed using the methodology proposed by (Herold et al., 1996), based on balances of energy, mass and species.

Regarding the solar field, simplified models based on empirical characteristics are commonly employed to simulate transient solar collector performance. In this study, a single glazed flat plate collector was considered, considering a 2nd order incident angle modifier (IAM). Thus, the TRNSYS Type 1b module was employed. This module is based on the quadratic instantaneous efficiency equation, as indicated by (Duffie and Beckman, 2013),

$$\eta_c = F_R(\tau\alpha)_n - F_R U_L \frac{(T_i - T_{amb})}{G_T} - F_R U_{LT} \frac{(T_i - T_{amb})^2}{G_T} \qquad \text{(eq.1)}$$

where G_T is the total incident solar radiation on the collector plane, F_R is the heat removal factor, $(\tau\alpha)_n$ is the effective transmittance-absorptance product normal to the collector, U_L is the overall heat loss coefficient, U_{LT} is the correction factor of overall heat loss coefficient, T_i is the inlet water temperature in the collector, and T_{amb} is the ambient temperature. The collector considered is the FCC-1S, manufactured by Bosch. The efficiency parameters of the collector are $F_R(\tau\alpha)_n$=0.686, F_RU_L=3.8622 W/(m^{2}K) and F_RU_{LT}=0.01372 W/(m^{2}K^2) (SRCC, 2010). The mass flow rate under the test conditions was $\dot{m}_{test}$=0.0206 kg/(m^{2}s) and the solar collector has an aperture area of 1.94m^2. The solar field comprises 40 collectors in four series of 10 collectors each.

The solar field is coupled to the absorption system by a heat exchanger, which was modelled considering it as a countercurrent heat exchanger with a constant effectiveness of 0.4769, estimated at the nominal operating conditions. The temperatures of the fluids at the inlet of the heat exchanger are evaluated by TRNSYS in every timestamp simulated. Hence, the heat transferred by the solar field determined by a dedicated Type which estimates the heat transfer rate by the following equation

$$\dot{q} = \varepsilon \dot{C}_{min}\left(T_{H,out} - T_{C,in}\right) \qquad \text{(eq.2)}$$

where, $T_{H,out}$ and $T_{C,in}$ are the hot outlet and cold inlet temperatures, respectively. $\dot{C}_{min}$ is the lower capacitance rate of the flows entering the heat exchanger.

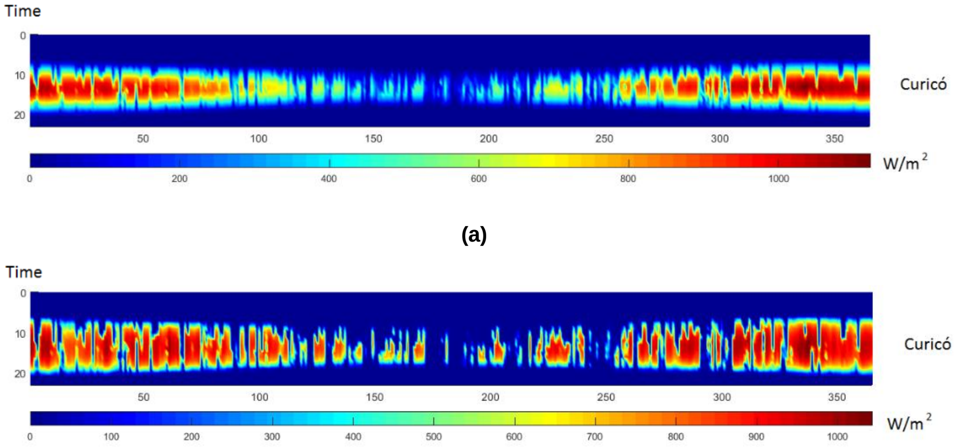
The storage tanks allows coupling the production process and the heating/cooling system, ensuring that the fermentation and maceration processes are conducted within the appropriate temperature range. Therefore, a dedicated TRNSYS type was considered in order to take into account the heat fluxes through the storage tanks surfaces as well as the stratification phenomenon. Hence, different heat transfer parameters were defined for the ceiling, floor, and wall of the tanks, depending if it is in contact with air or water, according the methodology proposed by (Kumana & Kathari, 1982).

Within the simulation, the system is controlled by a PID controller, which is simulated using a dedicated TRNSYS Type (type 23). In this simulation the proportional factor (k_p) is considered as 1000, the integral factor (k_i) is assumed as 1, and the derivative response (k_d) , which determines the slope of the error is 0.1. Additionally, the mass flow rate is constrained by the operating conditions suggested by the manufacturer of the Absorption Chiller. In this context, the datasheet indicates that the mass flowrate of heat source should be between the 30% and 120% of the nominal flow rate, 1.2 kg/s. On the other hand, both Chilled water and cooling water flow rates are kept at the nominal conditions: 0.77 kg/s and 2.55 kg/s, respectively.

Considering the aforementioned conditions, the system was simulating operating in year period. The summer mode is considered from September to April; meanwhile the heating demand starts in April too. Hence, in April the system operates as summer mode and the heat released by the absorption chiller is used for heating some of the vats. Then, from May to July the system operates in winter mode, as only heating demand is present. Finally, during August neither cooling nor heating is required so the system is shut off.

4. Results

The system was simulated using TRNSYS software, considering the climatic conditions of Curicó, where the actual winery is located. The TMY considered was derived by (GeoModel-Solar, 2015). Figure 3 shows hourly totals of GHI and DNI for each day of the TMY at Curicó (34°5S, 71°1W), where the Miguel Torres Winery is located. Curicó is a small city inserted in an agricultural region where the solar resource variability is high due to its Mediterranean climate with occurrences of cloudy and clear days throughout the year with a strong summer/winter seasonality. Episodes of persistent cloud covers during several days are common during the year although less common in summer. In winter, cloud covers are more common, days are shorter, and radiation levels are highly reduced. The yearly totals are 1791 kWh/m^2 for GHI and 1952 kWh/m^2 for DNI.



(a)

(b)

Figure 3: Hourly irradiation values for the TMY in Curicó: a) GHI, and b) DNI.

The irradiation data shows that, although the solar resource available at the site is relatively high in terms of annual totals, it is also very variable during the year and therefore a solar energy conversion system designed to operate throughout the year must include proper thermal storage capacity for acting as a buffer against the resource variability.

Figure 4 shows the hourly temperature profiles in the absorption chiller flows for a clear day in the Summer mode, where CHW corresponds to the chilled water flow temperature, CW is the cooling water flow temperature, and HW is the hot water flow temperature. It can be observed that in a clear sky day the HW inlet temperature decreases after the solar heat supply decreases at the end of the day and then increase after sunrise from approx. 45°C to slightly more than 90°C during the early afternoon when the highest solar resource is available. The HW inlet to the absorption chiller activates the cooling process, and therefore the CHW outlet temperature decreases. In turn, the CW temperature rises in proportion to the CHW temperature decrease. The CHW temperature decrease causes a reduction in the cooling demand at the cold water tank from the mechanical compression chiller, thus producing a net electricity saving. A similar situation is observed for a cloudy sky, although the HW temperature levels increase to a lower maximum level below 80°C. In such a case, the heat supplied to the system is lower, and as it generates a lower cooling effect in the absorption chiller then the electricity saving is also lower.

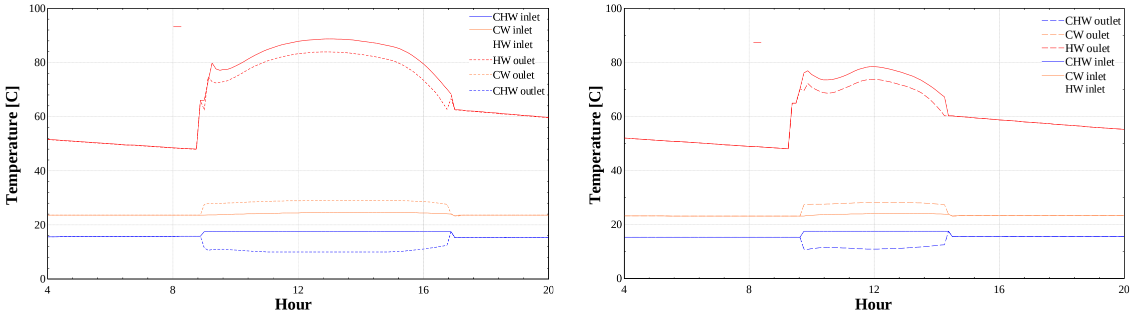


Fig. 4: Hourly temperature profiles in different components of the polygeneration system on summer mode. Left: clear sky day. Right: cloudy sky day.

Figure 5 shows the hourly heat flow rates for the three flows in the absorption chiller: hot, cooling, and chilled water. The absorption chiller is activated by means of automatic pumps that start as the HW temperature reaches a pre-determined level of 75°C. The flow rates during a clear sky day increase after the pumps start, and reach a maximum at the time of highest irradiation, to then remain relatively constant for 2 hours and then decrease until the moment in which the HW temperature reaches a value lower than 75°C when the pumps stop. In total, during a good sunny day in summer the system is capable of operating in solar mode from 9am to 5pm generating savings on LPG and electricity consumption. For a cloudy sky condition (Fig 5 right), the situation is similar to that observed for clear sky, although oscillations on the flow rates are observed as the flow temperatures also oscillate as result of variable solar irradiation. The system is capable of operating for less hours and generates lower savings.

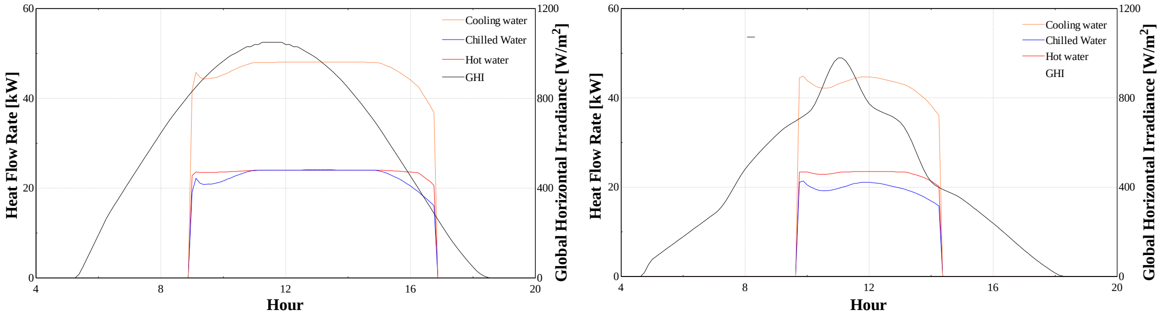


Fig. 5: Hourly heat flow rate profiles in different components of the polygeneration system in summer mode. Left: clear sky day. Right: cloudy sky day.

During winter months, the system operates in the winter mode configuration, in which the mechanical compression chiller is not used, but the absorption machine is operated as a heat pump supplying additional heat to that delivered by the solar field at 30°C water tank, thus generating a net fuel saving on the water heater. Figure 6 shows the heat flow rates in the winter mode for a clear and cloudy sky conditions. It is observed that in clear sky conditions the solar field is able to supply all heat demand, causing that the biomass heater is turn off in 3 to four hours. The operation temperatures during the winter mode operation are stable, since the operation of the absorption machine depend of the temperature of heat medium, which in this case is the biomass heater, set at 95°C. The cooling water temperature is the water returning from the vats, which do not vary significantly and the chilled water temperature is assumed constant at 15°C.

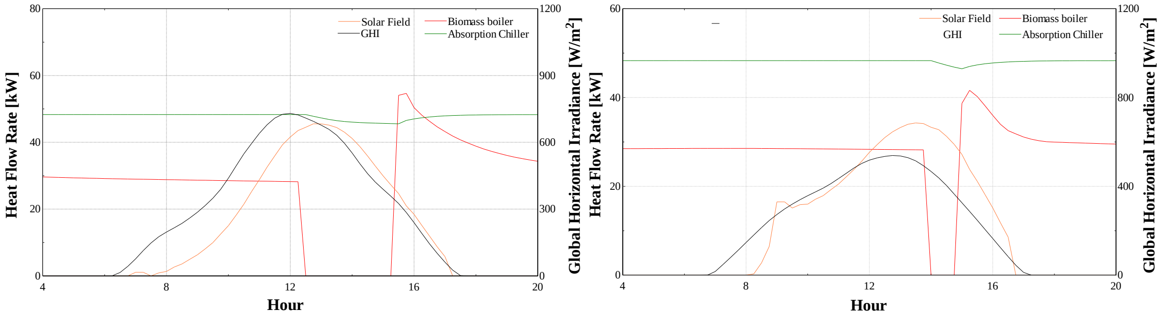


Fig. 6 Winter mode operation during clear sky (left) and cloudy sky (right) conditions. Left: clear sky day. Right: cloudy sky day.

Daily totals of heat and cooling supply for the polygeneration system are summarized in Fig. 7. As observed, the system is able to supply around 150 kWh of cooling per day, during the summer and a similar amount of thermal energy during the winter with peaks over 250 kWh in good days. However, high variability on both the heat and cooling supply are observed, since the system is highly dependent on the availability of solar radiation and the region during most of the year displays a high cloud cover variability as previously indicated. A marked seasonality also exists, with the cooling supply from the absorption chiller being higher during the summer months, decreasing during the fall and then increasing during the spring. The cooling supply from the absorption chiller is directly related to the solar heat production in the collector field. On the other hand, during the winter mode, the biomass boiler is turned on and therefore it is used as a heat source for the absorption chiller, which operates as a heat pump. Because of that, the energy delivered by the system during the winter is higher than the cooling effect supplied during the summer, since it considers the heat released by the absorption machine and the heat delivered by the solar field. Hence, since a significant part of the heat is delivered by the solar field, the high variability on the availability of solar radiation affects significantly the yield of the system.

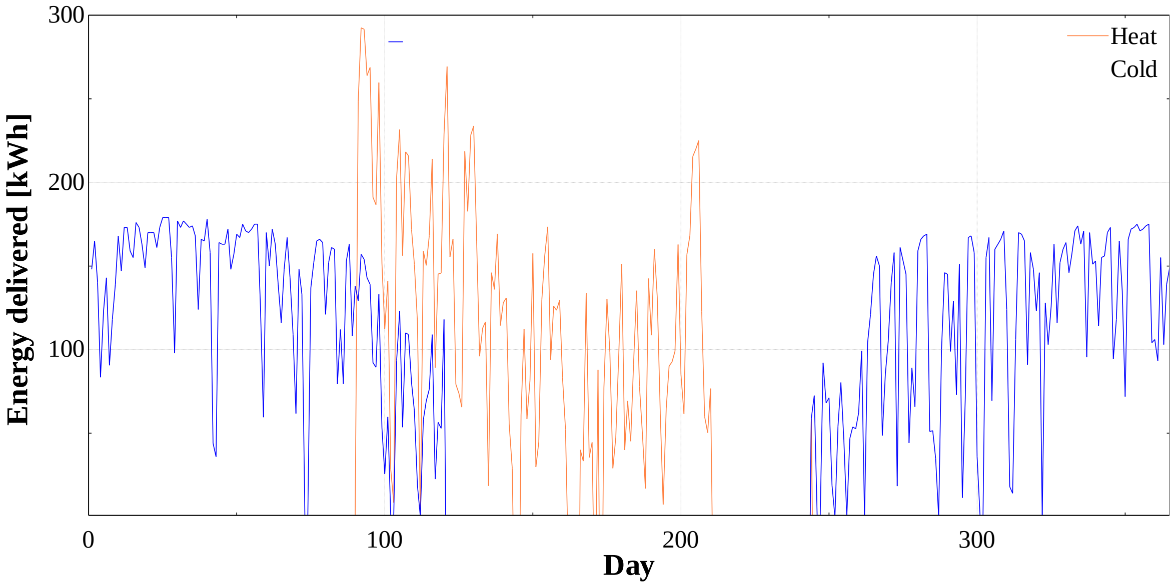


Fig. 7: Thermal energy delivered to processes in a daily basis

The thermal energy displaced by the polygeneration system represents energy savings in terms of the electricity and LPG consumption. The electricity savings are obtained as the absorption chiller cooling supply reduces the cooling supply needed from the compression chiller that keeps the low temperature water tank at 7°C, which is electrically-driven. Therefore, in order to assess the amount of electricity savings, the simulations consider that the operation of the conventional mechanical compression chiller occurs with a coefficient of performance (COP) of 3, which is a reasonable value for a commercial mechanical compression chiller of the type used in the winery. The combustion efficiency at the gas heater is estimated at 85%, and a net heating value for LPG of 12,100 MJ/kg was considered. With these assumptions, the monthly LPG and electricity savings estimated for to the operation of the pilot system are shown in Fig. 8.

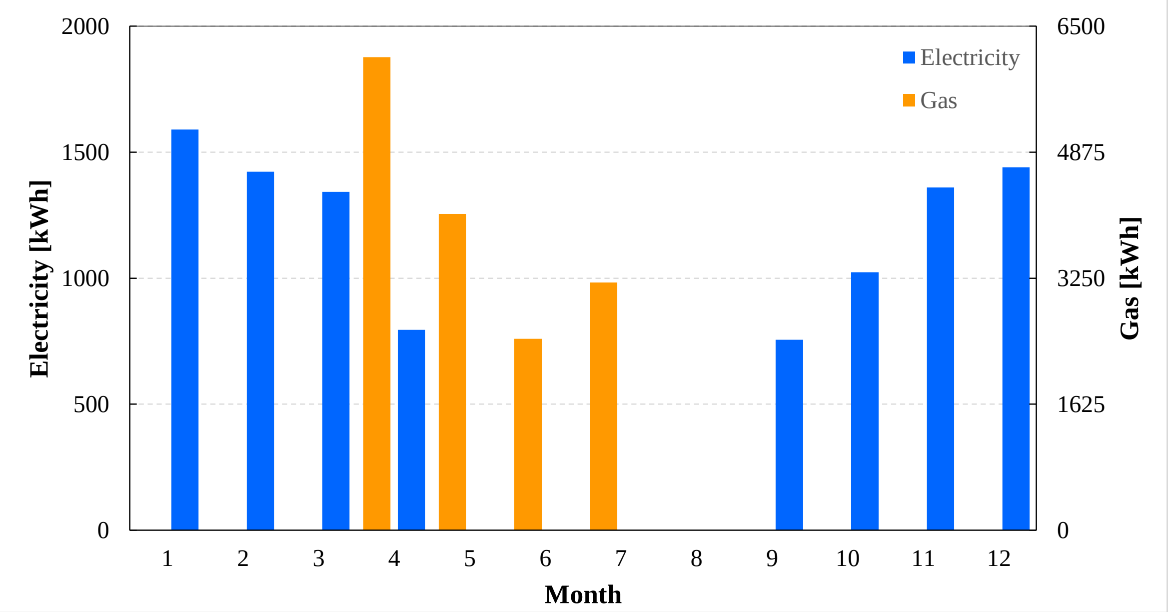


Fig. 8: Energy displaced in a monthly basis

The electricity savings reach a maximum value of 1500 kWh/month for December and January, and then decrease to slightly less than half that value, close to 750kWh/month for April and September, when the solar resource is low at the end of autumn and the beginning of spring. The solar cooling contribution is only a fraction of the available solar heat depending on the typical low value of COP for absorption chillers. From May to August, the heat delivered by the system is due to the solar field and also to the heat released by the absorption chiller. Both contributions results in the LPG savings, which range between approximately 750 kWh/month during June and almost 1400 kWh/month during august. LPG savings are produced when the solar heat is supplied as useful heat to the tank at 30°C. There is a multiplying effect on the LPG savings as the energy conversion chain is as follows: the energy supplied to the 80°C tank is given by the fuel heating value times the boiler efficiency, and then is reduced again by the heat exchanger effectiveness before reaching the 30°C tank. Thus, any heat directly supplied to the 30°C tank as is the solar heat will result in a larger saving of LPG. Additionally, when the operating conditions allow it the hot water delivered by the biomass boiler is used to drive the absorption machine, which released heat at 30°C. The COP of the absorption machine operating as a heat pump is about 1.7, so it allows to amplify the heating effect as a heat transformer, since it absorbs heat from a low temperature source.

5. Conclusions

Winemaking processes utilize heating and cooling systems in order to control the fermentation vat temperatures with variable and seasonal demand. Heating demands are supplied with LPG burning in a water boiler, while cooling demands are met by using a mechanical compression chiller electrically driven. A solar polygeneration system able to supply heat from a solar flat plate collector field and cooling water from an absorption chiller is proposed as an alternative with lower electricity and LPG consumption, thus allowing the winery to decrease its carbon footprint.

The system is composed by a solar field, an absorption chiller, three water tanks of high, medium, and low temperatures, plus the LPG water boilr and the mechanical compression chiller. Two operation modes are proposed for dealing with the high seasonality of both the solar resource and the heating and cooling demands.

The system was simulated using TRNSYS software, complemented with EES routines. Hence, the performance of the system is evaluated in terms of the reduction on the energy consumption, reduction on the carbon footprint and the exergy utilization. The results indicate that the proposed system is able to supply 48% of the cooling demand during the summer and over 90% of the heating demand during the winter, when compared to conventional systems of equivalent capacity of the pilot plant at Miguel Torres winery. This result is even more attractive when the system is scaled up, between 50 to 100% of the current cooling capacity installed at the winery. In addition, an optimization routine has been conducted in order to determine the best operation conditions for the system. Therefore, this hybrid system presents several economic advantages, enabling the possibility of an energetically autonomous winery and presents a vast potential for improvement allowing to produce a zero emissions wine.

Acknowledgement

The authors would like to acknowledge the Chilean Foundation for Agricultural Innovation (FIA) that supported this effort through Grant PYT-2013-0021 P690 with financial contributions from Miguel Torres Winery.

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