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Enhancing energy efficiency in wineries: A novel benchmarking approach

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ABSTRACT

This article introduces an innovative method to foster energy efficiency in the wine industry, focussing on the benchmarking of Energy Performance Indicators (EnPIs). It facilitates the evaluation and monitoring of wineries' performances over time, allowing for comparison with similar entities, through the categorization of wineries into eleven distinct reference-models based on their process types, enhancing the understanding of energy use. Additionally, three "outsourcing" indices are introduced to identify significant energy consumption in key production stages. The methodology is designed for simplicity, requiring only basic input and product output data, readily available to companies. To validate this approach, a specially-developed data collection form was proposed to 20 Italian wineries, ranging from small producers to large-scale operations. The results illustrate some important limitations in methods that solely rely on EnPIs for energy performance benchmarking, which may lead to inaccurate conclusions. The proposed categorization and outsourcing indices allow for a more comprehensive energy consumption analysis related to the actual production process. Interestingly, some companies, initially perceived as efficient, exhibit instead critical performances, which entails the need for further analysis. Correlation analyses confirm the efficacy of these methodological choices, underscoring the robustness of the proposed approach and proving its potential as an asset for companies, decision-makers, and stakeholders aiming at sustainability improvement, including all those boards involved with certification standards.

Introduction

In recent years, the wine sector, strategic for the European Union's economy [1], has witnessed a strong variability in terms of productive volumes [2] and consequently, energy consumption. According to the "TESLA" (Transferring Energy Save Laid on Agroindustry) EU-funded project [3], the consumption profile of wineries at the EU level is about 1,750 million kWh per year. Energy consumption is roughly similar in Italy and France and around 500 million kWh, it is around 400 million kWh in Spain and 75 million kWh in Portugal. According to Vela et al. [4], the primary source of energy is still fossil-generated electricity (around 90 %). Fossil fuels are also consumed for thermal processes (e.g., water heating before bottling), accounting approximately for the remaining 10 % of the total energy consumption. In this context, a reduction of wineries primary energy consumption and related greenhouse gas emissions through energy efficiency improvement, and the increase of the share of energy needs covered by renewable sources is crucial to fit the objectives of the 2050 European Union strategy [5].

State of the art

The topic of energy efficiency in wineries has begun to be explored by scientific researchers quite recently, although some pioneering studies can be dated back to the early 2000s [6]. The topic has become increasingly interesting as the issue of sustainability in this production sector has grown in importance, also thanks to its promotion by various certification standards and indicator systems at an international level [7]. A comprehensive review on this subject has been provided by De Castro et al. [8]; it includes various aspects such as: sustainable energy utilisation, thermal performance analysis of buildings, energy efficiency assessment of systems and technologies, integration of renewable energy sources. A comparative technical–economic analysis of measures to enhance energy efficiency has been provided by Vela et al. [4]. Some authors [9] investigated the reduction of energy consumption associated with refrigeration in different phases of the production process,

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providing some technical solutions supported by case studies. The topic of wineries energy efficiency was also addressed by a point of view involving the building envelope performance, for example in the study by Nocera et al. [10], referred to the context of southern Italy. Regarding the wine-ageing rooms, Arredondo-Ruiz et al. [11] provided an extended review on the design for energy-efficient wine cellars. Benni et al. [12] assessed the energy efficiency of different design solutions for wine storage through digital modelling and thermal simulations.

As regards the possibility of exploitation of renewable energies, wineries typically have large areas available e.g. for the installation of photovoltaic modules on roofs, and, in some cases, even on the ground. Wine sector's attitude towards the incorporation of renewable energies has been investigated by Garcia-Casarrejos et al. [13] with specific reference to the Spanish context. An investigation on the feasibility of solar energy in the same territory has been conducted by Goméz-Lorente et al. [14]. Even if this technology is surely promising also for this industry, a critical issue for the use of solar energy in wineries is the unavoidable mismatch between energy generation and demand, as analysed by Jia et al. [15]. A possible solution could encompass the creation of more complex systems, e.g. making use of multiple technologies, one of which involving energy storage. For example, the combined production of electricity and hydrogen from solar energy has been proposed by Carroquino et al. [16]. The complexity of multi-energy conversion systems requires a careful optimization of their design and operation, as addressed by Pivetta et al. with regard to a system based on a natural-gas-fuelled cogeneration unit, absorption chillers and a biomass boiler [17]; all these systems aim at finding the highest profit, efficiency and share of renewable energy by an utilization perspective.

When tackling an energy efficiency improvement process, it is essential to firstly understand "where" and "when" energy is requested. To achieve this purpose, an energy breakdown analysis is typically used [18]. The characterization of the winemaking process energy requirements has been addressed by some other authors [19]. Concerning the analysis of the energy consumption profiles in wineries, a methodology based on two factors was hence proposed. The consumption profile over a representative period of an Italian case-study, namely a winery producing still white wines and Prosecco, has been analysed and discussed, demonstrating how it is strongly related to seasonality of the production process [19]. The energy audit is typically the main tool for analysing the energy consumption in an industrial plant. Within the above-cited TESLA project, 39 energy audits were conducted in wineries of different sizes in four countries (Italy, France, Spain, and Portugal). The collected information allowed to characterize the energy requirements of a typical winery [4]. It is worth noting that the focus of the TESLA project was mainly the production of red wines, so the characterization of white wines' energy consumption still needs further deepening. However, pressing, alcoholic fermentation and stabilization stages, which are common to the productive cycles of both red and white wines, impact for more than 50 % on the entire energy consumption [3]. Malvoni et al. [20] proposed an energy audit of an Italian winery, identifying the electric energy consumption in each process phase. In [21], a detailed characterization of a winery's energy consumption has been obtained through an energy audit as part of the implementation of the ISO 50001 energy management system scheme. A characterization of the energy uses in the winemaking process is also provided in [22], with a focus on energy requirements of cooling phases. It is noteworthy that most of a winery's energy demand is related to the refrigeration equipment: according to [23], indeed, about 45 % of energy is spent by refrigeration systems to control fermentation processes. Moreover, a significant share (40 % - 60 %) of the electrical energy consumption relates to the product refrigeration and to the heating and cooling of the work environments [24].

A fundamental tool for evaluating and monitoring over time the energy performance of a production company, as well as for comparing it with other companies belonging to the same productive sector, is represented by the so-called energy performance indicators (EnPIs). To date, there are few studies that have focused on calculating the energy consumption of wineries per unit of released product, namely the *specific energy consumption* (SEC) [25], i.e. one of the most important EnPIs. A volunteer survey, which involved principally small and medium enterprises and producers' consortia, has been carried out by ENEA [26]; the aim was to check the current state of resources used in Italian wineries, and identify the key elements for improving their efficiency. Concerning energy consumption, the study highlighted that extremely-conflicting data were obtained, and this fact did not allow obtaining an affordable average value of energy consumption per hectolitre of produced wine. A comparison between the environmental performances of winemaking organizations registered according to the EMAS (Eco Management and Audit Scheme) standard has been presented in [27], distinguishing between different companies' sizes. Considering the SEC indicator, the sector average value ranges from 60.0 $kWh \cdot hL^{-1}$ to 106.0 $kWh \cdot hL^{-1}$, although it has been found that companies with different sizes show significant differences, thus indicating that some scale-effect is present. A study by Smyth and Nesbitt [28] analysed the energy demand in the English winemaking context, assessing an average energy benchmark equal to 55.7 $kWh \cdot hL^{-1}$, ranging from a lower value of 4.0 $kWh \cdot hL^{-1}$ to an upper value of 206.5 $kWh \cdot hL^{-1}$, hence with an extremely wide range of values. In order to justify this gap, a correlation is identified between the company size, in terms of production volumes, and the overall energy consumption (excluding vineyard activities), and a categorization of wineries has been consequently proposed: *small* (less than 10,000 bottles per year), *medium* (10,000 to 50,000 bottles per year) and *large* (greater than 50,000 bottles per year). It is worth noting that medium wineries, according to this classification, present the highest SEC (97.5 $kWh \cdot hL^{-1}$), whilst the SEC average value for small wineries stands at 35.2 $kWh \cdot hL^{-1}$ due to lower levels of mechanization, and the large wineries at a mean value of 51.0 $kWh \cdot hL^{-1}$ thanks to scale-economies, according to those authors' interpretation. In literature, some others energy benchmark values for various region of the world can be found [29]. For example, considering all the possible energy uses in wineries, SEC average values of 47 $kWh \cdot hL^{-1}$ have been found for New Zealand [30], 70 $kWh \cdot hL^{-1}$ for Nova Scotia (Canada) [31], 214 $kWh \cdot hL^{-1}$ for South Australia, and 201 $kWh \cdot hL^{-1}$ for Mexico [32]. As regards the European context, the TESLA project found a medium value of 11 $kWh \cdot hL^{-1}$ for electric energy and 1 $kWh \cdot hL^{-1}$ for thermal energy characterizing an "average-size winery", i.e. a facility with a yearly production capacity of 30,000 hL [4], although a wide variability in EnPIs was found between the energy audits carried out, even considering the different sizes of the analysed companies. The main cause for this behaviour was attributed to the different energy efficiency performances.

From the above-exposed literature review, it emerges that some aspects, fundamental for the enhancement of energy efficiency benchmarking in wineries, have not yet been fully addressed, leaving opened some important questions. In particular, all the aforementioned studies refer only to a EnPI consisting of the ratio between the total energy consumption of the company (considering various energy sources or carriers involved) and the overall quantity of produced wine, hence it represents the specific energy used to produce a unit of product. As highlighted by Lawrence et al. [25], the calculation of the variable "product" to be used in such EnPI is based on some assumptions, which are often not made explicit; this is precisely the case with energy efficiency studies in wineries. First of all, it is not specified the type of the obtained wine (e.g.: still/sparkling, red/white). A second important disclaimer to be accounted for when using the above presented EnPI, is the reference period for the data used in the calculation of that indicator. Indeed, this reference period should be clearly defined, as the production process is often not entirely comprised in a single calendar year, and sometimes it requires more than 12 months for some types of products. Again, there is not a unique definition of "produced wine", although most of the literature works implicitly refer to company's total production relating to a one-year period (i.e., twelve months), without specifying e.g. whether it is processed wine (and which type of process is included) or simply wine sold by that company.

Furthermore, a deep analysis had not been carried out to support the actual significance of this indicator for the wineries reference context, i.e., by demonstrating the existence of an experimental correlation between the two above-mentioned quantities in this EnPI. Hence, the suitability of such an indicator to evaluate the specific energy consumption of a winemaking facility and above all, to use it for comparisons with other companies, needs to be further explored, also due to the following reasons. Firstly, the winery sector includes a multitude of companies producing different types of products, with different qualities, through many kinds of production processes, which are expected to be characterized by different energy needs. Indeed, technologies and productive processes, and, consequently, their energy consumption, are strongly related at least to the type of produced wine. Indeed, despite the several similarities among white and red wines production processes, there are important differences in technologies and approaches. Moreover, in the case of sparkling wines, all the activities and technologies related to the refermentation phase, together with their energy needs, should also be considered. For example, in the TESLA project [4], the production of a young red wine is used as a reference, not allowing the extension of the results extensively to the entire sector.

Therefore, an innovative approach to enable EnPIs' benchmarking is proposed in this study with the aim to foster an improvement of energy efficiency in the wine sector. It provides the companies a tool that could be useful to evaluate and monitor their performance over time and compare them with other companies that carry out similar productive process. A methodology for the assessment of energy performance indicators has been proposed by [30], with the fundamental difference that it requires the availability of a complete database of energy audits for a considered productive sector. The present approach, instead, has been designed to be easily implemented, as it requires few input data surely available to the company management, without the need to carry out an in-depth energy audit. An energy audit is actually a highly-demanding activity in terms of resources (particularly financial and of time [32]) so that companies, in most cases, carry out such a survey only if mandatory or incentivized in some form. Instead, the opposite situation is more likely to occur, namely that a company will endorse an energy survey after becoming aware that it is underperforming from a benchmarking analysis of indicators within its production sector.

Aims of this study

The main aims of the proposed approach are to:

- establish a database of significant and representative EnPIs for wineries belonging to each of the subsets of production activities;
- allow companies to self-assess the performance of their production cycle as far as concerns the energy use and sustainability, thanks to the individuated EnPIs; in this way, a first comparison can be made with the average value of the industry, specific to the same business subset to which a company belongs, thanks to the database mentioned in the previous point;
- allow companies to monitor over time their energy performance, thanks again to the individuated EnPIs; this allows assessing the real benefits of any implemented improvement actions, evidencing weaknesses and points of improvement, and defining the strategies to be implemented.

The present article is structured as follows. In the following Materials and methods, the approach developed for the evaluation of the energy efficiency performance of wineries is proposed; it is based on a conceptualization of different types of companies in terms of energy needs. Its validation has been carried out by analysing data collected from 20 factories in Italy, representative of the heterogeneity of the sector in terms of types of companies and products, sizes and geographical locations, and the results of the processing of the collected data are presented in Results and discussion. Finally, the conclusions of the study and the future developments are drawn in Conclusions.

Materials and methods

To better frame the proposed EnPIs within a company scenario, it is necessary to progressively enlarge the observation boundary (i.e., the so-called "control surface", as it is referred to in Physics) from including only a single piece of equipment up to encompass the entire production department of a company (or the company in its whole). In this schematization, it is so possible to identify up to *four levels* that correspond to as many different "*domains of study*", namely: (1) "*Company*", (2) "*Macro-process*", (3) "*Process stage*" and (4) "*Equipment*". From level 4 to 1, the attention shifts from a particular to the general, from level 1 to 4 the number of observed items lowers, up to focus to a single machine. It is possible to define specific EnPIs for each level.

Within this representation, the proposed approach focuses on the top level (company) in terms of EnPIs calculation. This first level considers the enterprise as a black box, i.e. the boundaries of the observed system enclose the entire production process without giving details about the included departments/divisions, sub-processes, production phases, machines. Such a level consists of macro-indicators, obtainable from data already available in any business context, namely: the energy supply bills and the production data.

Other EnPIs can be defined also in the lower levels, when there is the need for an in-depth analysis aimed at the characterization of the performance of a specific process phase, e.g. as part of an energy audit carried out with the support of experienced consultants.

Reference production models

All types of wine on the market are derived from white and red winemaking processes, to which additional specific steps can be added depending on the product to be obtained. These specific steps can include, for example, those related to the production of sparkling products characterized by an overpressure relative to atmospheric pressure, namely sparkling wine, semi-sparkling wine, aerated sparkling wine and aerated semi-sparkling wine, in accordance with the EU regulation 479/2008 on "the common organization of the market in wine". Within this article, for this reason, all the above-cited categories of product are therefore grouped under the term "overpressure wines". Thus, both wines made by natural overpressure (i.e., sparkling and semi-sparkling wines) and those made by creating an artificial overpressure through gasification (i.e., aerated sparkling and aerated semi-sparkling wines) fall within this category. In the first case, the reference model will be indicated to as "refermentation company", while, in the second case, as "gasification company".

The identification of different reference models of production process for the sector (hence: different reference models for companies involved in wine production) is critical, because it is expected that different reference models could imply different energy requirements. A comprehensive investigation about all possible types of companies related to wine processing has been presented in [33]. From this study, only 11 out of 225 theoretical possibilities are really present on the market, considering also the two above-referred alternative processes to create a sparkling wine (i.e., refermentation in autoclaves or bottles, or gas addition by means of dedicated equipment). The proposed wineries reference models are, therefore, 11 in total:

1. *Winemaking company:* it has the exclusive task of transforming the grapes and/or must (inputs) into still wine (output), ready to be sold in bulk to other companies in the supply chain. This type of company receives, as input, grapes (and possibly must) from its own vineyards and/or conferred/purchased from third parties,

such as members or private individuals. It produces and sells only bulk still wine.

2. *Refermentation company:* its exclusive task is transforming still wine or must (inputs) into a wine with natural overpressure (hence performing a refermentation in autoclaves or bottles), ready to be sold in bulk to other parties in the supply chain. This type of company exclusively receives, in input, still wine conferred/purchased from third parties, such as members or private individuals. In output, it produces and sells exclusively bulk wine with naturally obtained overpressure.
3. *Gasification company:* its exclusive task is transforming still wine (input) into a wine with artificial overpressure (hence adding gas by means of dedicated equipment), ready to be sold in bulk to other parties in the supply chain. This type of company exclusively receives, in input, still wine contributed/purchased from third parties such as members or individuals. In output, it produces and sells exclusively bulk wine with artificially obtained overpressure.
4. *Bottling company:* it has the exclusive task of bottling the received wine. This type of company receives, in input, exclusively bulk wine, still or with (natural or artificial) overpressure, conferred/purchased from third parties, such as members or individuals. It produces and sells bottled wine of any type.
5. *Winemaking and bottling company:* its main task is transforming the grapes and/or must input into still wine, which can be sold in bulk or bottled. In input, the winery receives grapes, must, or even directly wine (still or with overpressure) from its own vineyards or conferred/purchased from third parties, such as members or private individuals. It produces and sells still wine in bulk or bottled wine.
6. *Winemaking and refermentation company:* its main task is transforming the input grapes, must or still wine into a wine with natural overpressure sold in bulk. In input, the winery receives grapes, must or even directly wine (still or with overpressure) from its own vineyards or conferred/purchased from third parties, such as members or individuals. It produces and sells bulk wine (still or with natural overpressure).
7. *Winemaking and gasification company:* its main task is transforming the incoming grapes, must or still wine into a wine with artificial overpressure sold in bulk. In input, the winery receives grapes, must or even directly wine (still or with overpressure) from its own vineyards or conferred/purchased from third parties, such as members or individuals. It produces and sells bulk wine (still or with artificial overpressure).
8. *Refermentation and bottling company:* its main task is transforming the input wine or must into wine with natural overpressure, which can be sold in bulk or bottled. In input, the company receives wine (still or with overpressure) conferred/purchased from third parties, such as members or individuals. In output it produces and sells wine with natural overpressure in bulk or bottled wine.
9. *Gasification and bottling company:* its main task is transforming the input wine into wine with artificial overpressure, which can be sold in bulk or bottled. In input, the company receives wine (still or with overpressure) conferred/purchased from third parties, such as members or individuals. It produces and sells wine with artificial overpressure in bulk or bottled wine.
10. *Winemaking, refermentation and bottling company:* its main task is transforming grapes, must and input wine into still wine and/or wine with natural overpressure, which can be sold in bulk or bottled. In input the company receives grapes, must or even directly wine (still or with overpressure) from its own vineyards or conferred/purchased from third parties, such as partners or private individuals. It produces and sells wine (still or with overpressure) in bulk or bottled wine.
11. *Winemaking, gasification, and bottling company:* its main task is transforming grapes, must and wine input into still wine and/or wine with artificial overpressure, which can be sold in bulk or bottled. In input the company receives grapes, must or even directly wine (still or with overpressure) from its own vineyards or conferred/purchased from third parties, such as partners or private individuals. It produces and sells wine (still or with overpressure) in bulk or bottled wine.

Process mapping and identification of inputs and outputs

Following the identification of wineries' reference models for the production process, it is necessary to map it by identifying its main stages, since each of them involves different energy requirements.

In Fig. 1, a flow chart of the main phases of the most general production process for a winery is represented. It should be specified that some general steps may not apply depending on the considered reference production process model F_k.

The developed reference models ("$O_j = F_k(I_i)$", with: $i = 1$ to 4, $j = 1$ to 4, $k = 1$ to 11) of the production process can be divided into two types:

- "Basic" models, which represent the smallest group of significant production activities for the wine sector ("F_k", with k = 1, 2, 3 and 4);
- "Compound" models, which represent the combination of several basic models to constitute the multitude of production activities found within the wine sector ("F_k", with k = 5, 6, 7, 8, 9, 10 and 11).

By mapping the production process, it is also possible to identify all input- and output-items. Four possible inputs (I_i) are identified ($i = 1$ to 4):

- *Grapes* (I_1): this input represents the total amount of input grapes, expressed in quintals.
- *Must* (I_2): it represents the total amount of must input, expressed in hL.
- *Still wine* (I_3): it represents the total amount of still wine input, expressed in hL.
- *Overpressure wine* (natural or artificial) (I_4): it represents the total amount of overpressure wine input, expressed in hL.

Four possible output products (O_j) are also identified ($j = 1$ to 4):

- *Must (O_1):* this output represents the total amount of must output, expressed in hL, ready to be sold as must.
- *Still wine (O_2):* it represents the total amount of bulk still wine output, expressed in hL, ready to be sold as bulk wine.
- *Overpressure wine* (natural or artificial) *(O_3):* it represents the total quantity of bulk overpressure wine in output, expressed in hL, ready to be sold as bulk wine.
- *Packaged* (still and overpressure) *wine (O_4):* it represents the total quantity of still and overpressure wine in output, expressed in hL, packaged by the company.

Table 1 shows the correlation between the above-listed input- and output-products and each reference model for the production process F_k.

Definition of outsourcing or externalization indexes

In addition to the type of production process, there is another factor that is crucial in terms of its impact on the winery's energy consumption: the amount of process phases that are outsourced to external companies. It is related to energy consumption, but there is no possibility of tracking those phases during the performance evaluation of the winery under consideration. Hence, in order to account for this contribution, a simplified approach has been developed in this research: it allows, to some extent, to delve with the analysis of EnPIs to the macro-processes

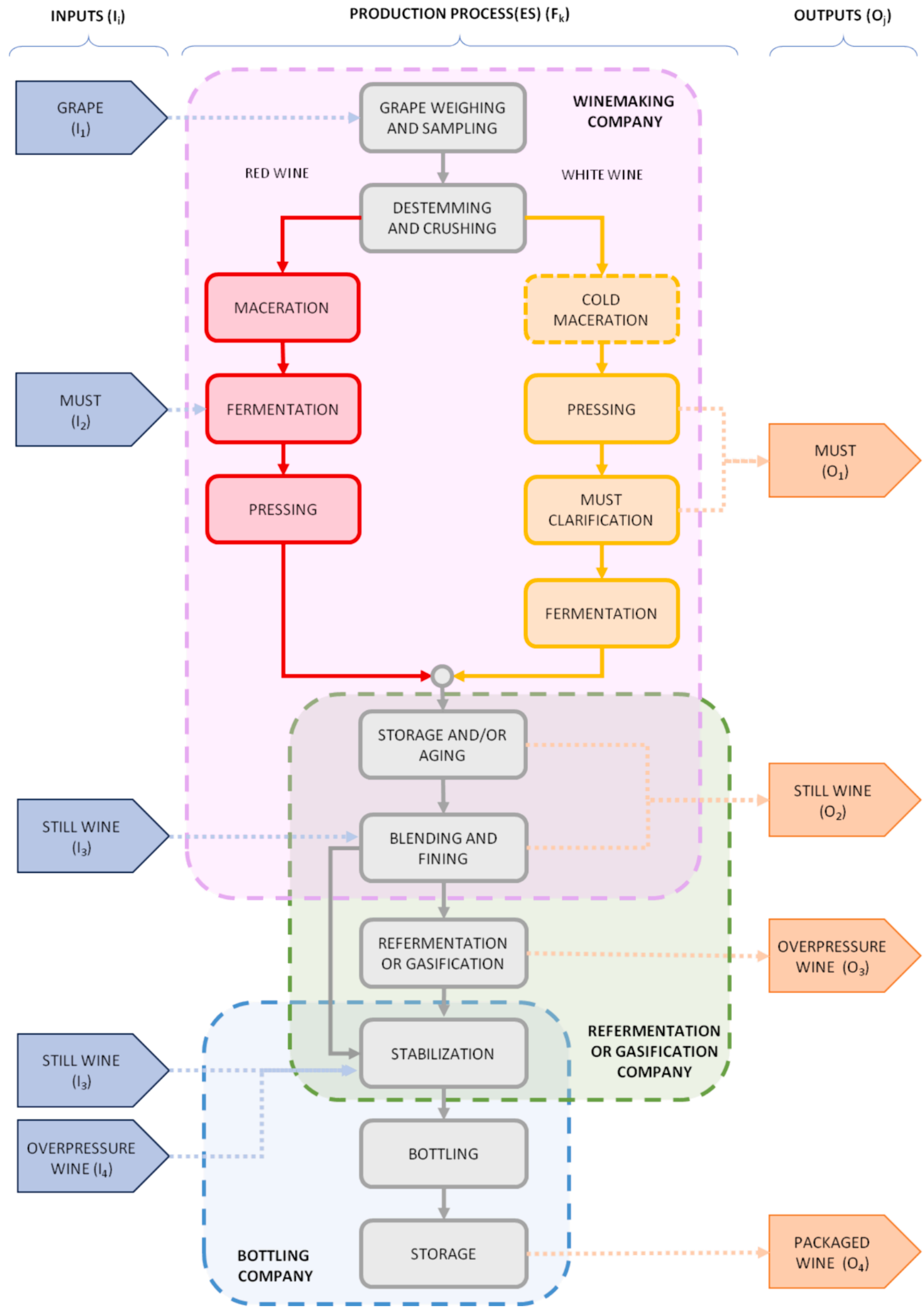


Fig. 1. Wineries' general reference production process model; the dotted lines boxes enclose the main reference models.

level. The advantage of this approach lies in the fact that it does not require to collect detailed energy data within the winery, or to conduct an energy audit at the outsourcers; it makes use only of the input and output data as above defined. Three "outsourcing" indices have been defined, functional to characterize the missed energy consumption related to three main macro-stages of the production process: still wine winemaking, overpressure winemaking and packaging of the finished products.

1. The "*winery outsourcing index*" (WOI) allows comparing the quantity of bought wine (hence, produced by an external company) and for which it is correct to impute only partial energy consumption. This index is calculated as the ratio of semi-finished input bulk wine (still and overpressure), purchased from outside, and the whole output product (i.e., the sum of product entirely processed by the winery, and the product that requires only partial processing).

$$\mathrm{WOI}\,[\%] = \frac{\sum_{i=3}^{4} I_i}{\sum_{j=1}^{4} O_j} \bullet 100 \tag{1}$$

2. The "*overpressure wine share index*" (OWSI) describes the incidence of winery activity devoted to overpressure winemaking related to total

Table 1
Correlations between inputs/outputs (column headers) and reference production process models (rows headers); a black dot indicates the presence of that parameter in the reference model.

F_k	Inputs				Outputs			
	I_1	I_2	I_3	I_4	O_1	O_2	O_3	O_4
F1	•	•			•	•		
F2			•				•	
F3			•				•	
F4			•	•				•
F5	•	•	•	•	•	•		•
F6	•	•	•		•	•	•	
F7	•	•	•		•	•	•	
F8			•	•			•	•
F9			•	•			•	•
F10	•	•	•	•	•	•	•	•
F11	•	•	•	•	•	•	•	•

winery activity, i.e., including sparkling wine. It is calculated as the ratio of the amount of overpressure wine, purchased by the winery, and the sum of purchased still and overpressure wine.

$$\text{OWSI}\,[\%] = \frac{I_4}{I_3 + I_4} \bullet 100 \tag{2}$$

3. The "*wine packaging index*" (WPI) provides breakdown information on the incidence of the packaging department's activity. It is calculated as the ratio of the amount of wine packaged by the winery and its total production output, i.e. the sum of must, bulk (still and overpressure) wine ready for sale, and packaged wine).

$$\text{WPI}\,[\%] = \frac{O_4}{\sum_{j=1}^{4} O_j} \bullet 100 \tag{3}$$

In this way, it is possible to analyse the energy behaviour of the system by only knowing the reference process model F_k and the input I_i and output O_j flows.

To give the reader some hints about these indices, it is possible to observe that:

- the higher the WOI, the lower the impact of products processed externally by the company on the energy request; this is because products bought from outside have already undergone partial processing;
- the higher the OWSI, the lower the incidence of the winery activity dedicated to sparkling wine on energy request;
- the higher the WPI, the higher the incidence of the packaging department on the energy requests.

Data collection

After mapping and identifying input and output products, it is possible to proceed with the data collection phase. For this purpose, a spreadsheet document, organized into three macro-sections, was created to be compiled by companies.

In the *first macro-section*, companies are asked to enter some general company data, such as geographical location, turnover rate, company type and number of employees. In addition to these data, companies are asked to select to which reference production process model F_k they belong amongst those above presented (i.e., which one is more suitable to describe them).

In the *second macro-section*, process data entry is required. This section is divided into sub-sections:

- *Input products:* in this section it is required to enter data for I_1, I_2, I_3 and I_4;
- *Output products:* in this section it is required to enter data related to O_1, O_2, O_3 and O_4;

In the *third macro-section*, companies are asked to enter data on yearly energy consumption referred to the last three years, on a monthly base, in particular:

- the electric energy consumption from the grid;
- the amount of self-generated energy from renewable sources (e.g., from photovoltaic modules);
- the amount of consumed fuels (LPG, natural gas, diesel oil, etc.).

It was considered more appropriate to collect and, subsequently, plot data for each company and each year, rather than collapsing them in single points representing each company with numerical values equal to the three-year averages. Indeed, by doing so, it is possible to preserve the temporal variability that, from an industrial standpoint, can occur in companies of this type. In wine production, there are, in fact, *three main sources of variability* that can affect the final product, which are typically compensated for through different process setups:

1. *Variability of the raw material*; grapes are strongly influenced, both quantitatively and qualitatively (e.g., in the sugar content and acidity level), by the meteorological-climatic conditions (primarily: rainfall and temperatures) that occurred during the growth and maturation season. For wines that do not use commercial yeasts (starter yeast), the influence of meteorological-climatic conditions is twofold, as it extends also to the populations of naturally occurring strains of yeast that are present on grape skin. Even with consistent climatic conditions in the usual grape conferring area, there can be variability in the raw material due to economic influences affecting the supply mix; for example, market contingencies could make it particularly advantageous to source grapes from agricultural companies / conferring areas outside of usual suppliers, thus with products having characteristics not aligned with those usually worked with.
2. *Variability of climatic conditions* in the area where the facility is located; some phases of the winemaking process require a fine control over the temperature of semi-finished products and of products in aging, for example, to limit the development of heat generated by the biological processes responsible of the sugar-to-alcohol transformation. Since temperature control is performed by machines operating according to the thermodynamic cycle of vapour compression, a variation in external temperature imposes a different temperature on the condenser, and this fact affects the machine's COP. Similarly, heat losses from installations located in warehouses, where no internal temperature control is provided, are influenced by (external) ambient temperature. Finally, if there is a need to age wine in wooden barrels and, thus, control the humidity of the involved environments, the initial humidity of the air can also affect the amount of water that dehumidifiers must remove.
3. *Variability* (or, better, in this case, modifications) *of the production layout*; the set of machinery involved in the winemaking process can vary from one year to the subsequent one, due to a request to change the final production mix (spec., the subdivision of production between white and red, still and sparkling wines), thus engaging some machines more than others. Additionally, every year new machines can be introduced in addition to existing ones (new purchases), or other machines may be decommissioned without immediate replacement (thus changing the percentages of use/occupancy of the remaining machines), or some other machines may be replaced with different models, thus having different performances. In the case of rented machinery (typically concerning containerized refrigeration systems), the service provider might change for many reasons, including economic ones, and, therefore, the machines made available could be different from one year to the other.

The above-described scenarios would have required a very important addition of information to be collected. As this would have been in contrast with the purpose of the study, this additional information was not detected through the information sheet. Since all the situations outlined above were completely unknown, the authors then deemed it more correct to use disaggregated data, which is also useful for outlining temporal trends and, thus, improvements or deterioration.

EnPIs definition

Regarding the definition of the energy performance indicators, this research aligns with the indications present in the international standards. The ISO 50006:2023 standard [34] provides guidelines to establish an appropriate energy performance indicator aimed at measuring and monitoring the energy efficiency of a process, and recommends the use of specific energy consumption indexes defined as follows:

$$\mathrm{EnPI}_e = \frac{\textit{Electric energy consumption}}{\textit{Production}} \tag{4}$$

$$\mathrm{EnPI}_t = \frac{\textit{Thermal energy consumption}}{\textit{Production}} \tag{5}$$

In both of them, the production term represents the total amount of finished products, pertaining to the calendar year considered in the analysis, ready to be sold. Regardless of the reference model for the production process F_k, the EnPIs to be analysed are always calculated in the same, above-illustrated way: each EnPI is given by the ratio between a value, expressed in kWh, and another value, expressed in hL.

Results and discussion

Data from 20 firms were collected, spanning the three most recent full annals available (2020–2021–2022) leading to a total of 60 data. More than 70 % in quantity [35] and value [36] of Italian wine production in 2022 is attributable to seven regions: Veneto, Puglia, Emilia-Romagna, Abruzzo, Toscana, Friuli-Venezia Giulia, Trentino-Alto Adige. Therefore, the companies selected for this research are located just in the above-cited seven regions: Veneto (tot. 7 companies), Abruzzo (tot. 4), Friuli-Venezia Giulia (tot. 3), Puglia (tot. 2), Toscana (tot. 2), Emilia-Romagna (tot. 1), Trentino-Alto Adige (tot. 1). In the case of enterprises affiliated with larger conglomerates operating in multiple production sites, a separate form for each individual production facility was submitted.

It is worthy evidencing that the companies included in this study belong all to the following 5 types: F1 (tot. 2), F4 (tot. 1), F5 (tot. 10), F6 (tot. 1), F10 (tot. 6). As evident, notwithstanding the efforts of the authors to have an as-wide-as-possible variability, 5 out of the 11 possible reference business models are not represented (F2, F3, F7, F8, F9, F11).

General results

The analysis encompasses a wide spectrum of company sizes, ranging from very small firms, through medium-sized entities, to large-scale companies (i.e., whose yearly output exceeds 150,000 $\mathrm{hL\cdot yr^{-1}}$). The yearly maximum production capacity considered in the study is approximately 350,000 $\mathrm{hL\cdot yr^{-1}}$. In terms of numerousness of the data collected, there is a clear predominance (tot. 32, i.e. about 53 %) of companies that produce up to 30,000 $\mathrm{hL\cdot yr^{-1}}$, a good presence (tot. 20, i.e. about 33 %) of companies that produce from 30,000 $\mathrm{hL\cdot yr^{-1}}$ up to 150,000 $\mathrm{hL\cdot yr^{-1}}$, and only few companies (tot. 8, representing 14 % of the complete samples' set) that exceed 150,000 $\mathrm{hL\cdot yr^{-1}}$.

The dependence of the variable "electric energy consumption", "thermal energy consumption" and "total primary energy consumption" from the independent variable, i.e. the produced wine quantity, has been evaluated here below. The linear regression has been used to relate the dependent and the independent variables in all the previous cases because it is widely used both in the literature [37] and in the common industrial practice (for auditing). Furthermore, polynomial degrees higher than 1 should have been justified at least by a physical point of view, and this would have required the knowledge of many technical details about the processing plants, out of the scopes of this study. The regression analysis presented in Fig. 2(a, b, c, d) demonstrates a notable statistical significance for the indicator $\mathrm{EnPI_e}$. This is evidenced by a linear correlation between electric energy consumption and company production, exhibiting (see Fig. 2a, b and c) an R^2 value rather similar over the three years (between 0.62 and 0.68) and, on average (i.e., if the whole observation period is considered), equal to 0.6371 (Fig. 2d). An analysis of variance (ANOVA) performed on the terms of the proposed regression model (linear in all the cases) shows the adequateness of this model (p-value < 0.0001). It warrants mention that every case of this regression analysis is based on all available data, regardless of the specific type of production process/company.

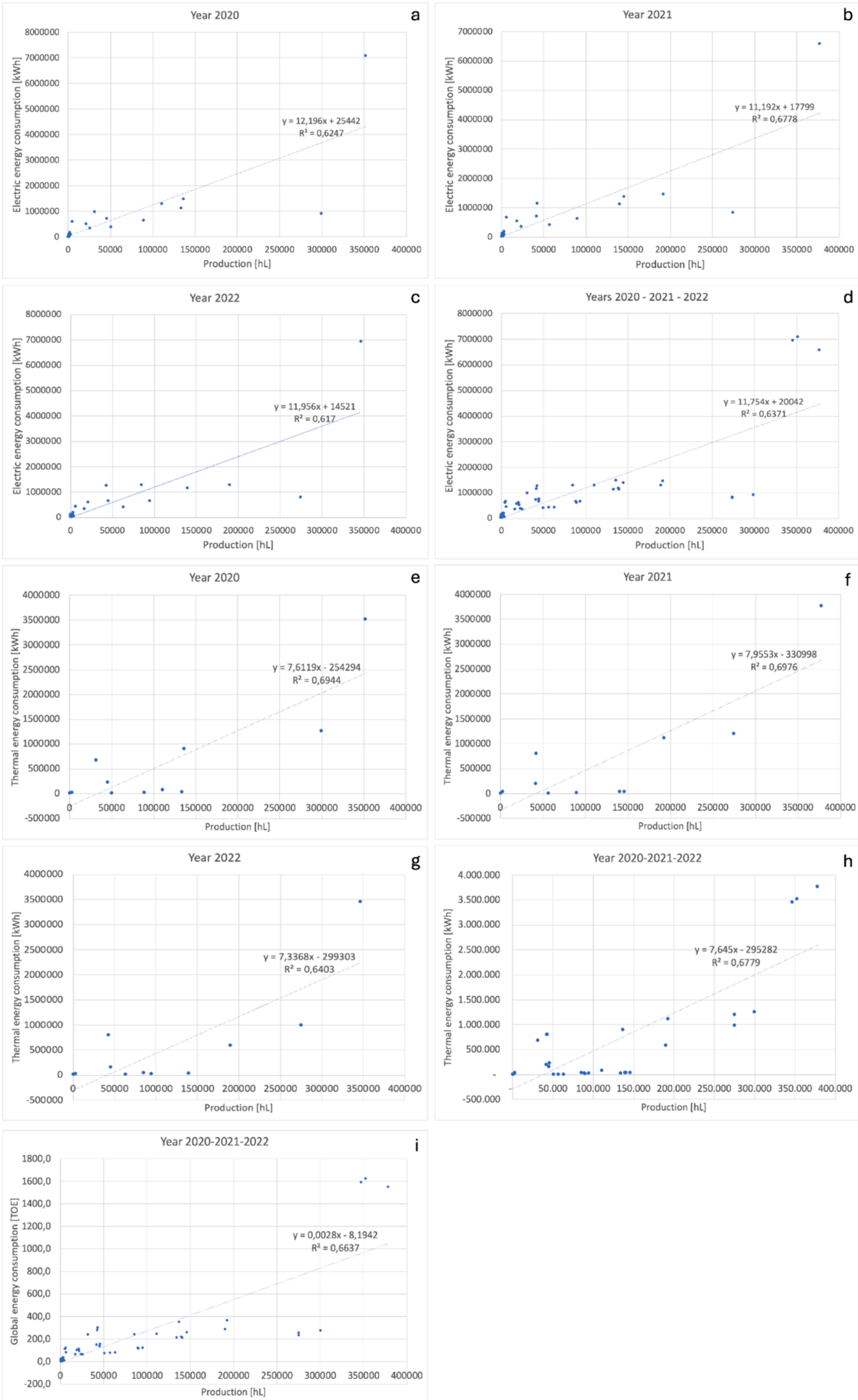
As the regression analysis shows a good degree of statistical significance, it emerges that production is a critical determinant, but it is not the only factor impacting electric energy consumption in wineries. The positive slope of the regression line suggests the existence of a scale effect in the relation between electric energy consumption and production, mathematically made explicit in Fig. 2d by the proportionality coefficient equal to 11 $\mathrm{kWh\cdot hL^{-1}}$.

The regression analysis presented in Fig. 2(e, f, g, h) evidences a linear correlation between the thermal energy consumption and the company production, exhibiting an R^2 value rather similar over the three years (between 0.64 and 0.70) and, on average, equal to 0.6779 if the whole period is considered. The presence of a markedly negative intercept value suggests that such a correlation fit between these two quantities is unrealistic from a physical point of view (at least below 50,000 hL). Indeed, industrial activities are characterised by not-null energy consumption even in the case of zero production (to keep plants ready for production). For this reason, a positive intercept would have been more expectable, because coherent with the physical point of view.

In order to analyse the relative weights of the electrical and thermal EnPIs to characterize the processes, the global energy consumption (namely, the total contribution of electricity and fuels) in terms of primary energy has been determined by applying the appropriate conversion coefficients. With reference to Italy, those coefficients are: $0.187 \bullet 10^{-3}$ $\mathrm{toe\cdot kWh^{-1}}$ for electricity, $0.836 \bullet 10^{-3}$ $\mathrm{toe\cdot Sm^{-3}}$ for natural gas and $0.572 \bullet 10^{-3}$ $\mathrm{toe\cdot L^{-1}}$, where toe stands for "tonnes of oil equivalent", i.e. 41.868 GJ, according to the International Energy Agency - IEA [38].

The regression analysis presented in Fig. 2i demonstrates a statistical significance for the correlation between the global energy consumption and the company production similar to the electric correlation, exhibiting an R^2 value of 0.6637 if the whole period is considered. It can be noticed that the intercept has a negative value (although close to zero), due to the influence of the thermal energy contribution (already presenting this peculiarity) on the global consumption.

Regardless of the statistical correlation aspect, it is worth notice that the share of thermal energy on companies' global energy consumption is very small. From the collected data it emerges that only 55 % of the wineries use fuels (e.g. LPG, natural gas and diesel oil) in their production process; only six out of twenty present a relevant share of thermal energy consumption (more than 10 %, i.e., aligned with the literature reference value [4]). Therefore, only the 25 % of the analysed wineries exhibits substantial thermal energy consumption in the form of fuels. Specifically, when the average values over the three-year period are considered, companies ID02 and ID17 show shares of 11 % and 12 %, respectively; companies ID08, ID09, and ID10 present a share of approximately 22 %, and finally, company ID19 consumes slightly less than 40 % of its total primary energy consumption in the form of natural gas.



(caption on next page)

Fig. 2. Linear regression between electric energy consumption, thermal energy consumption and production data (a – electric energy consumption vs. production for year 2020; b – electric energy consumption vs. production for year 2021; c – electric energy consumption vs. production for year 2022; d – electric energy consumption vs. production for years 2020–2021–2022; e – thermal energy consumption vs. production for year 2020; f – thermal energy consumption vs. production for year 2021; g – thermal energy consumption vs. production for year 2022; h – thermal energy consumption vs. production for years 2020–2021–2022; i – total energy consumption vs. production for years 2020–2021–2022).

Therefore, for the sole purpose of validating the proposed methodology it was decided not to analyse the thermal energy from fuels (and consequently, the total primary energy consumption) in the remainder of the study, as they hold little significance. Nonetheless, considerations regarding the thermal energy consumption and the corresponding indicator will be presented where they can contribute to a better characterization of the production processes and of their associated EnPIs, as will be elucidated later.

Validation of the proposed methodology

A more detailed examination, as presented in Fig. 3a, reveals that the $EnPI_e$ displays a broader distribution range, characterized by a substantial variability and by the presence of outliers. This suggests that the energy performance of some companies could even markedly deviate from the average. In contrast, $EnPI_t$ exhibits a more constrained distribution profile, due to the above-mentioned reasons, i.e., the limited impact of the thermal energy in wineries, as compared to the electricity.

Therefore, relying solely on specific energy consumption indicators ($EnPI_e$, $EnPI_t$) with the goal of benchmarking energy efficiency performance among different companies may lead to inaccurate conclusions. Instead, the incorporation of indices WOI, OWSI and WPI in the analysis is helpful in differentiating companies based on their energy needs associated with various production processes and their overarching phases. The graphic representation of Fig. 3b, c and d delineates the distribution of the sample size in relation to the distinct values of the externalization indices WOI, OWSI and WPI (i.e., at increasing values of these indices).

WOI index reveals that, in most cases, companies buy a minor amount (<10 %) of products from external sources. There is, however, a non-negligible portion of cases in which firms purchase a variable percentage of products from outside (>10 %), which needs to be considered as it reduces the extent of in-house processing of the products and the associated demand for energy.

In a similar way, the WPI index demonstrates that most of the companies in this research bottle only a fraction of their overall processed products. This should lead to a reduced energy consumption of packaging operations. Instead, a detailed examination of energy requests of the companies of this sample, based on the OWSI index, was not feasible, due to the limited number of firms that use to buy sparkling wine from suppliers.

Therefore, to investigate the energy performance of wine making companies, it becomes more meaningful to analyse the graph represented in Fig. 4a, which provides additional information relevant for interpreting the results. Besides the externalization index WOI and the $EnPI_e$ value, reported on the x-axis and y-axis respectively, the production in hL is represented by the size of the bubbles. A comparison of the observed data with those cited in the international literature about wine industry indicates that most of the surveyed companies demonstrate favourable levels of specific energy consumption (i.e., below

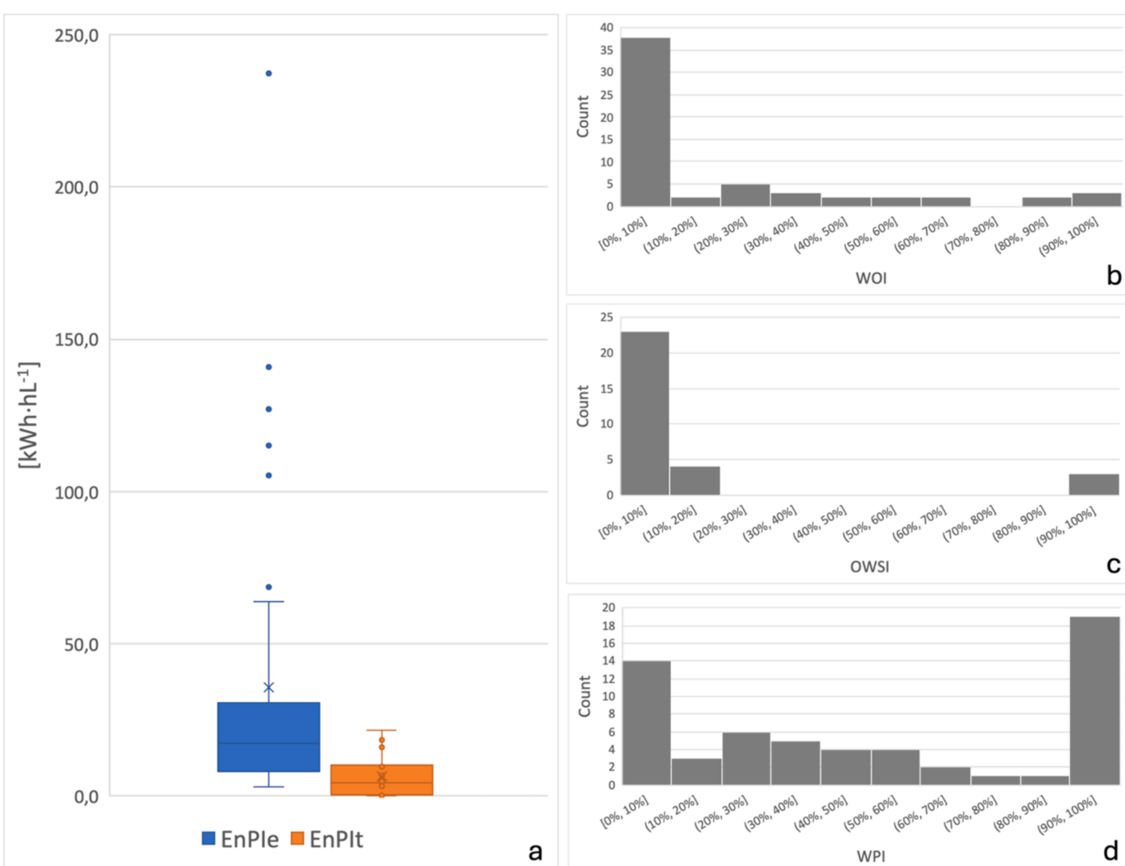


Fig. 3. Boxplot of $EnPI_e$ and $EnPI_t$ (a), distribution of companies according to the calculated values of WOI (b), OWSI (c), and WPI (d).

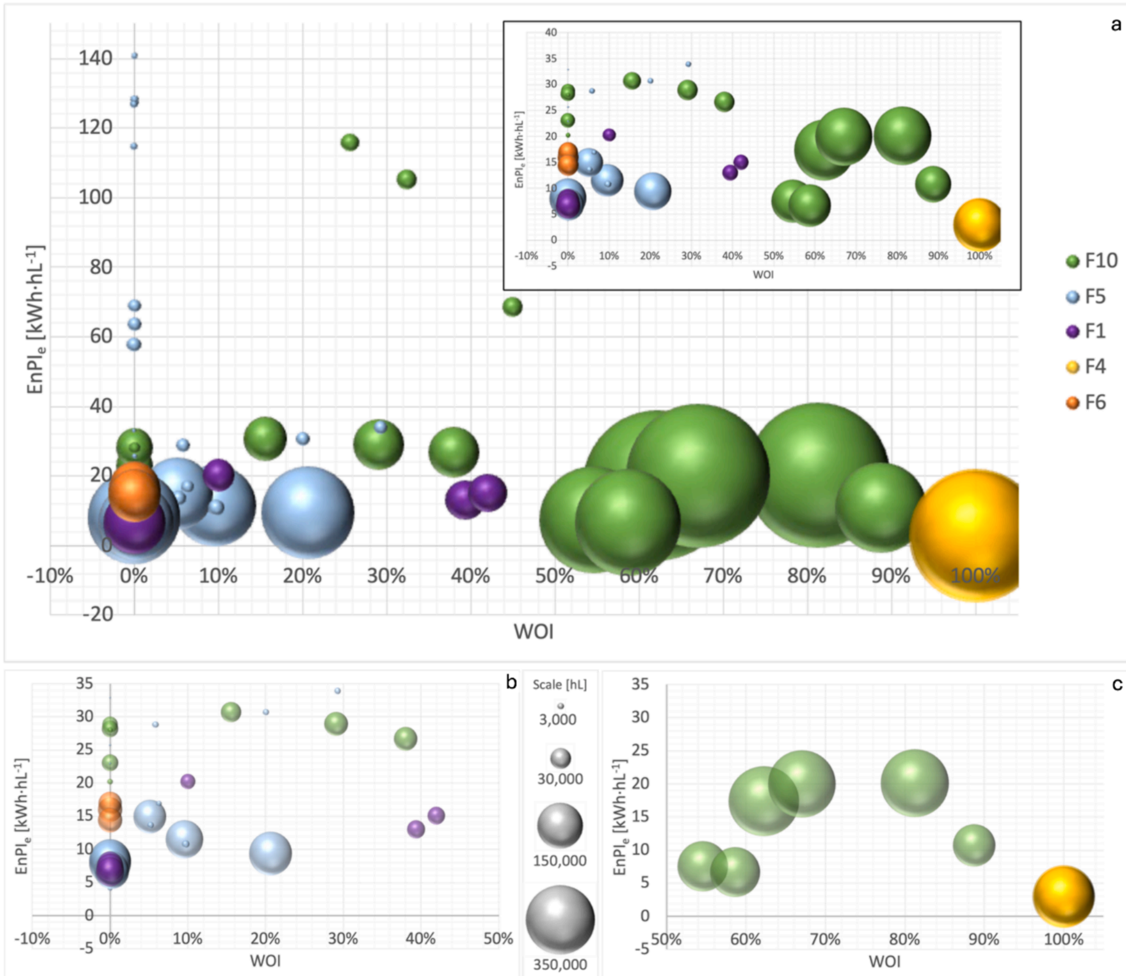


Fig. 4. $EnPI_e$ vs. WOI (a: overall results; in the top right box a detail of companies with consumption up to 40 kWh·hL^{-1} is provided; b: detail of companies internally processing the bulk of their final product. c: detail of companies predominantly engaging in outsourcing) – The bubble area represents the company size (pay attention: the reported scale refers only to graphs b and c).

Table 2
Data pertaining the 20 companies of the sample examined in this study, ordered by a descending value for $EnPI_e$; cells without any value indicate that the index cannot be calculated due to the absence of some inputs and outputs.

ID	F_k	WOI [%]	OWSI [%]	WPI [%]	$EnPI_e$ [kWh·hL^{-1}]	St. Dev. for $EnPI_e$ [kWh·hL^{-1}]	$EnPI_t$ [kWh$_t$·hL^{-1}]	St. Dev. for $EnPI_t$ [kWh$_t$·hL^{-1}]	Production [hL]
03	5	0 %	–	100 %	164.3	63.2	–	–	763
16	5	0 %	–	95 %	127.6	12.9	12.8	4.9	637
04	10	34 %	0 %	100 %	96.6	24.8	–	–	5,927
18	5	0 %	–	100 %	63.5	5.6	–	–	2,877
02	5	18 %	0 %	29 %	31.1	2.6	12.2	3.3	2,981
10	10	28 %	0 %	78 %	28.8	2.0	19.7	1.5	39,000
07	5	0 %	–	69 %	27.2	5.1	–	–	322
06	10	0 %	–	48 %	26.7	3.2	–	–	20,453
12	10	0 %	–	41 %	24.1	5.5	–	–	2,014
08	10	70 %	9 %	100 %	19.2	1.5	10.0	<0.1	359,007
20	1	30 %	0 %	0 %	16.1	3.7	–	–	22,026
17	6	0 %	–	0 %	15.8	1.3	4.4	0.8	44,150
05	5	7 %	0 %	17 %	13.8	3.1	–	–	3,298
01	5	12 %	0 %	30 %	12.0	2.8	0.5	0.2	114,057
09	10	67 %	0 %	48 %	8.3	2.2	5.2	1.8	173,071
11	5	0 %	–	26 %	8.2	0.2	0.2	<0.1	138,053
14	1	0 %	–	0 %	7.2	0.6	0.2	<0.1	57,023
15	5	0 %	100 %	19 %	6.9	0.2	0.3	<0.1	91,326
13	5	0 %	–	0 %	6.3	2.0	–	–	1,556
19	4	100 %	16 %	100 %	2.9	0.1	4.1	0.4	283,333

30 kWh·hL^{-1}), despite producing a wide range of products (red, white, still and sparkling wines).

The graphs of Fig. 4(b and c) clearly distinguish companies predominantly engaging in outsourcing (Fig. 4c), alongside those internally processing the bulk of their final product (Fig. 4b). It would be expected that these different production approaches would influence the companies' energy performance, but this is not so evident. Surprisingly, the analysis of this graph reveals that the specific energy consumption of both groups is similar, notwithstanding companies in the first group do not implement some production stages.

By considering, for instance, companies ID11 and ID09 (Table 2), it is possible to notice that their $EnPI_e$ values are quite similar, 8.2 kWh·hL^{-1} and 8.3 kWh·hL^{-1}, but the WOI externalization coefficients are 0 % and 67 %, respectively. Unlike what might be expected by observing only the values of the $EnPI_e$, considering that a phase is outsourced for ID09, the two companies are not comparable, since the latter buys most of the wine in partially-processed form.

Moreover, $EnPI_e$ of companies ID03, ID04, and ID08 shows a pronounced increase in energy efficiency related with the company size: the indicator decreases from 164.3 kWh·hL^{-1} to 96.6 kWh·hL^{-1}, and further down to 19.2 kWh·hL^{-1}. These companies are comparable, as each one of them bottles 100 % of their production. If the analysis were limited to the $EnPI_e$ only, the observed trend might be attributed to a scale effect, according to which an increase in production capacity typically should result in a disproportionately-lower increase in energy consumption. Instead, the index WOI indicates that the notable reduction in $EnPI_e$ should also be related to a rise in outsourcing levels, which span from 0 % to 34 %, and ultimately to 70 % for the largest company of the three. Therefore, overlooking this externalization index might lead to misinterpretations in energy benchmarking across these different companies.

Considering the four companies ID13, ID05, ID02, and ID04, characterized by increasing production capacities and levels of outsourcing (which somewhat offsets the rise in processed volume), it is possible to notice a higher specific energy consumption (indicating a lower efficiency) than the other companies. This observation, to be further detailed with an analysis of absolute figures and percentage increases on both axes, reinforces the argument that benchmarking evaluations must consider additional information, specifically differentiating production process reference models.

Hence, in Fig. 4, the set of companies has been segmented according to their production models F_k and indicated with different colours.

Collected data indicate that all the considered companies belong mainly (80 % of them) to two reference production models, specifically F5 (50 %) and F10 (30 %), which differ in the presence or not of the refermentation phase. Analysing the graph of Fig. 4b and c, it is possible to focus on the $EnPI_e$ values characterizing most companies. It is interesting to note that, while for F10 the companies are quite evenly distributed according to different WOI values (Fig. 4b and c), for F5 all the companies show limited WOI values (Fig. 4b).

From the analysis of the overall results, summarized in Table 2, several key insights can be discerned. Firstly, the F4 companies exhibits a higher energy efficiency, witnessed by an $EnPI_e$ average value of 2.95 kWh·hL^{-1}, in contrast to 11.7 kWh·hL^{-1} for the F1 group, 46.1 kWh·hL^{-1} for the F5, 15.8 kWh·hL^{-1} for the F6 and 34.5 kWh·hL^{-1} for the F10.

This result is aligned with expectations, since the F4 reference production model incorporates a lower number of stages in comparison to the others. Indeed, it indicates a company specialized in bottling, and hence it experiences a decrease in energy consumption due to improved production adaptability and a more dispersed electricity demand across various times of the year.

An additional noteworthy finding pertains to the $EnPI_e$ across the two groups F5 and F10. In accordance with predictions, results corroborates that those two kinds of firms, engaged in more extensive processing operations, incur higher energy consumption. This is

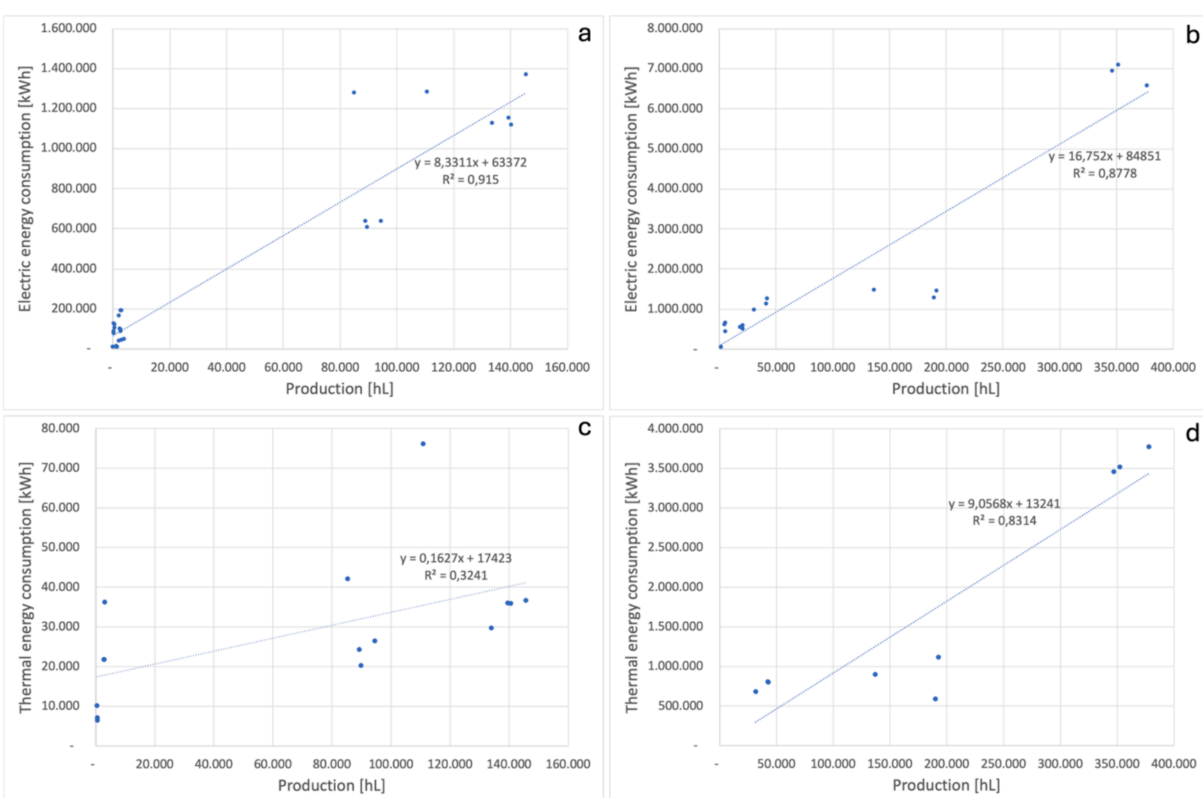


Fig. 5. Linear regression between electric energy consumption and production for reference production process model F5 (a) and F10 (b), and between thermal energy consumption and production for reference production process model F5 (c) and F10 (d).

somewhat concealed due to the outsourcing of certain production process phases. Consequently, if the assessment of energy efficiency across various wineries had been solely based on the consumption per unit of product, it could have led to a notably-significant conceptual misjudgement. This would involve erroneously deeming companies with high outsourcing rates are efficient in terms of SEC.

The graphs in Fig. 5 underscore a pronounced linear correlation between production and energy consumption across two distinct reference production models, namely F5 (Fig. 5a) and F10 (Fig. 5b). This is an advancement from the preliminary analysis in Fig. 2d, which showed an electric overall R^2 value of about 0.6371 (calculated on the whole experimental dataset). Segmenting the data by F_k resulted in an R^2 of about 0.9150 for F5 and about 0.8778 for F10, thus validating the cluster categorization employed in this study. With regard to thermal aspects, on the other hand, the graphs in Fig. 5c and d show a marked correlation only for F10, with a R^2 value of 0.8314, while a low correlation for F5, with a R^2 value of 0.3241. Upon investigating the issue, it was discovered that companies ID08, ID09, and ID10 in the F10 category all have industrial steam-production boiler systems for various uses within the production process, resulting in significant thermal energy consumption. Additionally, company ID19, which has the largest share of fuel in its global primary energy consumption (approximately 40 %), falls under the F4 category as a “pure bottler”. In this case, a frequent use of steam for process needs was also observed.

It can be inferred that there is a correlation between thermal energy consumption and production. This correlation is not closely related to production process reference models, but, rather, to the adoption of steam within the process.

Final remarks

Considering the illustrated findings, it is therefore cautious to distinctly assess wineries’ energy performance based on cluster association, specifically in terms of reference production models and outsourcing indexes. For F10 companies, while the scale effect appears to be evident, their diverse outsourcing levels make direct comparisons challenging. If considering, for instance, companies ID08 and ID09 from the F10 cluster, which includes sparkling wine production, it is possible to observe that they exhibit similar outsourcing indices (average WOI around 70 % and 67 %, respectively), making them comparable in terms of energy consumption. Notably, ID08 has nearly twice the production of ID09 but displays an $EnPI_e$ more than twice as high, defying the expected scale effect. A contributing factor, as inferred from comparing the WPI index, could be that ID08 packages its entire production, whereas ID09 packages less than half of it. Given that, typically, far less than 50 % of electricity consumption is attributed to the packaging stage, and this suggests other underlying reasons for the higher specific consumption, to be inquired by performing an energy audit in the plant facility.

Furthermore, examining companies ID04 and ID10, both in the F10 and comparable in terms of WOI outsourcing index (around 34 % and 28 %, respectively) and WPI bottling index (around 100 % and 80 %, respectively), it is possible to observe that the specific consumption of the former, approximately 97 $kWh \cdot hL^{-1}$, is more than three times that of the latter, which is around 29 $kWh \cdot hL^{-1}$ (an average on the three available years is considered). Since the production volume of the former is roughly 6.5 times smaller, this behaviour could be partly attributed to climatic factors, especially its location in Southern Italy.

A comparison between two similarly-sized companies in the F5 cluster, namely ID03 (average total production of 763 hL) and ID07 (average total production of 322 hL), is insightful. Both wineries have a WOI externalization index of 0 % (i.e., they have an entirely internal production) and WPI indices of approximately 100 % and 69 %, respectively. The $EnPI_e$ for the former is 164 $kWh \cdot hL^{-1}$, i.e. six times higher than for the latter (approximate 27 $kWh \cdot hL^{-1}$), suggesting the presence of other factors influencing this significant disparity in energy efficiency.

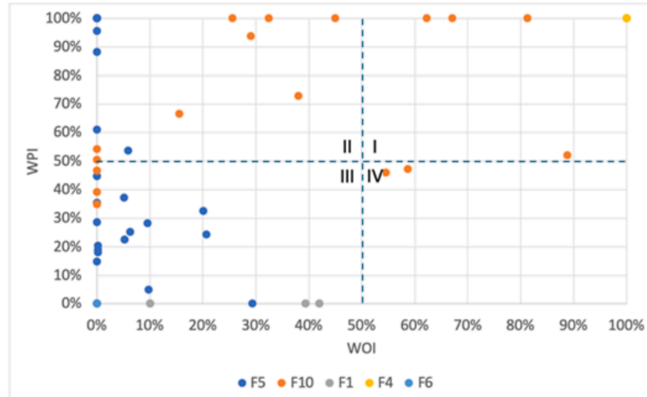


Fig. 6. WOI vs. WPI: scatter plot.

Considering the cases discussed above, the indicator’s value, determined through immediate benchmarking using the outlined methodology, should trigger a more comprehensive analysis of a company’s energy efficiency. The objective would be to explore the causes behind the observed specific consumption levels and prevent any potential inefficiency. It circumvents erroneous and premature judgements, relying on a data collection approach that is both time-efficient and universally applicable across the industry’s varied production contexts.

The scatter plot in Fig. 6 displays the correlation between the externalization index WOI and the packaging index WPI. The graph can be conceptually divided into four quadrants, symmetrical across the 50 % lines, as indicated in the figure.

- Quadrant I encompasses wineries that acquire most of the final wine product’s total volume in partially processed form, and handle a major portion of its packaging. These entities are generally known as “pure bottlers,” selecting products to meet specific market or customer needs and fully leveraging the cost of transformation, given their direct link to the supply chain’s end segment.
- Quadrant II includes wineries that perform the bulk of the production and packaging processes for the final wine product “in-house”.
- Quadrant III is marked by low values in both the externalization index WOI and the packaging index WPI, identifying “service” companies. These companies predominantly internalize the production of the final wine product and sell a significant share of it in bulk.
- Lastly, quadrant IV identifies companies that procure most of the total volume of the final wine product and chiefly sell it in bulk. Labelled as “outsourcing” companies, they delegate the majority of their operations to external entities.

Note that some types of companies have a specific placement on this scatter plot: the points representative of bottling companies (F4) are always in correspondence to WOI=100 %, the winemaking companies (F1), and the winemaking and refermentation companies (F6) are always placed in correspondence to WPI=0% (hence, on the horizontal axis). Even if not present in Fig. 6, also the points representative of companies F2, F3, F7 would have the same specific placement of the points pertaining to the company type F6 on the horizontal axis, i.e. at WPI=0%.

As regards the placement of analysed companies within the different quadrants, it becomes apparent that most of them are in quadrants II and III, indicating a strong inclination towards the internalization of the fermentation activities. Both quadrants are populated by companies belonging to various reference production models, with a clear predominance of F5 and F10. Companies favouring externalization of that process phase, are limited in number in the considered sample, and are evenly distributed across quadrants I and IV. These quadrants are exclusively occupied by companies from F10. This result suggests an aptitude of F5 wineries to purchase a minority share of the already-vinified product, while F10 wineries are more likely to purchase inputs from outside, up to majority shares (>50 %).

Conclusions

This article presents an innovative approach aimed at enhancing energy efficiency in the wine industry by allowing EnPIs benchmarking between comparable entities, enabling both the assessment and the monitoring of wineries performance over time. The proposed method is designed for ease of implementation, requiring minimal input data, typically readily available. Specifically, it eliminates the need for collecting detailed energy data within the winery or conducting extensive energy audits, and, instead, it relies on basic input and output product data. To provide a more nuanced understanding of energy usage, wineries are classified into eleven distinct reference models, categorized by their process types. Additionally, three “outsourcing” indices have been defined (namely: WOI, OWSI, WPI); they are useful in identifying the energy consumption related to some key-stages of the production process, particularly impactful.

To validate this methodology, a data collection form was developed and submitted to twenty wineries across Italy, representative of the sector in terms of size and range of products (red, white, still, and sparkling wines).

The results highlight the existing constraints of the conventional methodology, based exclusively on the EnPIs for benchmarking energy performance, and, for the explained reason, potentially leading to erroneous conclusions. Indeed, the most used EnPI is calculated by simply dividing the energy consumption by the produced volume of wine, regardless the type of production process and the phases effectively performed within the considered facility. Instead, the categorization into distinct reference production process models and the incorporation of the three above-mentioned indices enable a more thorough analysis of a winery’s energy consumption across the entire production process. This approach allows revealed that some companies, which seem highly efficient if considering only the global EnPI, have, in reality, critical areas that underscore the necessity for more detailed evaluations. Thus, the methodology advocated here demonstrates its effectiveness in enabling accurate benchmarking of energy performances in wineries. The validity of these methodological choices is further reinforced by correlation analyses, whose outcomes substantiate the effectiveness of the proposed method.

For all these reasons, it represents a valuable tool not only for winemaking companies, but also for the decision-makers and the various stakeholders dedicated to sustainability enhancement. Specifically, given the robust commitment to enhancing the environmental sustainability performance of the whole wine sector, this tool could facilitate the development of an international energy efficiency database of all companies operating in this sector. Furthermore, it would allow extending and deepening the energy assessments in the wine sector carried out so far by numerous researchers, thus opening new scenarios and research horizons.

In the authors’ intent, this database would support, besides the improvement of energy performances, also the planning, promotion, and establishment of certification standards. Such a resource would be precious in guiding industry-wide efforts towards sustainability, enabling the sharing of best practices, and fostering a collaborative approach in the wine industry. Concluding, such an international database, when available, could serve as a central repository for data on energy efficiency and sustainability metrics, aiding the management in the benchmarking and in the continuous improvement of environmental performance across the sector.

CRediT authorship contribution statement

Gellio Ciotti: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Zironi:** Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Bietresato:** Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Rino Gubiani:** Supervision, Resources, Project administration, Funding acquisition. **Roberto Zironi:** Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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