COMBINED INVESTIGATION OF INDOOR CLIMATE PARAMETERS AND ENERGY PERFORMANCE OF AGRO-INDUSTRIAL UNITS IN WESTERN MACEDONIA

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ABSTRACT

In the key challenges facing the agricultural sector nowadays, that is the economic and sustainable development, issues as the respect for the environment and the rational use of all forms of energy prove to be significant. It should be noted that high energy demand is not the case during cultivation, rather throughout transport, processing, packaging and especially conservation; the above processes take place in the so-called agro-industrial units.

The proposed work deals with the presentation of a methodology for evaluating the potential of agro-industrial units to achieve the aforementioned targets of improved indoor climate and energy performance. The effectiveness of the proposed methodology is validated upon the results and the experience gained upon three case studies in Western Macedonia, Greece; a warehouse, noting that warehouses are characterized by significant refrigeration loads, while thermal comfort issues are also of interest, given the low temperatures workers face, a winery, noting that wineries present significant interest on a research level, combining Indoor Air Quality (IAQ) issues related with substances emitted through the wine production, and the need for minimizing conventional energy consumption, as well as the case of an agricultural products drying unit, pointing out the dominant role of the drying process on energy quantities.

KEYWORDS

energy; IAQ; thermal comfort; warehouse; winery; agriculture

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1. INTRODUCTION

The discussion about the global warming and the climate change is very intense lately. The Paris agreement aimed at limitating the global temperature increase, while adopted the so-called 20/20/20 targets of the EU, as they are reflected in the relevant EU Directives [1, 2]. In addition, the oldest human-developed sector, the agricultural sector, continues to grow and evolve globally, with the ultimate goal of fully meeting the alimentary needs of modern societies. The difficulty of achieving this goal is commensurate with the increase in the world population and rising standard of living, as these situations automatically lead to an increase in demand for food [3]. Compensation is seen as the development of technology, which allows for increased production without the parallel increase in arable land or the demand for more labor

force. In all this, the only variable that has not been taken into account is the demand for any form of energy. All activities in the food sector depend on some form of energy; as a result, demand for the agribusiness sector has grown exponentially over the years. Indicatively, it can be said that direct energy consumption in agriculture was about 2% of total energy consumption in 2011-2013. Greece is above the average of OECD countries, with the agricultural sector consuming about 4% of total energy produced [4]. In addition to the energy required to grow the crops, even greater amounts are required for the processing, packaging, maintenance and marketing (transportation and sale) of food items [5]. The wine sector is highly vulnerable to climate change, especially due to the dependence of vine growing on climatic and environmental conditions, while their carbon footprint is significant, taking into consideration aspects of energy use, waste management, water use, soil management and transport of production [6]. The need for increasing the sustainability of wineries, as well as the important role of research on achieving this aim, is highlighted in the work of Santini et al. [7]. Regarding energy issues, Smyth and Nesbitt [8] review energy usage in English wineries, indicating specific points of the production process where energy efficiency can be implemented. Malvoni et al. [9] concentrate on a specific winery in South Italy; cooling proves to be the most energy intensive use, while RES solutions are also examined. The implementation of RES in Spanish wineries is investigated by Garcia-Casarejos et al. [10]. Da Ros et al. [11], investigate the potential of producing biogas from thermophilic anaerobic digestion of winery residue, quantifying the values of energy that can be produced on the level of the installed wineries in Italy. Filho et al. [12] investigate biogas and methane production potential, on a winery in Brazil. Carroquino et al. [13], evaluate the operation of a standalone renewable energy system, installed in a winery in the North-east of Spain.

Regarding warehouse units, Li et al. [14], on the basis of simulation analysis, discuss the advantages of integrating energy storage in refrigerated warehouses. Ho et al. (2010) [15] numerically investigate air temperature and velocity distribution inside a refrigerated warehouse, through different positions of cooling units. On a wider perspective, Hacket et al. (2005) [16] present the results of plant-wide energy audits of seven fresh-fruit and vegetable processing plants in California, demonstrating significant opportunities of energy efficiency for both small and large size processing plants.

The proposed work, aims at presenting a methodology for evaluating the indoor environmental conditions, as well as the energy performance of agro-industrial units. The methodology is evaluated and validated upon three case studies in Western Macedonia, Greece, i.e. a warehouse, noting that warehouses are characterized by significant refrigeration loads, while thermal comfort issues are also of interest, given the low temperatures workers face, a winery, noting that wineries present significant interest on a research level, combining Indoor Air Quality (IAQ) issues related with substances emitted through the wine production, and the need for minimizing conventional energy consumption, as well as the case of an agricultural products drying unit, pointing out the dominant role of the drying process on energy quantities.

2. MATERIALS AND METHODS

2.1 Description of Units

All units are located in Western Macedonia, Greece. The climate in this region is characterized as the coldest one, ranked on D climate zone according to the Greek version of the EPBD [17]; rainfall is generally moderate, summers are mild and snowfall is frequent in the winter months. Average annual temperature of 15.5 °C is reported [18], while in the winter months, temperature may reach -15°C or even lower; the relative humidity is 72.2%, while 63.8% annually. It should be noted that the climatic conditions in the area of the winery and the warehouse are slightly different compared to those presented, as they are affected by the respective Lakes of Polyphytos and Vegoritida respectively.

The winery premises are comprised of three floors, while a house is attached to the premises (figue 1); the screening of the grapes takes place on the upper floor, while the grapes fall on the stainless tank located on the ground floor, with the help of gravity. This floor is the main place of vinification, where most of the tanks lie; in this floor the only office room of the premises is also located. On the, mostly, underground floor, the remaining vinification tanks lie (architecturally constituting a common place with the ground floor), and two storage rooms for the conservation of the champagnes, as well as a room where bottling process takes place.

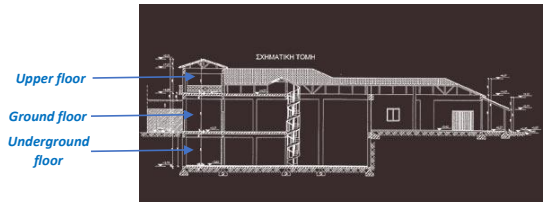

Figure 1. Lay-out of the examined winery

The warehouse premises, covering an area of 4000 m^2, are used for collecting, processing and packaging of fresh fruit. Producers, after collecting and packing the fruit at their place of cultivation, transport it and deliver it to the cooperative's landing ramp. This is where the first quality control of products is done by specialized auditors. Subsequently, depending on the results of the inspection, the quality and size of the products, these are either directed to the sorting line for further processing, or to the workplace where they are rechecked, processed and packaged, or directly to the labeling line (most quality products), where they receive the corresponding sticker, are palletized and marketed immediately. At the sorting line, fresh fruits are washed, re-checked, calibrated and driven to the workplace where, they are subjected to more stringent quality control, processed and packaged according to commercial requirements. Processed fruit packs pass through the labeling section, then palletized and stored in the cooling chambers, where they are maintained until sold. Products that have been damaged during the maintaining time must be re-inspected in order to avoid the export products which do not meet the requirements for their sale.

Finally, the drying units installation are comprised of the quality analysis and offices zone, and the main area, hosting the dryers.

2.2 Methodology

The proposed methodology is based on experimental and theoretical analysis, including the exploitation of simulation means. Experimental investigation includes extensive measurement campaign regarding indoor climate thermal parameters, considering also the concentration of substances affecting IAQ. The results of the parameters can be exploited for the assessment of indoor

climate. Moreover, in the development of the energy model, data from indoor climate measurements regarding thermal parameters can be utilized, while values of specific parameters related to the efficiency of the individual devices of the plants can be determined. Formulation of a reliable energy model for the plants allows the evaluation, on an economical and environmental basis, of proposals for improving indoor climate and/or reducing energy consumption.

Regarding the calculation of the energy consumption of the respective devices, it has been preferred to adopt simple approaches, taking into consideration the limitations with the availability of input data for the cases of more sophisticated models.

Focusing on the case of the winery, the energy consumption related to the covering of heating/cooling loads (E_{th}) of the offices is based on EN ISO13790 [19] monthly method, anticipating the calculation of heat losses and heat gains, internal and solar, while taking into consideration the performance of the heat pumps (eq. 1a):

$$E_{el} = \frac{E_{dth}}{SEER\ (SCOP)} \qquad (1a)$$

where:

- E_{dth}, the thermal energy load (demand) of the storage spaces
- SCOP (SEER), the seasonal efficiency of the heat pump for heating or cooling respectively

The SCOP of the heat pump (air-to-air one) refers to seasonal performance; given that the value of this index depends on ambient temperature (heat source temperature) and room temperature (heat sink temperature), as well as to the working load imposed, the determination of this index is too demanding, requiring measurements over a sufficient time-period. In the proposed approach, it has been preferred to use a representative value, based on the treatment of similar devices according to the Greek version for the adoption of European Performance Buildings Directive (EPBD) [17, 20].

The energy consumption related to the covering of cooling loads (E_{dth}) of the cooling chambers was also based on EN ISO13790 [19], monthly method, while taking into consideration the performance of the cooling units (eq. 1b):

$$E_{el} = \frac{E_{dth}}{SEER} \qquad (1b)$$

In terms of the SEER for the cooling chambers, the respective Directive for Greek version of the EPBD (TEE, 2017; EU, 2010) [20] has been used as reference guide.

Electrical consumption of the appliances (on site processes, lighting, other) was calculated on the basis of a simple equation, where P indicates the appliances power and t time:

$$E_{el} = P \cdot t \qquad (2)$$

The estimation of the time the respective appliances operate is a rather complicated task, presenting significant uncertainty. For that reason, it has been preferred to suppose a value characterizing the complete category of appliances (on-site processes and other equipment).

3. RESULTS AND DISCUSSION

In table 1, the values of measured thermal comfort and IAQ parameters (namely CO_2 concentration) are presented for the main area of the winery. As one may see, indoor conditions are rather warmer than ambient ones, nevertheless, especially after fermentation period, which is by winter time, the non-conditioning of the vinification area is responsible for the temperature lying below thermal comfort

level. Relative humidity is high, on the edge of the thermal comfort limits; this can be potentially attributed to the rather low temperatures of the specific space. Inadequate ventilation, combined with the fermentation or the presence of people leads to values of the CO_2 concentration exceeding acceptable limits.

Table 1. Meteorological and environmental parameters at the installation site and at the office throughout fermentation period and after fermentation

Parameter	During fermentation		After fermentation	
	Indoor	Ambient	Indoor	Ambient
	Mean	Mean	Mean	Mean
T (°C)	21.4	17.8	19.5	8.2
RH (%)	59.5	65.2	60.7	74.3
CO_2 (ppm)	1414.8	-	1040.9	-

Regarding the main area of the winery, in figure 2, the CO_2 concentration during fermentation period is presented. Again, one may see the effect of night ventilation on decreasing CO_2 concentration, while the values of the various sensors are quite close, demonstrating rather homogeneous environment in terms of (unfortunately not acceptable) air quality.

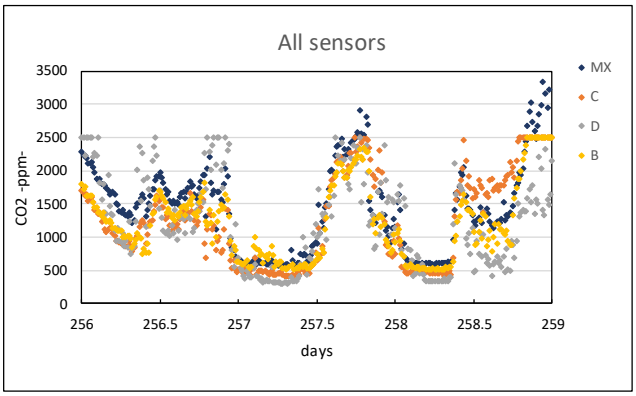

Figure 2. CO_2 concentration in vinification area over a specific period of measurements

In table 2, the values of thermal comfort and IAQ parameters (namely CO_2 concentration) are presented for the main area As one may see, during fermentation indoor conditions lie close to thermal comfort ones on a temperature level; nevertheless, after fermentation period, which is by winter time, the non-conditioning of the vinification area is responsible for the temperature decreasing and lying below thermal comfort level. Relative humidity is high, on the edge of the thermal comfort limits; this can be potentially attributed to the rather low temperatures of the specific space.

Table 2. Environmental parameters at the main vinification area

	During Fermentation		After Fermentation	
	Mean	Min-max	Mean	Min-max
T (°C)	18.3	14.6-22.0	14.5	11.4-16.1
RH (%)	70.8	40.6-100	71.0	54.2-99.4
CO_2 (ppm)	1966.9	239-5000	562.7	325.0-1155.0

Regarding VOCs, which were also detected and quantified, the effect of night (and partially daily) ventilation resulted to the detection of higher VOCs concentrations for the non-winemaking period, taking place by winter time. The predominant VOCs for the storage room are a-pinene and 3-carene, i.e. terpenes, naturally emitted from the cork and wood (pine) made barrels of the wine storage tanks.

In terms of energy analysis, simulated results present a deviation of 16.1%, which is quite satisfactory given the related uncertainties (devices operation times, heat pumps/chillers performance, etc.).

in figure 3, the share of the main processes to the total energy consumption is presented for the case of the winery, according to the developed energy model. It is evident that the cooling and refrigeration processes, together with heating, constitute the most important share, in agreement with the findings of existing literature [8-9].

The replacement of the winery chillers with more efficient ones, leading to energy consumption reduction of 38.5 %,

and the installation of PV panels of an area of 250 m^2 covering 70% of the energy needs of the plant, demonstrate a pay back period of 3.6 years; evaluation has been based on the formulated energy model.

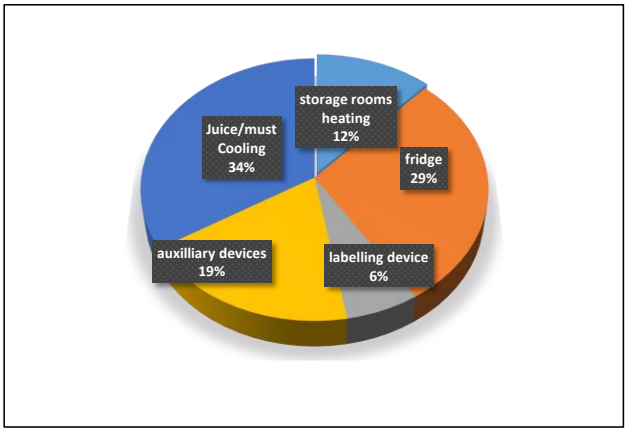

Figure 3. Calculated energy consumption share of main processes for the winery

Figure 4 provides some insight on the operation of the refrigeration chambers of the warehouse. One may see the temperature fluctuation inside the storage chambers; temperature ranges between 0.8°C and 2.2°C with an average value of 1.3 °C, that is, the fruit preservation temperature, in other words the set-point of the cooling units, are observed. A time-step of 2 mins has been selected, in order to accurately record the temperature fluctuation.

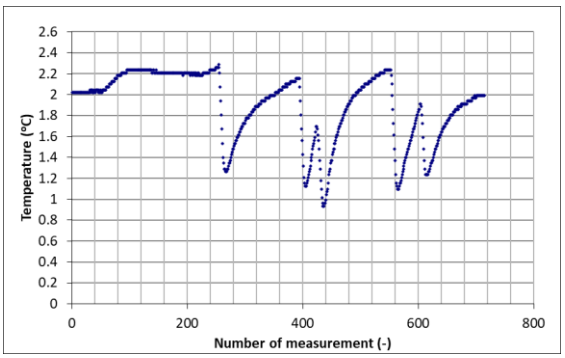

Figure 4. Cooling chambers temperature throughout a typical operation period

In order to assess the satisfaction of workers regarding their working environment, mainly on thermal level, but regarding IAQ issues also, and how this could potentially affect their working efficiency, a questionnaire has been developed and shared to 15 people of the warehouse. This action has been considered necessary, due to the fact that the priority of the premises is sheltered, but not closed on all sides with regard to the ambient environment; consequently the workers are exposed on low temperatures by winter time, and potentially high by summer time. The respondents of the questionnaires hold different positions in the company, working either in the workplace area, or frequently entering the storage chambers or mainly staying in the office. Figure 5 demonstrates the above in terms of sensation.

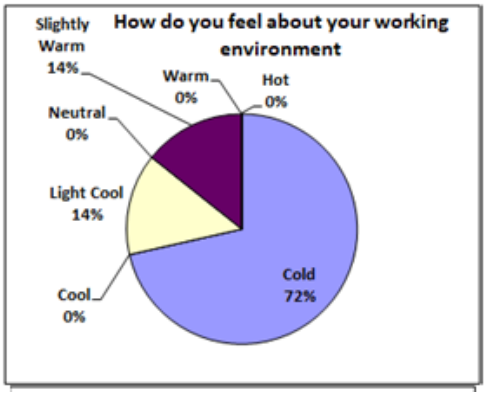

Figure 5. Questionnaires' analysis

It is evident that workers consider their workplace cold (72%) or slightly cool (14%). With the evaluation of the questionnaires, it is also understood that the employees would work in a warmer workplace, while the lighting of the facilities is incomplete. In conclusion, it should be emphasized that in a general context, employees are dissatisfied with the thermal comfort conditions in the business premises and this is something that directly affects their work efficiency.
Regarding the drying unit, the analysis demonstrated that the most important

consumption is that of the drying process. Within this context, it has been decided to put more emphasis on the operation of the respective systems, attempting to optimize their energy performance.

4. CONCLUSIONS

The elaborated indoor climate measurements have allowed the evaluation of the environmental conditions the workers are subject to. Moreover, the indicated parameters proved to be helpful for the energy analysis. For all cases, main difficulties were related to the requirements of the measuring procedure, regarding time, equipment and minimization of the interaction with the workers, as well as to the high uncertainty accompanying the parameters entering the energy model, including agricultural products quantities and devices operation time. Validation results demonstrated that the proper design of the analysis may lead to the development of safe conclusions, regarding indoor climate and energy consumption. The proposed methodology may be exploited towards the environmental and energy upgrade of units with special and diverse characteristics, as the agro-industrial ones.

AKNOWLEDGMENTS

The authors of this work would like to thank the owners of the respective agro-industrial units, Karanikas winery, ASEPOP Velvento Cooperative, and 4G Foods for allowing their access and work on the premises, as well as for the provision of all necessary data for the analysis.

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