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Discounted cash flow analysis of greenhouse-type solar kilns

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ABSTRACT

This paper describes the overall discounted cash flow (DCF) analysis of two greenhouse-type solar kilns (Oxford and Boral) for hardwood drying processes. The financial performance of both the kilns was found to be mainly dominated by the costs/benefits associated with the model-predicted future thermal energy flows. All the costs and benefits were calculated based on the current energy prices, while adjusting all future cash flows (either costs or benefits) to their respective present values by incorporating appropriate inflation and discount rates. The overall results indicated that the net present cash benefit and the present drying energy benefit were larger for the Oxford kiln than those for the Boral kiln, by approximately 38% and 16%, respectively, while the present energy-loss cost was smaller for the Oxford kiln by 23% than that for the Boral kiln. A sensitivity analysis was carried out in order to assess the robustness of the results against the uncertain parameters. In general, the Oxford kiln design was found to be more cost-effective and environmentally beneficial than the Boral kiln design for hardwood drying.

1. Introduction

One of the most attractive and promising applications of solar energy is the drying processes for a wide range of materials, including forest, agricultural, and bio products, as mentioned by Refs. [1–4]. Drying operations are diverse in nature, and thus has caused solar dryers to evolve in a wide range of designs, sizes, and shapes over the last three decades [5]. 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. [6]. For example, solar drying of agricultural and bio products has been discussed and analyzed in Refs. [7,8]. One of the forest products that is required to be dried down to an appropriate moisture content level (typically 10%–20%) before its end use applications is hardwood. Drying of hardwood is an energy intensive process, particularly in the use of thermal energy for drying the material (timber), as mentioned by Refs. [3,9–11]. In Australia, hardwood producers process and dry a wide variety of native hardwood species into relatively high quality visual and commodity structural products. However, most of these processors use conventional kilns (based on fossil fuels) to produce the end-use timber. There is significant evidence, including [12–14], that solar drying of timber is not only a low cost and environmentally friendly process, but also a process for improving the quality of the end-use timber. However, some effects, e.g. the cleanliness of solar energy, the economic aspects of drying processes, the energy effectiveness of the drying system, and the quality of the dried products are often undervalued for solar kilns. The Oxford kiln, which was originally designed by Ref. [15] in Oxford, England, uses two solar absorbers (north and south) in order to collect solar energy for the drying process. In this design of solar kiln, one of the north/south collectors, depending on the location of the kiln, are placed parallel to the inclined roof, while the other absorber is positioned horizontally. Another popular solar kiln design in Australia is known as the Boral kiln, which was manufactured in Western Australia by Advanced Environmental Structures Pty Ltd, as mentioned by Ref. [16]. Unlike the Oxford kiln, this kiln consists of a horizontal roof absorber, with two vertically oriented north and south absorbers. The assessment of the operational performance for these two different solar kilns, as given in Ref. [17], indicated that both the kilns were likely to be suitable for hardwood drying in Australia. Another study [18] found that a relatively low amount of energy and carbon were embodied within the materials used in the construction and maintenance of the solar kilns.

A few studies about the life-cycle economic return associated with solar kilns for wood drying applications are available in the literature. An economic analysis of solar drying systems for

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Nomenclature

D	diffusion coefficient (m^2 s^{-1})
d	discount rate (%)
DCF	discounted cash flow
D_E	activation energy (K)
DPB	discounted present benefit (AUD)
DPC	discounted present cost (AUD)
D_r	reference diffusion coefficient (m^2 s^{-1})
FB	future benefit (AUD)
FC	future cost (AUD)
GHG	greenhouse gas
h	heat transfer coefficient (W m^2 K^{-1})
i	inflation rate (%)
MC	moisture content (kg kg^{-1})
n	number of years into the project life (years)
N	service life (years)
NPCB	net present cash benefits (AUD)
OLD	original linear dimension (m)
OSA	original surface area (m^2)
OSV	original stack volume (m^3)
OV	original volume (m^3)
PB	present benefit (AUD)
PC	present cost (AUD)
PDEB	present drying energy benefits (AUD)
PELC	present energy losses costs (AUD)
PFEC	present fan energy costs (AUD)
PLC	present loading/unloading costs (AUD)
PMLC	present material & labor costs (AUD)
SLD	scaled linear dimension (m)
SSA	scaled surface area (m^2)
SV	scaled volume (m^3)
TPB	total present benefit (AUD)
TPC	total present cost (AUD)
X	timber moisture content (kg kg^{-1})
Z	distance through the timber thickness (m)

Greek symbols

C_{pt}	specific heat of timber (J kg^{-1} K^{-1})
k	timber thermal conductivity (W m^{-1} K^{-1})
ρ_t	timber density (kg m^{-3})

seaweed was carried out by Ref. [19]. A similar study analyzing the relations between the technical solutions and the economy of solar dryers was carried out by Ref. [20]. However, most of them were either type or site-specific approaches or did not consider the long-term costs or savings in their calculations.

The total life cycle financial and environmental performance evaluation of solar kilns includes the material costs, the labor costs, the maintenance costs, the on-going operational energy costs/savings, and the GHG emissions savings over the whole operational life of the kilns. One of the key challenges in carrying out the financial analysis of solar kilns is the projection of future on-going energy flow profiles over the kiln's service life. The authors previously developed, as given in Ref. [21], a relatively robust simulation procedure for predicting the future energy flows around solar kilns with varying climatic and geographical conditions. This computer simulation technique of estimating the future energy flows for the solar kilns has been adopted in this paper in order to estimate the corresponding future cash flows associated with the solar kilns. In order to evaluate the overall life cycle economic and the environmental performance of the solar kilns, there is a key need to analyze the total energy costs/gains (the capital energy and the annual, on-going operating energy costs/savings), together with the GHG emissions savings, associated with solar-kiln operations for drying processes. To address these financial and environmental aspects of solar kilns for wood drying, the objective of this paper has been set to carry out a discounted cash flow (DCF) analysis of solar kilns over an expected service life of 20 years.

2. Materials and methods

The materials and methods of this study are described in the following sections.

2.1. Scaling and basic description of the kilns

Two greenhouse type wood-drying solar kilns of different designs, namely the Oxford kiln and the Boral kiln, have been used for the analysis in this paper. The thermal performance of these two kilns was previously studied by Ref. [17], while the energy and the carbon embodied in the construction and maintenance of the kilns were presented in Ref. [18]. The lightweight and simple design, together with the simple operational procedure, of these kilns means fewer resources and less supervision are required in manufacturing and maintaining them than conventional kilns. Unlike some solar energy capturing systems that require resource-intensive photovoltaic solar panels, these greenhouse-type kilns produce solar energy through a simple combination of layered plastic, a ventilation chamber, and an air circulation system. This natural system of heat generation means that these kilns produce no or little by-products other than heat. Also, these types of solar kilns do not need boilers and wood-waste burners to provide heat, so there are less pollutants and environmental hazards. The low infrastructure requirements for greenhouse-type solar kilns, as studied in this paper, mean that the kilns do not have to be installed around a high-energy supply centre and or static boiler system, resulting in flexibility with choosing the location of the kilns.

In this paper, a discounted cash flow (DCF) analysis was carried out for the two kilns (Oxford and Boral kilns) based on the same timber load capacity of 10 m^3 and over a service life of 20 years. The original dimensions for the Boral kiln, as studied by Ref. [16], have been scaled down to give the same timber load capacity (i.e. 10 m^3) as the Oxford kiln. This scaling approach was adopted without affecting the basic kiln design, and was also successfully applied in Ref. [17]. The scaling method used in this study may be given in the following mathematical forms:

$$(SLD)_{Boral} = k*(OLD)_{Boral} \tag{1}$$

$$(SSA)_{Boral} = k^2*(OSA)_{Boral} \tag{2}$$

$$(SV)_{Boral} = k^3*(OV)_{Boral} \tag{3}$$

$$Here,\ scale\ factor,\ k = \left[\frac{(OSV)_{Oxford}}{(OSV)_{Boral}}\right]^{\frac{1}{3}} \tag{4}$$

Here, *SLD, OLD, SSA, OSA, SV, OV,* and *OSV* are the scaled linear dimension (m), the original linear dimension (m), the scaled