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BIOELECTRICITY GENERATION FROM SUGARCANE WASTE IN QUEENSLAND: MODEL FOR OPTIMAL SITING AND SIZES FOR BIOMASS ENERGY PLANTS

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ABSTRACT

Minimizing cost and greenhouse gas (GHG) emissions associated with the transport of biomass feedstocks are a major focus in sustainable bioenergy production. The issue of determining appropriate candidate sites for large green-field bioenergy plants and subsequently choosing between these site options continues to involve complex decision-making processes. This paper reports on a geographical information system (GIS) based optimization model developed to identify optimal sites that minimize the biomass delivery costs and associated GHG emissions under different biomass supply scenarios. The model used extended GIS-based Fuzzy multi-criteria methods to identify candidate sites and location-allocation analysis to identify optimal energy plant locations. The model was configured to investigate sugarcane waste for bioelectricity production in Queensland, Australia. Results for the siting of bioelectricity generation capacity in Queensland identified optimally located plants with installed capacity ranges from 57 MW to 185 MW and average transportation distances of 27 km to 64 Km. The Burdekin cane growing region was identified as the most favoured location when considering feedstock transport costs and associated GHG emissions.

Keywords: GIS, Biomass energy plant, Bioelectricity, Location-allocation model

1. INTRODUCTION

As a renewable substitute for fossil-based fuels and electricity, bioenergy derived from forest residues, agricultural residues and energy crops have the potential to provide up to 96 EJ a^{-1} to the global energy mix by 2050 [1]. The high cost of feedstock transport compounded by a lack of analytical tools to minimize these costs continue to provide barriers to the increased large-scale investment in bioenergy capacity [2].

Biomass from forest plantations, agricultural waste and organic waste represents less than 5 % of current primary energy use in Australia. The lack of cost-effective biomass supply chains and efficiency issues related to energy conversion technologies are identified as two of the main barriers to greater utilization of biomass as a renewable resource [3]. Sugarcane residue is one of Australia's largest sources of biomass and potentially a major contributor in meeting national GHG mitigation targets. The Australian sugar industry is predominantly concentrated in the state of Queensland where around 95% of the national crop is grown [3]. Although, sugarcane is primarily used to produce sugar, it is recognized as an ideal crop for producing various bio products such as fuels, plastics and acids [4]. The fibre remaining after sugar extraction (bagasse) and the leafy component of the crop which is left in the field (trash) have significant potential to produce renewable stationary energy and second-generation biofuel. Annually the industry produces over 11 million dry tonnes of bagasse and 9 million dry tonnes of cane trash. Although a sizeable proportion of this bagasse and trash is required to provide energy for sugar processing and maintain soil health respectively, sugarcane fibre is sufficiently abundant to remain a significantly underutilized biomass resource [5].

To date the majority of studies of biomass energy production from sugarcane waste have utilized non-spatially explicit techno-economic methods of biomass energy production from sugarcane waste at plant level to establish production costs [6, 7]. By contrast Tittmann et al. [8] have utilized a GIS integrated mixed integerlinear programming (MIP) optimization model of bioenergy production in California to establish feedstock supply curves as well as optimal locations, capacities and appropriate technology types for large scale bioenergy production. Recently, Khatiwada et al. [6] have used the asset tracking software BeWhere1 to develop a mixed integer, spatially explicit model to analyze electricity and/or ethanol production utilizing surplus bagasse and cane trash under different conversion technology scenarios.

The study presented here provides a spatially explicit analysis of the potential use of sugarcane waste (bagasse and cane trash) for renewable stationary electricity production in Queensland, Australia. A GIS based model has been developed to identify economically optimal locations and sizes of conversion plants. The associated avoided global warming potential of these optimally located plants is also presented.

2. MATERIAL AND METHODS

This study utilized a preliminary suitability analysis of potential locations for sugarcane-based biomass energy plants in Queensland and a subsequent spatial optimization of selected plants based on logistical costs associated with biomass transport and storage. Data on the availability of sugarcane waste (both bagasse and cane trash) at a local government area (LGA) level (Fig 1) was sourced through the Australian Renewable Energy Mapping Infrastructure (AREMI) platform. AREMI is an Australian federal government funded spatial data platform developed for the renewable energy industry (https://nationalmap.gov.au/renewables/).

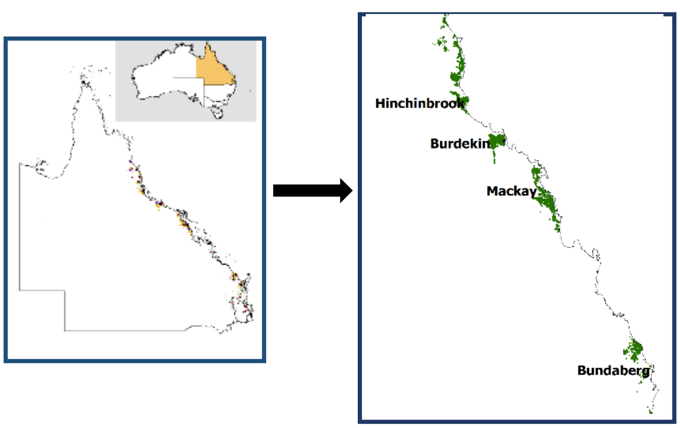

Fig 1 Spatial distribution of sugarcane biomass sources in Queensland

2.1 *Preliminary selection for potential bioelectricity sites*

GIS based Fuzzy Multi-Criteria Analysis (Fuzzy MCA) was used to identify a number of candidate locations suitable for siting sugarcane biomass electricity generation plants. Fuzzy MCA was developed and implemented in the ArcGIS model builder environment utilizing advanced exclusion analysis, preference analysis and combing of normalized layers featured in this software platform.

2.2 *Spatial optimization*

A GIS location-allocation analysis was implemented to estimate the optimal capacity of the energy plants considering real road network data and spatial biomass availability. A so-called p-median problem solver technique [9] was used to select p energy plants from n candidate plants, minimizing total weighted distances between each demand point and facility as follows.

$$\min \sum_{ij} w_i \, x_{ij} d_{ij}$$

where w_i is the weight associated with each biomass supply point i, d_{ij} is the distance between biomass supply point i and candidate facility j and the factor x_{ij}=1 if the biomass source point i is assigned to a facility j; x_{ij} = 0 otherwise.

The results of the location-allocation model provided the basis of several key decisions such as the location and size of the energy plants, the number of biomass supply points to be allocated to each of the plants and the amount of biomass to be transport between supply point and facility.

The objective function minimized was the total delivered biomass costs in terms of component transport, storage and farm gate costs (includes growing, harvesting and pre-processing). The input cost factors associated with biomass delivery were retrieved from a variety of commercial consulting studies (unpublished) undertaken by the authors for the Australian sugar industry. Finally, the environmental impacts were measured in terms of GHG mitigation potential in CO2-equivalent (CO2eq) per unit of bioenergy resulting from the replacement of coal and gas fired electricity generation with bioelectricity [10]. A summary of costs and factors used in determining GHG mitigation potential based on data available in the open literature [4, 10, 11] and unpublished data are shown in Table 1.

[1] www.BeWhere.com

Table 1 Logistical costs and GHG mitigation potential factors used in the analysis

Name	Unit value
Unit fixed transportation cost	10 AUD/dry tonne
Unit variable transportation cost	1.5 AUD /km/dry tonne
Unit storage cost	10 AUD/dry tonne
Unit farm gate cost	81 AUD/dry tonne
Unit GHG mitigated	917 kg CO2-e GWh^{-1}

3. RESULTS AND DISCUSSION

3.1 Preliminary selection of potential sites

Using Fuzzy MCA, a total of 13 candidate sites were identified for bioelectricity production in Queensland. These plants were located in the LGA divisions of Hinchinbrook, Burdekin, Mackay and Bundaberg. The logistical costs and GHG mitigation impacts were calculated for all candidate sugarcane biomass energy plants (Table 2).

Table 2 Candidate bioelectricity generation plants in Queensland determined using Fuzzy MCA

Plant ID	Biomass supply (kt)	Average biomass transport distance (km)	MWe	Total biomass delivery cost (AUD t^{-1})	% of cost attributed to transport	Emission mitigation $MtCO_2$-e	LGA
S-2	1944	53	135	181	50	0.99	Hinchinbrook
S-3	1946	47	135	173	47	0.99	Hinchinbrook
S-7	2668	36	185	156	42	1.36	Burdekin
S-9	2015	46	139	171	47	1.03	Mackay
S-10	2034	51	141	178	49	1.04	Mackay
S-11	1748	62	121	195	53	0.89	Isaac
S-15	832	43	57	167	45	0.42	Bundaberg
S-16	834	27	57	142	36	0.42	Bundaberg
S-20	831	64	57	198	54	0.42	Gladstone
S-21	832	47	57	172	47	0.42	Bundaberg
S-22	832	57	57	188	52	0.42	Bundaberg
S-24	832	60	57	192	53	0.42	Bundaberg
S-25	949	43	65	166	45	0.48	Bundaberg

The total biomass delivery cost of potential sites varied from AUD 142 to AUD 198 per dry tonne. Approximately half of the total biomass delivery costs were attributed to transport, the cost balance being related to harvesting, pre-processing and storage. GHG mitigated potential ranged from 0.42 to 1.36 MtCO2-e being primarily a function of plant capacity (57-185 MW respectively).

3.2 Spatial optimization - centralized and distributed plants scenarios

For the 13 candidate plants (n = 13) in Table , GIS location-allocation analysis was used to locate sites for bioelectricity production assuming the total allowable number of optimum sites were allowed to vary from one (p = 1) to seven (p = 7). A maximum road transport distance of 100 km was assumed. The results presented in Fig show the effects of optimal plant number on annually aggregated biomass transport distance and bioelectricity plant capacity. The trend shown in Fig2 was found to differ from that reported for some previous studies [12, 13] which show weighted transportation distance for optimally located sites simply decreasing with an increasing number of plants due to resource competition between neighbouring potential plants. In the current study, the geographical extent of the Queensland sugar industry is such that aggregated transportation distance increases as the number of optimally located sites are increased from one to three due to the isolation of these plants relative to each other. As the number of optimally located sites increases beyond three, competition between sites begins to impact on sugarcane residues available to each plant and the aggregated transport distance travelled starts to decrease (Fig 3).

For a single centralized plant scenario (p = 1), the aggregated transportation distance was found to be 47000 km annually with 185MW of electricity production capacity, whereas with a multiple bioelectricity scenario (e.g. p = 7) the aggregated transportation distance and average production capacity was reduced to 25000 km and 10 MW respectively.

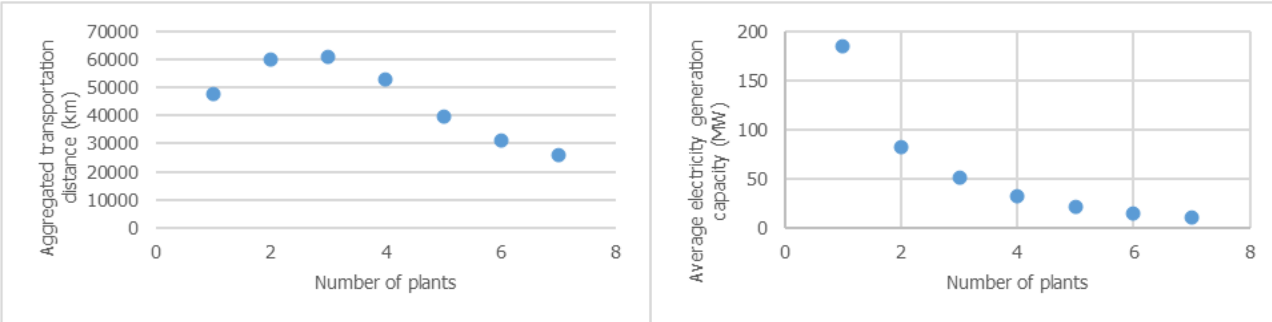

Fig 2 Variation of aggregated biomass transport distance and average bioelectricity production capacity with increasing number of optimal sites

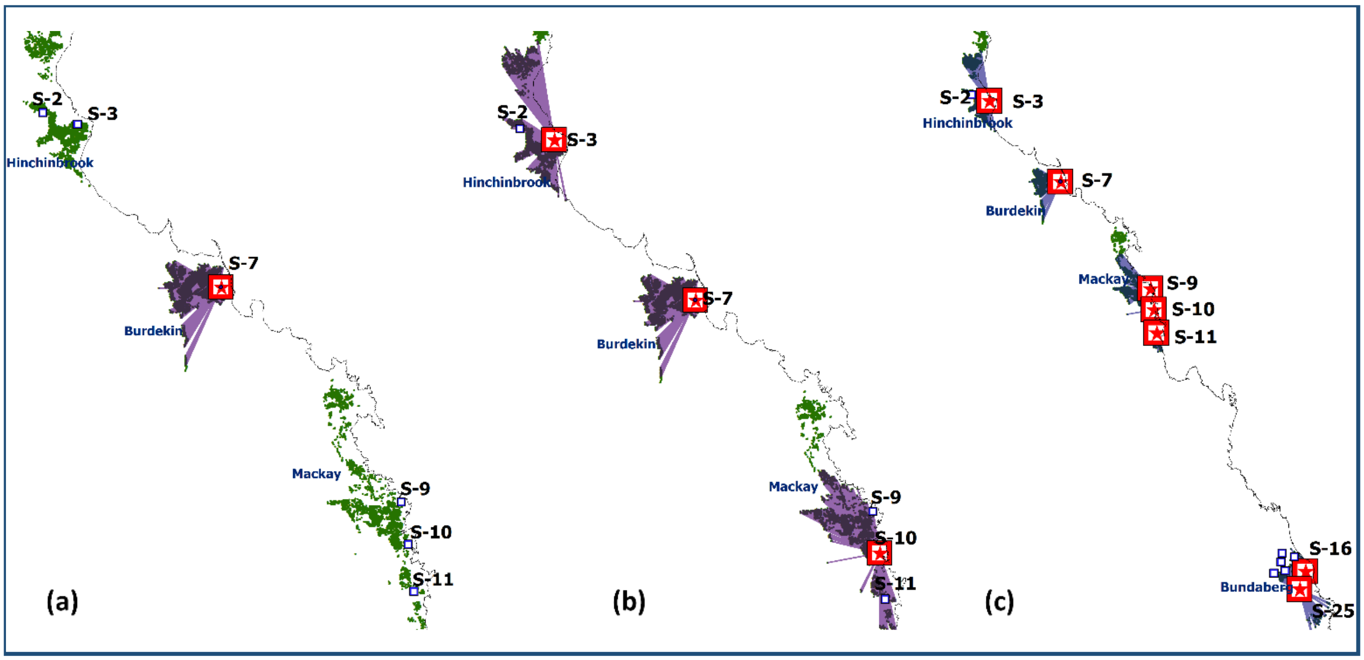

Fig 3 Optimally located bioelectricity plant sites within the Queensland sugar industry for (a) a single centralized plant (p = 1), (b) three distributed (p = 3) and (c) multiple distributed plants (p = 7) scenarios.

3.3 Regional variation in biomass availability and cost

The relationship between biomass availability and associated cost was analyzed by varying the maximum feedstock transportation distance (maintained previously at 100 km). The analysis was undertaken for two sites, S-7 and S-25 located in the Burdekin and Bundaberg regions respectively. Inspection of the results of this analysis (错误!未找到引用源。4) reveals that as the maximum transport distance is increased, the unit transportation cost associated with site S-7 increases less rapidly relative to the increase in the corresponding costs for site S-25. This can be explained by the density of cane in terms of the geographical distribution of farms and the per hectare yields both of which are higher in the Burdekin relative to the Bundaberg regions. For all practical purposes the maximum biomass availability and price for the S-7 site is approximately 2 600 000 dry tonnes per year and AUD 155 per dry tonne respectively and occurs at a 60 km maximum transportation distance. The maximum biomass availability and price for the S-25 site is approximately 940 000 dry tonnes per year and AUD 160 per dry tonne respectively and occurs at a 70 km maximum transportation distance.

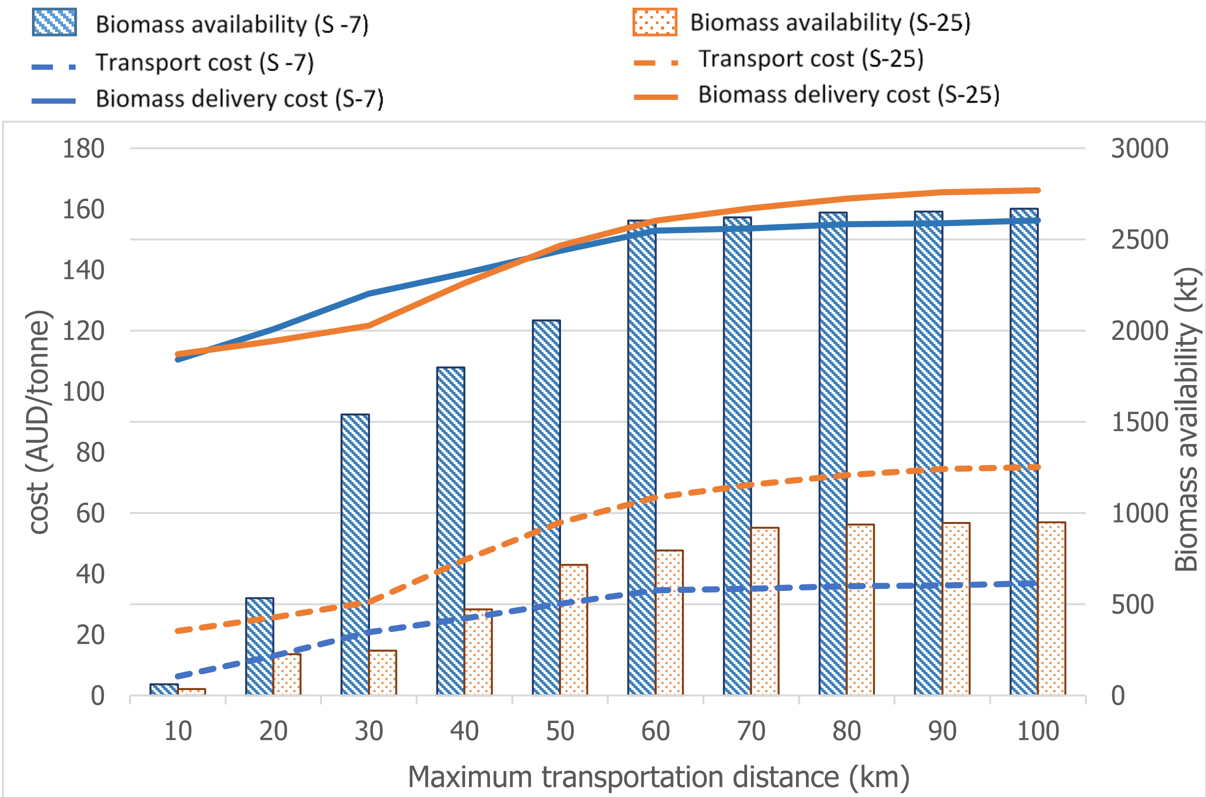

Fig 4 Variation of biomass availability (dry basis) and biomass supply costs with different maximum transportation distances.

4. CONCLUSION

In this study a GIS based optimization model was developed and used to select optimal locations for potential bioelectricity plants, their export capacities and GHG mitigation potential based on weighted feedstock transportation distance. The biomass delivery costs of optimally located bioelectricity plants utilizing sugarcane residues were in the range of AUD 142 to AUD 198 per dry tonne with average transportation distances ranging from 36 km to 54 km. The GHG mitigation potential ranged from 0.42 to 1.36 MtCO2-e annually. The results of the analysis show that weighted average transportation cost was a significant contributor to (up to 40% of) total biomass delivery costs. The model is currently being developed to further understand and optimize the use of multiple biomass types to mitigate against seasonal uncertainties in and reduce storage costs associated with the use of single crop (sugarcane) residues for bioelectricity production.

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