Towards a competitive use of solar driers
A case study for the lumber industry

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Abstract

The aim of this paper is to contribute to the discussion of the methodology that leads to a better systematization of the knowledge on solar drying. Based on a case study for the lumber industry, the options and solutions adopted will be reported, along with their evaluation criteria and existing or developed tools. The kilns have 50 m3 interior capacity and proved the capability to dry maritime pine 27 mm thick, from green to 12% moisture content in about 33 days. The performance of the drying process has a significant seasonal and weather dependence, so an interactive control system is essential in order to profit as much as possible from the favorable exterior conditions.

Keywords: *solar dryer, wood, kiln, energy, heat, drying control*

1 Introduction

The use of solar energy for drying purposes is in general meant to save drying costs, primary energy and to reduce CO_2 emissions. For these reasons over the last few decades, several solar drying systems have been described for agriculture and forest products, many of them reported in Europe [Ronald Voskens, et al] where the performance of the drying process has a significant seasonal dependence. This trend has been triggered by the promotion of rational energy use and renewable energies sources by European Union next to industrial manufactures.

Although several innovative versions and applications have been reported, there is an important lack of reliable information on the energy efficiency of solar energy based driers which is essential to gather in order to establish such driers as an acceptable industrial alternative when compared with traditional types based on fossil sources of energy.

The aim of this paper is to contribute to a discussion on the methodology that leads to a better systematization of the knowledge about the solar drying area, namely on the energy efficiency, wood quality, drying duration and drying costs. Based on a case study for the lumber industry, the options and solutions adopted will be discussed, along with their evaluation criteria and existing or developed tools.

The information provided in this paper is a result of an applied research and demonstration project, partially financed by EU founds, and included in PRIME program, under the financial management of Innovation Portuguese Agency. The name of the project was – SECMAD which means "energy efficient wood drying".

The topic of this paper is included in the theme of energy efficiency processes.

2 Brief description of wood drying

To dry wood the surrounding air must be sufficiently dry so as to absorb its moisture. This can be accomplished either by ventilating or heating the kiln air. During the first stage of the drying cycle, air easily absorbs the moisture and relative humidity inside the chamber may keep close to 100%, with water often beading on the walls in a based-greenhouse structure. As the process evolves wood moisture expelling turns increasingly difficult, mainly due to the low diffusion speed of moisture in wood. At a final stage, when all free water has been lost, only cell bonded moisture is left to be extracted. This final stage is more time and energy consuming, since it requires additional energy supply to break the bonds. Quality regards are present in the intermediate and final drying stages. In this process temperature, relative humidity and wood moisture content are the most relevant quantities (Titta et al. 2002, Steinmann 1995, Joly et al., 1980)

2.1 Air and conventional drying

The main purpose of lumber air drying is to evaporate as much water as possible before end use or transfer to a kiln drier. Air drying can usually proceed until wood moisture content attains 25% to 20%. Another drying methodology must follow if a lower target value is desired. Air drying saves energy costs and reduces required dry kiln capacity, but presents the usual limitations of an uncontrolled process and in Winter months drying rates cold be very slow, particularly in raining periods. By other hand under hot dry winds in Summer, quality may be degraded as a result of surface shrinking and end splitting, due to severe differential drying (surface vs. interior). Another drawback of this method is the space and long time storage costs of wood stacks, implying large immobilization periods (Leavengood, 1998)

In kiln drying processes, higher temperatures and faster air circulation are used to considerably increase drying rate. Specific drying schedules/profiles have been developed to control temperature and relative humidity in accordance with the moisture content and stress situation within the wood, in order to minimize shrinkage-caused defects and improving quality. Conventional drying is one of the most expensive processes in wood industry, due to the enormous thermal energy expenditure (Joly et al, 1980).

2.2 Solar dryer

In solar kilns thermal energy comes from solar radiation and can be a reasonable and promising method for almost any wood industry to gain the capacity to dry wood at reduced costs (Awadalla et al. 2004, Greensfelder 1998, Reuss et al. 1997). Known past implementations rarely use control embedded in the drying process, resulting in poor quality and dry time improvements. However, current instrumentation capabilities allow cost effective control solutions.

In the SECMAD Project, the whole concept of a kiln drier has been reviewed, namely to reduce its cost and enhance solar energy collection (side walls, double ceiling, etc.). The concept uses natural and mechanical ventilation controlled by an instrumentation and control system, accounting for both internal kiln and external environment conditions. Fig. 1 and 2 illustrates the drier prototypes' structure and Fig. 3 shows the ventilation and heating model, with colors indicating the inside psychrometer conditions of the air: red arrows give indication of direction of hot and dry air while blue ones indicate the direction of cold and humid air. Green arrows indicate the entrance of outside air, being heated by solar air collector at side wall and ceiling. Moisten air is expelled through vents by forced flow, while the fan is turned on. This solar and ventilation dryer is intended to be considerably faster than the traditional open air method and much lesser energy consumption and cost expensive than conventional kilns.

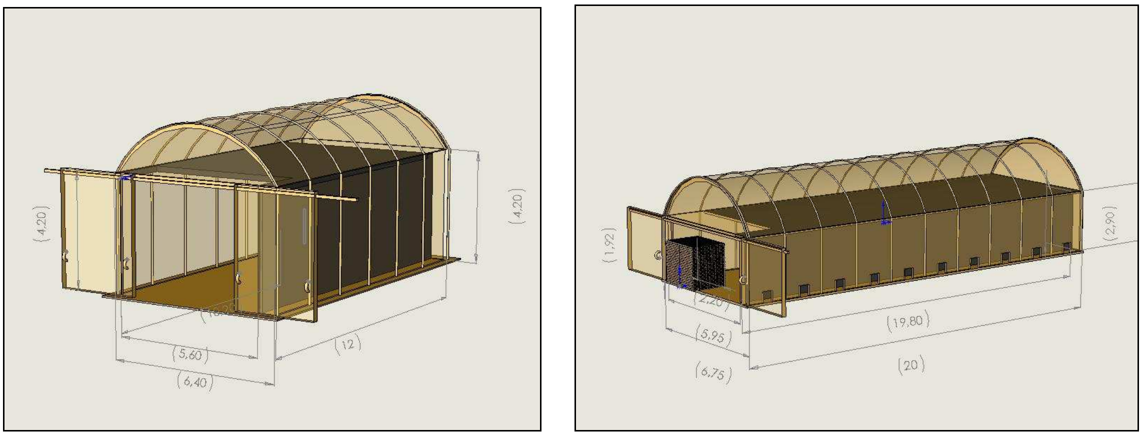
Fig.1. *Solar lumber kiln dryer (prototype 1).*

Two prototypes were installed in two different industries. Prototype I is more appropriate for fresh water charged lumber, which is necessary to remove as fast as possible in order to avoid mould and blue stain when drying

softwoods. Prototype II is more appropriate to dry products that need higher temperature and prove easier to remove the water without risk of checks and deformations (poles, agriculture fruits, etc.).
Dimensions of kilns are represented in both figures. In the example of Fig. 2, where the dimensions are

Door and interior height – 4 m
Inside length – 10 m
Inside width – 5,60 m

the interior available volume is 224 m^3, but the stacking of the wood, ventilation requirements and spaces from the rear wall and from front door gives a real maximum usable wood volume of approximately 75 m^3.
In practical tests and later in normal industrial production the volume of wood was 40 m^3 which correspond to an amount of water to be removed from green wood to 15 % M.C. of approximately 16 000 liters.



(a) (b)

Fig. 2. *Dimensions and concept of two different prototypes,*
a) ventilation priority; b) temperature priority.

The model of temperature distribution and air circulation is shown in fig. 3.

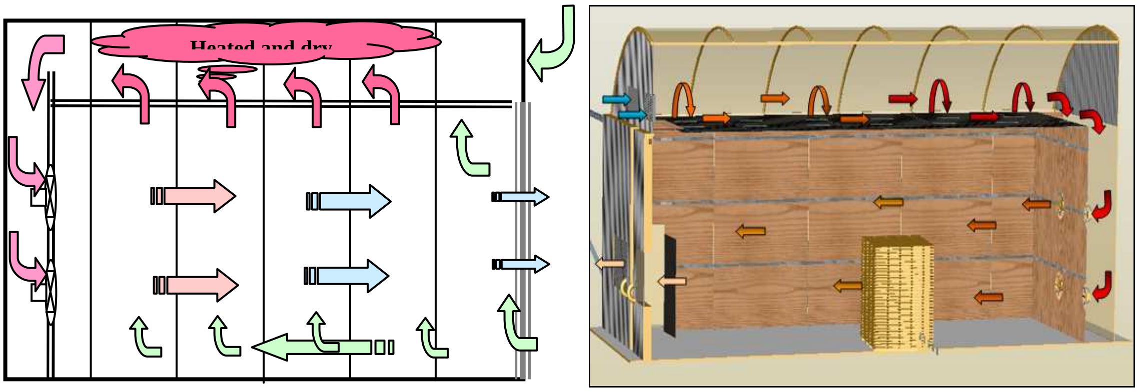


Fig. 3. Heat model of solar lumber kiln dryer. (cut sights).

The air speed on the ventilators was 13,5 m/s witch provides a volumetric speed of 160 m^3 per minute, or in other words, an average of 50 renovations per hour. The average air speed on the surface of the boards was 1,7 m/s on the stacks near the ventilators and 0,7 m/s on the surfaces of stacks more far way from the ventilators.

3 Evaluation methodology and drying control

To establish solar kilns as an industrial tool, performance tests must be carried out during different season periods, based on objective data taken from measurement and analysis of several parameters. In this work, the inclusion of permanent measurement and control instrumentation has been adopted , which is an innovative aspect introduced by INETI's SECMAD project.

The main objective of the measurements and analysis is to characterize solar kiln performance, regarding operation time and costs under several weather conditions, as well as the related evolution of relevant physical quantities like:

- temperatures, relative humidities (RH) and moisture contents (MC) of drying wood, inside the kiln chamber;
- temperature and relative humidity on the outside environment;
- temperature and relative humidity in the solar collector zone;

Wood equilibrium moisture contents (EMC) in the interior and exterior of the kiln are also calculated from these measurements, as they are usual and useful drying indicators in the lumber sector that integrate the contribution of both temperature and relative humidity conditions. Additionally, energy expenditure, solar radiation and air convection can also be measured.

Optimization of operational conditions to reduce drying time was considered and can be carried out automatically by the control instrumentation, where a dedicated fuzzy algorithm takes into account the restrictions imposed by quality issues and acts upon the ventilation system, presenting a flexible response to the natural change of exterior conditions (solar radiation, and psychrometric conditions of external air, etc.).

Measurements and control can be taken at operator's defined constant intervals, that can lay in the range of 1minute to several hours, with an usual value of 15 minutes. Instrumentation system also offers data logging and monitoring capabilities.

4 Results and discussion

A major problem with solar kilns is related with the uncontrollability of environment conditions and the difficulty / impossibility to repeat them in consecutive drying operations. Therefore, all results are dependent on the specific weather conditions, besides of kiln structure, drying product and control strategy.

However, for similar weather conditions (solar radiation and relative humidity), some common evolution patterns have been noticed. Figures 4 and 5 represent one entire week evolution of temperatures and equilibrium moisture contents in the exterior and in the interior of a solar kiln charged, respectively, with moisture saturated wood and medium dried wood (MC ≈ 30%). In both situations, there was sunny weather and the ventilation was switched on during the day period. Data on fig. 4 and 5 were acquired, respectively, during autumn and winter.

The efficiency of the kiln, illustrated by EMC values, is lower in the early hours of the morning, but increases with radiation intensity. As can be seen, EMC values present always less amplitude variation inside than outside the solar kiln. Although EMC values at the interior are higher during winter than in autumn, as expected, drying conditions can be quite favourable inside of the kiln during the winter period.

In spite of ventilation, chamber peak temperatures (around 11:00am-13:00pm) showed to be, in the worst case, 3-5ºC higher than the outside ones. These small increments in temperature are sufficient to low relative humidity and EMC, in a significant way, causing these quantities to attain their lowest levels at this time and promoting wood moisture loss, in a more effective way. In fact, wood moisture loss increases with the decrease of relative humidity, mainly due to the increase of the water vapour pressure differential, which is the key factor for moisture evaporation. In this way, wood works as an additional moisture source inside the kiln, increasing RH and EMC. This effect is more intense if the wood is saturated as in the case of fig. 4, where the chamber EMC values are bigger than the exterior ones (contrary of fig. 5, where wood has already attained 30% of moisture content), in spite of the ventilation. If, in this case, exchange with the exterior is prevented, internal RH and EMC values would attain much bigger values. In such situations air has to be continuously expelled to the exterior and renovated at a high rate, forcing air circulation through the wood-stack.

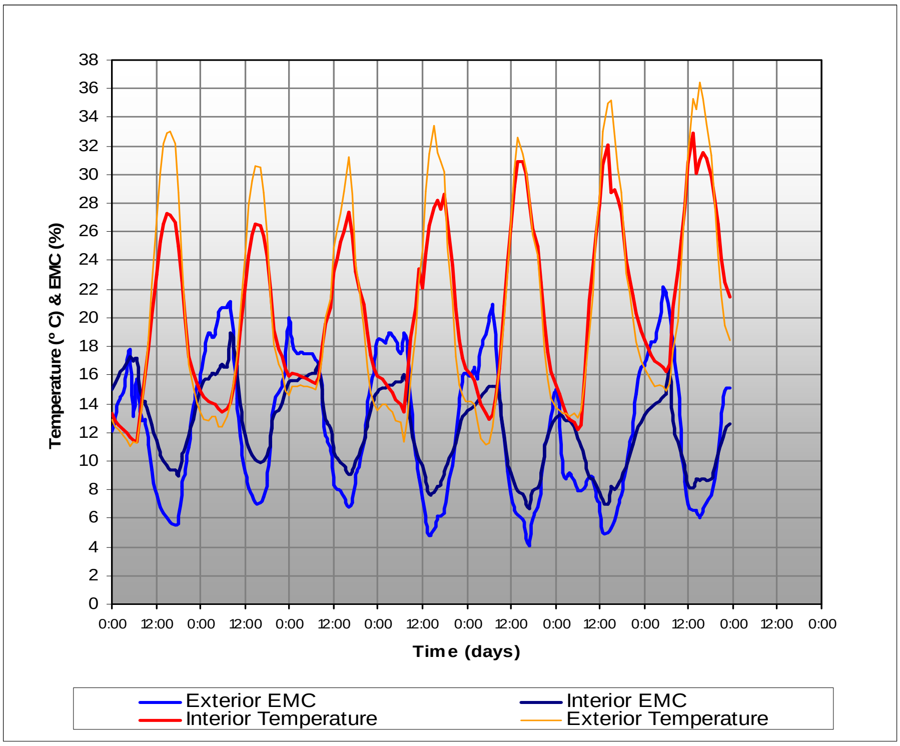


Fig. 4. *Evolution of temperature and wood equilibrium moisture content inside and outside of the kiln, during one week, in November (Autumn).*

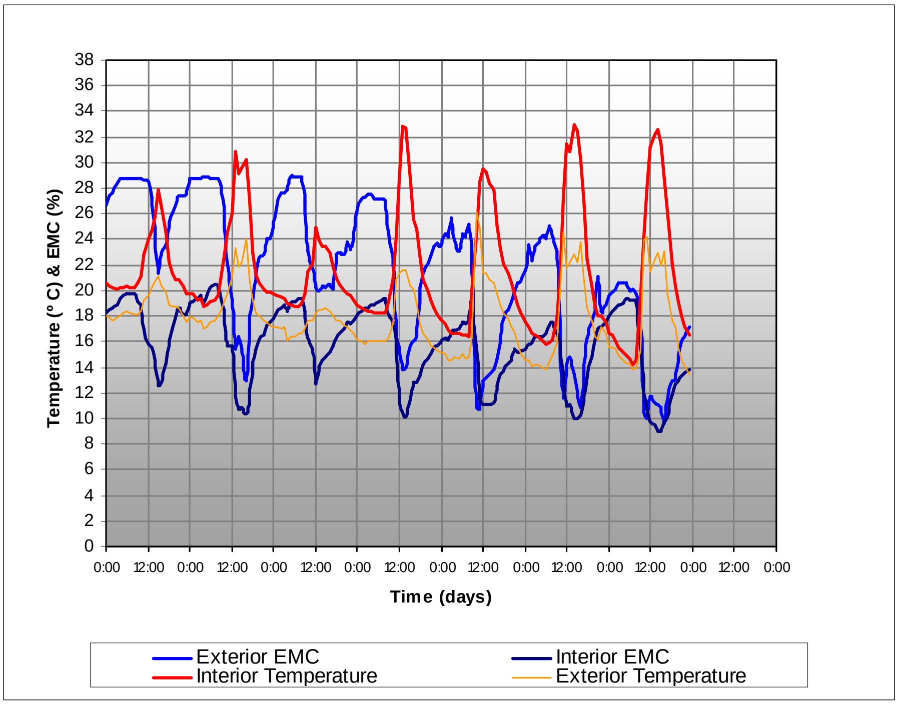


Fig. 5. *Evolution of temperature and wood equilibrium moisture content inside and outside of the kiln, during one week in December (Winter).*

A different wait standard is observed on Fig. 6, where outside values of EMC reach inferior values to the ones of the inside, as well as the ones of the temperature that reaches superior values to the ones inside of the solar kiln.

The rank of the exterior sensor in the admission zone of solar kiln is the reason of the interference with the exterior real values.
Figure 6 shows the detail of another typical evolution pattern of the equilibrium moisture content and temperature during a summer sunny day, both inside and outside the solar kiln, charged with saturated pine wood. Vertical lines correspond to the beginning and end of ventilation period, during which the ventilators were switched on and off.

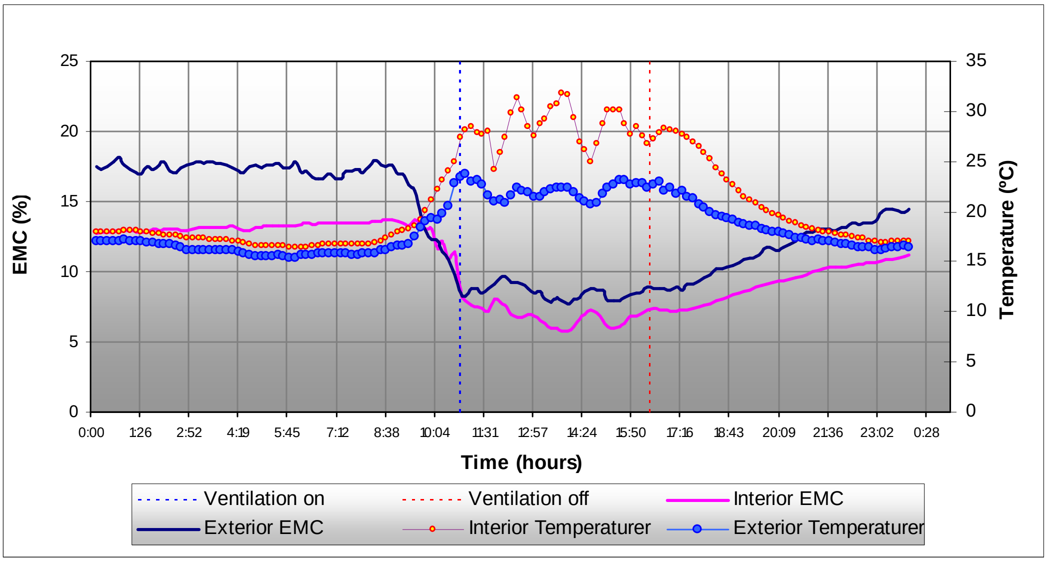


Fig. 6. *Typical sunny day equilibrium moisture content and temperature evolution inside and outside the solar kiln..*

It can be noticed, that even though the ventilation is on, during the hours of bigger incidence of solar rays, chamber temperature suffers a bigger increase than in autumn or winter, causing a bigger drop in the interior EMC values and offering better drying conditions

Global results of an entire drying operation, during the end of autumn and the beginning of winter, using 27 mm thickness boards of pine wood, in a total wood volume of 40 m^3, are illustrated in fig. 6, 7 and 8. Expelled moisture rate was increased by proper exposition of the wood boards to the air. The 40 m^3 of 27 mm thickness boards presented a total surface exposition (two faces for one board) of 3000 m^2.

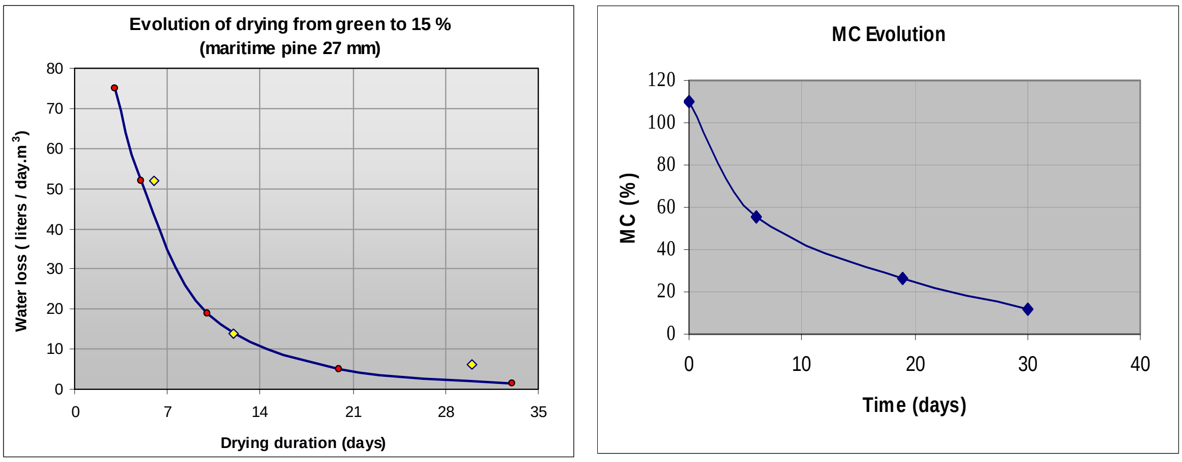


Fig. 7. *Evolution of water loss (left) and moisture content (right) during drying process.*

In the first drying phase, high air circulation was provided, in order to speed as much as possible the drying rate. It should be emphasized that another important reason to quickly reduce wood moisture content at the initial stage, is to prevent the development of mould or blue stain specially when drying softwoods, namely pine. In the illustrated example, at the beginning of the process, an extraction of 75 liters of water per cubic meter was achieved (Fig. 7). This represents a total water removal from wood in 24 hours about 3000 liters. This water removal rate dropped in seven days to about 35 liters per cubic meter and a value of 12 % in moisture content was reached in 33 days.

Fig. 8 shows some details of the final stage of the drying operation. Although temperature has not exceeded 30ºC the wood moister content (MC) was reduced from 30 % to 15 % in only 7 days. This is quite significant, taking into account that the final drying stage is the slowest in a solar kiln. As can be seen, the EMC during this phase reached an average value of 9 % along the day when temperature increases and relative humidity was at its lowest (RH).

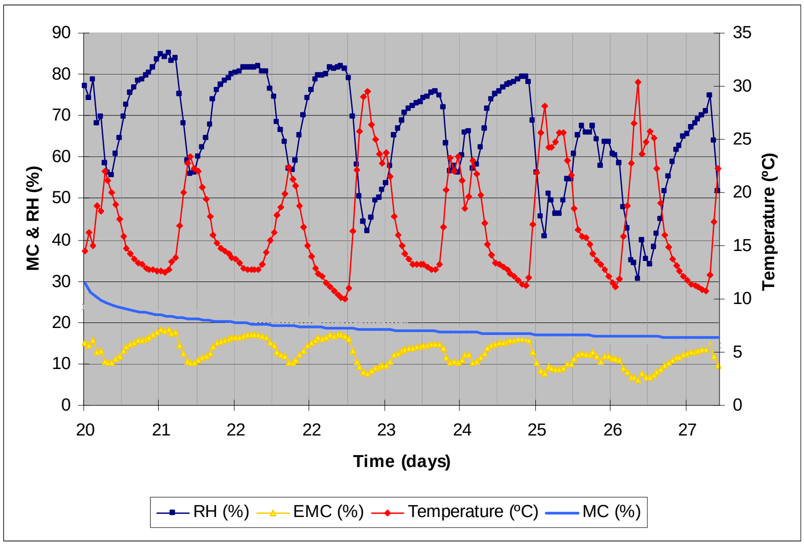


Fig. 8. *Evolution of inside kiln parameters during the last 7 days.*

Final stage 20th to 27th day of drying, in April.

Data acquired during several runs under variable conditions, in all prototypes, allow the proposal of expected durations for the drying of softwood according to the different weather conditions. Table I summarizes the expected drying duration for different board thicknesses and favorable or less favorable conditions, based on the tests carried out during the project.

Table 1. Expected solar kiln drying duration for a Softwood (*Pinus pinaster*, Aitim.), from 120 % to 14 % M.C.

Thickness	27 mm	35 mm
Total drying duration with favorable conditions	15 days	25 day
Total drying duration with non favorable conditions	45 days	60 day

Regarding energy, it must be said that the total amount needed to dry wood is the same whatever the method. For pine wood, the heat energy needed is about 494 kW.h / m^3. In conventional kilns, this energy is usually obtained from burning residues that can be quite cheap, but it must be remembered that the investment on a boiler is very high and the combustion produces CO_2 emissions. In air or solar drying, the use of solar energy greatly reduces the expense and gas emissions. In the case of the present study, the kiln has a low cost structure and only energy spent in electrical ventilation has a cost per operation.

Table 2. Compared energy use in a solar kiln drier
and in a conventional kiln drier for a Softwood
(*Pinus pinaster*, Aitim.), from 120 % to 14 % M.C.

	Electrical energy for ventilation per cubic meter	Heat energy per cubic meter
Conventional kiln drier	32 kW.h / m^3	460 000 kcal / m^3 494 kW.h / m^3
Solar kiln drier	28 kW.h / m^3	0

5 Conclusions

The present work showed that low cost solar kilns can be competitivelly used to dry wood, presenting balanced benefits regarding operation time vs final quality, energy expenditure and gas emissions.

A performance evaluation based on relevant physical quantities measurements and analysis is being carried on, during different season periods and weather conditions, constituting an essential tool to gather knowledge about the process. The results, documenting kiln functionality, strongly contribute to adjust the control to specific needs of products to be dried and to establish confidence in this kind of drying methods for industrial use.

As referred, in the first stage, wood drying requires a great capacity of water extraction, so strong ventilation should be carried, being necessary to extract the moisturized air from the kiln trough entire air renovations (1 to 3 per minute). In these circumstances, during sunny hours the gain in temperature inside the kiln can be as small as 2 to 5 degrees. Although this apparently low increase in temperature, the equilibrium moisture content can drop about 5 to 8 %, which is enough to dry wood at a very satisfying rate, even at its final stage.

Electric power reduction can be achieved through ventilation control, according to exterior conditions and drying level already obtained. It was found out that even forced air convection is always of great benefice, exchange with the exterior can be restricted, most of the time, to day hours (8h per day approximately).

A well designed structure and ventilation control strategy are the key factors for the economic success and drying quality. Even though drying times and energy expenditure have been acceptably low, more improvements can be eventually achieved.
One example is the possibility of allowing internal air recirculation in some circumstances, without exchange with external environment. This will account with another important ventilation effect, that wasn't addressed in the present work, which is the removal of water vapor accumulated around the wood as a thin skin, whose presence diminishes the vapor pressure differential and favors the occurrence of mould blue stains that can affect final apearence and quality.

Combination of solar drying with conventional layout drying processes, including an adequate active control for optimization purposes, is another open possibility to achieve competitive substitution of fossil sources of energy, with significant decreasing of CO_2 emissions, while still requiring low cost investments. Modifications of the industrial process are claimed to be minimal since the system requires no specialised buildings or electrical works [4], but should be clarified.

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