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Solar assisted absorption machine for the fermentation cooling and maceration heating processes in the winemaking industry

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Abstract

Two of the key processes in winemaking are alcoholic fermentation and must maceration, both of which have a high demand of energy. Fermentation is an anaerobic process carried out by the metabolic action of a microorganism. During this process the temperature has an important effect on the fermentation kinetics [1, 2]. As the fermentation is exothermic, most of the wineries use a cooling system composed of mechanical refrigeration cycles and cooling towers in order to control the process temperature. After the fermentation, the must is macerated at temperatures close to 30°C, during which the phenolic materials (e.g. tanins and coloring agents) are leached and balanced. The aim of this study is to assess the thermal performance of a novel system composed of an absorption machine driven by solar and biomass energy sources, thus investigating the behavior of the system in an industrial winemaking process. This system consists of a lithium bromide absorption machine, a solar thermal collector field and a biomass water heater. The system operates in different modes during summer and winter seasons, taking advantage of the seasonality of both the solar resource availability and the heating and cooling demands of the processes. The results indicate that the proposed system is able to supply 25% of the cooling demand during the summer and between 30 to 50% of the heating demand during the winter.

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

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Nomenclature

E	Total energy
C	Purchase cost of an equipment
X	Size of the equipment
α	Scaling exponent
Subscript	
$abs, chilled$	Chilled water stream from absorption chiller
$abs, cool$	Cool water stream from absorption chiller
$coll$	Solar field
$solar$	The sun
$supply$	Supplied by the system
$supply, hot$	Supplied by the system of the absorption chiller
y, w	Equipment item

1. Introduction

Alcoholic fermentation is one of the key processes in winemaking. It is a metabolic process whereby yeast cells convert the sugar present in the grapes into ethanol, organic acids and CO_2. The process occurs in the absence of oxygen, and the yeast cells are submitted to several stresses from different environmental factors, which can significantly affect the quality of the final product [3,4]. For instance, the operating conditions of physico-chemical factors such as the temperature in the vats, are controlled during the fermentation process [5]. The temperatures applied in the fermentation in winemaking varies typically from 15°C for white wines to more than 25°C for red wines [6]. The fermentation is an exothermic process, therefore the temperature of the wine increases, so in order to keep the temperature at the aforementioned values wineries commonly use a conventional refrigeration system during the summer. These systems allow the temperature level of the fermentation vats to be kept within a range that enables the metabolic action of the yeast.

After the fermentation process, the must is kept warm at around 30°C for several days in a process called maceration. In this process, most of the phenolic components are leached and balanced. Maceration commonly occurs during the winter, and so a heating system helps keep the vats at the required temperature. These water heaters are commonly driven by liquefied petroleum gas (LPG). Considering the heavy dependence of the Chilean electricity grid on fossil fuels, the use of electricity results in a significant carbon footprint for each bottle of wine [7]. In addition, as Chile has limited fossil resources, the use of LPG is associated with high operation costs. For similar reasons, several wineries in Europe have implemented absorption chillers in their production process, which allows the use of residual heat sources to drive the absorption machine and reduce the electricity consumption. This scheme has also been used in the sugarcane industry for the same purposes (controlling the temperature of the fermentation process) [8]. The aim of this study is to assess the performance of an integrated system for combined generation of heat and cooling for these processes, by harnessing the solar resource available in central Chile and the biomass self-generated by the vineyard. The annual global solar irradiation in the winemaking region of Chile is approximately 2000 kWh/m^2, according to the measurements and estimations reported in literature [9]. This level of global irradiation allows for effective utilization of solar thermal technologies. Therefore, in this study, we present the results of simulations of the operation of an absorption chiller powered by a solar thermal collector field and a biomass boiler. A transient simulation were developed in TRNSYS software to assess the performance of the system, considering the actual meteorological data of a region in central Chile where several wineries are located. The area of the solar thermal collector field has been varied in a range between 250 and 1000 m^2 and these results have been compared to the base case of the existing infrastructure. The solar collector field consists of flat plate collectors, selected for their suitability in supplying heat within the required low temperature ranges.

2. System Description

The system proposed was designed to supply 25% of the summer peak cooling demand corresponding to 880 kW. A Lithium-Bromide absorption machine is considered, coupled with a field of solar thermal collectors, where the area of the solar field is varied in order to evaluate the effect of the scale on system´s performance. The model includes a biomass burner, a cooling tower and a conventional refrigeration system to provide the remaining demand (considering the existing facilities generally present in the industry). The system includes three storage tanks to supply heat or cold to the vats according to the season and the stage of fermentation or maceration process.

The system was simulated in two different operation modes, according to the heating and cooling demands of the plant. In the summer mode shown in Fig. 1. Summer mode, the solar field and biomass burner directly supply the required thermal energy to drive the absorption machine, while the chilling effect is used for reducing the temperature of the water returning from the fermentation vats. The cooling water for the absorption chiller circulates in a cooling tower releasing the heat to the environment.

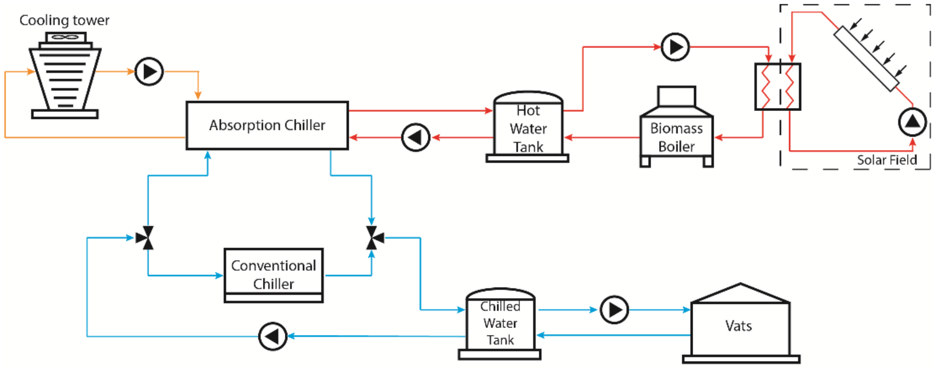

Fig. 1. Summer mode

The second operation mode shown in Fig. 2 corresponds to winter season, where the solar resource available is considerably reduced. The heat driving the absorption chiller comes from the high temperature tank, heated by the biomass water heater. During this operation mode, the maceration process requires heat at 30°C, which is provided by the cooling water stream from the absorption machine. In this configuration, the solar thermal collectors operate as a low temperature heat source in order to deliver heat to the chilled water stream. In addition, during the night time the hot water tank delivers heat directly into the medium temperature tank, in order to maintain the operation of the system.

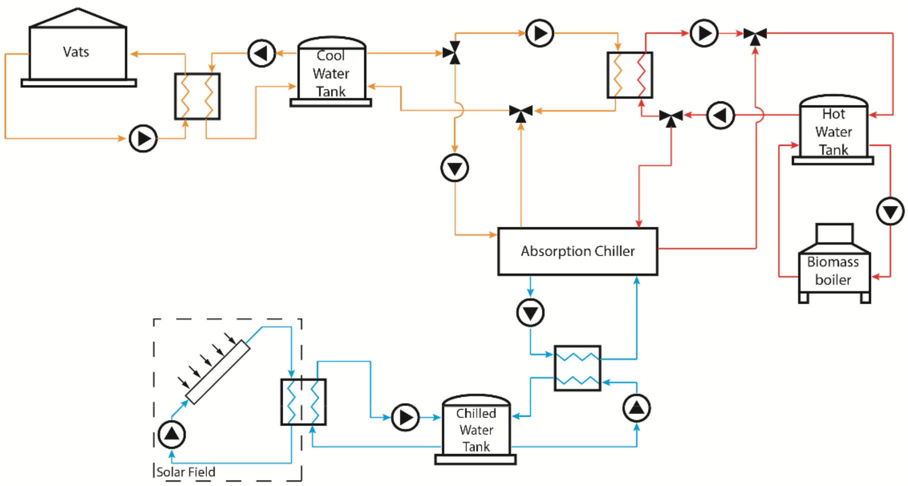

Fig. 2. Winter Mode

3. Methodology

The present study is based on a winery located in Curicó, Chile. The vineyard has been the focus of an energy audit process and a pilot plant based on a similar concept is present on site as detailed in [10]. The climate data has been taken from this site, and the TMY considered in the simulation was provided by GeoModel-Solar [11], where the year totals are 1791 kWh/m^2 for GHI and 1952 kWh/m^2 for DNI.

The simulations were carried out using TRNSYS a transient system simulation program [12] where the system was modelled using dedicated mathematical models and TRNSYS components (Type). The TRNSYS program is based on the methodology developed by the Solar Energy Laboratory at the University of Wisconsin-Madison [13]. In addition, the parametric analysis was programmed using a Python code [14], to call TRNSYS and assess the system performance with different collector areas.

This study presents an evaluation of the scaling up of the system proposed in [10]; the parametric analysis evaluates the performance of the system in both summer and winter for different collector areas. The economic analysis assesses the benefits in terms of energy and cost savings by the implementation of the proposed system compared to the base case.

3.1. Baseline Demand

The baseline values for cooling during the summer and heating during winter have been determined from energy audits, and compared to theoretical values. The plant operation schedule varies from one year to other depending on the weather conditions. However, for sake of simplicity, the present study considered the following schedule

Table 1. Baseline parameters from the winery.

Season	Months	Process	Set Point Temperature	Hourly Heat Demand	Current devices used
Summer	Sept – Apr	Fermentation	8°C	-200 kWh	Conventional Chiller
Winter	May – Aug	Maceration	30°C	175 kWh	LPG Boilers

The heating and cooling demand is 24 hours a day 7 days a week during the required months; however the use of the biomass boiler is limited to working hours at the wineries between 5am to 7pm daily.

3.2. Simulation Parameters

The following inputs were used for the TRNSYS simulation. The inputs for the absorption chiller were based off the nominal values from technical data for the Thermax Vapour Absorption Chiller 5G 2A C and were used with the TRNSYS type 107 with the performance matrix obtained from the study in [10].The solar collectors are Bosch FCC-1S flat plate collectors. The cooling tower was modelled based on an evapco 559kW machine. The conventional chiller is an 800kW model manufactured by Carrier with a COP of 2.81. The storage tanks have volumes of 60, 20 and 30 m^3 for the hot, cool and chilled water tanks respectively.

The system was simulated over an entire year with a time step of 4 minutes.

3.3. Absorption chiller, solar utilization and solar fraction

The performance of the system is evaluated in terms of different figures of merit, depending on the mode of operation, and the source being used.

Table 2. Equipment utilization and solar fraction.

	Summer Mode	Winter Mode
Solar Fraction	$\frac{E_{coll}}{E_{supply,hot}}$	-
Solar Utilization	$\frac{E_{coll}}{E_{solar}}$	
Absorption chiller utilization	$\frac{E_{abs,chilled}}{E_{supply}}$	$\frac{E_{abs,cool}}{E_{supply}}$

In summer, the solar fraction represents the portion of solar energy provided to the hot stream of the absorption chiller, which is supplemented by heat from the biomass boiler. The absorption chiller utilization refers to the cooling provided by the absorption chiller as opposed to that from the conventional chiller. In winter, the absorption chiller runs only when there is heat provided from solar energy so the solar fraction can be represented by the absorption chiller utilization, compared to the heat provided from the biomass boiler. In both seasons the solar utilization refers to the collector output divided by the solar irradiation incident on the collectors.

3.4. Economic analysis

An economic analysis was carried out to determine the economic feasibility of the integration. The costs of electricity, LPG and the biomass boiler were determined from energy audits and from local data from an actual winery. The cost of the biomass was estimated to reflect the processing and storing of the self-produced biomass, and consequently has a very low cost when compared to the alternative pellet biomass available. The component costs such as the absorption chiller and solar field were obtained on the research developed by Zeiler [15].The cooling tower investment cost was obtained from the supplier EVAPCO. These prices were scaled up with the equation proposed by Bejan [16] as follows:

$$C_Y = C_W\left(\frac{X_Y}{X_W}\right)^{\alpha} \quad (1)$$

The main economic parameters used in this research are shown in Table 3.

Table 3. Economic parameters

Parameters	Value
Biomass	0.004 \$/kWh
Electricity	0.062 \$/kWh
LPG	0.075 \$/kWh
Absorption Chiller	\$222,000
Biomass Boiler	\$42,000
Solar Field	212 \$/m^2
Cooling Tower	\$39,000

The conventional chiller is not included on the investment costs, as it is already part of the existing heating and cooling system.

4. Analysis of Results

The system has been analyzed considering a base case and four different collector areas for both the summer and winter configurations. These results have been used to determine the savings in electricity and fuel that are achievable annually. The following results show a breakdown of the energy use in summer and winter, and the consequent system performance over the year.

4.1. Summer Performance

The incorporation of the absorption chiller during the summer, reduces the load on the conventional chiller, thus replacing a portion of the electricity consumption with solar and biomass energy. The solar energy heats the hot stream of the chiller, with the biomass boiler meeting the remaining demand. Fig. 3 shows the changes in energy use for the base case compared with the four different collector areas.

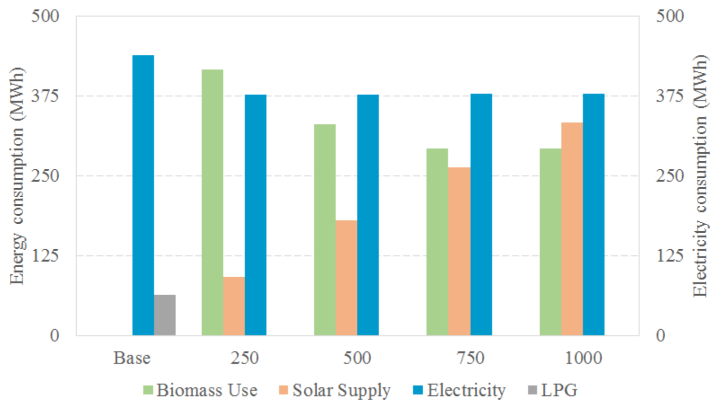

Fig. 3. Solar, biomass and electricity use in summer for the base case and different collector field areas

The solar energy provided to the system shows a relatively linear increase with collector field area. This is reflected in the solar fraction, which represents the use of solar energy in supplying the hot water demand of the absorption chiller.

Fig. 3 additionally shows the increasing collector area increases the solar energy and reduces the dependence of the system on biomass. The reduction in biomass is not linear however, and begins to plateau for larger collector areas. This reflects the increased temperatures of the system and subsequent increase in losses.

The heat demand in the base case is independent of the cooling system. This demand reflects the losses from the hot water tank that is used for other heating purposes within the winery. These additional demands have not been incorporated in the simulation explicitly, however the LPG necessary to make up the losses from this tank have also been incorporated into the base case to provide a more realistic comparison case.

The reduction in electricity is not as significant as predicted, as the increase in system components particularly the pumps increase the auxiliary electricity demand. Fig. 4 shows that the auxiliary electricity use almost doubles when the absorption chiller and solar field are incorporated. The electricity consumption for differing solar fields remains relatively constant, with variation due only to the increased pumping requirement for the larger collector field.

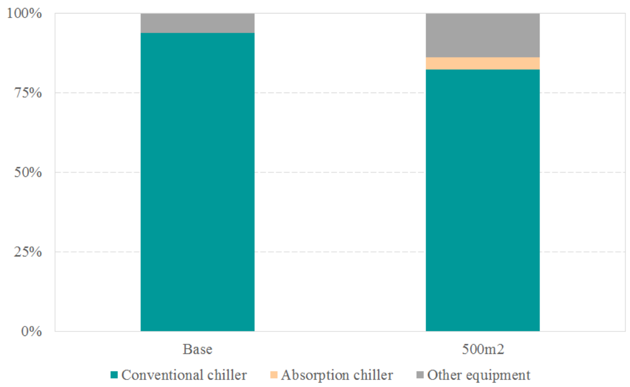

Fig. 4. Electricity Use in summer configuration.

Due to the high demand of biomass required in summer to supply the absorption chiller at the required temperature, two different options were considered for the use of the absorption chiller. The first was the use of the absorption chiller 24 hours a day, to provide 25% of the cooling demand via this means. The second was to use the absorption chiller only when the biomass boiler was in operation and supplemented by solar energy, during the working hours of the plant between 5am and 7pm, which reduces the utilization to 15% overall. This decision changes the demand for biomass and the solar fraction of the system significantly, as shown in Fig. 5.

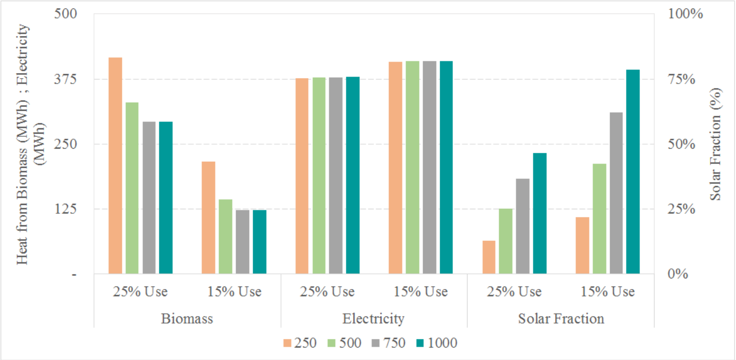

Fig. 5. Comparison of 15% and 25% usage of the absorption chiller.

The decision for the operation of the chiller depends on the ratio of cost of biomass to the electricity price. As the biomass is available very cheaply, running the absorption chiller for longer hours is viable, and has been incorporated as the preferred operating condition.

4.2. Winter Performance

The absorption chiller is used in winter to provide heat to the maceration process replacing a portion of the heat generation from the LPG boiler. The cool stream from the absorption chiller is used as it matches well with the temperature required to heat the vats. The solar collectors are used to heat the chilled water of the absorption chiller. This becomes the primary controller for the absorption chiller, which will only run when the temperature difference in the chilled water stream is sufficient. The biomass boiler provides the heat for the hot water stream.

Overnight, when the biomass boiler is not in operation, the absorption chiller is switched off, and the heat is provided to the vats from a combination of the residual heat in the cool water tank (45°C) heated by the chiller during the day and from the hot water tank (85°C).

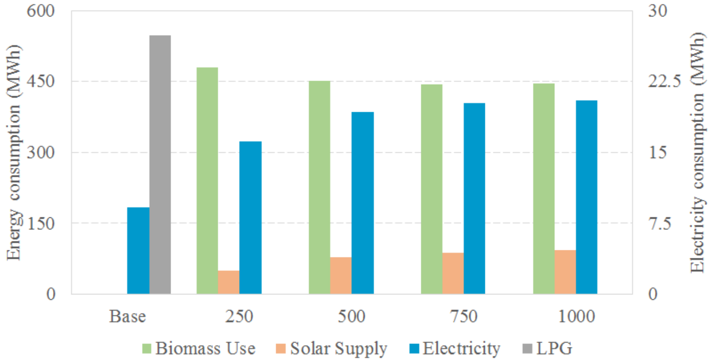

Fig. 6. Winter mode: solar, biomass and electricity use.

As the collector is providing heat to the cold water stream, a collector field above 500 m^2 is sufficient to meet this heat demand for the whole season. This is seen in the results as shown in Fig. 6 as the biomass use and solar are very similar for the collector areas between 500 and 1000 m^2 indicating similar chiller usage. The electricity use of the system compared to the base case reflects the increased demand from the pumps and chiller, and increases with the collector area pump demand.

The use of the solar heat to heat the chilled water flow was selected for two reasons:

- Optimum use of solar energy, as the very low temperature of this stream means that despite the decrease irradiation during winter, heat can still be provided easily
- The absorption chiller oversupplies heat to the process, so incorporating additional solar energy in this stream is unnecessary.

However, as the results have shown, with the large collector fields are over-sized for this demand. Additional configurations could be considered for the winter months to determine the optimum use of the system components.

4.3. Annual Performance

Overall the annual results show a reduction in biomass and electricity demand compared to the base case, with the exception of the biomass for a 250 m^2 collector as shown in Fig. 7.

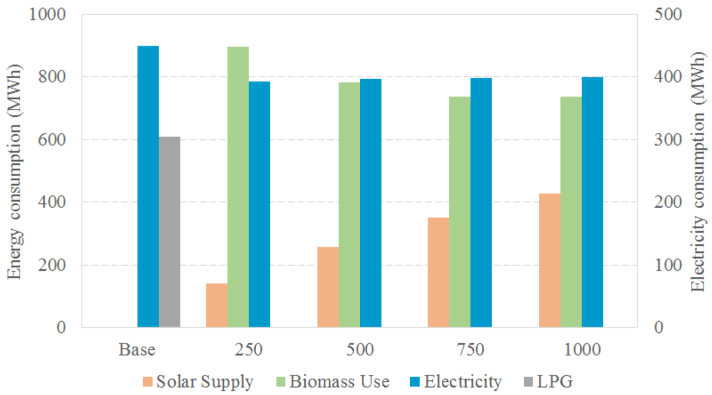

Fig. 7. Annual system performance.

The performance can be evaluated by considering the minimum use of both biomass and electricity. There is only a slight difference in these values for collector fields above 500m^2, therefore for these configurations it is expected that a collector area between 500 and 750 m^2 will yield the best results.

For a collector area of 500 m^2 the solar utilization and the solar fraction over the year was analyzed.

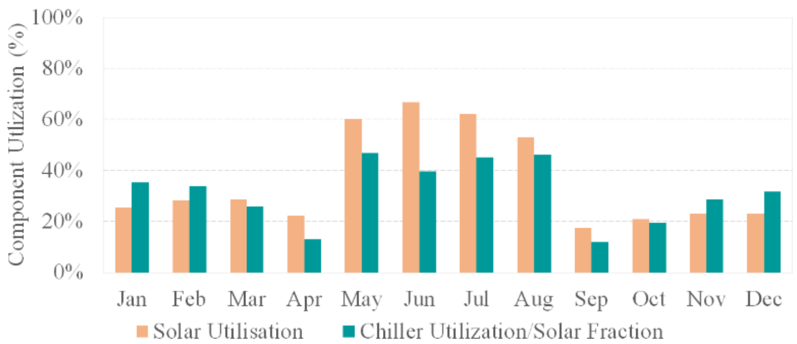

Fig. 8. Monthly performance of solar and chiller utilisation and solar fraction for 500m^2

Fig. 8 shows the performance of the collectors and of the system for the 500 m^2 collector area over the year. During summer, the peak in solar fraction is seen in the months of January and February with the peak in the solar irradiation. For the four months of the winter mode, the chiller utilization reflects the solar fraction, as the chiller is only on when the solar field provides sufficient heat. The solar utilization in this period is also significantly higher than the summer months. This reflects the setup configuration of the system, as the inlet temperature is very low, which allows for larger gains to be achieved, compared with the summer configuration, where the inlet temperature is approximately 80°C, so high irradiation is required to achieve a temperature increase.

5. Economic evaluation

An economic analysis was performed based on the results of the simulations. The economic analysis incorporates a comparison of the investment costs, operation costs and energy savings, to determine a net present value, internal rate of return and payback period for each collector area. The results are summarized in Table 4. These are based on the following project economic parameters:

1. Project time frame: 20 years
2. Discount rate: 5%

The main investment costs comprise the absorption chiller, solar field, biomass boiler and cooling tower. The electricity consumption is reduced with the incorporation of solar energy, due to the substitution of the use of the conventional chiller, although an additional demand is incurred from the pumps. The incorporation of the absorption chiller increases the demand for heat however this is reduced with increasing solar collector field area. The total energy savings reach an optimum with a collection area of 500 m^2 due to the low incremental gains of the solar collectors with higher collector areas during the winter time.

Table 4. Annual economic results from the absorption chiller integration.

	Parameters	Base	250 m^2	500 m^2	750 m^2	1000 m^2
Investment costs	Absorption chiller		$ 221,979	$ 221,979	$ 221,979	$ 221,979
	Solar field		$ 53,000	$ 106,000	$ 159,000	$ 212,000
	Biomass boiler		42,000	42,000	42,000	42,000
	Cooling tower		$ 39,087	$ 39,087	$ 39,087	$ 39,087
	Total		$ 356,066	$ 409,066	$ 462,066	$ 515,066
Annual operation costs	Electricity	$ 28,030	$ 24,544	$ 24,777	$ 24,874	$ 24,931
	Fuel	$ 38,941	$ 4,006	$ 3,493	$ 3,297	$ 2,299
	Maintenance		$ 3,561	$ 4,091	$ 4,621	$ 5,151
	Total per year	$ 66,970	$ 32,110	$ 32,361	$ 32,792	$ 33,380
Annual operation cost savings compared to base case	Electricity		$ 3,486	$ 3,253	$ 3,156	$ 3,099
	Fuel		$ 34,935	$ 36,447	$ 35,643	$ 35,642
	Total saving per year		$ 34,860	$ 34,609	$ 34,178	$ 33,590
Evaluation	Net Present Value		$ 78,370	$ 22,243	-$ 36,127	-$ 96,458
	Internal rate of return		7%	6%	4%	3%
	Payback period (years)		10	12	14	15

The economic peak in this analysis is achieved for the smallest collector area considered, 250m^3, due to the lowest capital cost. The savings from the system are generally not sufficient to provide a quick return on investment and a payback period of at least 10 years is expected. The use of the larger collector areas is not very effective in winter, so perhaps an alternative configuration would see an improved result with lower dependence on electricity to drive down the prices.

6. Conclusions

The incorporation of a solar driven absorption chiller into a winery to meet both cooling and heating demands shows great potential. There is an opportunity to cut the use of electricity in summer by the replacement of the conventional chiller with an absorption chiller. This increases the heat demand in this period, however this can be met by incorporating a solar field and biomass boiler to reduce the carbon dioxide emissions of the plant. Similarly in winter, the absorption chiller can be used to meet the heating demand driven again by the solar field and biomass boiler. However as the heating demands for winter are lower than the cooling demands of summer, the sizing of the chiller and collector area need to be carefully considered to determine the optimal configuration for the annual performance.

There is further potential to optimise the configuration of this system. Currently the sizing of the absorption chiller is based on meeting 25% of the summer load. The opportunity to meet a greater portion of this with a larger chiller should be investigated. Consequently the sizing of the collector field to meet a greater energy demand could be optimised as well. Furthermore, incorporation of waste products rather than pellets as a source of fuel for the winery could also realise an improved economic result.

Acknowledgements

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