Energy xxx (2015) 1–13

Contents lists available at ScienceDirect

Energy

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

Renewable energy from pyrolysis using crops and agricultural residuals: An economic and environmental evaluation

Chih-Chun Kung [a], Ning Zhang [b, *]

[a] Institute of Poyang Lake Eco-economics, Jiangxi University of Finance and Economics, Nanchang 330013, China
[b] School of Economics, Jinan University, No. 601, West of Huangpu Avenue, Tianhe District, Guangzhou, Guangdong 510632, China

ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form
11 June 2015
Accepted 29 June 2015
Available online xxx

Keywords:
Agricultural waste
Biochar
Pyrolysis
Renewable energy
Mathematical programming

ABSTRACT

This study examines pyrolysis-based electricity generation and ethanol production using various crops and agricultural residuals in Taiwan. It analyzes the net economic and environmental effects within the framework of the Extended Taiwanese Agricultural Sector Model by incorporating ongoing and potential gasoline, coal and GHG (greenhouse gas) prices. The study discusses the effects of agricultural shifts, which have several important implications for the Taiwanese bioenergy development. First, the cost of collecting rice straw is much lower than the production cost of other energy crops, implying that the efficient use of agricultural waste may eventually result in positive social effects in terms of farmers' revenue, the renewable energy supply and GHG emissions offset. Second, farmers with idle land usually suffer a lower steady income. Encouraging the development of the renewable energy industry increases the demand of raw feedstocks, which involves converting the idle land into cultivation and increasing farmers' revenue. Third, agricultural waste is usually burned and emits CO_2, which accelerates the global climate shift. Approximately one third of emissions could be offset by rice straw-based bioenergy in certain cases. Turning this waste into bioenergy, which offsets net GHG emissions, has positive effects on the climate change mitigation.

1. Introduction

In the past decade, accelerated resource depletion and a deteriorated environmental system have made sustainable development one of the most important issues for many countries. Sustainability involves the continuous availability of almost every visible and invisible resource among current and future generations. Therefore, if the current generation runs out of most of its resources, and few or none can be used by subsequent generations, whose development also depends on the use of the same resources, their development will be seriously restricted and prohibited. This concern pushes countries to find ways to ensure that our children can have access to quantities of resources that are similar to what we have so that social development can continue. Because renewable resources can be reproduced in the relative short-term, resources that are reproduced over thousands or even millions of years are considered non-renewable resources and are likely to be depleted by the current generation. Among all non-renewables, fossil fuels might most strongly affect our life, and their use ultimately pushes technological innovation and social reform. However, the quantity of fossil fuels is fixed underground, and the over-exploitation of fossil fuels reduces not only its availability to future generations but also the quality of atmospheric conditions. The use of fossil fuels emits greenhouse gases, which results in the greenhouse gas effect, which causes extreme climate shifts [6,36]. Therefore, finding alternative sustainable energy to ensure future socio-economic development is an emergent task of modern society. Many renewable energy technologies are currently available, but most of which are still carbon positive and thus cannot alleviate the negative effects of climate change due to high emissions from processing and the transportation of bioenergy [16,44,52]. Ref. [16] indicate that biofuel production could be a potential low-carbon energy source if a proper process is adopted, and [17] show that the net climate effect of bioenergy could be either positive or negative, depending on various factors such as the crop selection, the technology used and the difference in carbon stocks. Therefore, conventional bioenergy may provide sustainable energy but

Abbreviation: CO, monoxide; CO_2, carbon dioxide; H_2, hydrogen; CH_4, methane; GHG, greenhouse gases.

* Corresponding author. Tel.: +86 13870952683.
E-mail address: zn928@naver.com (N. Zhang).

http://dx.doi.org/10.1016/j.energy.2015.06.114
0360-5442/© 2015 Elsevier Ltd. All rights reserved.

contributes less to environmental improvement in terms of GHG emissions.

One technology called pyrolysis is an attractive alternative in addition to bioenergy because of its carbon negative property [18,19,29–31]. Pyrolysis is a process by heating biomass without oxygen, which decomposes feedstocks into bio-oil, bio-gas and biochar [2,3], all of which could be used for electricity generation. However, if biochar is not used to generate electricity in the pyrolysis plant but applied in the cropland as a soil amendment, net carbon dioxide (CO_2) emissions could actually be achieved [31]. They show that when biochar blends with fertilizers and is applied to cropland, it enhances the crop yield, increases water and fertilizer efficiency and stores carbon in a more stable form [5,33]. Based on previous results, it is clear that pyrolysis and biochar application not only provide renewable energy but also offers potential economic and environmental benefits. Basically, pyrolysis and biochar technology is one form of bioenergy that requires sufficient land to support its development. In addition to agricultural feedstocks, almost every type of organic matter can be paralyzed, such as municipal solid wastes, but high costs associated with removal of heavy metal and other toxic components make this type of input less attractive.

Taiwan is interested in renewable energy because most energy is imported. Domestic energy production can ease the pressure of international political issues and the fluctuation of energy prices [9,53]. In addition to energy security concerns, the geographic characteristics of Taiwan make Taiwan vulnerable to strong climate change consequences, such as rising sea levels and increases in the incidence of tropical cyclones [22]. Collectively, these forces raise interest in establishing a bioenergy industry in Taiwan. Although some studies show that bioenergy could increase Taiwan's welfare in terms of energy supply and GHG emissions reduction [9,26,27], agricultural residuals, such as rice straw, are treated as a waste in agricultural production activities. However, this treatment of rice straw might truly be a waste due to its potential value from pyrolysis [28,54]. To examine how rice straw can contribute to the domestic energy supply and climate shift, this study analyzes the amount of bioenergy produced by conventional energy crops, such as the sweet potato and poplar, along with agricultural residuals, such as rice straw. The study also aims to explore the potential economic contribution and environmental impacts from a combination of bioenergy production strategies and patterns including direct firing (co-firing), pyrolysis-based electricity and ethanol production under multiple energy and GHG prices scenarios. Government subsidies are also incorporated due to its importance [46]. The main contributions of this study include (1) the analysis of competition and cooperation among multiple energy crops and crop residuals, given the reported amount of idle land. The simulated scenarios will inform the Taiwanese government about the amount of bioenergy that can be produced under different market conditions; (2) potential GHG effects from bioenergy and feedstocks, which provide useful information on Taiwanese environmental policies regarding carbon emission taxes, abatement requirements and government subsidies; and (3) the location selection of bioenergy processing plants. Rice straw is accompanied by regular rice planation, but the sweet potato and switch grass are primarily cultivated on set-aside land. Therefore, collection and transportation costs of feedstocks could vary significantly, and the bioenergy production pattern is likely to be different from previous research. The results provide an alternative possibility to current bioenergy strategy and agricultural policies regarding existing agricultural residuals treatment, which may be modified and switched to another potential valuable use. However, the simulation results provide only potential possibilities and are subject to errors; therefore, further environmental and agricultural policies require additional investigation under the current social-economic conditions.

2. Method

The study utilizes a price endogenous mathematical programming method that was originally introduced by Ref. [45] because this technique could derive the equilibrium in the perfect competition market by maximizing the consumer surplus and producer surplus. A spatial model based on this idea is constructed by Refs. [38] and [50] show that the property of price endogeneity is helpful in policy analysis by comparing the price endogenous model to many other linear programming models. Ref. [56] use the mathematical programming approach to measure economy-wide energy efficiency. This section first introduces associated pyrolysis and biochar studies and then outlines the theoretical framework used in this study.

2.1. Pyrolysis and biochar works

New and many forms of the bioenergy production process could be considered and developed to avoid a future energy shortage [1]. Pyrolysis is an interesting alternative that involves the chemical decomposition of organic materials through heat in the absence of oxygen [3], and biomass is converted into three outputs during pyrolysis, including (1) a liquid product called bio-oil; (2) a solid charcoal product (the biochar) that can be used in various processes and (3) a non-condensable gas product containing methane (CH_4), hydrogen (H_2),carbon dioxide (CO_2),carbon monoxide (CO) and higher hydrocarbons, which have been called bio-gas [3,14]. Fast pyrolysis and slow pyrolysis are predominantly used in biochar production. Their differences depend on their heating rate and heating duration; hence, they have a different output ratio. Slow pyrolysis produces less bio-oil and more biochar, whereas fast pyrolysis produces less biochar and more bio-oil [32,48]. Output yields could vary significantly. Ref. [55] show that fast pyrolysis yields approximately 130 percent more of bio-oil but55 percent less of biochar than those from the slow pyrolysis study in Ref. [43]. Many organic material scan be used in pyrolysis such as forestry and crop residuals, municipal solid wastes, industrial wastes, animal manure and urban sewage sludge. For example, rice straw, manure, corn stover, orchard wastes and animal waste are pyrolyzed in many studies [20,24,39,51], and the output yield changes substantially. If municipal solid wastes are pyrolyzed, toxic heavy metal may be included in outputs, and additional processes are required. Ref. [14] shows that bio-oil can be upgraded and processed to produce higher quality fuels, or refined to produce slow-release fertilizers. Biochar was burned to reduce fuel costs and provide energy in plant operation. However [31], show that if biochar is used as a soil amendment, the CO_2emissions offset can be 12–84% greater than if it is burned to offset fossil fuel. Offset efficiencies of pyrolysis can be greater than 100%, compared to the emissions from the replaced fossil fuel inputs [28,37] indicate that the biochar application in some places in China is economically feasible. Because carbon constitution of biochar is more stable, biochar can last more than thousands of years, and its GHG offset can be assumed permanently [19,31]. However, it is potentially eroded by precipitation and runoffs [34].

In addition to GHG offset, biochar also brings economic benefits. Since 1980, the applications of biochar to crop yields have been studied [19,23,25,42,49]. Ref. [5] shows that biochar can increase crop yields because more nutrients are retained. Their experiment shows that simultaneous application of biochar and N fertilizer has a significant the biochar/nitrogen fertilizer interaction. Moreover, biochar can improve the N fertilizer use efficiency during plantation, resulting in a 95%–266% increase on the dry material of radish.

Please cite this article in press as: Kung C-C, Zhang N, Renewable energy from pyrolysis using crops and agricultural residuals: An economic and environmental evaluation, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.06.114