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Evaluation of energy savings in white winemaking: impact of temperature management combined with specific yeasts choice on required heat dissipation during industrial-scale fermentation

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Abstract

Heat removal significantly impacts energy request in the winery and is related to the temperature control of wine tanks during the fermentation process and the wine maturation phase. The aim of this work was to determine the heat required to be dissipated from wine tanks under different temperature programs, in order to evaluate the potential effects on energy saving during industrial-scale fermentations of Glera and Pinot Grigio wines. Comparative tests were carried out by using properly chosen yeast strains during fermentation at usual winery temperature (15 °C or 17-15 °C) and 19 °C and verifying the quality of the resulting wines in term of sensory, chemical and aromatic features. Fermentation required on average 7.0 Wh dm^{-3} must at 19 °C and 10.3 Wh dm^{-3} must at 15/17-15 °C, reducing energy use by ~32 % at the higher temperature.

The tested fermentation protocols, coupled with the use of some specific selected yeast strains, have positive effects on energy saving without compromising sensory, chemical and aromatic profiles of the resulting wine. This work suggests how wineries can adopt a more sustainable winemaking process with low energy consumption, and consequently to propose eco-labeling strategies and price-premium policies.

Key words: alcoholic fermentation, energy saving, yeast, sensory profile, sustainability

Introduction

The gained awareness among non-governmental associations, industries, retailers and consumers about environmental impact of wine production has prompted many wine producers to move toward sustainable grape growing and winemaking practices (Santini et al., 2013). Moreover, recent analyses of consumer perceptions, preferences, and willingness to pay for wine showed that producing and marketing wine with sustainability features is a promising strategy for quality differentiation, providing an additional stimulus for the wine industry to proceed toward a larger adoption of sustainable practices (Galletto and Barisan, 2019; Pomarici and Vecchio, 2019). Several programs for wine life cycle assessment (including initiatives following the EMAS Regulation (European Commission, 2009)) have recently started to account, among other factors and inputs used along the winemaking phases, equivalent emissions for electricity consumption in the vinification phase, which is in turn influenced by microbial transformations and their management (Merli et al., 2018; Nardi, 2020; Trioli et al., 2015).

This increasing interest on limiting the inputs used all along winemaking phases will arguably drive wine suppliers to provide quantitative information on their energy saving solutions for their processes and products, and its impact on the environment. The lack of knowledge of energy efficiency opportunities, on the other hand, provides an important barrier to improving efficiency, even though many operators in wine sector are inclined to innovative approaches for energy saving (Giovenzana et al., 2016).

Certainly, temperature control during fermentation significantly impacts the energy demand of wineries. The majority of the electricity used by wineries (about 90%) is consumed by refrigeration systems for process cooling, that is, fermentation control, cold stabilization, and cold storage (Galitsky et al., 2005; Malvoni et al., 2017). The fermentation process takes place at a controlled temperature for quality purposes, to which the wine needs to be cooled at the beginning of fermentation and throughout the process; and the fermentation reaction also generates heat that needs to be removed (Galitsky et al., 2005). Overall, fermentation temperature control accounts for as much as 45% of the total energy demand of wineries (Celorrio et al., 2016; Schwinn et al., 2019). Regarding alcoholic fermentation, it is known that different fermentation managements lead to wines with different characteristics depending upon yeast strain, fermentation temperature, oxygen and nitrogen management (Bartowsky and Henschke, 1995; Fleet, 2003; Ugliano and Henschke, 2009). In particular, literature has extensively described the effect of temperature on yeast metabolism during wine fermentation (Deed et al., 2017, 2015; Masneuf-Pomarède et al., 2006; Molina et al., 2007; Torija et al., 2003). As shown in the last decade, the effect of low temperature on fermentation efficiency and aroma production varies markedly among different *S. cerevisiae* strains, although little of the above-mentioned research works assess the influence of temperature on aromatic profile in the specific context of industrial white wine production.

The exploitation of microbial resources involved in fermentation for improving sustainability of the winemaking process, nonetheless, is a very recent approach and only a few research studies have addressed it (Carrau et al., 2020; Nardi, 2020). Specifically, only two works addressed the quantification of required heat dissipation during alcoholic fermentation, coupling innovative thermal protocols with rationally chosen yeast strains (Giovenzana et al., 2016; Schwinn et al., 2019). Firstly, a newly selected *Saccharomyces* wine strain was tested in the production of sparkling base wine, fermented at a temperature higher than the winery standard. The quantification of electric energy consumption and estimation of energy conservation showed that increasing the temperature from 15 °C to 19 °C during the fermentation process yielded an energy saving of ~65% (Giovenzana et al., 2016). In a successive work, required heat dissipation was measured in Riesling fermentations and the results confirmed and further illustrated the relevance of the temperature program employed with regard to energy demand for cooling (Schwinn et al., 2019). Approximately 70% less heat had to be dissipated for fermentation at 19 °C, compared with that for fermentation at 14 °C. Approximately 30% less heat had to be dissipated under a 16–11–17 °C temperature program, compared with that for fermentation at 14 °C. Overall, the abovementioned papers, carried out with different selected yeast strains, showed promising results about energy savings that can be achieved by reducing the required dissipated heat through temperature management of fermentations without compromising wine composition, although depending on the technical configuration of the cooling system. At the same time, various mathematical models have been developed to solve energy-optimal control problems and to describe heat transfer in tanks during winemaking fermentations (Celorrio et al., 2016; Colombié et al., 2007; Schenk et al., 2017). Therefore, a potential future application of data obtained in energy-saving studies is to feed and implement models, as it has been recently reported

(Schwinn et al., 2019) how experimental data are essential for the improvement of existing models and for the development of new mathematical models,

In this context, this study aims at evaluating and quantifying, in a wider range of situations, the potential energy savings coming from a "sustainable" management of yeast fermentation (avoiding cooling during alcoholic fermentation when unnecessary). In particular, the effect of scaling-up the fermentation size (compared with previous studies) was evaluated, together with the influence of different yeast strains. Beyond investigating if energy savings were confirmed (and to what extent) at such a scale, this approach had the secondary goal of testing energy consumption in technical situations encompassing several winemaking conditions, to gradually universalize the results, and therefore make them applicable by winemakers at a production scale.

Industrial-scale fermenters (450 hectoliters each) were monitored for the first time. Experimental trials included two different grape varieties, in two subsequent vintages. Two fermentation temperatures were tested for the quantification of the potential energy savings: the usual winery protocol (specific per grape variety) and an innovative protocol (isothermal 19 °C). Two different yeasts have been included in the study, each selected among the winery best players for the specific grape variety: yeast characteristics and expected aromatic profile have been carefully considered as strain-choice criteria, when deciding on temperature management. Moreover, aromatic profile and sensory properties of the wines were evaluated for validating the process results at industrial scale.

2. Materials and methods

2.1 Experimental design and winemaking procedures

Fermentations were performed at industrial scale at Santa Margherita winery, Fossalta di Portogruaro, Italy, during two subsequent vintages (2019 and 2020), as summarized in Table 1. 450 hL-size, standard white-winemaking -fermenters by Lasi (https://www.lasi-italia.com/) were employed, holding a thermo-insulating polyurethane layer (12 cm) and equipped with both cold and warm thermal control.

In 2019, two fermenters were employed. Glera grapes from Santa Margherita, Fossalta di Portogruaro, VE, Italy, were harvested at ripening. Two vinifications were prepared by crushing the grapes and dividing the resulting liquid (juice) into 2 aliquots after must clarification, performed following the usual winery white winemaking procedure for sparkling base wines. The specific composition of the grape must is reported in Table 2. Two fermentation temperatures were tested for the quantification of the potential energy savings: the usual winery protocol (isothermal 15 °C) and an innovative protocol (isothermal 19 °C), as detailed also in Figure 2.

In 2020, four fermenters were employed. Pinot Grigio grapes from Santa Margherita, Italy, were harvested at ripening. Four vinifications were prepared by crushing the grapes and dividing the resulting liquid (juice) into 4 aliquots after must clarification, performed following the usual winery procedure for Pinot Grigio (white winemaking for non-sparkling wines with slight pre-fermentative cold maceration). The specific composition of the grape musts is reported in Table 2. Two fermentation temperatures were tested for the quantification of the potential energy savings: the usual winery protocol (stepwise decreasing from 17 °C to 15 °C, as detailed in figure 2) and an innovative protocol (isothermal 19 °C).

2.2 Yeast strains

The *Saccharomyces cerevisiae* yeast strains used in 2019 fermentations (Glera must) were LaClaire CGC62/SP665 (50:50 mix) (Perdomini-IOC, Verona, Italy). The *Saccharomyces cerevisiae* yeast strain used in 2020 fermentations (Pinot Grigio must) was Mycoferm IT-07 (Ever-Intec, Pramaggiore, Italy). All yeasts were rehydrated from active dry form according to manufacturer instructions, then added to the must at a final concentration of 0.20 g/L.

2.3 Chemical analyses of musts and wines

Standard must/wine parameters were analysed at the set-up of the trial and at the end of alcoholic fermentation. The analytical methods used were those recommended by the International Organization of Vine and Wine (OIV, 2018): sugars were analysed by alkylamine resin HPLC (OIV-MA-AS311-03), alcohol by volume by densimetry using hydrostatic balance (OIV-MA-AS312-01A), pH by potentiometry (OIV-MA-AS313-15) and sulfur dioxide (free and total) by titration after distillation (OIV-MA-AS323-04A). During alcoholic fermentation, alcohol content, acidity and sugars were followed by FT-IR spectroscopy. Volatiles were analysed at the end of the trial (after alcoholic fermentation, racking off and stabilization, before wine blending) by gas chromatography—mass spectrometry (GC–MS) after solid-phase extraction (SPME), as previously described (Giovenzana et al., 2016; Nardi et al., 2014) Except for FT-IR determinations, which were run at the winery in-house laboratory through a Winescan™ instrument (FOSS, Hilleroed, Denmark), analyses were performed at ISVEA s.r.l. laboratory (Poggibonsi, Siena, Italy), harboring HPLC (Agilent 1200 Series HPLC System; Agilent Technologies Italia S.p.A., Cernusco sul Naviglio, Italy) and gas chromatography (Agilent 7890 Gas Chromatograph System) equipment. For volatile molecules quantitation, a SPME method based on (Bueno et al., 2014) was employed. The fiber was desorbed directly in the injection port of the GC-MS in split less mode for 2.5 min at 250 °C and a pressure pulse of 80 kPa was applied during the injection (column flow 3.45 mL min^{-1}). The carrier gas was He at constant linear velocity of 40 cm s^{-1}(≈1.23 mL min^{-1}). The column was a SPB-1 Sulfur capillary column 30 m × 0.32 mm I.D., with 4 m film thickness. Temperature was held at 40 °C for 3 min, then raised to 280 °C at 10 °C min^{-1} and finally the temperature was held at this temperature for 10 min. The temperature of the ion source was 220 °C and the interface was kept at 280 °C. The mass analyzer was operated in single ion monitoring (SIM) mode, according to (Bueno et al., 2014). The list of the analyzed molecules can be found in Supplementary Material S1

2.4 Electric energy consumption evaluation

Comparative tests were carried out during fermentation at different temperatures for the quantification of the energy consumption and the estimation of the energy saving. The studied fermentation plant is located at the “Santa Margherita” winery at Fossalta di Portoguraro (VE), Italy. The monitoring of an industrial-sized plant is more complicated than a laboratory pilot-sized one, therefore a methodology to measure energy consumption at different fermentation tanks in the plant was developed. All the utilities located in the winery requiring temperature control are served by a centralized refrigeration system. The refrigeration system supplies a closed loop cooling circuit in which circulates cold water and glycol. Depending on the amount of heat to be subtracted at each fermentation tank, a system of valves controlled by thermostats controls the cooling fluid flow in order to keep constant the temperature inside the tank. Tanks at different temperatures were monitored for the quantification of the energy consumption. Table 3 shows the density and heat capacity of grape must and plant parameters. The opening times of the valves regulating the liquid refrigerant input were recorded and the temperature differences associated to each opening was measured.

The amount of heat subtracted (Q_{ferm}, kcal, Table 4) from each tank during the fermentation process was calculated (eq. 1).

$$Q_{ferm} = m * C_p * \Delta T \qquad \text{(eq. 1)}$$

Where:

Q_{ferm}= Heat subtracted from fermentation process

m= Wine mass processed for each tank

C_p= Specific heat capacity

Δt= Temperature changes during fermentation process

The opening times of the valves (t, h, Table 4) regulating the liquid refrigerant input were recorded and the temperature differences associated to each opening was measured, in order to quantify the effective total cooling load (P_e, kW, Table 4), according to:

$$P_e = Q_{ferm}/t \qquad \text{(eq. 2)}$$

Where:

P_e = Effective total cooling load

Q_{ferm} = Heat subtracted from fermentation process

t = Time of valves opening

The experimentation was set out as comparative study among tanks in the same conditions, therefore the potential simplifications due to the non-quantifiable heats exchanges have a negligible effect on the results.

Electricity η_e and mechanical η_m efficiencies were considered in order to calculate the effective powers of compressor and pump, and an efficiency of 85 % regarding the circuit of glycol water was taken into account.

Moreover, energy consumption due to pump use was considered and total energy for the fermentation process was determined. Finally, a comparison between the fermentations carried out at the two different temperatures in the two different years was performed, and the energy savings were calculated.

2.5 Sensory analysis

In 2019, the panel that carried out the sensory experiments described in this work was composed of 12 expert individuals working in wine research or in the wine business, trained for assessing attributes of young unrefined wines (samples were taken from the tanks at the winery before the usual operations of wine blending in early December). A Triangle Test (ISO 4120:2021 – Methodology) was carried out for determining whether a perceptible sensory difference or similarity existed between the wines fermented at different temperatures. The method is a forced-choice procedure. The 2 wines (fermented at 15 °C and fermented at 19 °C) were presented at random regarding the nature of the repeated wine and to the order of the wines within each triad. Judges were asked to assess which wine was different from the others (ISO, 2021).

In 2020, due to the COVID-19 emergency and restrictions thereof, tastings could not be performed according to the ISO methodology. Instead, a wine tasting was performed by the winery staff (panel composed of 6 expert individuals, 4 working in winery and 2 representative of buyers) following a protocol aiming at ranking the 4 wines (2 fermented at 17-15 °C, 2 fermented at 19 °C) according to overall quality attribute and preference (Lesschaeve, 2007) following a sensorial tasting sheet for non-sparkling white wines (ONAV, 2018) complying with the the “Union Internationale des Oenologues” method, recommended by the OIV in: “OIV STANDARD FOR INTERNATIONAL WINE AND SPIRITUOUS BEVERAGES OF VITIVINICULTURAL ORIGIN COMPETITIONS”, Annex 3.1, Wine score sheet, available in English at (OIV, 2021). The overall scoring (“total”) was considered for classing the wines in groups.

2.6 Statistical treatment of data

Student t-test (xl-STAT for Windows) was used for treating data about wine compounds and sensory scores to evaluate the differences in the samples.

3. Results and discussion

3.1 Fermentation kinetics

The progress of the fermentations at different fermentation temperatures is shown in

Figure 1 (A and B), which also displays that in 2020, when fermentations were run in duplicate, the kinetics resulted similar in each couple of tanks fermenting at the same temperature (Fig. 1b). As expected, the fermentations run at the usual winery-cooling (15 °C in 2019 and 15-17 °C in 2020) were slightly slower compared to the 19°C ones, also ending later in 2019. In all the tanks, a quick beginning of the fermentation was detected, probably as a consequence of a good implantation of the yeasts (Fig. 1A and 1B). Sugar consumption started after the inoculation of the commercial *Saccharomyces cerevisiae* strain, as confirmed by data from a small control tank containing the same must in which the yeast was not inoculated and the fermentation did not start in one week at 19°C (data not shown). During the whole process, sugar decrease and alcohol increase was constant and reliable in all the fermentations, although with different rates depending on the temperature. In 2019, the 19 °C tanks fermented in 5 days, while the 15 °C tanks took 7 days. In 2020, most of the differences in kinetics between the usual winery protocol (17-15 °C) and the innovative one proposed (19 °C) are visible in the time window between 1 and 5 days.

3.2 Electric energy consumption evaluation

Experimental results for the energy analysis on the tank monitored at 19 °C, 15 °C, and 17-15 °C are reported in Table 4. The refrigerator operated in 2019 for 26.1 h for Tank V101_19 °C and for 32.0 h for Tank V102_15 °C, corresponding to a temperature decrease of 11.2 °C and 18.2 °C respectively (Figure 2). Regarding 2020, for the fermentation temperature of 19 °C, the system works for 38.4 h for Tank V121_19 °C and 34.4 h for Tank V123_19 °C, corresponding in these cases to a temperature decrease of 18.1 °C and 17.3 °C respectively (Fig. 2A and 2B); for the fermentation temperature of 17-15 °C, the system works for 70.8 h for Tank V122_17-15 °C and 64.7 h for Tank V124_17-15 °C, corresponding in these cases to a temperature decrease of 23.6 °C and 22.7 °C respectively. The working time of the refrigerator system during fermentation was reduced by 73,6 % to 80,2 %. Figure 2 shows temperatures trend, for each tank monitored, during the fermentation process at 19 °C, 15 °C (2A), and 17-15 °C (2B). For all the fermentation temperatures considered, Figure 2 indicates that the refrigerator switching frequency tends to decrease with time. In fact, the available sugars for fermentation tend to disappear and consequently the exothermic reaction tends to cancel out, and therefore the temperature tends to stabilize. This behavior is more noticeable at 19 °C after 120 h of fermentation.

Results showed that in 2019 to maintain the fermentation tank at 15 °C, 383 kWh were necessary while to keep the temperature at 19 °C 249 kWh were only required, allowing an energy saving equal to 35 %. Similarly, for 2020 considering fermentation tanks at 19 °C and 17-15 °C, the energy saving was equal to 29 %.

3.3 Temperature impact on yeast performance and final properties of the wines

To verify whether the temperature change had affected the quality of the wines, the main chemical properties were measured after the end of alcoholic fermentation. Final concentrations of relevant parameters under different conditions are summarized in Table 2. Most of the parameters (alcohol, residual sugars, total acidity, malic and lactic acid) did not shift due to temperature change. The only, slight significant differences were found in volatile acidity and SO_2, which varied only in 2020 (Pinot Grigio must fermented with Mycoferm IT-07 yeast), being higher at 15/17 °C and marginally lower at 19 °C. The overall result is consistent with the characteristics of the two yeast strains, expected to keep their characteristics essentially stable among the tested temperatures, according to technical information provided by the manufacturers and to winemaking experience ("La Claire range | Perdomini-IOC," 2021; "Oenological wine yeasts - Mycoferm," 2021). At the same time, it also brings some confirmations to the impact of temperature on their metabolism, showing limited temperature-driven shifts.

To ensure that the temperature shift from the usual winery protocol (15 °C or 15/17 °C) to 19 °C did not affect the aromatic quality of the wines, analysis of volatile aromas has been performed at the end of alcoholic fermentation on final wines for both vintages. Indeed, winemakers traditionally associate improved aroma production with cold fermentation, although experimental data on the key aroma changes that occur in cold-fermented white wines have been ambivalent, as previously summarized by (Deed et al., 2015). A number of 42 analyzed volatile molecules are reported in this study, belonging to families of terpens and norisoprenoids (7), esters and acetates (9), fatty acids (8), alcohols and benzenoids (7), lactones (5), sulphur compounds (4) and ageing markers (2). Since grape variety and fermenting yeasts were different between the two subsequent vintages, results have been analyzed and presented separately for 2019 and 2020. Aromatic compounds are grouped in families and their relative presence is calculated and showed in a heatmap, in order to ease the comparison between the two thermal protocols (the full data set is also included in Supporting Information S1, where sensory thresholds are also reported, together with the statistical significance calculated on 2020 data). Indeed, absolute concentrations of most of the molecules differ between Glera (2019) and Pinot Grigio (2020) wines, due both to grape variety and fermenting yeasts, as previously observed in other research works commparing the impact of fermentations on VOCs in different grape varieties (Binati et al., 2020)

Most of the aromatic compounds (28 on 42, spread among Terpens and Norisoprenoids, Acids, Lactones, Esters and Acetates, Ageing markers) displayed an opposite trend linked with temperature increase in the two vintages (e.g., rising in 2019 and lowering in 2020), which testifies that aroma production did not consistently decrease (or increase) at higher temperature for these compounds. This was largely expectable since the yeast strains involved were different in the two experiments (2019 and 2020), moreover different grape varieties and vinification styles were implied (sparkling base wine for Glera in 2019 and finished still wine in 2020) and, last but not least, the "normal" winery thermal protocol compared with the new proposed protocol (19 °C) was different (15 °C in 2019 and 15-17 °C in 2020).

Overall, among the 14 molecules for which the concentration change can be related to temperature increase, transversally among the yeast strains, grape varieties and vinification styles tested in this work, only 3 were present at concentrations above sensory threshold. Although this observation would require a verification in further experiments for being validated, these results are in line with the sensory findings of this study (see par 3.4) and can be considered compatible with previous studies, since sensory analysis never showed, so far, any impact of the fermentation temperatures tested for energy savings on wines organoleptic perceivable properties (Giovenzana et al., 2016; Schwinn et al., 2019).

Looking in particular to Esters and Acetates, compounds that make a positive contribution to the general quality of wine being responsible for their “fruity” and “wine-like” sensory properties (Ferreira et al., 2002; Perestrelo et al., 2006) and are strongly linked to fermentation (Deed et al., 2015), this family showed a very limited change due to temperature shift (with only 3 on 9 compounds varying consistently with temperature, all slightly increasing at 19 °C). In terms of yeast metabolism during fermentation, these results show that the production of one of the main fermentative aroma families did not widely change at higher temperature for these selected yeasts, although in terms of individual molecules, the longer chain ethyl esters, that is ethyl hexanoate, ethyl heptanoate and ethyl decanoate, were those found at the highest final concentration in wines fermented at 19 °C, as previously observed (Giovenzana et al., 2016; Schwinn et al., 2019).

3.4 Sensory analysis

Finally, a sensory test was performed to guarantee a product with the desired sensory characteristics for the consumers. In 2019, a ‘forced choice’ technique was employed in a triangular test with 12 judges, as detailed in the Materials and Methods section (ISO, 2021, 2004). The results showed that there are no significant differences between the two Glera base wines (fermented at 15 °C and 19 °C) analyzed from a sensorial point of view. Indeed, only 6 judges on 12 were able to recognize the different sample, whereas 8 correct answers are needed to establish significance at 95 % confidence and 9 correct answers for 99 % confidence (Roessler et al., 1978). In 2020, due to the COVID-19 emergency and restrictions thereof, tastings could not be performed according to the ISO methodology. Instead, a wine tasting was performed by the winery staff (panel composed of 6 expert individuals) following a protocol aiming at ranking the 4 wines (2 fermented at 17-15 °C, 2 fermented at 19 °C) according to overall quality attribute and preference, following a sensorial tasting sheet for white wines (ONAV, 2018). The results clustered the wines into 2 of the structured preference groups of the sheet (groups 5 and 4, scoring 90-94 and 89-89 respectively, data not shown): the first group comprised one wine fermented at 19 °C (v123) and one wine fermented at 17-15 °C (v122), the second group comprised one wine fermented at 19 °C (v121) and one wine fermented at 17-15 °C (v124) as well, this confirming that fermentation temperature did not significantly impact wine sensorial quality. This result is consistent with aroma analyses, since most of the tested molecules showed very low variation among wines (Fig. 3), with only 14 on the 42 tested aromatic molecules showing a consistent change in concentration due to the different fermentation temperature (either decreasing at 19 °C in both years, either increasing), of which only 3 being above the sensory threshold. Thus, although the aromatic profile was partially changing at 19 °C, the panel could not recognize (in 2019) or rate differently (in 2020) the wines.

4. Conclusions

In the present study, 2 properly selected wine yeasts available on the market were tested in white winemaking (including sparkling base-wine production) demonstrating that they were able to ferment with good sensorial results at higher temperatures than standard ones. These features have positive effects on energy saving and therefore in reducing the environmental impact of the wine production. Indeed, results of energy consumption quantification and energy saving estimation showed that a difference, during fermentation process, equal to 4 °C and 4-2 °C between the two conditions allows an energy saving about 35 % and 29 %, respectively.

Regarding the main chemical wine parameters, no significant differences were found in terms of alcohol content, total acidity, pH, malic acid degradation, volatile acidity of the final wines. Finally, aroma analyses and sensory tests showed that the temperature increase did not cause any significant differences in organoleptic wine properties, consistent among different vintages and yeast strains, between the two theses. Hence, the usage of the tested yeasts and fermentation protocols allowed energy savings for temperature control and thus a direct economic benefit to the producers, without compromising wine quality.

This study was the first to scale-up the evaluation of energy conservation from sustainable temperature management during base wine fermentation at industrial scale (>20 hL), confirming the benefits of such an approach for wineries, which may on turn include the possibility to propose ecolabeling strategies and price premium policies that presently have marketing benefits (Nardi, 2020). The significance of the study, beyond confirming the energy savings, was also to assess energy consumption in several winemaking conditions (including different grape varieties and sugar concentrations in the musts but also various equipment and industrial settings) to gradually universalize the research results.

As a last remark, a potential future application of the data obtained in this study is to feed and implement models developed to solve energy-optimal control problems and to describe heat transfer in tanks during winemaking fermentations, so as to these models in the future may also aim at enhancing cooling concepts and estimating potential energy savings.

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Table 1.

Experimental design: number and characteristics of fermentations.

Tank ID	Vintage	Grape variety - wine	Volume	Temperature	Yeast
V101	2019	Glera - Prosecco	450 hL	19 °C[§]	SP665/CGC62
V102	2019	Glera - Prosecco	450 hL	15 °C [†]	SP665/CGC62
V121	2020	Pinot Grigio	450 hL	19 °C[§]	IT07
V122	2020	Pinot Grigio	450 hL	17 °C-15 °C [†]	IT07
V123	2020	Pinot Grigio	450 hL	19 °C[§]	IT07
V124	2020	Pinot Grigio	450 hL	17 °C-15 °C [†]	IT07

[†] Usual winery protocol for the must; [§] innovative protocol proposed in this study

Table 2

Composition of grape musts and wines produced in the different vinifications. t-test significance (two-tailed t-student Excel test) is given for 2020 data, when fermentations were performed in double (two tanks per temperature).

Year	**Sample** (tankID)	**Alcohol** (g L^{-1})	**Glu + Fru** (g L^{-1})	**YAN** (mg L^{-1})	**Total acidity** (g L^{-1})	**pH**	**Volatile Acidity** (g L^{-1})	**Malic Acid** (g L^{-1})	**Tartaric Acid** (g L^{-1})	**Glycerol** (g L^{-1})	**Free SO$_2$** (mg L^{-1})	**Total SO$_2$** (mg L^{-1})
2019 Glera	Grape Must	0.23	159.67	110		3.51		2.97	4.5			
	19 °C wine (v101)	10.13	1.05		7.03	3.17	0.11	2.07	3.97	5.5	22	62
	15 °C wine (v102)	9.96	4.91		7.08	3.11	0.11	2.16	3.97	5.13	24	65
2020 Pinot Grigio	Grape Must		209.54	159.93		3.23		2.04	4.58			
	19 °C wine (v121)	12.51	0.87		5.43	3.32	0.25	1.56	3.08	6.17	25	63
	19 °C wine (v123)	12.48	0.72		5.74	3.28	0.24	1.63	3.49	5.9	22	62
	17-15 °C wine (v122)	12.43	0.92		5.39	3.35	0.3	1.81	2.99	6.16	24	75
	17-15 °C wine (v124)	12.45	0.92		5.49	3.35	0.3	1.81	2.99	6.16	24	75
		ns	ns		ns	ns	*	ns	ns	ns	ns	**

ns:non significant; *pval<0.05; **pval<0.01

Table 3

Input data necessary for the energy analysis.

Parameters	Symbol	Units	Values
Wine processed	Tank V101_19 °C	dm^3	45,000
	Tank V121_19 °C		45,000
	Tank V123_19 °C		45,000
	Tank V102_15 °C		45,000
	Tank V122_17-15 °C		45,000
	Tank V124_17-15 °C		45,000
Grape must density	ρ	$kg\ dm^{-3}$	1.05
Grape must specific heat capacity	Cp	$kcal\ kg^{-1}\ °C^{-1}$	0.855
Refrigerator coefficient of performance	COP		4.00
Pump power	P	kW	3.0
Electricity efficiency	η_e		0.90
Mechanical efficiency	η_m		0.70
Circuit glycol efficiency	η_g		0.85

Table 4

Experimental results for each tank monitored, at 19 °C, 15 °C, and 17-15 °C .

				2019	**2020**	**2020**	**2019**	**2020**	**2020**
PARAMETERS	**Symbol**	**Units**		**V101_19 °C**	**V121_19 °C**	**V123_19 °C**	**V102_15 °C**	**V122_17-15 °C**	**V124_17-15 °C**
Refrigerator compressor									
Grape must processed		dm3		45000.00	45000.00	45000.00	45000.00	45000.00	45000.00
Grape must density	ρ	kg dm^{-3}	1.05						
Mass of grape must processed		kg		47250.00	47250.00	47250.00	47250.00	47250.00	47250.00
Grape must specific heat capacity	Cp	kcal kg^{-1} $°C^{-1}$	0.86						
Temperature changes during fermentation process	ΔT	°C		11.23	18.11	17.27	18.17	23.63	22.68
Heat subtracted from fermentation process	Q_{ferm}	kcal		453593.13	731593.08	697803.57	734194.76	954582.06	916150.73
Time of valves opening	t	h		26.09	38.42	34.37	32.02	70.75	64.68
Effective total cooling load	P_e	kW		20.22	22.14	23.61	26.67	15.69	16.47
Circuit glycol efficiency	η_g		0.85						
Total cooling load of refrigerator	P_e_tot	kW		23.79	26.05	27.78	31.37	18.46	19.38
Coefficient of performance	COP		4.00						
Effective compressor load	P_c	kW		5.95	6.51	6.94	7.84	4.61	4.84
Electricity efficiency	η_e		0.90						
Mechanical efficiency	η_m		0.70						
Compressor power	C	kW		7.65	8.37	8.93	10.08	5.93	6.23
Energy consumption of compressor	E_{acc}	kWh		199.45	321.69	306.83	322.83	419.74	402.84
Energy consumption of compressor	E_{acc}	%		80.18	81.58	82.53	84.22	75.84	76.72

Pump									
Pump power	P_p	kW	3.00						
Electricity efficiency	η_e		0.90						
Mecanical efficiency	η_m		0.70						
Effective pump power	P_e	kW	1.89						
Energy consumption pump	E_{pump}	kWh		49.30	72.62	64.95	60.51	133.72	122.25
Energy consumption pump	E_{pump}	%		19.82	18.42	17.47	15.78	24.16	23.28
System									
Total energy consumption	E_{tot}	kWh		248.75	394.31	371.79	383.34	553.46	525.09
Variation between tanks at the same temperature 2020		%			5.71			5.13	
Means 2020		kWh			383.05			539.28	
Energy saving between tanks at different temperatures 2019		**%**	**35.11**						
Energy saving between tanks at different temperatures 2020		**%**	**28.97**						
Specific energy consumption	E_{spec}	Wh dm^{-3}		5.53	8.51		8.52	11.98	
Variable cost of electricity		€ kWh^{-1}	0.16						
Specific energy cost	C_{spec}	€$_{cent}$ dm^{-3}		0.88	1.36		1.36	1.92	

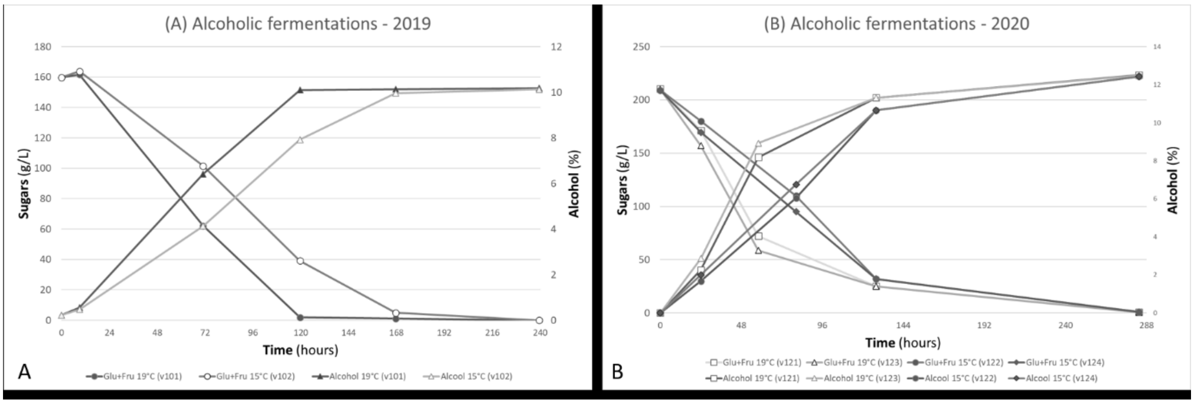

Figure 1. Evolution of sugars (glucose + fructose) and alcohol during the different fermentation conditions in 2019 (A) and 2020 (B); filled symbols: innovative protocol (19°C), empty symbols: winery protocol (15°C or 17°C-15°C).

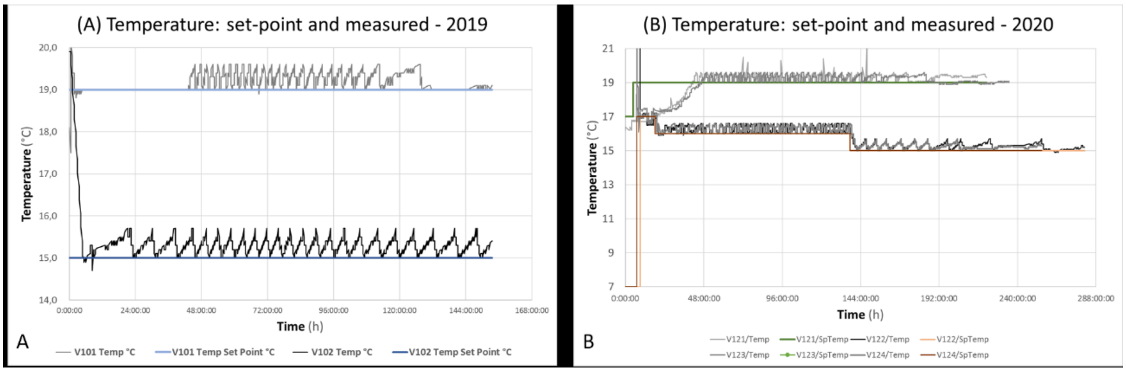

Figure 2 Temperatures trend during the fermentation in 2019 (A) and 2020 (B): for each tank monitored, both measured values and set-point are shown.

Figure 3 Heat-map representing the increased or decreased production of each volatile compound in each wine produced with a specific thermal protocol in comparison with the average of the volatile production (specific yeast and specific variety). Compounds in concentrations above the odor threshold are in red, compounds displaying statistical significance are in *italics (p-val<0.05) and* ***bold, italics*** **(*p-val<0,01)*** (2020 trials, t-test).