Performance of a solar/wood energy kiln in tropical latitudes

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Abstract

In recent years, the USDA Forest Service, Forest Products Laboratory, has been involved in an ongoing project to design, build, and test prototype low-cost solar dry kilns for use in tropical climates. The culmination of this project is a 6,000-board-foot combination solar and wood energy kiln built and in commercial operation at a factory in Sri Lanka utilizing rubberwood (Hevea brasiliensis) to manufacture furniture and laminated beams. A series of operational tests were performed, largely to evaluate performance from an energy efficiency standpoint. The results show that the kiln can operate effectively both when solar input is large and minimum wood energy is required, and when solar input is small (in cloudy weather) and wood must be relied upon for the majority of energy.

Over approximately the past 8 years, the USDA Forest Products Laboratory (FPL) has designed and built several prototype solar dry kilns for use in tropical latitudes. With support from the U.S. Agency for International Development and the United Nations, we worked through design, prototype, and scale-up phases. At present, we have a commercial dry kiln with a capacity of 6,000 board feet G3F), which uses both solar energy and energy from burning wood residue to dry rubberwood (Hevea brasiliensis) at a furniture factory in Sri Lanka. The kiln was built in December 1984 and has been operating successfully since then. During this time, we have been gathered operational data on the kiln, and this paper reports observations on the energy efficiency of the kiln, its durability, and its overall ability to dry lumber.

Description of the solar/wood residue kiln

Principles of operation

The scaled-up solar/wood energy kiln has been described in detail in a previous publication, but a brief description is included here. A schematic of the dryer is shown in Figure 1, a section view in Figure 2, and a section view of the solar collector in Figure 3. Air circulates through two intersecting loops, one through the collectors and/or wood residue burner and the other through the lumber (Fig. 1). The volume of airflow through the lumber stack is twice the volume through the collectors, which are two independent pairs of two parallel collectors. Airflow in each half of a collector is counter to the flow in the other half, so that only one duct (Fig. 1, C) is necessary to carry air from the paired collectors to the manifold (Fig. 1, D). Four ventilators (Fig. 1, K) remove humid air from the leaving-air side of the lumber stack. The makeup air from outside enters the system at four points (Fig. 1, J) and into the collectors at points B (Fig. 1). Heated air from the collectors is pulled into the dryer by two blowers (Fig. 1, C) and discharged from a manifold (Fig. 1, D) directly into four nonreversing overhead fans (Fig. 1, E) that circulate air through the stacked lumber.

Automatic control of the solar dryer is desirable to efficiently accommodate 1) the intermittent delivery of...
solar energy to the collector; 2) the variable relative humidities within the drying compartment, which depend upon the ambient relative humidity and the temperature in the compartment; and 3) the variable drying rate of the lumber. Without such controls, almost continuous manual observation would be required to approach the high quality and efficiency of drying with automatic controls. Controls include 1) two differential thermal comparators (Fig. 1, Fc and Fd) that sense the difference between dryer and collector temperatures and turn the solar blowers (Fig. 1, C) on and off accordingly; 2) a humidistat (Fig. 1, RH1) to allow automatic venting as needed to control relative humidity; 3) a second humidistat (Fig. 1, RH2) to establish a maximum relative humidity above which the dryer will shutdown to prevent lumber from regaining moisture during extended rainy periods that might occur near the end of a drying schedule (when operating in solar-only mode); and 4) a third humidistat (Fig. 1, RH3) that operates a humidifier (Fig. 1, G) to raise the humidity in the kiln if necessary.

A low-cost combustion system fueled by wood has been incorporated into the kiln design. A simple burner is located in a furnace compartment on the side of the drying compartment opposite the solar collector (Fig. 1, A). The furnace can be operated either simultaneously...
with or separately from the solar collector, but the usual mode of operation is solar when available and wood burner during the night or extended cloudy periods.

**Construction details of the kiln**

Figures 1 and 2 show construction details of the kiln. Figure 3 is a cross section of the end of one of the two pairs of collectors. Figure 4 is a photograph of the finished kiln. The solar collector is external to the drying compartment so the collector area and orientation are not limited by the geometry of the dryer. The collector is horizontal, except for a 1/2-degree north-south drainage tilt, and it is built into the ground for low cost and ease of construction. The horizontal orientation is particularly effective near the equator and was designed for that location, but the kiln can be effective at higher latitudes.

A foundation of concrete blocks or poured concrete form the perimeter of the collector. A 12-inch-deep excavation is filled with gravel or pebbles to within approximately 8 inches of the top of the foundation. A 2- to 3-inch-thick layer of charcoal pieces sized 1/2 to 1 inch covers the gravel. Charcoal is an inexpensive energy-absorbing surface and heat transfer medium, as well as a good insulator that reduces heat loss to the ground. The interior surfaces of the foundation are painted flat black. The collector cover spans the 4 feet between sections of the foundation.

The collector cover is 3/16-inch-thick common window glass. The sections of glass that makeup the cover are each approximately 45 inches wide by 36 inches long and are installed to overlap (by about 1/2 in.) as shingles do. The collector is under negative pressure when the solar blowers are operating, and sealants prevent air and water from leaking into the collector. The collector is 50 feet long, and each section is slightly less than 4 feet wide. Because of overlap at the edges, the actual collector area is 1,469 ft². The path of airflow into and through the collector and into the drying compartment is shown in Figure 1.

The inside dimensions of the drying compartment are approximately 10 feet wide by 34 feet long by 11 feet high, with a capacity of approximately 6,000 BF of 4/4 lumber. The kiln is single-track loaded and is designed for a 5-foot-wide load of lumber (Fig. 2). The walls are 8-inch-wide by 16-inch-long by 4-inch-thick concrete blocks constructed in a double thickness with a 4-inch insulation-filled gap between layers. The ceiling of the drying compartment consists of 2- by 4-inch boards on edge, with a space for insulation above, and then a sealed roof. Above that, an open-pitched shed-type roof of corrugated metal painted black serves the dual role of providing for water runoff and as a preheater for makeup air entering the solar collector (Fig. 1, J).

Wood is burned in a simple, low-cost burner housed in a furnace chamber (Fig. 1, A; Fig. 2). Each of two burner systems consists of two steel drums mounted on a framework. One drum is the combustion chamber. The other, along with the chimney, serves as an additional heat transfer surface. A blower (Fig. 2) discharges kiln air into the furnace compartment, which forces heated air from the furnace compartment through a duct to a manifold in the drying compartment (Fig. 1).

**Automatic operation in the solar mode**

The kiln operates automatically when in the solar mode but requires manual operation of the burner when operated in that mode. The solar part of the kiln is shut off at night. At some predetermined time (e.g., 8 a.m.) a timer activates the solar control system. Presumably, the firing of the furnace has been stopped by the operator at some point shortly after sunup and the drying compartment has cooled. When the sun heats the collector to a temperature above that in the drying compartment, the differential temperature comparators (Fig. 1, Fc and Fd) activate a relay to turn on the solar blowers (Fig. 1, C) and at the same time open the dampers between the collector and the drying compartment (Fig. 1, H). These dampers reduce energy losses from the dry-
ing compartment to the collector when the solar blow-
ners are off. The differential temperature comparators ac-
tivate the solar blowers intermittently throughout the
day and can thus provide efficient operation even on
days when there is extended cloud cover. When the so-
lar blowers are off, the fans and vents continue to op-
erate. Drying can proceed without solar input because of
energy stored in the wood/dryer system, energy stored
in the collector (as long as the collector temperature is
above the drying compartment temperature), and the
drying capacity of the ambient air. The solar operation
will discontinue in the late afternoon or early evening,
and the solar blowers will stop. A thermostat will keep
the fans and vents operating for as long as the tem-
perature of the drying compartment remains above the
thermostat set point, e.g., 90°F. After that, the furnace
can be fired for night operation.

**Energy supply and demand**

One of the principal objectives of the study was to
examine the energy efficiency of the kiln to evaluate its
performance and look for areas that could be improved.
To do this, it was desirable to break the energy gains
and demands into the following components.

**Energy gains.** Energy gains include: 1) solar in-
put to the collector; 2) solar energy delivered to the
drying compartment from the solar collector; 3) elec-
trical energy from the fans and blowers; 4) sensible en-
ergy released from the wood and kiln structure when they
cool; and 5) energy delivered to the drying compartment
from the wood burner.

**Energy demands.** Energy demands include: 1) en-
ergy lost from the collector; 2) energy lost through the
drying compartment surfaces by conduction; 3) sensible en-
ergy to heat the wood to drying temperature; 4) ener-
gy to evaporate the water; and 5) energy lost through
the vents.

**Experimental methods**

Data were collected on 11 kiln runs. In nine of these
kiln runs, the data collected included information that
only allowed breaking down the energy into solar, wood,
and electric inputs. For the 10th and 11th runs, the kiln
was instrumented so that the more detailed analysis
itemized above was possible. There were plans to con-
duct a total of four runs where this more detailed analy-
sis could be conducted, but events allowed only two to
be completed in a timely way. However, information
gathered in the two detailed runs was used in the less
detailed analysis of the other nine runs.

**Instrumentation of the kiln**

In the first nine runs the only measurements taken
were initial and final moisture content (MC), drying time
required, solar radiation as recorded on a horizontal sur-
face by a pyranometer, weight of firewood into the burn-
ers, and the power consumed by the fans and blowers.

**Energy gains**

The energy gains for the 10th and 11th runs were
estimated as follows.

Solar input to the collector. - Solar radiation was
measured, recorded, and integrated for daily solar radi-
ation totals. An estimate was made of the percent
transmission of window glass, and this was done sever-
al times throughout a typical day so the effect of the
varying angle of incidence was included. This was done
by comparing the instantaneous solar radiation readings
with and without a glass cover. The percent transmit-
sion varied from about 60 percent in the early morning
or late afternoon to 84 percent at noon. The average
value of 78.3 was used in the collector efficiency calcu-
lations.

Solar energy delivered to the drying compartment
from the collector. - Solar energy from the collector was
estimated by measuring the inlet and outlet tempera-
tures of the air entering and leaving the collector, the
volume flow of air (which requires knowing the relative
humidity of the air leaving the collector and entering
the drying compartment). The equation is:

\[ Q = V \rho C_p (t_i - t_o) \]

where:

- \( Q \) = energy in BTUs
- \( V \) = volume of airflow in cubic feet per minute
- \( \rho \) = density of the air-water mixture in pounds per
cubic foot
- \( C_p \) = specific heat of the air-water mixture in
\( \text{BTUs/lb.} \cdot \text{°F} \)
- \( t_i \) = inlet temperature in °F
- \( t_o \) = outlet temperature in °F

Temperatures were measured with thermocouples
and recorded every hour throughout the run. Airflow
measurements were taken on the four solar duct out-
lets (Fig. 1, D). Each of the 4 duct openings was divided
into 16 segments of equal area with wire across the open-
ings. The air velocity was measured in each of the 16
segments, and the average of the 16 readings was taken
as the airflow rate. The air delivery to the drying com-
partment was thus estimated at 4,240 ft³/min. An
elapsed time meter was connected to each solar blower
to total the time the blowers ran, and these meter read-
ings were recorded hourly throughout the run.

Electrical energy from the fans and blowers. - Elec-
trical energy from the fans and blowers was measured
directly with power meters.

Sensible energy released from the wood when it
cools. - Depending on weather and how the kiln is oper-
ated, there may be times during a daily cycle when there
is no energy input. For example, if a sunny period is fol-
lowed by a cloudy period, the lumber will continue to
dry and cool in this cloudy period because of energy
stored in the lumber and in the kiln structure. This
energy needs to be accounted for, just as does the reverse,
i.e., the energy required to heat the lumber to drying
temperature.

These calculations require knowledge of the weight
of the lumber and water lost in a given time interval.
The first requirement is to know the initial green weight
of the lumber with its water. This was estimated from
the initial MC, the specific gravity (SG), and the volume
of lumber in the kiln. Twelve moisture sections were
taken for the MC and SG estimates. With an estimate
of the green SG (green volume, ovendry weight) of the lumber, we can estimate the ovendry weight from the relationship between specific gravity, ovendry weight, and green volume:

\[ \text{Ovendry weight} = \text{green SG} \times \text{green volume} \]

The green volume of the kiln load was estimated from the average board thickness (1.16 and 1.07 in. in runs 10 and 11), the number of courses of lumber, and the width and length of the stack. Since every course was not packed to the full 100 percent of the stack dimensions, a percent fullness was estimated measuring the length and width of every board in 6 of the 34 courses. The percent fullness was then taken as the average layer area of these board dimensions from the six courses as a percentage of the available stack area. With the estimate of green MC and ovendry weight, an estimate of the green weight of the lumber can be made from the standard MC formula. With periodic weighings of the six kiln samples used, MC and corresponding lumber weight were estimated daily during drying. Specific heat of the lumber can be estimated knowing MC, and the energy released can be estimated as the product of specific heat, lumber weight, and temperature change between any two times.

Energy delivered to the drying compartment from the wood burner. — Energy delivered to the drying compartment from the wood burner was estimated in a way similar to the way energy from the solar collector was estimated. Inlet and outlet temperatures were recorded, airflow to the kiln was measured at 730 ft.\(^3\)/min., and the length of time the furnace blower ran each day was recorded. The weight and MC of the wood that went into the burner each day was also recorded.

**Energy demands**

The energy demands for the 10th and 11th runs were estimated as follows.

Energy lost from the collector. — In addition to the transmission loss of the collector cover, there were also conduction losses through the bottom and edges of the collector and convection and radiation losses through the top. These losses were estimated as:

\[ Q_c = q_r - q_t - q_d \]

where:

- \( q_r = \) collector losses
- \( q_t = \) available solar radiation
- \( q_d = \) transmission losses
- \( q_d = \) energy delivered to the drying compartment

Collector efficiency can then be estimated as:

\[ CE = \frac{q_d}{q_r} \]

where:

- \( CE = \) collector efficiency
- \( q_d = \) energy delivered to the drying compartment

Energy lost through the drying compartment surfaces by conduction. — Conductive heat losses from the drying compartment were estimated by:

\[ Q = (U/A)(A)(\Delta t)(\Theta) \]

where:

- \( Q = \) heat loss in BTUs
- \( U = \) heat transfer coefficient in BTUs/hr./ft.\(^2\)/°F
- \( A = \) surface area in square feet
- \( \Delta t = \) temperature difference between the inside and outside of the drying compartment, °F
- \( \Theta = \) time interval, hours

The heat transfer coefficients were estimated from the components of each surface as:

- Walls: 0.053 BTUs/hr./ft.\(^2\)/°F
- Roof: 0.048 BTUs/hr./ft.\(^2\)/°F
- Floor: 0.75 BTUs/hr./ft.\(^2\)/°F

Sensible energy to heat the wood to drying temperature. — An estimate of sensible energy to heat the wood to drying temperature is made in the same way as for the energy gain from cooling of the lumber. When the temperature in the kiln rises between two times, the result is an energy demand; when it falls, the result is an energy gain.

Energy to evaporate the water. — Energy to evaporate the water was estimated from the initial green weight and the daily moisture loss of the six kiln samples. The energy of evaporation was taken as 1,030 BTUs/lb. of water evaporated.

Energy lost through the vents. — Energy lost through the vents was estimated in the same general way as the energy delivered to the drying compartment by the solar collector or the wood burner. The main difference was in obtaining an estimate of the air flow delivery of the ventilators. The axial fans in the vents complicated air delivery measurements compared to the delivery from the manifold openings. The air delivery from the vents is not uniform over the circular opening because of the axial fan. A duct with air straighteners was built to receive the air from the vents in order to improve the uniformity of air flow during the measurements. Air velocity readings were taken at radius points that corresponded to equal area concentric rings in the straightener duct, and averaged for the estimate for each of the four vents. The total vent rate is 3,492 ft.\(^3\)/min. The straightener was in place only for the flow measurements.

**Results and discussion**

The first nine kiln runs were conducted between January and early June 1985. This falls within the dry season in Sri Lanka, and thus more solar energy was available than in the monsoon seasons. The average daily solar radiation during that time was 1,434 BTUs/ft.\(^2\). The general mode of operation was to start the furnace about 6 p.m. and stop firing so that by about 8 a.m., the solar collector could take over for the daytime hours. The average initial MC of the rubberwood lumber was 71 percent, and the average final MC was 14 percent. Target MC is in the 12 to 15 percent range because of the high equilibrium MC conditions in Sri Lanka. On the average, the wood burner supplied about 30 percent of the energy in these nine kiln runs, the fan and blower motors about 22 percent, and the solar collector about 48 percent. The energy consumption of the drying compartment, based on the energy delivered there by the three sources, was 1,972 BTUs/lb. of water evaporated, which is an efficiency of about 52 percent.
The energy details of the fully instrumented 10th run are summarized in Table 1. The MC of the wood fuel was 17.7 percent (wet basis). The initial MC of the rubberwood lumber was about 73 percent (dry basis), and the final MC was about 18 percent. This kiln run was conducted in September 1986 during the monsoon season, and the 2-week period was quite cloudy and rainy. The average daily solar radiation during that period was 665 BTUs/ft.

The summary shows that the wood burner supplied about 66 percent of the total energy, the fan and blower motors about 15 percent, and the solar collector only about 18 percent. The energy consumption of the drying compartment in this run was 3,124 BTUs/lb. of water evaporated, which is an efficiency of about 33 percent.

The energy details of the 11th kiln run are summarized in Table 2. The MC of the wood fuel was 15.3 percent (wet basis). The initial MC of the lumber was about 69 percent (dry basis) and the final MC was about 14 percent. The run was conducted in May 1987, and there was considerably more solar radiation available than for the 10th run. The average daily solar radiation during the 9 days required for drying was 1,293 BTUs/ft.

The summary shows that the wood burner supplied about 54 percent of the total energy, the fan and blower motors about 12 percent, and the solar collector about 34 percent. The energy consumption of the drying compartment in this run is estimated at 2,007 BTUs/lb. of water evaporated, which is an efficiency of about 51 percent.

One observation from the data is that delivery of wood energy from the burner to the drying compartment is inefficient—only a little more than 20 percent efficiency. An analysis of the losses due to water content and stack losses, and conductive heat losses through the walls account for only a small part of the losses. Other possible losses are air leaks from the furnace room (it is under positive pressure because of the location of the furnace blower) and the ducts to the drying compartment. The burner operators also tended to leave the burner doors open, which could cause large losses due to the high air-fuel ratio. Also, in the transition from wood to solar operation, some wood energy was lost because the fire was still burning when the shift to solar was made. Some of the daily temperature records also suggest that the burner was stoked during the day when it was in solar mode with the furnace blower off. Another possible source of error is in the airflow measurements that are used in the energy calculations. If wood fuel is abundant, this inefficiency is not of great concern, considering the very low cost of the burner system. However, steps are being taken to locate the major sources of the inefficiency and correct them.

Another observation from Tables 1 and 2 is that there is a 10 to 20 percent discrepancy between energy gains and losses in the energy balance. If the energy gains have been estimated closely, then about 10 to 20 percent of the energy losses are unaccounted. Probably the major source of unaccounted losses are undetectable air leaks in the system. The doors provide one avenue, and the vents, solar ducts, and furnace ducts provide other possible sources. For example, the internal fans for air circulation through the lumber could cause leakage through the vents even when the vent fans were off and even though the vents had louvers that closed when the vent blower was off. Flow measurements through the vents were made with vent fans off and the internal fans on. They did not register on the flow meter, but there still could be a small flow that would add up over a long period of time. Similarly, such low-volume, long-time induced losses could occur through the solar or furnace ducts at certain times. A summary of the possible sources of error and their estimated significance is given in Table 3.

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Maximum and minimum temperatures and relative humidities were taken at various places in the dryer. Maximum temperatures in the drying compartment were about 100°F early in drying and increased to as high as 120°F later in drying. Percent relative humidity ranged from the mid-80s early in drying to about 50 percent near the end of drying. Collector temperatures were quite variable because of the variable solar input. Temperature rise through the collector ranged from over 50°F near midday on good solar days to about 10° to 15°F near the beginning or end of good solar days. On poor solar days, the maximum temperature rise near midday was 25° to 30°F and 5° to 10°F near the beginning and end of those days. The temperature of air delivered from the furnace was also quite variable, depending on the manual firing rate, but typical maximum temperatures during a day were above 250°F, and minimum temperatures were between 150° to 200°F.

Temperature measurements showed that the shed-type roof over the drying compartment and the vent makeup air preheater (Figs. 1 and 2) are effective in preheating the air entering the collector. The temperature of the makeup air entering the preheater ducts under the shed roof averaged 5°F above ambient temperature (averaged hourly over runs 10 and 11 for the hours 10 a.m. to 2 p.m. each day), and the air entering the preheater ducts is further preheated by an average of 0.5°F.

A long-term evaluation of the durability of the kiln was not possible. It was built and put in operation in early December 1984, and the 11th run as defined in this paper was in May 1987. However, there have been many more than 11 kiln loads of lumber dried. The factory personnel assured the authors that the kiln had been in nearly continuous use since it was finished. They also assured us that there had been no malfunctions during that time. The first author was present for the 10th run in September 1986, and structurally the kiln and collector looked as good it did in 1984.

The kiln was sized at 6,000-BF capacity according to the factory director's wishes. However, the design is flexible enough that other sizes are possible. As the design now stands it can be built in 3,000-BF modules (Fig. 1), at least up to the point where it becomes too long to be practical. Thus, to build a 3,000-BF kiln, the 6,000-BF design of Figure 1 would be cut in half lengthwise.

### TABLE 3. Summary of comments on the accuracy of the estimates of energy gains and losses.

<table>
<thead>
<tr>
<th>Energy component</th>
<th>Comment on accuracy</th>
<th>Accuracy rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gains</td>
<td>Variable cleanliness of cover a factor; transmission estimate not exact.</td>
<td>1</td>
</tr>
<tr>
<td>Solar input to collector</td>
<td>Flow rate estimates may be poor because they could not be measured with internal fans on; temperature and humidity measurements considered reliable.</td>
<td>2</td>
</tr>
<tr>
<td>Solar energy delivered to drying compartment</td>
<td>Meter readings considered reliable.</td>
<td>1</td>
</tr>
<tr>
<td>Electrical energy from fans and blowers</td>
<td>Estimates of MC, SG, and volume of lumber not precise, but only small error suspected. No attempt made to account for energy in kiln structure; temperature measurements considered reliable.</td>
<td>1</td>
</tr>
<tr>
<td>Sensible energy released when wood cools</td>
<td>Flow rate estimates may be poor because they could not be measured with the fans on; temperature and humidity measurements considered reliable.</td>
<td>3</td>
</tr>
<tr>
<td>Energy delivered to drying compartment from wood burner</td>
<td>MC and weight estimates considered reliable.</td>
<td>3</td>
</tr>
<tr>
<td>Potential wood energy into burner</td>
<td>MC and weight estimates considered reliable.</td>
<td>3</td>
</tr>
<tr>
<td>Demands</td>
<td>This estimate is by subtraction and should be as good as that for energy delivered to the drying department.</td>
<td>2</td>
</tr>
<tr>
<td>Energy lost from collector</td>
<td>Estimates of the heat transfer coefficients were made from handbook values for wall, roof, or floor components, and their applicability to this kiln is unknown. However, these losses are not a large part of the total energy flow in the system and probably have a small effect on the balance estimates.</td>
<td>1</td>
</tr>
<tr>
<td>Energy lost through drying compartment</td>
<td>Same comment as under gains when wood cools.</td>
<td>1</td>
</tr>
<tr>
<td>Sensible energy to heat the wood to drying temperature</td>
<td>Estimates of MC, SG, and volume of lumber not precise, but considered reliable.</td>
<td>1</td>
</tr>
<tr>
<td>Energy to evaporate water</td>
<td>Airflow measurement accuracy of concern because of the difficulty in straightening the flow for measurements.</td>
<td>1</td>
</tr>
<tr>
<td>Energy lost through the vents</td>
<td>No real attempt was made to analyze these losses, and they are not considered in the energy balance. However, they were largely due to several possible factors. There was no poor transition from wood to solar energy with consequent wasted energy; burner doors left open often; positive pressure in the furnace room probably causes large air leaks.</td>
<td>2</td>
</tr>
<tr>
<td>Energy losses from furnace room</td>
<td>The interaction between the four airflow loops, i.e., collector dryer; furnace room dryer; internal circulation through the lumber stack; and vent makeup air is unknown. Different combinations of the four airflow systems operated at different times, and we suspect that the volume of air delivery between subsystems, as well as leakage, depends on the combination operating at any time. We did not attempt to measure airflow for all possible combinations. This interaction, as well as unaccounted air leaks, may be the main reasons for the imbalance.</td>
<td>3</td>
</tr>
</tbody>
</table>

*Exact estimates of accuracy are not possible, but in an attempt to convey our level of confidence to readers, we have rated our estimates on a scale of 1 to 3, where 1 = small error (perhaps 1% to 5%); 2 = medium error (5% to 10%); and 3 = large error (10%+).*
This would reduce the amount of building materials as well as the number of fans, blowers, and vents.

In moving to a capacity larger than 6,000 BF, the most economical way would be to first widen the kiln to accommodate an 8-foot-wide load rather than the current 5-foot-wide load. This enlargement could be made with only a modest increase in materials cost and no change in controls, fans, blowers, or vents would be necessary, although fan reversal might become necessary. A third steel drum burner should be added to the furnace room at this point. The drying time might be increased a little from the 5-foot-wide load design, but the cost effectiveness of the increased capacity would more than offset that increase. This modification would bring the capacity up to about 9,600 BF.

With this modification of increased load width, the basic module would increase from 3,000 to 4,800 BF. Thus, the next increment of increase would be from 9,600 to 14,400 BF, and the kiln would become 1-1/2 times as long as the two-module, 9,600-BF kiln. This would increase the materials of construction by about 50 percent and require additional fans, blowers, and vents, as well as more burner capacity. The addition of more modules could then progress to capacities of 19,200 BF, 24,000 BF, and 28,000 BF, etc., until the limits of practical length were reached.

The economic feasibility of constructing a solar kiln can be assessed on the basis of expected drying time and savings realized by buying green lumber instead of dry lumber.¹

**Conclusions**

The solar/wood energy kiln design described in this paper is capable of drying lumber from the green in a reasonable time period (7 to 14 days) to MCs low enough for use in furniture. The solar collector operates at about 36 to 40 percent efficiency, and in periods with minimum cloudy weather it can supply up to 50 percent of the required energy when coupled with nighttime supplemental wood energy. Alternatively, in periods of cloudy weather the wood burner can supply enough energy to accomplish the majority of the drying. The drying compartment operates at about 33 to 50 percent efficiency. The wood energy system as designed and built is not as efficient as expected, delivering only about 23 percent of the potential energy of the fuel, and consideration is being given to ways of improving that performance.