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A regional optimization model for waste-to-energy generation using agricultural vegetative residuals

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ABSTRACT

The spatial distribution of vegetative agricultural residuals (VAR) implies that any waste treatment system (WTS) designed to manage VAR is particularly sensitive to transportation costs. Additionally, a wide range of treatment technologies is potentially available for VAR treatment, but some of them lack a well-developed market for their output products. This study develops a method to design an economically feasible VAR treatment system, analyzing the profitability of the system as a function of logistics and uncertain market prices of the available treatment technologies' products. The design method includes an economic optimization model followed by a sensitivity analysis of the potential changes in the system's profitability. The results show that the market price of the treatment technologies' products has a larger impact on the system's profitability than transportation costs. Specifically, if biochar prices reach the level forecasted by experts, pyrolysis will become the dominant technology of the WTS. The research highlights the importance of the treatment technology selection and the location of treatment facilities in the design of an optimal WTS for VAR.

1. Introduction

The agricultural and forestry sectors produce yearly substantial amounts of vegetative agricultural residuals (VAR), characterized by their wide spatial distribution, and high disposal costs imposed on the producers. Using these residuals as feedstock of an economic feasible waste management system (WMS) can transform VAR into a valuable resource instead of a nuisance.

Academic articles and policy reports dealing with the economic analysis of a WMS focus mainly on municipal solid waste, and rarely consider VAR as an integral part of the potential WMS feedstock (e.g., Rentizelas et al., 2014; Madar, 2015). The studies which analyze the economic feasibility of WMS for VAR, focus mainly on a few types of assessments: (a) investment and operational costs of a single waste-to-energy technology using different feedstock types or different levels of feedstock capacity (e.g., Baruya, 2015; Tidaker et al., 2014; Srivastava et al., 2014; Brown et al., 2013); (b) a combination of several waste-to-energy technologies, while assessing the potential different feedstock types and production costs (e.g., IRENA, 2012; IRENA, 2014; UK, 2014; UNEP, 2009); (c) the environmental costs of a specific treatment facility, or one of the treatment stages, such as transportation (e.g., Delivand et al., 2015; Favero and Massetti, 2013), and (d) the generation of a bio-fuel (e.g., Ayalon et al., 2013; Petrakopoulou, 2015). Economic studies which address both energy and non-energy treatment technologies, and analyze the WMS profitability as a function of uncertain market prices of the treatment facilities' products, and logistics aspects, are scarce. Several recent studies suggested that in order to assure waste-treatment facilities profitability, the implementation of a gating fee is required (Goldfarb, 2015; Greenhut et al., 2015; Hadas et al., 2013).

The present research highlights the importance of a holistic WMS analysis approach, focusing on the treatment of all the VAR in a predefined area, while considering all energy- and non-energy-related potential treatment technologies. The objective of the research is to present a method to design a profitable WMS for VAR which do not require any gating fee and minimizes transport costs.

The design stages of the WMS for VAR are the following: (1) technology selection as a function of the type and amount of available residuals (Section 2.2.1); (2) economic feasibility of the treatment facility as a function of the investment and operational costs compared to the market prices of the products (Section 2.2.2); (3) location of the treatment facility as a function of the available

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capacity and the potential market for the products (using optimization modeling, Section 2.3), and (4) profitability of the WMS as a function of uncertain market prices of the treatment facilities' products and logistics (using sensitivity analysis, Section 3).

The sensitivity analysis focuses on the impact of two different parameters: First, the impact of the market price for waste treatment end-products, and second, the impact of transportation costs. The uncertain market price of the facility's product depends on its potential use and the availability of similar products in the market. Biochar is one example of an interesting waste treatment end-product, since, on the one hand, it has several potential applications and a high market price, and on the other hand, the uncertainty regarding its market price dramatically affect the economic feasibility of the waste system. Logistics costs depend on the transportation means, the availability of residuals, and the distance between them and the location of the treatment facility.

2. Material and methods

The first designing step towards a sound WMS for VAR is the identification of the available residual types and location, on one hand, and the economically feasible technologies to treat them, on the other. Based on that, modeling scenarios with specific facilities deployment can be defined, as detailed in Sections 2.1–2.3.

This research uses as a case study the agricultural and forestry sectors of Israel. There are 15 differentiated agricultural districts in the country, producing together more than a million tons of VAR every year (details in Table 1), but has no WMS to treat them. Currently, about 75% of the orchard and forest residuals are chopped and left for land cover on the orchard or forest soil and most of the field crops are chopped and buried within the farm field area, whereas most of the woody materials are used for bio-coal production.

Untreated VAR constitute a health risk and potential environmental issue (Hadas et al., 2013; Goldfarb, 2015; Greenhot et al., 2015). Policy assessments recommend the reuse of these residuals as a feedstock to produce soil amendment, animal food, or energy via gasification, but highlight the implementation challenges, as the high costs of transporting the spatially distributed residuals to the treatment facilities, the non-stable nature of the feedstock availability (based on the agricultural seasonal residuals), and the high energy generation costs using the gasification technology. Therefore, choosing the right treatment technology is a crucial element, planning an economically feasible WMS. Since most of the agricultural areas have dry weather during large part of the year, most treatment processes require dry materials as feedstock, and there are different types of residuals throughout the year from different crops, we assume that the residual supply is stable throughout the year, with no major gaps that might affect the economic feasibility of the treatment facilities.

Table 1
The types of agricultural and forest residuals in all districts.

District	*Foliage[ton/year]*	*Woody[ton/year]*	*F&V[ton/year]*
North East (1)	42,676	12,181	9223
North East (2)	67,012	18,680	15,821
North East (3)	13,787	883	2398
North West (1)	73,424	6487	13,264
North West (2)	48,303	8926	12,617
North (1)	68,389	4109	9127
North (2)	164,315	12,618	11,593
Center (1)	38,355	15,733	11,998
Center (2)	24,938	6861	5217
South West (1)	197,866	22,925	14,839
South West (2)	54,784	7470	6870
South East (1)	41,595	6490	3076
South East (2)	31,895	5187	4371
South (1)	284,116	39,623	18,528
South (2)	16,038	4247	2565
Total	1,167,492	172,421	141,508
% out of all	79%	11%	10%

2.1. Waste types and spatial diversity

The VAR considered in this research are of three main types: "foliage" includes all green leaves and non-woody shrubs and field crops biomass; "woody" includes most orchards and forest branches and trunks, and "F&V" includes all fruit and vegetable residuals.

2.2. Waste treatments and product's markets

Each treatment technology requires a different type of feedstock whereas some of the treatment facilities operate best with only certain kinds of field crops (e.g., animal feed is based on the animals' dietary requirements and physical digestion ability). The waste treatment facilities also generate various products, which include heat and biochar for multiple purposes, charcoal for cooking, steam for industrial processes, electricity, RDF (refused derived fuel), animal food, or compost (details in Section 2.2.1). Bio oil is another application but is beyond the scope of this research.

In addition to the theoretical ability of a treatment facility to reuse the available crop residuals, its economic feasibility depends also on the availability of local markets for the waste treatment facility products. Therefore, the criterion defining the treatment facilities' siting for the WMS design analysis (Section 3) is based on both the residual (feedstock) availability and the market availability for the different waste treatment products, within the different districts analyzed (Section 2.2.1). The economic feasibility of each treatment facility was the criterion defining which technology will, eventually, be selected for each district (Section 2.2.2). The logistics (transportation) cost, or its effect on the treatment facility's economic feasibility, will be assessed in Sections 2.3 and 2.4.

2.2.1. Feedstock and products

The potential treatment technologies, which have the required feedstock and a market for their products, are detailed in Table 2, together with the assumptions used in this research.

2.2.2. Economic feasibility

The economic feasibility is of a standalone facility is represented by the net present value (NPV), which is calculated as the sum of the benefits minus the sum of the costs, throughout the 10 years of the waste treatment facility operation. The sum of the benefits is represented by the market price paid for the generated products (assuming fixed price throughout the 10 years). The sum of costs is represented by the construction and operational costs. The external environmental costs are assumed to be internalized in the construction and operational costs, as required by local environmental regulations.

The yearly average benefits, costs, and profit (benefits minus costs) of every treatment facility are shown in Table 3, in which the treatment facilities are ordered from the most to the least profitable. The NPV calculation does not consider the transportation costs of the residuals from the crop field to the treatment facility, as these costs will be discussed in Section 3.

Pyrolysis, torrefaction, animal feed, and RDF production are the most profitable technologies (Table 3). Composting has been excluded from the WMS design since it uses mainly municipal solid waste as a feedstock within the districts under study. The production process of the four selected facilities uses one cycle of energy conversion to generate their products. This makes them more efficient and profitable compared to the other processes,

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