Renewable Energy 63 (2014) 286–291

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Design of a biomass power plant for burning date palm waste to cogenerate electricity and distilled water

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ARTICLE INFO

Article history:
Received 24 October 2012
Accepted 25 September 2013
Available online

Keywords:
Biomass energy
Date palm
Cogeneration
Thermal desalination
Rankine cycle

ABSTRACT

Date palm trees (*Phoenix dactylifera* L.) produce approximately 40 kg of burnable waste including dried leaves, spathes, sheaths, and petioles annually. In this paper, the potential of date palm waste as a bioenergy source has been investigated. As a sample project, a power plant has been preliminary designed to simultaneously generate electrical power using a steam Rankine cycle and distilled water by the thermal desalination of seawater using a multiple effect evaporator. The results indicated that a small plant in Bushehr Province in southern Iran which burns 140,000 tons of waste annually can produce approximately 62 GWh of electricity in conjunction with 2.27 million tons of distilled water. This production is equivalent to 75 GWhe/year. Environmental assessments revealed that the use of this amount of biomass leads to a net green-house gas (GHG) reduction of 40,500 tCO_2/year.

1. Introduction

Date palm (*Phoenix dactylifera* L.) is a tropical tree found primarily in the Middle East. According to the UN Food & Agriculture Organization (FAO), the Persian Gulf countries account for approximately 50 percent of the global date production [1]. A mature tree has approximately 30–140 leaves with spines on the petiole and renews 10–30 leaves each year [2]. The same amount of leaves dries out annually and must be removed. This dried organ is not consumed by animals and has traditionally been used in shading, house construction, and crates, ropes, baskets, and other handicrafts [3]. However, aside from a few modern applications, *e.g.*, as soil amendments and in panel boards, palm date waste is now most often burned.

This paper suggests that palm date waste, including dried leaflets, midribs, spikelets, spathes, sheaths, and petioles, can be used in a biomass burning steam power plant as fuel. Due to the rich oil and gas resources available in the Persian Gulf countries, very few biomass energy projects have been developed. Thus, the capital cost of such a project must be very low to make the use of biomass and other low-carbon energy sources economically viable. Although the gasification and pyrolysis of biomass have received much attention in recent decades, the most common approach to obtaining biomass energy is still burning solid waste due to its low cost and the ready availability of solid waste and wood burners with adequate efficiency. Furthermore, steam power plants utilizing the Rankine cycle are well established and comprise mature technologies. Therefore, a steam Rankine cycle with a wood waste burning boiler is used in this work to produce electrical energy.

Cogeneration in power plants is an approach to increase energy efficiency and is often used as a combined heat and power (CHP) technique. CHP techniques have been successfully applied in some European and North American industrial and residential areas [4]. However, for warm climates, such as the Persian Gulf, which features with hot summers and above-zero winters, this approach is less promising. Another option to increase energy gain is combined cooling, heating and power (CCHP), which can also handle cooling loads while still being appropriate for plants close to industrial and residential centers.

In this work, because the selected fuel type is produced in rural and agricultural regions, the most desirable placement of the power plant is between or near the palm orchards to reduce fuel transportation costs. Under these conditions, the cogeneration of power and distilled water is proposed as an ideal option.

The lack of potable water is a critical issue in the Middle East, especially the lands around the Persian Gulf. All countries in this region have considered seawater desalination as an alternative potable water source [5]. There are two major approaches to desalinating seawater: thermal and membrane-based methods. The former is more common in installed plants due to the existence of mature technologies, which lead to lower construction and maintenance costs. Here, a multiple-effect evaporation (ME)

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0960-1481/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.09.036

Fig. 1. Date palm tree before (left) and after (right) pruning. Note that this tree had 12 dried leaves.

method is chosen for the desalination unit due to its high energy efficiency relative to other thermal methods, especially the most common multi-stage flash technology [6].

In recent decades, the use of renewable energy, such as solar, wind, and geothermal energy, and waste heat recovery in desalination have received significant attention. Nevertheless, a review of desalination using renewable energy by Garcia-Rodriguez [7] concluded that the use of biomass in desalination is inefficient because the amount of distilled water obtained by this method is less than the amount of water needed to grow the biomass. However, for the type of biomass suggested in the present work, *i.e.* date palm tree waste, the above conclusion is not valid. Date palms consume little water and have a high tolerance for salt (up to 700 ppm for some species) relative to other crops [2]. In addition, as noted before, the biomass sources used in this work are waste; therefore, this biomass is available as a date production by-product without additional water or land consumption and would otherwise be burned with no useful gain.

This paper describes the preliminary design and evaluation of a biomass power plant that burns date palm wastes for simultaneous electricity generation and seawater desalination. In the following, the thermal properties and estimated contribution of date palm waste are first explained. Next, a diagram and thermo-hydraulic data of the proposed cogeneration plant are introduced and the thermal performance is evaluated. Finally, after an economic analysis, the effectiveness of this biomass energy utilization and the environment impact are discussed.

2. Date palm waste

As mentioned above, each date palm tree produces 10 to 30 dried leaves annually (See Fig. 1). An average naturally dried leaf has a mass of 2–3 kg. Hence, considering other valuable waste, such as spathes, sheaths, and petioles, each date palm tree yields approximately 40 kg of burnable waste annually. Barreveld [2] studied the composition of fibrous date palm parts (adapted from Ref. [8]), reporting averages of approximately 50% moisture and 9–10% ash by dried weight. However, sun-drying can reduce the moisture content to 20%, whereas the ash percentage can be reach 15% of the dry material by weight due to the presence of dust, soil or other impurities.

Calorimetry was used evaluate the heat value of the proposed fuel. Sampling was performed in June 2011 from orchards in the village of Faryab in Dashtestan County, 80 km east of Bushehr, Iran. The samples comprised 13 different cultivars, including one male and 12 females ranging from 1 year to approximately 120 years old. Samples were taken from different burnable parts, including leaflets, midribs, spikelets, spathes, frond bases, offshoots, and exposed roots. The samples were dried under direct sun, heated in an oven for 48 h at 40–60 °C, and milled down to three different sizes: 0.5, 1 and 2 mm. Next, the different samples were thoroughly mixed together. Three final samples were chosen for calorimetry.

Table 1
Date palm waste heating values obtained from calorimetry.

Sample number	Heating value (kJ/kg)
1	17987
2	17586
3	17577

The heats obtained from adiabatic bomb calorimeter are given in Table 1. The average is approximately 17600 kJ/kg. Note that because the experiment was performed below the boiling point of water, the water in the combustion products is in liquid phase; thus, this result is the high heating value (HHV). The low heating value, necessary for some thermodynamic calculations, can be estimated as 16500 kJ/kg.

In stoichiometric conditions, the air-to-fuel molar ratio is approximately 25, which means that the weighting ratio is 8.2. In this study, an air-to-fuel ratio (AFR) with 65% excess air, which is equivalent to AFR = 13.5, is used to improve the combustion performance.

Although biomass fuels, especially wood, have low sulfur and nitrogen contents relative to coal and petroleum fuels [9], they contain approximately 0.1% sulfur by dry weight [10]. A recent measurement of the composition of date palm wood [11] confirms this value. The presence of sulfur trioxide in flue gas may lead to the condensation of sulfuric acid on the walls of the system. To avoid this issue, the flue gas temperature should not drop below the acid dew point temperature.

3. Plant design

The above-mentioned wastes are burned to produce power in a steam Rankine cycle. Here, water is chosen as the working fluid, although the literature suggests the use of other fluids, such as ammonia, alcohols, and freons, in an organic Rankine cycle for a biomass power plant (for examples see Refs. [12,13]). These suggestions are based on the use of a low-temperature evaporator. However, in present work, the flame temperature and superheater output are high enough for efficient steam operation.

The plant location is chosen as Bushehr Province, southern Iran, along the northern coast of the Persian Gulf. Based on local statistical reports, 38846 ha are currently being used for date palm cultivation. At 155 trees per hectare, this value yields approximately 6 million date palm trees. In average, each tree produces 40 kg of waste annually, which means 240,000 tons per year. In a conservative estimation, only 140,000 tons are available as biomass fuel.

The climate in Bushehr is warm and humid. Based on 30 years worth of World Meteorological Organization (WMO) data (1961–1990) [14], the mean monthly average of the daily maximum temperature from June to September is 36.5 °C. The national meteorological organization also reports a long-term average relative humidity of 65% in the summer.