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Supply chain optimisation of pyrolysis plant deployment using goal programming

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ABSTRACT

This paper presents a goal programming model to optimise the deployment of pyrolysis plants in Punjab, India. Punjab has an abundance of waste straw and pyrolysis can convert this waste into alternative biofuels, which will facilitate the provision of valuable energy services and reduce open field burning. A goal programming model is outlined and demonstrated in two case study applications: small scale operations in villages and large scale deployment across Punjab's districts. To design the supply chain, optimal decisions for location, size and number of plants, downstream energy applications and feedstocks processed are simultaneously made based on stakeholder requirements for capital cost, payback period and production cost of bio-oil and electricity. The model comprises quantitative data obtained from primary research and qualitative data gathered from farmers and potential investors. The Punjab district of Fatehgarh Sahib is found to be the ideal location to initially utilise pyrolysis technology. We conclude that goal programming is an improved method over more conventional methods used in the literature for project planning in the field of bio-energy. The model and findings developed from this study will be particularly valuable to investors, plant developers and municipalities interested in waste to energy in India and elsewhere.

1. Introduction

The Indian state of Punjab, like the rest of India, has seen a rapid growth in demand for energy and waste management services. Unlike other Indian states, Punjab does not have access to hydroelectric, coal, or similar resources, and thus relies heavily on imports of energy from other states. However, Punjab does have an abundance of agricultural waste biomass, particularly rice and wheat straw. Singh et al. [1,2] determined the spatial availability of unused agricultural biomass in Punjab using a Geographical Information System (GIS). They found that 14 mega tonnes of waste biomass was produced every year; the majority of which was waste straw (3 mega tonnes of wheat straw, 7 mega tonnes of rice straw).

Energy conversion of waste biomass is not widely practiced in Punjab or the other states of India, and the majority of waste straw is disposed of through open field burning. This has severe environmental and social impacts, including greenhouse gas, carcinogenic and particulate matter emissions. The carbon dioxide and carbon monoxide emissions from wheat straw burnt with a low combustion efficiency range from 1400 to 1600 g CO_2/kg and 35–60 g CO/kg [3–5]. As a result of straw being burnt, fields lose nutrients and carbon, thus additional fertiliser, pesticides and irrigation are required [6]. Particulate matter is a major nuisance, causing a range of health problems: allergies, asthma, eye irritation, bronchial problems and other respiratory issues. It has been reported that the average household in Punjab has to spend more than Rs.1000 ($18.5) per year to address these medical conditions. It has been estimated that the total cost incurred as a result of pollution from straw burning in Punjab is as high as Rs.76 million/year ($1,270,000) [7]. Thus there is an urgent requirement for innovative solutions to provide energy services and alleviate the problems from open field burning in Punjab.

Straws and cereal crops are particularly difficult to process via controlled combustion methods. Due to a high alkali, silicon, chlorine and sulphur content, they are highly fouling and slagging. Rice straw for example has an ash content of around 15% comprising of approximately 75% silicon and 10% potassium. Combustion of rice straw also results in high levels of oxides of

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Nomenclature

ARice	availability of rice straw (ktpa)
AWheat	availability of wheat straw (ktpa)
Bo	percentage of bio-oil blended with diesel (%)
Ca	cost of accessories (million$)
Capex	capital cost (million$)
cd	cost of diesel ($/l)
Ce	cost of diesel engine (million$)
CO2R	prevented carbon dioxide emissions (tpa)
Cp	cost of pelletiser (million$)
Cpyro	cost of pyrolysis unit (million$)
CRice	cost of rice straw ($/kg)
cw	wage of tractor driver ($/h)
CWheat	cost of wheat straw ($/kg)
DRice	demanded rice straw (ktpa)
ds	average distance of feedstock from plant (km)
DWheat	demanded wheat straw (ktpa)
Ec	engine capacity (kW)
Efc	engine fuel consumption (kg/h/kW)
fc	fuel consumption of tractor (l/km)
FCR	fixed charge rate (%)
Income	plant income (million$/year)
kd	discount rate (%)
LCOE	levelised cost of electricity ($/kWh)
LCOO	levelised cost of bio-oil (Rs./kg)
lt	capacity of tractor trolley (tonnes)
n	period of loan (years)
NP	number of plants (–)
$O\&M_{total}$	total operations and maintenance costs (million$/year)
Oe	annual operating cost of engine (million$/year)
Of	annual purchasing cost of feedstock (million$/year)
Op	annual operational cost of pelletiser (million$/year)
Opyro	annual operational cost of pyrolysis unit (million$/year)
Ot	annual operational cost of transporting feedstock (million$/year)
Ow	annual operation cost of storing feedstock in a warehouse (million$/year)
P	profit of plant (million$/year)
Pc	plant capacity (kg/h)
Pl	plant's parasitic load (kW)
PLCapex	percentage of capital cost paid for by loans (%)
PMR	prevented particulate matter emissions (tpa)
PP	payback period (years)
Qc	quantity of char produced (tpa)
Qe	quantity of electricity produced (kWh/year)
Qo	quantity of bio-oil produced (tpa)
QSe	quantity of surplus electricity after parasitic requirements (kWh/year)
QSo	quantity of surplus bio-oil after parasitic requirements (tpa)
Sc	sale price of char ($/kg)
Se	sale price of electricity ($/kWh)
So	sale price of bio-oil ($/kg)
ta	total area of target location (km^2)
ts	tractor speed (km/h)
Yc	yield of bio-char (%)
Yo	yield of bio-oil (%)

Sub- super- script

$+d$	positive deviation from goal
$-d$	negative deviation from goal
l	variable site locations
w	weighting of goal deviation

nitrogen and sulphur being emitted. Special solution are therefore required to process rice straw and other waste crop residues for the purposes of energy generation [8].

Pyrolysis is a thermochemical conversation process that converts organic materials at high temperatures in the absence of oxygen to produce alternative bio-fuels: bio-oil, bio-char and pyrolysis gas [9]. Resulting bio-oil has low alkali metal content and can be used as an alternative fuel by blending with conventional liquid fuels [10]. Fermentation and hydrocracking enable transportation fuels to be produced and other chemical feedstocks such as phenols and organic acids can be extracted. Pyrolysis gas is useful as it contains methane and hydrogen, though its calorific value is much lower than that of convention fuels due to the substantial fraction of nitrogen and carbon dioxide present. Bio-char is the remaining solid residue and acts as a carbon sequestration material and can be used for soil amendment and water treatment [11–13]. Though pyrolysis has started to gather much interest in the field of waste to energy, as there is significant revenue potential in these alternative products, to the authors' knowledge, no installed facilities exist in India and research into these types of systems remains limited [14]. There are many options for deploying pyrolysis plants in India and the alternative upstream and downstream activities for generating bio-fuels from residue straws are numerous and complex. The main supply chain and logistic issues for producing energy from biomass are reviewed by Gold and Seuring [15]. The five main system components of the extended supply chains for biomass utilisation are harvesting and collection, preparation/pretreatment, storage, transport and energy conversion.

1.1. Multi-criteria decision-making

Multi-Criteria Decision-Making (MCDM) methods enable a systematic and holistic approach to be taken to strategic decision-making and supply chain design. Thus, the uptake of MCDM for renewable energy planning has increased significantly in recent years. Pohekar and Ramachandran [16] provided a review of MCDM techniques and studies that have been performed for sustainable energy planning and Scott et al. [17] reviewed MCDM methods for bio-energy systems. In the field of bio-energy, several authors have used MCDM to optimise biomass supply chains focussing on specific aspects of the logistical operations; applications include resource allocation, site selection, vehicle scheduling and technology selection [18,19]. Miet Van Dael et al. [20] outlined an MCDM tool for determining potential sites for bio-energy projects in Belgium. Cornelissen et al. [21] used MCDM to rank different biopolymer options for blending with biomass for flash pyrolysis. Iakovou et al. [22] reviewed research that has been carried for strategic, tactical and operational decision-making in the five main areas of the biomass to energy supply chain and concluded that more work is required to evaluate the entire supply chain, rather than decision-making at a single stage of the supply chain.

Mixed integer programming is one of the most widely utilised MCDM tools for biomass supply chain optimisation. The approach involves optimising a range of decision variables in order to minimise or maximise a particular objective function. Frombo et al. [23] developed a tool that uses Mixed Integer Linear Programming (MILP) and GIS for evaluating alternative scenarios for forest