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Probabilistic multicriteria analyses for optimal biomass power plant design

A. D'Ovidio, M. Pagano*

Department of Electrical Engineering, University of Naples Federico II, Via Claudio, 21, 80125 Naples, Italy

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ABSTRACT

The design of biomass power plants is traditionally performed by using a deterministic approach. The deterministic model takes into account energetic, local and social factors to maximize the plant economic profit. When dealing with renewable energy applications, uncertainty, which involves unpredictable factors having a major influence, has recently been recognized as an important factor. In order to take into account the stochastic nature of uncertainty, probabilistic approaches have been widely applied to electric power system design and management [G.J. Anders, Probability Concepts in Electric Power Systems, Wiley-Interscience, 1990].

In this paper, a stochastic approach to optimal biomass plant design is proposed. The approach relates the plant economic index to the technological design. The paper extends the deterministic approach previously proposed in the literature [M. Fiala, G. Pellizzi, G. Riva, A model for the optimal dimensioning of biomass-fuelled electric power plants, J. Agric. Eng. Res. 67 (1997) 17–25, A. Cano, F. Jurado, Optimum location of biomass-fuelled gas turbines in an electric system, in: IEEE Power Engineering Society General Meeting 2006, 18–22 June, 2006, p. 6], and characterizes the uncertainty which concern the model by introducing random variables and probability functions. The stochastic model is formalized, the plant profitability index (PI) in an uncertain scenario is assessed.

The results of the performed numerical applications are expressed in terms of probability density functions. Observing that, under circumstances characterized by uncertainty, the traditional evaluation methods, like cost-benefit analysis, can result ill-suited, a suitable tool is proposed. Thus, a stochastic multicriteria discriminat approach, able to focus on the features of the stochastic model to compare technological solutions in terms of alternative design criteria, is proposed and performed.

Introduction

To limit the problems related to the natural global greenhouse effect, the Kyoto Protocol forces the Industrialized Countries to reduce gas emissions. The protocol recognizes the energetic sector as priority, defining references to electric energy production and use. Potential solutions address production of electric energy by means of renewable and innovative sources including photovoltaic, wind, fuel cell and biomass.

However, the availability of renewable resources varies over time and among locations and is relative to geographical, techno-economic and institutional factors. In Table 1 the assessments of current and forecasted costs for renewable resources are reported [4,5]. In particular, data focus on the economical viability of wind and biomass in respect to photovoltaic system.

Due to the current price rising for fossil energy, biomass energies are becoming increasingly interesting and important subjects for public and policymakers. Moreover, analyses performed on biomass potential and use underline a low use/potential ratio, focusing on the opportunity to increase the use of biomass as renewable energy resource [5]. In this work, a review of studies on design and operation of biomass plants is presented [2,3,6–9], with a special focus on optimal plant size for converting biomass into energy. Biomass plant rate is suited according to the amount of biomass resource available where the plant operates; the optimal rate must maximize the economic profit, which is generally related to the plant profitability index (PI) [2,3,8].

Determination of profitability indexes for renewable resources is based on optimal energy models, which minimize the cost/efficiency ratio. The amount of renewable resource is the solution to analytical approaches, which minimize the objective function of the total annual cost, subject to the constraint of the balance between energy produced and used. As far as the biomass, the determination of the plant PI is performed by means of a mathematical model, which takes into account electrical and thermal requirements and depends on technological factors (i.e. biomass conversion technologies) and local aspects (i.e. extension and typology of the agricultural cultivation, territory infrastructures and

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* Corresponding author. Tel.: +39 081 7683504; fax: +39 081 2396897.
E-mail address: marpagan@unina.it (M. Pagano).

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Table 1
Estimates of current and future costs for renewable sources.

Resource	Current cost [$/kWh]	Short time cost [$/kWh]	Medium time cost [$/kWh]
Wind	0.05–0.13	0.03–0.08	0.03–0.05
Photovoltaic	0.25–1.25	0.25–0.40	0.15–0.30
Biomass	0.05–0.10	0.03–0.08	0.03–0.04

transportation costs). Traditionally, a deterministic approach which uses a set of predefined parameters as certain input data, is formulated [2,3]. A comprehensive analysis is formulated to compare the optimal PI values obtained for different technological conversion processes, and is aimed to verify the best choice among technological alternatives.

It is noteworthy that the deterministic approach is not adequate to consider model uncertainties, as the nature of several model parameters is random. It has been observed that in recent years the probabilistic approaches have been widely used to characterize the inherently random nature of renewable sources. In order to capture the effective efficiency of improving the use of biomass energy resource in an unpredictable context, a stochastic approach can be formulated.

This paper aims at expanding the deterministic approach applied to define biomass plant design. A stochastic methodology, which considers the input factors as random variables, is proposed here. The approach to the biomass plant design is formulated focusing on the relation between economic index and technological design. The comparison of alternative technological solutions is proposed. The stochastic methodology is able to evidence the uncertainties which concern the model input factors and can condition the plant design.

The results of the numerical applications are expressed in terms of probability density functions [10]. Thus, a stochastic multicriteria decision (SMD) tool, able to compare the technological solutions in terms of alternative design criteria, is proposed and applied.

The paper is divided as follows: in Section 2, the biomass conversion technologies and the deterministic approach to the optimal plant design are described. In Section 3, the stochastic approach aiming to assess the PI in an uncertain scenario, is discussed. Moreover, as some traditional evaluation methods (like cost-benefit analysis) are ill-suited under circumstances characterized by uncertainty, in Section 3.1 a methodology based on a SMD tool is introduced [11]. In Section 4, the results of the numerical applications are presented and discussed. Finally, in Section 5, some final considerations on CO_2 reduction focusing on the biomass role in reducing greenhouse gases are reported.

Biomass technologies

Biomass describes all organic matter produced by photosynthesis. Through the process of photosynthesis (which captures sun energy), complex compounds of carbon, hydrogen, and oxygen are obtained. When these carbohydrates are burned, they turn back into carbon dioxide and water and release the sun's energy they contain. Biomass functions as a buffer of sun energy and is renewable in the sense that only a short period of time is needed to replace what is used as energy resource. Biomass includes all water- and land-based vegetation, solid waste, forestry and agricultural residues, certain types of industrial wastes, and specified cultivations [12].

Biomass can be converted to energy by means of several processes. For instance, biomass can be burned to produce steam, for turning a turbine coupled with an electrical generator. Biomass can also produce gas, via a high temperature and limited oxygen process, for driving a high efficiency gas turbine (GT) or gas combined-cycle (GCC) turbine. Power plant rate starts from 10 kW for village-power applications, to 250 kW for industrial application, until to tens of MW for utility electricity generation.

Biomass conversion process overview

Biomass power technologies include direct combustion, co-firing, gasification, pyrolysis, anaerobic digestion, and fermentation [12]. At the present, biomass power plants are usually based on mature direct-combustion technology and on anaerobic digestion (for the plants up to 1 MW of electric energy); in the near future, introduction of high-efficiency gasification, and combined-cycle systems will be expected.

Direct combustion boiler/steam turbine technology involves the oxidation of biomass with excess air, giving hot flue gases that produce steam in the heat exchange sections of boilers. The steam is used to produce electricity in a Rankine cycle. The average size of the power plants is tens of MW and the electrical energy produced varies in the interval 20/25%. Economic estimations on operating plants, performed on a 1998-dollars base, evidence that the cost per kW varies from 2000 $/kW to 3300 $/kW [13,14]. The limited plant sizes (which leads to higher capital cost per kWh) and low efficiencies (which increase sensitivity to fluctuation in feedstock price) lead the electricity costs to about 8–12 ¢/kWh. Today, direct-fired combustion technologies offer new options, especially with retrofits of existing facilities to improve process efficiency. The addition of dryers and incorporation of more-rigorous steam cycles are expected to raise the efficiency of direct combustion plants by about 10%, so that it can be forecasted lower capital investments to about 1275 $/kW [13]. The most promising future power plants are the GCC, which are expected to operate by efficiencies nearly double that of the existing processes [13]. The cost of GCC plants, at the present estimated in 3000 $/kW, is expected to drop rapidly to 1400–1600 $/kW for the new generation of mature plants by 2010 [14].

Deterministic approach to biomass plant design

Biomass plant design is based on an analytical model, which involves geographical and social factors often difficult to characterize. An optimal design has been proposed, aimed at maximizing the PI as function of plant operation area and specific investment I_s [€/MW] [2,3]. Assuming the annual available biomass as the product of the net density σ [t/(km^2 year)] and total area of production S [km^2], the annual electrical energy which can be produced by biomass plant, is equal to:

$$E_e = S\sigma H_b \eta_e \left[\frac{\text{MWh}}{\text{year}}\right] \tag{1}$$

where H_b [MWh/t] is the net calorific value and η_e the electrical efficiency. If we assume that the production area is centred on the plant, with a radius R [km], the annual energy can be expressed as

$$E_e = \pi R^2 \sigma H_b \eta_e \left[\frac{\text{MWh}}{\text{year}}\right] \tag{2}$$

According to (2), the thermal energy produced by the plant can be expressed as

$$E_t = \pi R^2 \sigma H_b \eta_t \left[\frac{\text{MWh}}{\text{year}}\right] \tag{3}$$

where η_t is the plant thermal efficiency. Assuming that only an amount of E_t can be sold, and introducing the specific factor f_u, it is possible to determine the amount of thermal energy which is