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 requests in the winery and is related to the temperature control of wine tanks during the fermentation and wine maturation phases. This work aimed to determine the heat required to be dissipated from wine tanks under different temperature programmes 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 the usual winery temperature (15°C or 17-15°C) and 19°C and verifying the quality of the resulting wines regarding sensory, chemical, and aromatic features. Fermentation required, on average, 7.0 Wh dm^{-3} must be at 19°C, and 10.3 Wh dm^{-3} must be at 15/17-15°C, reducing energy use by ~32% at the higher temperature.

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

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Introduction

The gained awareness among non-governmental associations, industries, retailers, and consumers about the 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 more extensive 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 in limiting the inputs used in all along winemaking phases will arguably drive wine suppliers to provide quantitative information on their energy-saving solutions for their processes and products and their impact on the environment. On the other hand, the lack of knowledge of energy efficiency opportunities provides a critical barrier to improving efficiency, even though many operators in wine sector are inclined to innovative energy-saving approaches (Giovenzana *et al.*, 2016).

Indeed, 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, 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 management 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*., 2015, 2017; 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. However, few of the research mentioned above 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 to improve the winemaking process's sustainability is a very recent approach; 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 cerevisiae* wine strain was tested in producing 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 concerning energy demand for cooling (Schwinn *et al.*, 2019). Approximately 70% less heat had to be dissipated for fermentation at 19°C compared with that at 14°C. Approximately 30% less heat had to be dissipated under a 16-11-17°C temperature programme compared with 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, 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 to evaluate and quantify, in a broader range of situations, the potential energy savings coming from "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) and the influence of different yeast strains were evaluated. 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 universalise results gradually and therefore make them applicable by winemakers at a production scale.

Industrial-scale fermenters (450 hectolitres each) were monitored for the first time. Experimental trials included two different grape varieties in two subsequent vintages. Two fermentation temperatures were tested to quantify 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's 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, the aromatic profile and sensory properties of the wines were evaluated to validate the process results at an industrial scale.

Materials and Methods

Experimental design and winemaking procedures

Fermentations were performed at an industrial scale at Santa Margherita winery, Fossalta di Portogruaro, Italy, during two subsequent vintages (2019 and 2020), as summarised 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 two aliquots after must clarification, following the usual winery white winemaking procedure for sparkling base wines.

Table 1. Experimental design: number and characteristics of fermentations.

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

*Usual winery protocol for the must; **innovative protocol proposed in this study.

The specific composition of the grape must be reported in Table 2. Two fermentation temperatures were tested to quantify the potential energy savings: the usual winery protocol (isothermal 15°C) and an innovative protocol (isothermal 19°C), as detailed in Figure 1. 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 four 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 to quantify the potential energy savings: the usual winery protocol (stepwise decreasing from 17°C to 15°C, as detailed in Figure 1) and an innovative protocol (isothermal 19°C).

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). According to manufacturer instructions, all yeasts were rehydrated from active dry form, then added to the must at a final concentration of 0.20 g/L.

Chemical analyses of musts and wines

Standard must/wine parameters were analysed at the set-up of the trial and 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 sulphur 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 stabilisation, 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), harbouring 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. An SPME method based on (Bueno *et al.*, 2014) was employed for volatile molecules quantitation. The fibre was desorbed directly in

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 (g L^{-1})	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	Grape must	0.23	159.67	110		3.51		2.97	4.5			
Glera	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	Grape must		209.54	159.93		3.23		2.04	4.58			
Pinot	19°C wine (v121)	12.51	0.87		5.43	3.32	0.25	1.56	3.08	6.17	25	63
Grigio	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; *p<0.05; **p<0.01.

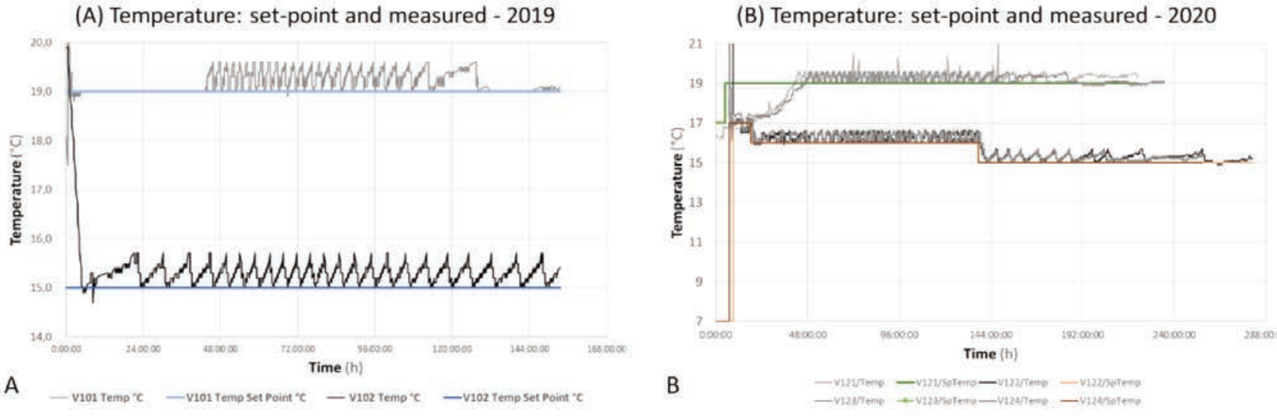

Figure 1. Temperatures trend during the fermentation in 2019 (**A**) and 2020 (**B**): for each tank monitored, both measured values and set-point are shown.

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 a constant linear velocity of 40 cm s^{-1}(≈1.23 mL min^{-1}). The column was an SPB-1 Sulphur capillary column 30 m×0.32 mm I.D., with 4 m film thickness. The 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 ion source temperature was 220°C, and the interface was kept at 280°C. The mass analyser was operated in single ion monitoring mode, according to (Bueno *et al.*, 2014). The list of the analysed molecules can be found in *Supplementary Material S1.*

Electric energy consumption evaluation

Comparative tests were carried out during fermentation at different temperatures to quantify the energy consumption and estimate the energy saving. The studied fermentation plant is located at the "Santa Margherita" winery at Fossalta di Portogruaro (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. A centralised refrigeration system serves all the utilities located in the winery requiring temperature control. 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 to keep the temperature inside the tank constant. Tanks at different temperatures were monitored for the quantification of 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 with each opening were measured.

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

$$Q_{ferm} = m*C_p*\Delta T \quad (1)$$

where:
Q_{ferm} = Heat subtracted from the fermentation process
m = Wine mass processed for each tank
C_p = Specific heat capacity
Δt = Temperature changes during the fermentation process

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

$$P_e=Q_{ferm}/t \quad (2)$$

where:
P_e = Effective total cooling load
Q_{ferm} = Heat subtracted from the fermentation process
t = Time of valve opening

The experimentation was set out as a 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 to calculate the effective powers of the compressor and pump and an efficiency of 85% regarding the circuit of glycol water was considered.

Moreover, energy consumption due to pump use was considered, and the 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.

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 the wine business, trained to assess 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 to determine 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 randomly regarding the nature of the repeated wine and the order of the wines within each triad. Judges were asked to assess which wine differed 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 (a panel composed of 6 expert individuals, 4 working in the winery, and 2 representatives of buy-

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 have a 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	ηe		0.90
Mechanical efficiency	ηm		0.70
Circuit glycol efficiency	ηg		0.85

ers) 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 "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 classifying the wines in groups.

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.

Results and Discussion

Fermentation kinetics

The progress of the fermentations at different fermentation temperatures is shown in Figure 2, 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 (Figure 2B). 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 due to good implantation of the yeasts (Figure 2). 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

Table 4. Experimental results for each tank were monitored, at 19°C, 15°C, and 17-15°C.

Parameters Refrigerator compressor	Symbol	Units		2019 V101_19 °C	2020 V121_19 °C	2020 V123_19 °C	2019 V102_15 °C	2020 V122_17-15 °C	2020 V124_17-15 °C
Grape must be processed		dm^3		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 be processed		kg		47250.00	47250.00	47250.00	47250.00	47250.00	47250.00
Grape must have 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	ηg		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 the compressor	E_{acc}	kWh		199.45	321.69	306.83	322.83	419.74	402.84
Energy consumption of the 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						
Mechanical 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 in 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		

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 were 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.

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 32.0 h for Tank V102_15°C, corresponding to a temperature decrease of 11.2°C and 18.2°C respectively (Figure 1). 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 (Figure 1); 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 1 shows the temperature trend, for each tank monitored, during the fermentation process at 19°C, 15°C (2A), and 17-15°C (2B). Figure 1 indicates that the refrigerator switching frequency tends to decrease with time for all the fermentation temperatures considered. 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 behaviour 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%.

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. The final concentrations of relevant parameters under different conditions are summarised in Table 2. Most parameters (alcohol, residual sugars, total acidity, malic and lactic acid) did not shift due to temperature change. The only slightly significant differences were found in volatile acidity and SO_2, which varied only in 2020 (Pinot Grigio must be fermented with Mycoferm IT-07 yeast), 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 confirms 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 was 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 summarised by (Deed *et al.*, 2015). Forty-two analysed volatile molecules are reported in this study, belonging to families of terpenes 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 differed between the two subsequent vintages, results have been analysed and presented separately for 2019 and 2020. Aromatic compounds are grouped in families, and their relative presence is calculated and shown 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 signif-

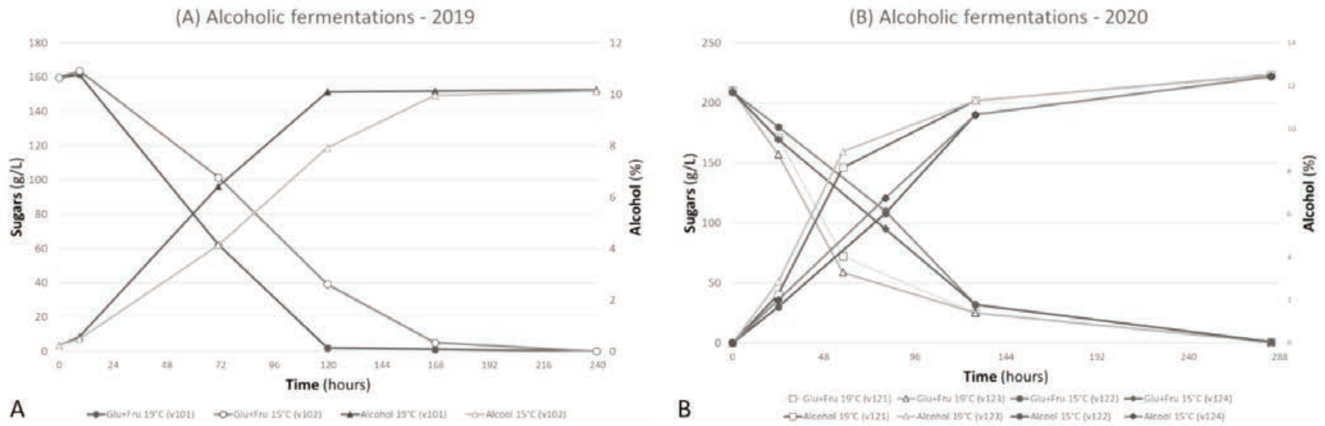

Figure 2. Evolution of sugars (glucose + fructose) and alcohol during the different fermentation conditions in 2019 (**A**) and 2020 (**B**); filled symbols: innovative protocol (19°C), empty symbols: winery protocol (15°C or 17°C-15°C).

Figure 3. Heat map representing the increased or decreased production of each volatile compound in each wine produced with a specific thermal protocol compared to the average of the volatile production (specific yeast and specific variety). Compounds in concentrations above the odour threshold are in red; compounds displaying statistical significance are in italics (p<0.05) and bold italics (p<0.01) (2020 trials, *t*-test).

icance 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 comparing the impact of fermentations on VOCs in different grape varieties (Binati *et al.*, 2020). Most of the aromatic compounds (28 on 42, spread among Terpenes 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 a 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 newly 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 a sensory threshold. Although this observation would require verification in further experiments to be validated, these results are in line with the sensory findings of this study 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 minimal 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 leading fermentative aroma families did not widely change at higher temperatures for these selected yeasts. However, 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).

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 no significant differences between the two Glera base wines (fermented at 15°C and 19°C) analysed from a sensorial point of view. Indeed, only 6 judges on 12 could recognize the different samples, 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 (Figure 3), with only 14 of 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 recognise (in 2019) or rate differently (in 2020) the wines.

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 could ferment with good sensorial results at higher temperatures than standard ones. These features positively affect energy saving and therefore reduce the environmental impact of wine production. Indeed, energy consumption quantification and energy saving estimation results showed that a difference, during the fermentation process, equal to 4°C and 4-2°C between the two conditions allows an energy saving of about 35% and 29%, respectively.

Regarding the main chemical wine parameters, no significant differences were found regarding alcohol content, total acidity, pH, malic acid degradation, and volatile acidity of the final wines. Finally, aroma analyses and sensory tests showed that the temperature increase did not cause significant differences in organoleptic wine properties, consistent among different vintages and yeast strains, between the two theses. Hence, using 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 an industrial scale (>20 hL), confirming the benefits of such an approach for wineries, which may ,in turn, include the possibility to propose ecolabeling strategies and price premium policies that presently have marketing benefits (Nardi, 2020). Beyond confirming the energy savings, the study's significance 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 universalise 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 to these models in the future may also aim at enhancing cooling concepts and estimating potential energy savings.

References

Bartowsky E.J., Henschke P.A. 1995. Malolactic fermentation and wine flavour. Aust. Grapegrow. Winemak. Aust.

Binati R.L., Lemos Junior W.J.F., Luzzini G., Slaghenaufi D., Ugliano M., Torriani S. 2020. Contribution of non-

Saccharomyces yeasts to wine volatile and sensory diversity: A study on Lachancea thermotolerans, Metschnikowia spp. and Starmerella bacillaris strains isolated in Italy. Int. J. Food Microbiol. 318:108470.

Bueno M., Zapata J., Ferreira V. 2014. Simultaneous determination of free and bonded forms of odor-active carbonyls in wine using a headspace solid phase microextraction strategy. J. Chromatogr. A 1369:33-42.

Carrau F., Boido E., Ramey D. 2020. Chapter Three - Yeasts for low input winemaking: Microbial terroir and flavor differentiation. In: Gadd G.M., Sariaslani S. (Eds.). Adv. Appl. Microbiol. 89-121.

Celorrio R., Blanco J., Martínez E., Jiménez E., Saenz-Díez J.C. 2016. Determination of Energy Savings in Alcoholic Wine Fermentation According to the IPMVP Protocol. Am. J. Enol. Vitic. 67:94-104.

Colombié S., Malherbe S., Sablayrolles J.-M. 2007. Modeling of heat transfer in tanks during wine-making fermentation. Food Control. 18:953-60.

Deed R.C., Deed N.K., Gardner R.C. 2015. Transcriptional response of Saccharomyces cerevisiae to low temperature during wine fermentation. Antonie Van Leeuwenhoek 107:1029-48.

Deed R.C., Fedrizzi B., Gardner R.C. 2017. Influence of fermentation temperature, yeast strain, and grape juice on the aroma chemistry and sensory profile of Sauvignon blanc wines. J. Agric. Food Chem. 65:8902-12.

European Commission, 2009. REGULATION (EC) No 1221/2009 (EMAS). in: Official Journal Volume 52, 2009.

Ferreira V., Ortín N., Escudero A., López R., Cacho J. 2002. Chemical characterization of the aroma of Grenache rose wines: Aroma extract dilution analysis, quantitative determination, and sensory reconstitution studies. J. Agric. Food Chem. 50:4048-54.

Fleet G.H. 2003. Yeast interactions and wine flavour. Int. J. Food Microbiol. 86:11-22.

Galitsky C., Worrell E., Radspieler A., Healy P., Zechiel S. 2005. BEST Winery Guidebook: Benchmarking and Energy and Water Savings Tool for the Wine Industry.

Galletto L., Barisan L. 2019. Carbon footprint as a lever for sustained competitive strategy in developing a smart oenology: Evidence from an exploratory study in Italy. Sustainability 11:1483.

Giovenzana V., Beghi R., Vagnoli P., Iacono F., Guidetti R., Nardi T. 2016. Evaluation of energy saving using a new yeast combined with temperature management in sparkling base wine fermentation. Am. J. Enol. Vitic. 67:308-14.

ISO, 2021. ISO 4120:2021 Sensory analysis - Methodology, International Organization for Standardization Publ., Geneva, Switzerland.

ISO, 2004. ISO 4120:2004 (en), Sensory analysis methodology - Triangle test, International Organization for Standardization Publ., Geneva, Switzerland.

La Claire range - Perdomini-IOC [WWW Document], 2021. Available from: https://www.perdomini-ioc.com/en/oenological-products/la-claire-range/ (accessed on 24th June, 2021).

Lesschaeve I. 2007. Sensory Evaluation of Wine and Commercial Realities: Review of Current Practices and Perspectives. Am. J. Enol. Vitic. 58:252-8.

Malvoni M., Congedo P.M., Laforgia D. 2017. Analysis of energy consumption: a case study of an Italian winery. Energy Procedia 126:227-33.

Masneuf-Pomarède I., Mansour C., Murat M.-L., Tominaga T., Dubourdieu D. 2006. Influence of fermentation temperature on volatile thiols concentrations in Sauvignon blanc wines. Int. J. Food Microbiol. 108:385-90.

Merli R., Preziosi M., Acampora A. 2018. Sustainability experiences in the wine sector: toward the development of an international indicators system. J. Clean. Prod. 172:3791-805.

Molina A.M., Swiegers J.H., Varela C., Pretorius I.S., Agosin E. 2007. Influence of wine fermentation temperature on the synthesis of yeast-derived volatile aroma compounds. Appl. Microbiol. Biotechnol. 77:675-87.

Nardi T. 2020. Microbial Resources as a Tool for Enhancing Sustainability in Winemaking. Microorganisms 8:507.

Nardi T., Vagnoli P., Minacci A., Gautier S., Sieczkowski N. 2014. Evaluating the impact of a fungal-origin chitosan preparation on Brettanomyces bruxellensis in the context of wine aging. Wine Stud. 3.

Oenological wine yeasts - Mycoferm [WWW Document], 2021. Available from: https://www.ever.it/en/selected-yeasts.html (accessed on 24th June, 2021).

OIV, 2021. OIV STANDARD FOR INTERNATIONAL WINE AND SPIRITUOUS BEVERAGES OF VITIVINICULTURAL ORIGIN COMPETITIONS [WWW Document]. OIV Stand. Int. WINE Spirit. BEVERAGES VITIVINICULTURAL Orig. Compet. Available from: https://www.oiv.int/public/medias/7895/oiv-patronage-competition-norme-ed-2021.pdf (accessed on 20th May, 2022).

OIV, 2018. Compendium of International Methods of Analysis of Wines and Musts (vol. 2). Method Chromatic Characteristics - OIV-MA-AS2-07B. [WWW Document].

ONAV, 2018. SCHEDA DI VALUTAZIONE PER L'ASSAGGIO TECNICO DEI VINI TRANQUILLI [WWW Document]. Available from: https://www.onav.it/chisiamo/scheda-di-valutazione (accessed on 25th May, 2021).

Perestrelo R., Fernandes A., Albuquerque F.F., Marques J.C., Câmara J.D.S. 2006. Analytical characterization of the aroma of Tinta Negra Mole red wine: Identification of the main odorants compounds. Anal. Chim. Acta 563:154-64.

Pomarici E., Vecchio R. 2019. Will sustainability shape the future wine market? Wine Econ. Policy 8:1-4.

Roessler E.B., Pangborn R.M., Sidel J.L., Stone H. 1978. Expanded statistical tables for estimating significance in paired-preference, paired-difference, duo-trio and triangle tests. J. Food Sci. 43:940-3.

Santini C., Cavicchi A., Casini L. 2013. Sustainability in the wine industry: key questions and research trends a. Agric. Food Econ. 1:9.

Schenk C., Schulz V., Rosch A., von Wallbrunn C. 2017. Less cooling energy in wine fermentation – A case study in mathematical modeling, simulation and optimization. Food Bioprod. Process. 103:131-8.

Schwinn M., Durner D., Wacker M., Delgado A., Fischer U. 2019. Impact of fermentation temperature on required heat dissipation, growth and viability of yeast, on sensory characteristics and on the formation of volatiles in Riesling. Aust. J. Grape Wine Res. 25:173-84.

Torija M.J., Beltran G., Novo M., Poblet M., Guillamón J.M., Mas A., Rozes N. 2003. Effects of fermentation temperature and Saccharomyces species on the cell fatty acid composition and presence of volatile compounds in wine. Int. J. Food Microbiol. 85:127-36.

Trioli G., Sacchi A., Corbo C., Trevisan M. 2015. Environmental impact of vinegrowing and winemaking inputs: An european survey. Internet J. Viticult. Enol. 7:2.

Ugliano M., Henschke P.A. 2009. Yeasts and wine flavour. Wine Chemistry and Biochemistry. Springer, 313-92.