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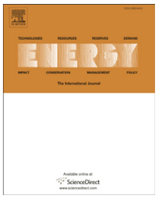

Time-valued net energy analysis of solar kilns for wood drying: A solar thermal application

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ABSTRACT

This paper describes a LNEA (life-cycle net energy analysis) for solar thermal applications with particular reference to two typical greenhouse-type solar kilns (Oxford and Boral) for wood drying. The analysis included the simulation of future flows of OE (operational energy), and the assessment of EE (embodied energy) for the two kilns over an expected service life of 20 years. The OE streams associated with the drying of a hardwood species (*Eucalyptus pilularis*) were estimated by solving a solar kiln model, while a LCA (life cycle assessment) model was used for the assessment of EE components. The key objective of this paper was to carry out a time-valued net energy analysis for two significantly different kiln designs. This approach of evaluating the energy-intensive facilities (e.g. solar kilns) is novel, and may result in a robust framework for further performance/design optimization study of solar kiln designs. Based on the chosen life-cycle performance parameters, the Oxford kiln was generally found to be more productive and energy efficient than the Boral kiln for hardwood drying in Australia.

1. Introduction

Timber drying is an energy intensive process, particularly in the use of thermal energy for drying the material (timber). Tsoumis, as cited by Ref. [1], mentioned that the required energy for drying wood in conventional dryers ranges from 600 to 1000 kWh m^{-3}, depending upon the wood types and thicknesses. The diversity of drying operations, particularly in chemical engineering, has been discussed in Ref. [2]. It mentioned that the typical features of drying operations include the variation in the material size and shape, the variety of drying media used, and the wide range of materials to be dried, each of them having different drying characteristics (i.e. drying rates). This diverse nature of drying operations has caused solar dryers to evolve in a wide range of designs, sizes, and shapes over the last three decades. A comprehensive review of the various designs, details of construction and operational principles of the wide variety of practically realized designs of solar-energy drying systems has been presented in Ref. [3]. In modern society, due to the depletion and general awareness about the ecological consequences of burning fossil fuels, it is desirable to implement alternative energy sources, such as solar energy for the use of this thermal energy. Solar drying of timber is not only an energy-intensive process that is carried out by the use of solar energy, but also a process for reducing the overall timber-processing time (increasing the productivity) and improving the quality of the end-use timber, as mentioned in many studies, including [4,5]. Traditionally, designing and choosing a particular solar kiln is based on small-scale testing to assess the kiln performance. However, this experimental procedure poses practical difficulties due the extremely large number of variables that must be considered and the significant time required, combined with the practical difficulties in repeating the testing environment (natural climatic situations), as mentioned by Refs. [4,6].

There is no or little information in the literature about the life cycle energy requirements of solar kilns for wood drying. Several experimental and modeling approaches have been reported in the literature to assess the timber properties during solar drying and the performance of the kiln itself. For example, the simulation study [7] investigated the effect of several design parameters (e.g. drying air velocity, timber thickness, and volume to absorber ratio) on the drying rate and described the optimization of a solar kiln design through a parametric study. A mathematical model of solar kilns was solved for experimental validation by Ref. [8]. The

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Nomenclature

DEPP	discounted energy payback period, years
DNEA	discounted net energy analysis, -
EE	embodied energy, J
FECV	future energy consumption value, J
FEPV	future energy production value, J
FEV	future energy value, J
i	discount rate, %
IRR	internal rate of return, %
ISO	International Organization for Standardization, -
LCA	life cycle assessment, –
LNEA	life-cycle net energy analysis, –
MARR	minimum attractive rate of return, %
MC	moisture content, kgkg^{-1}
n	time into the kiln service life, years
NEA	net energy analysis, –
NEPR	net energy profit ratio, –
NPECV	net present energy consumption value, J
NPEPV	net present energy production value, J
NPEV	net present energy value, J
OE	operational energy, J
PDEV	present drying energy value, J
PEV	present energy value, J
PVEE	present value of embodied energy, J
PVEL	present value of energy losses, J
PVFE	present value of fan energy, J
PVLE	present value of loading/unloading energy, J

predicted parameters (e.g. timber moisture contents, timber temperature, and the drying air humidity) were found to be in a good agreement with the experimental data. Another example is the comparative study [9] between solar wood drying and traditional air-drying, where only the results for a single drying cycle were discussed.

However, these studies were limited in their capacity to consider the variability of the ambient conditions and the likely change in the performance of the kiln over the life time of the drying system. Moreover, most of them were either type and site specific approaches or did not consider the long-term costs or energy-use sustainability.

The energy effectiveness of solar dryers is greatly affected by the energy flows associated with a particular kiln design. The future is likely to be described by increasing use of renewable energy sources, conventional oil production constraints, and fluctuating energy prices, so it is important that a robust and reliable methodology is used to comprehensively assess energy-intensive facilities, such as solar kilns for wood drying, so that the chosen solar kiln will remain superior to other kilns over the entire kiln operational life.

The total life-cycle energy use in solar kilns is the sum of the EEs and the total on-going OEs consumed over the whole operational life. EE (embodied energy) is the total amount of energy consumed during the extraction of raw materials, the transport, manufacturing, construction, use (maintenance and renovation) and disposal phases. By contrast, OE (operational energy) is the energy required to operate (or generated by operating) the built facility in terms of processes, such as space conditioning, lighting and operating other appliances. For the two solar kiln designs, the simulation procedure for estimating the OE requirements has been given in Ref. [10] while the model for assessing the EE has been presented in Ref. [11]. Assessing the OE flows means assessing the annual, on-going operating energy (costs) throughputs, while the EE assessment means assessing the capital energy (cost) requirements. There is a key need to combine the EE (capital cost) with the annual, on-going operating energy (costs) for wood-drying solar kilns in order to evaluate the overall energy effectiveness. Addressing this key requirement to combine a single capital-cost equivalent with an on-going operating-cost equivalent is one of the contributions of this paper.

Since the primary purpose of a solar kiln is to produce a net positive quantity of energy and consequently use this energy for drying timber as efficiently as possible, a direct net energy analysis should be used to achieve that goal. In this paper, we compare two overall kiln designs as part of an “option” analysis of two significantly different kiln designs. The key contribution of the paper is the time-valued net energy analysis in order to assess and compare the overall energy efficiency of the solar kilns in terms of their life-cycle performance. The value of a technology (a particular design of solar kiln) also depends on whether the ratio of the desired output to the input energy flows is growing, steady, or falling over the entire service life.

In this situation, three questions set the key objectives of the current study: (1) Does a particular solar kiln design utilize the incoming solar energy more or less effectively compared with other designs, considering the energy losses compared with the energy used for drying? (2) Does this utilization of solar energy rise, fall, or remain steady over a long period of time? (3) How does the amount of EE compare with the operating energy, both used for drying timber and lost from the kiln, for different kiln designs, considering the operating lives of the kilns? While the first question assesses the feasibility of using different solar kiln designs, the second question assesses the desirability of using that particular kiln over the specified operational life. The third question addresses the relative proportion of EEs needed for the different solar kiln designs in order to provide the target services. These three questions together form a set of necessary conditions for a comprehensive energy evaluation of a given solar kiln design for wood drying.

2. Overview and significance of the approach

Traditionally, manufacturers, investors, economists and decision makers choose projects based on their life cycle economic return, which is determined by the principal that governs the “time value of money”. This approach may need development when analyzing energy-intensive technologies/utilities, such as solar dryers, because it measures cash flow, an indirect and often inaccurate, measure of energy flow, as mentioned by Ref. [12]. Furthermore, the monetary value of energy does not always represent its true value to society because of subsidies, inaccurate pricing techniques and policies, and accounting confusion caused by inflation, as mentioned by Refs. [13,14].

There are a few studies in the literature regarding the overall energy benefits and energy costs associated with a particular process/system/built-facility. A benefit-cost analysis for renovation of existing residential buildings was carried out by Ref. [15]. The study considered a set of benefit-cost ratios calculated on annual basis in order to rank the alternative retrofit plans. The energy and economic analysis of a tri-generation plant (for electricity, thermal, and cooling energy production) [16], powered by solar and