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Optimizing the Location of Biomass Energy Facilities by Integrating Multi-Criteria Analysis (MCA) and Geographical Information Systems (GIS)

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Abstract: Internationally forest biomass is considered to be a valuable renewable energy feedstock. However, utilization of forest harvesting residues is challenging because they are highly varied, generally of low quality and usually widely distributed across timber harvesting sites. Factors related to the collection, processing and transport impose constraints on the economic viability of residue utilization operations and impact their supply from dispersed feedstock locations. To optimize decision-making about suitable locations for biomass energy plants intending to use forest residues, it is essential to factor in these supply chain considerations. This study conducted in Tasmania, Australia presents an investigation into the integration of Multi-criteria analysis (MCA) and Geographical Information systems (GIS) to identify optimal locations for prospective biomass power plants. The amount of forest harvesting biomass residues was estimated based on a non-industrial private native resource model in Tasmania (NIPNF). The integration of MCA and a GIS model, including a supply chain cost analysis, allowed the identification and analysis of optimal candidate locations that balanced economic, environmental, and social criteria within the biomass supply. The study results confirm that resource availability, land use and supply chain cost data can be integrated and mapped using GIS to facilitate the determination of different sustainable criteria weightings, and to ultimately generate optimal candidate locations for biomass energy plants. It is anticipated that this paper will make a contribution to current scientific knowledge by presenting innovative approaches for the sustainable utilization of forest harvest residues as a resource for the generation of bioenergy in Tasmania.

Keywords: biomass supply chain optimization; facility location; multi-criteria analysis; analytic hierarchy process; GIS; Tasmania; Australia

1. Introduction

As a response to increased fuel cost and environmental concerns, the use of renewable energy source is being highly considered as an alternative to fossil fuel [1]. Globally, forest biomass is considered one of the main renewable energy sources, and its utilization as an energy source has increased rapidly in the last decades [2]. Policies supported by the public and all political parties has resulted in financial support and subsidies by governments globally, especially in Europe [3]. In the case of the United States, forest residues are also becoming valuable materials such as biomass energy feedstocks and engineered wood products [4]. Wood residues from commercial timber harvesting have been utilized to make various timber products for decades. Nearly all particle boards in the United States are made from timber processing residues, and about one-third of all pallets produced annually are made from recycled wood [5].

Tasmania, Australia's southernmost state, has a long history of forest utilization for timber production. In the past, the majority of timber harvest concentrated on native forests, but in the future, plantations will become the primarily source of timber products [6]. In contrast to the bioenergy trends observed globally, forest biomass and residue utilization has been insignificant in Tasmania (as in the rest of Australia), and has got little political or public support. Because of the lack of economic incentives, a significant amount of harvesting and processing residues end up being burnt in the forest or dumped in landfills [7]. The harvesting and processing of native forests produce a significant volume of timber residues that could be utilized by biomass plants in Tasmania for the production of electricity from renewable forest biomass resources. Currently, there are no biomass plants in Tasmania; however, a project has been proposed to build and operate an energy plant near the town of Huonville, in southern Tasmania, but it is still under review waiting for its approval by the Tasmanian Government [7].

Forest residues, including unmerchantable trees, small-diameter trees, tops, limbs and chunks produced from mechanical thinning and conventional saw-timber harvesting operations provide an opportunity to produce bioenergy and bio-based forest products. New technologies that are capable of converting forest residues into high quality and sustainable bioenergy and useful bio-based products are emerging [8]. To a large degree, the underutilization of forest residues can be attributed to the high cost of collecting and transporting these residues to end user markets and the low market prices paid for delivered forest residues. Several studies have investigated innovative forest biomass operations that effectively improve access to harvesting sites and economic efficiency [9–11]. However, the inherent inefficiency of transporting low-density and high moisture content (MC) biomass feedstock to biomass facility still remains a fundamental economic barrier to its increased utilization.

The location of a bioenergy plant is affected by a wide variety of factors and criteria. For instance, the location of biomass facility is highly influenced by the location of biomass feedstock [12]. An effective and efficient supply chain and optimized logistics system are vital for the success of a biomass-based energy industry. Since transportation costs impact highly total biomass fuel costs, site selection for new biomass facilities in the proximity of currently non-used available biomass resources are the preferred option when designing biomass supply chain networks [13]. In addition, biomass plant design should factor in environmental and socio factors to determine the number, location, and size of biomass facilities within the network of feedstock collection points, plants, and storage units [14]. This design gives form, structure, and shape to the entire supply chain and logistics system [15]. For this reason, the optimal locations of the biomass facilities play a significantly important role in the biomass energy supply chain [16].

A Geographical Informational System (GIS) is a tool broadly used to investigate the potential availability of biomass feedstocks [17], and to minimize transportation costs through logistics analysis and distance calculations [18]. A GIS network analysis, location–allocation analysis tool can simulate the site competitions for biomass resources [19]. The integrated GIS and Multi Criteria Analysis (MCA) is one of the preferred tools for the selection and location of biomass facilities and for assessing the relative importance of the economic, environmental, and social criteria affecting this site selection [20–25]. The Analytical Hierarchy Process (AHP), which is based on outranking techniques, is one of the most applied techniques in MCA [26]. The methodology includes a system to get an estimate of weighting to factors that impact decisions. The influencing impact of the factors for the selection and location of biomass energy facilities are not always the same, and in reflection of regional priority demands, it is necessary to assign them a different relative weight [27].

This study aims to investigate the optimal location of prospective biomass power plants in Tasmania, Australia using forest harvesting residue estimation. Integrated GIS and AHP models, along with a supply chain cost analysis, were developed to determine the best candidate locations of biomass plants. Three main criteria (economic, environmental, and social) and sub-criteria were established and factored in to determine the best biomass facility location. Additionally, various moisture contents of biomass feedstock were assumed to determine their impact on biomass transportation cost. It is expected that the results of this study make a contribution to the future Tasmania biomass energy and provide vital information to stakeholders so that they make good planning decisions about the utilization of forest residues for heat and electricity production in the region.

2. Materials and Methods

The schematic overall flowchart of the approaches used and implemented in the study is presented in Figure 1. Available land areas were investigated using a GIS restriction model. Integrated GIS and the multicriteria assessment method AHP were applied to assign a weight to each main criterion (economic, environmental, and social) and each sub criteria [28]. Spatial analysis required a large GIS dataset, both in raster and vector formats. In this study, most of the GIS data was provided by industrial partners (Private Forests Tasmania—PFT, Esk mapping company and Sustainable Timber Tasmania—STT) and gathered from different institutional websites, such as the Australian Government National Map. The optimal location of biomass facilities comprised three analytical phases including, land availability, land suitability, and location–allocation of biomass facilities. A selection of the available land for the biomass plant construction was initially investigated applying a restriction model (land availability); then, a number of suitable locations were identified applying a land suitability model according to a set of specific criteria; finally, selected candidate optimal locations were found by minimizing the total transportation distance of the feedstock location to each plant (location–allocation analysis). Detailed information of the methods applied is provided in the following sections.

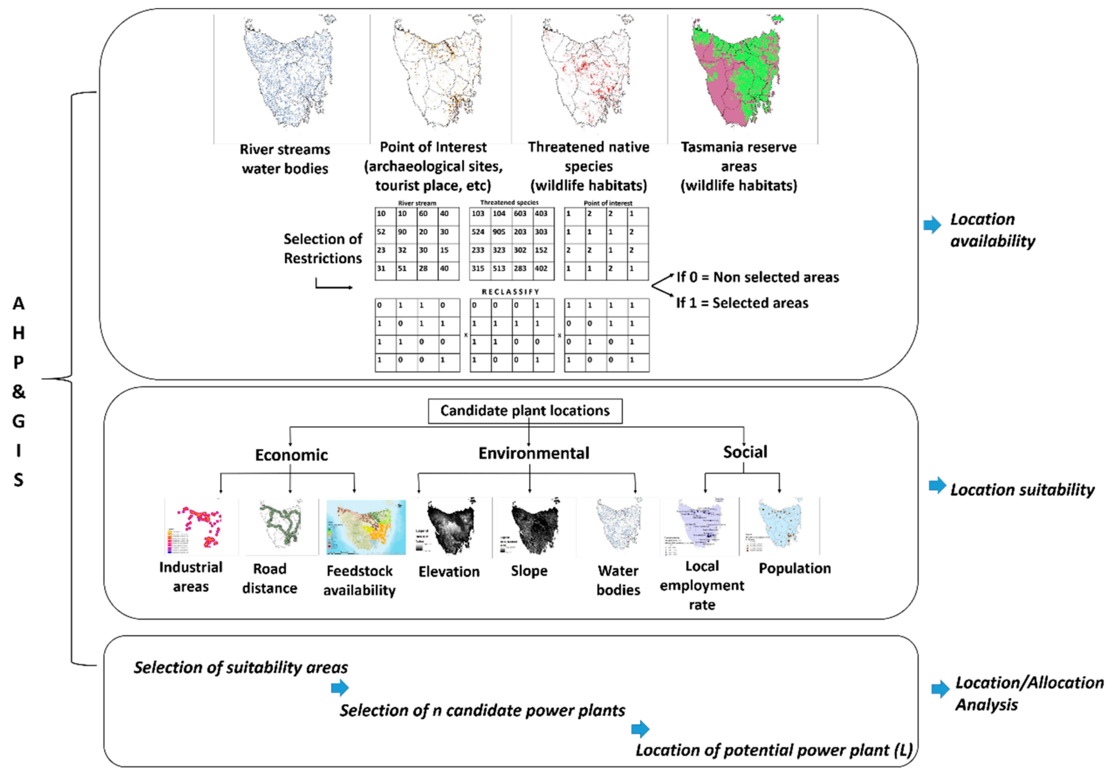


Figure 1. The overall approach to determine optimal locations of biomass facilities.

2.1. Estimations of Biomass Availability in Tasmania

Potential forest harvesting and availability of residues have been estimated for public and private managed forests by STT and PFT, respectively. Modelling of public native forests and plantations have been conducted by STT as part of Tasmanian Forests Agreement (TFA) implementation process, while wood flow modelling for private native forests and plantations have been completed by PFT. The definition of two types of forest residues is described in Table 1. STT forest modelling methodology for public eucalypt native forests was described in [29–31]. In the private forest sector, the native forest resource is highly dispersed; according to PFT, the forest estate is distributed across 7500 land owners. Due to the difficulties in aligning land owner objectives over a broad ownership range, residue volumes were estimated using a sustainable yield model developed by PFT in 2012 [32]. The model assumes that the available native forest resource has been harvested and reforested repeatedly over a period of 360 years to allow several rotations of slower growing dry eucalypt forests to be included in the wood flow. In addition, softwood residue estimation was concentrated on private ownership. The model used to estimate softwood residue availability was not based on softwood industry projections and may therefore not reflect actual yields. The details and key assumptions associated with these forest residue estimations were described in the Residue Solutions Project 2014 [33]. As part of the forecast residue modelling, STT and PFT estimated the volume of processing residues potentially available based on sawlogs and peeler log volumes. The analysis assumes that 60% of native forest and hardwood plantation sawlogs, 50% of softwood plantation sawlogs, and 11% of native forest and hardwood plantation peeler logs are converted into processing residues. Additionally, to account for supply chain costs, areas with residues under 1000 m^3 were not included in the biomass availability analysis. The potential Tasmanian harvest volumes were projected from 2014 to 2019.

This paper explores a range of biomass energy options, with modelling of a biomass combustion plant as the primary focus. As a result, non-woody and wet residues (from aquaculture processing, dairy processing, and waste water treatment) have not been considered. On-going research is examining these wet biomass residues, and this will be published in a subsequent research paper.

Table 1. Definition of forest biomass availability.

Biomass Type	Residue Source	Definition
Harvesting residues	Pulpwood	Logs of any size that are not suitable for solid wood processing to a small-end-diameter of 8 cm
	Other stem wood material	Non-merchantable stem wood that is usually left in the forest. It also includes stumps but excludes limbs, foliage and roots
Processing residues	Sawlogs or peeler log	Offcuts, woodchips and sawdust from timber processing

2.2. Land Availability Analysis Using a Restriction Model

The location of a biomass plant must satisfy a number of criteria and constraints such as geological and environmental reserve restrictions, which are imposed by several government regulations. Tasmanian forest ecosystems are largely protected within parks and reserves. This and the critical requirements outlined by the regional or national levels, limit the potential location of biomass energy plants. Given that energy plants are inexistent in Tasmania, constraints and restriction factors were established from a prefeasibility study conducted by Dorset [34] and from previous published articles [12,23,35–42]. Several constraints, both geological and environmental, were considered to select the potential location of biomass plants. Thus, protected and reserved areas, including threatened species areas, wildlife habitat areas, water pollution areas, and areas of interest for the communities were excluded for the location of biomass plants. The value related to spatial constraints in the dataset was arranged and converted into geo-referred layers. In the first step, buffer zones were created through a proximity analysis, using the GIS layers. Based on the constraint descriptions, buffer zones were created along the margins of some of these areas to delimit a minimum protection area. In this study, the available biomass plant locations were always established outside of buffer areas. A list of constraints for the selection of biomass plants is presented in Table 2. Each GIS data layer including specific information of constraint values was converted and reclassified into a binary raster data format (20 m × 20 m cell size). Reclassified binary raster data were assigned with a 0 or 1 value, in which cells assessed "0" were considered restricted area and cells assessed "1" were considered available area with respect to that factor. Using reclassified binary maps, a final combined binary map was generated by multiplying all the reclassified binary raster layers using the raster calculation tool in ArcGIS 10.6 (ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute) [43]. The output of the combined map was called "Available map".

Table 2. List of the constraints to build the restriction model developed in this study.

Constraint	Buffer (Meters)
Game reserve	-*
Historic site	-*
National park	-*
Nature reserve	-*
State reserve	-*
Wellington park	-*
Public authority land within world heritage area (WHA)	-*
Conservation area	-*
Nature recreation area	-*
Regional reserve	-*
Informal reserve on sustainable timber Tasmania managed land	-*
Future potential production forest	-*
Informal reserve on other public land	-*
Private land within WHA	-*
Private sanctuary	-*
Private sanctuary and conservation covenant	-*
Private nature reserve and conservation covenant	-*
Conservation covenant perpetual	-*
Indigenous protected area	-*
Conservation covenant	-*
Management agreement	-*
Management agreement and stewardship agreement	-*
Stewardship agreement	-*
Other private reserve	-*
Tasmania point of interest	-*
Tasmania threatened species	-*
Lake bordering area	Around lake bordering area 300 m buffer zones
River, streams and waterways	Around main river, river, streams area 150 m buffer zones

-* Constraint values were converted into a binary raster format (0 = restricted area, 1 = available area).

2.3. Land Suitability Analysis with a Weighted Linear Model

A weighted overlay function was used in ArcGIS 10.6 (suitability analysis), which included a multi-criteria evaluation. Through the suitability analysis, additional geographical information and other layers can be considered by decision-makers as factors that can positively affect the biomass plant location decision based on detected areas already classified as "Available" within the geographical areas [12]. The impact of each of these additional criteria varies, and, therefore, this step is required to correctly assign them a different relative weight [27,28]. This was done by applying an AHP algorithm, and the procedure is presented in detail in [28].

In this study, eight criteria were considered in the suitability analysis. The selected criteria were classified according to three different groups with different objectives, called "Economic", "Environmental", and "Social". In the Economic group, there were four sub criteria layers that had a high correlation with the economic influence of the biomass plants. It was assumed that biomass plants located closer to an industrial area would have a higher weighted value compared to further biomass plants. The distance from road and accessibility of the biomass plant also determined a high weighted value as short distances from existing roads can reduce biomass feedstock transportation costs substantially.

Regarding the second objective group (environmental), it was preferred to locate a power plant in a relatively flat area (slope less or equal to 15%) and in a middle elevation (elevation from 0 to 500 m) to avoid potential damage that could occur on steep sites and sites with sensitive geophysical conditions. In addition, to reduce water contamination risks, the locations of biomass plant were only possible in places located far away from main river and water bodies (interval from 0 to 500 m).

Finally, the criteria assigned to the social group included the local employment rate and the population density in the local government area of the identified biomass plant locations. To support local government economic impact, areas with a low and a middle employment rate were selected as preferred locations. In addition, middle population density areas (from 50 to 300 people/km^2) were prioritized for the location of the biomass plants. Weights obtained from an expert consultation survey were assigned to each objective group (economic, environmental, and social) and then to each sub criterion. The sum of the weights in different hierarchical level was equal to one.

Once the weights were assigned to each criterion, a weighted reclassified raster format layer (20 m × 20 m cell size), and corresponding final suitability map, were created by a weighted linear combination of the raster layers. The applied equation was as follows (Equation (1)):

$$S_i = \sum_{p=1}^{m} w_p \, C_{ip}, \tag{1}$$

where S_i is the suitability value of the ith cell in the final grid, w_p is the weight allocated to the pth criterion from the AHP analysis, C_{ip} is the ith cell value in the grid of the pth suitable criterion layer, and m is the total number of criteria in this analysis [19]. The values of all the criteria were standardized before including them in the equation. The calculated values Equation (1) in final raster were reclassified into seven level classes, where higher values represented more suitable places for the location of a biomass plant. After reclassified raster values were computed, cells that were assigned to levels 6 and 5 were identified as the most suitable locations for a potential biomass plant. A potential site was located in each cell by overlapping the areas under classes 6 and 5 within a grid mesh of 200 ha.

2.4. Biomass Energy Feedstock Supply Chain Costs

The Network Analysis tool in ArcGIS 10.6, which calculates transportation distances using a road network data set, rather than straight line or radius-based distances, was selected for the analysis. The location–allocation analysis was used to select potential bioenergy facility sites using the p-median problem solver included in the Network Analyst tool [44].

The aim of the location–allocation procedure (p-median problem solver) is to locate p candidate bioenergy facilities among n potential selected suitable bioenergy facility candidates ($n > p$) while satisfying a set of demands so that the total sum of weighted distances between each demand and facility location is minimized [45]. Additionally, the location–allocation procedure automatically selects the shortest travel or least cost distance so that the sum of the distance between the bioenergy facility candidates locations l and a set of biomass resource location points p is minimized (Equation (2)) [19]:

$$min \sum\nolimits_{lp} w_p \, d_{lp} \, x_{lp}, \tag{2}$$

where w_p = weight associated with each biomass available point p, d_{lp} = distance between available biomass point p and potential bioenergy facility l. x_{lp} = 1 if biomass available point p is assigned to bioenergy facility l, and zero otherwise.

Using Dijkstra's algorithm, the location–allocation solver generates an origin-destination matrix with the shortest-path costs between bioenergy plant candidates and available bioenergy resource points. It combines several techniques including a vertex substitution heuristic and a refining metaheuristic to achieve a near optimal solution [44]. Transportation costs (Equation (3)) were calculated using the travel distance along the optimal route derived from the location and allocation analysis. Equation (4) presents the equation to calculate the weighted transportation cost for bioenergy plant j (WTC$_j$):

$$C_{ij} = FC + 2VC\sum_{k=1}^{N} d_k, \quad (3)$$

$$WTC_j = \left(\sum_{i=1}^{m} B_i\, C_{ij}\right)/B_t, \quad (4)$$

where C_{ij} is the total transportation cost ($ per dry tonne) for the optimal route between the bioenergy plant candidate j and available bioenergy resource location i; B_i is the total biomass at source i; m is the total number of bioenergy resource locations assigned to plant j; B_t is the total bioenergy resource assigned to plant j; FC is the fixed cost related to collecting the biomass energy feedstock ($ per dry tonne); VC is the variable cost related to travel distance ($ per tonne-km); d_k and N are the length of the traveled road segment (km) and number of total segments along the optimal route between the plant j and the bioenergy resource location i, respectively [19].

This study also investigated the effect of MC on transport cost. For an MC of 55%, 50%, 45%, and <40%, transport costs (VC) were assumed to be $0.11/tonne/km, $0.10/tonne/km, $0.09/tonne/km, and $0.09/tonne/km, respectively [46]. This assumes a chip van truck with a volumetric capacity of 83.4 m^3 and net payload of 29.2 tonnes, which transports chips from residues with a basic density 450 kg/m^3. A value of $9.5 per tonne was assumed for FC, taking an in-field delimber, debarker, chipper machine (Peterson an Astec Inc., Eugene, OR, USA) as the basis for the calculation [47].

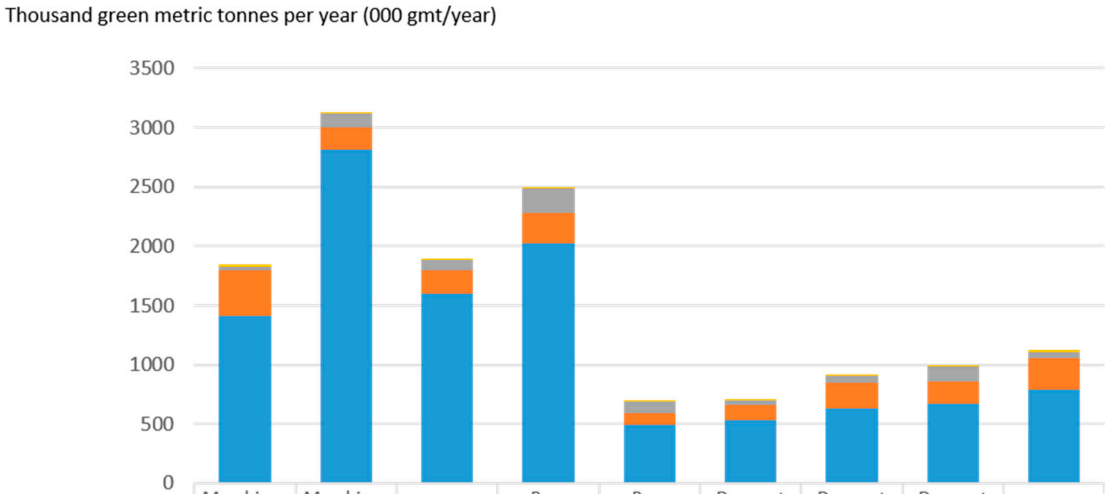
Several scenarios were simulated, assuming one to four potential biomass facilities. Through the location–allocation analysis, the locations of the most suitable bioenergy facilities were identified using available harvesting biomass sources in the Tasmania region. The transportation distances from every biomass availability location point to potential bioenergy facility locations were estimated with GIS software and using the actual road network date set. This calculation was applied for every candidate bioenergy facility location, ensuring that each biomass available location point was allocated to only one bioenergy facility.

The size of each facility is highly impacted by the number of bioenergy facility candidates and the extension of the associated biomass available supply zones. Greater and more dispersed feedstocks affect the size of the biomass facility and increase transportation distances and costs [48]. To determine the location and size of the biomass plants, the actual available biomass feedstock was re-estimated based on the results obtained from the location–allocation analysis. Subsequently, the selected supply points that resulted from the location–allocation analysis were extracted and clipped with the original biomass availability GIS data. Thus, the logistically available biomass feedstocks were calculated using the field calculator in ArcGIS 10.6.

3. Results and Discussion

3.1. Estimations of Biomass Availability in Tasmania

The results showed that a large base of biomass resources could be used as feedstock to supply biomass energy plants in Tasmania. The potential biomass availability is shown in Figure 2. The total forecasted biomass availability was 13,803,000 green metric tonnes per year (gmt/year) in the 5-year period from 2014 to 2019. Most of the biomass feedstock corresponded to residues from pulpwood and another stem wood harvesting operation. About 79% of the available biomass feedstock was produced from low quality logs not suitable for wood chipping to make pulp and paper. In addition, 95% of the total available biomass feedstocks were sourced from harvesting residue. Only 5% of total biomass availability was generated from processing residues. In the supply zone, Murchison East (ME) had the largest amount (3,125,000 gmt/year) of potential biomass availability in Tasmania. Bass North was the second largest biomass available zone with an availability of 2,499,000 gmt/year. Results obtained from the biomass availability analysis indicate that most of the available biomass feedstocks were produced from the northern side of Tasmania including Murchison West, East, Mersey, and Bass North supply zone. The distribution of biomass harvesting residue is shown in Figure 3.



	Murchison West(MW)	Murchison East(ME)	Mersey	Bass North(BN)	Bass South(BS)	Derwent East(DE)	Derwent Central(DC)	Derwent West(DW)	Huon
from Peeler log	18	4	4	8	6	2	2	8	18
from Sawlog	27	118	90	209	102	41	56	132	51
Other Stemwood	390	192	202	263	100	131	219	193	272
Pulpwood	1409	2811	1598	2019	491	529	632	666	786

Figure 2. The forecast Tasmania state-wide residue flow estimates annually in thousand green metric tonnes per year in the 2014 to 2019 period.

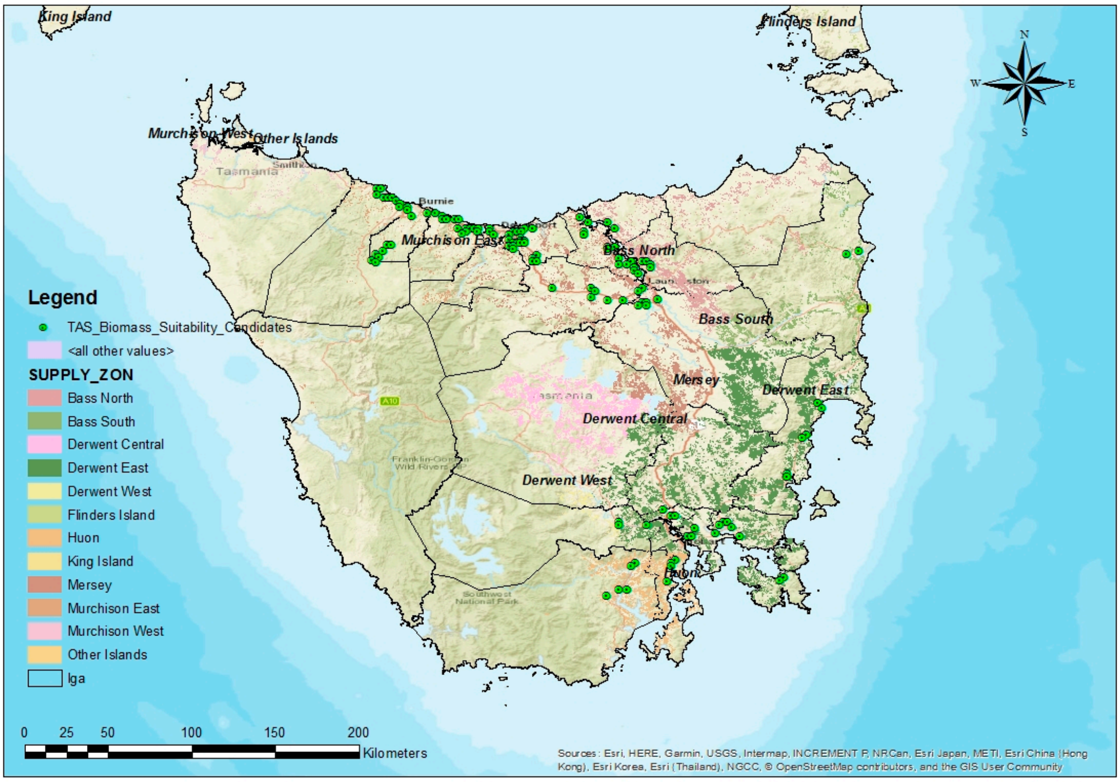


Figure 3. Suitability map with the final potential bioenergy plant locations in Tasmania.

3.2. Location of Bioenergy Plants

Figure 4 shows the availability map with the available areas for the location of bioenergy plants. About 49.6% of the Tasmanian land was accounted for as available area, while the non-available areas corresponded primarily to national conservation areas and areas prone to geological risk such as floods and natural disaster. White cells in Figure 4 represent unavailable areas where biomass energy plant cannot be located.

Following the AHP analysis, the first hierarchical level, main criteria, and the second one, sub-criteria, were weighted on the basis of a pairwise comparison from an expert surveying and through a matrix computation [12]. The results of the AHP analysis, including weights and corresponding consistency ratios, are presented in Table 3. The results indicated that the highest weight was given to the economic criteria. This was emphasized at the second hierarchical level (sub-criteria), where feedstock availability scored the highest weight compared to all the second level sub-criteria. In the social criteria (main criteria level), the population of the area was given the highest weight. Finally, environmental factors were considered as the third main criteria, with slope and flat areas located within a distance range between 100 m and 500 m from the water bodies as the preferred sites for the location of bioenergy power plants. The value of consistency ratio (CR) showed a high degree of consistency, confirming the adequacy of the weight values (Table 3). The results of the AHP analysis, and the corresponding weights, were included in the suitability model, where the reclassified weights were used to generate a final suitability map for the potential location of the bioenergy plants (Figure 4). Combined availability and suitability maps generated from raster calculations allowed the identification of the final possible biomass plant locations, with as many as 125 possible locations with a suitability value ≥ 5 being selected (Figure 4). Most of the highly suitable bioenergy plant candidates (suitability value = 6) were located in the Murchison East, Mersey, Bass North, Huon, and Derwent East supply zones. High suitability was attributed to sites with a large amount of biomass residue availability (Figure 2).

Table 3. Weights and preference factors in the Analytical hierarchy process (AHP) procedure.

Main Criteria	Weights (Criteria)	Second Level: Sub-Criteria	Weights (Sub-Criteria)	Total Weight	Consistency Ratio
Economic	0.540	Feedstock availability	0.747	0.403	0.04
		Industrial area	0.106	0.057	
		Transport logistics	0.147	0.079	
Environmental	0.163	Elevation	0.240	0.039	0.056
		Slope	0.400	0.065	
		Water bodies	0.360	0.059	
Social	0.297	Local employment rate	0.400	0.119	0.061
		Population	0.600	0.178	
Sum of the weights	1.0		3.0	1.0	

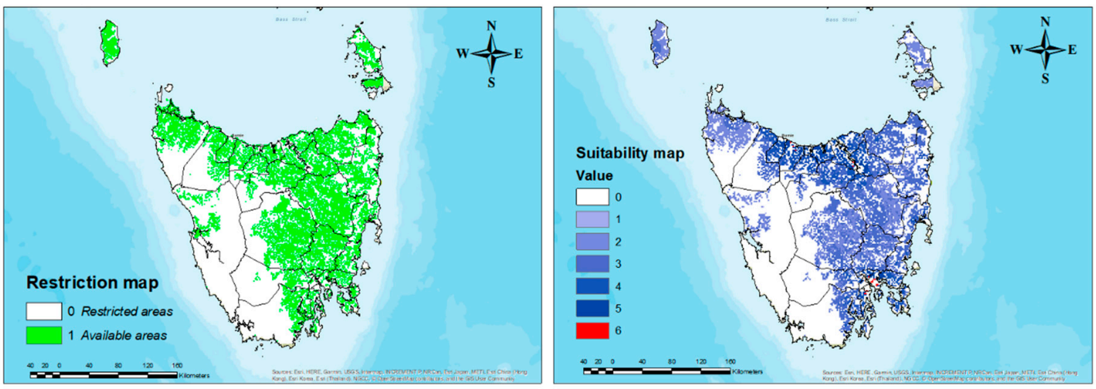


Figure 4. Map of restricted and available areas, and suitability map for bioenergy plant locations in Tasmania.

To secure enough feedstock for each final candidate location area, only selected locations larger than 10 ha were chosen as potential candidates for the location of the bioenergy plants. The candidates also required to be located near the road network and major roads to allow shorter transportation distances. The most suitable candidates were located close to the Tasmanian road network, indicating that the transport logistics criteria were satisfied. Figure 4 shows the 125 potential bioenergy facility locations that resulted from the suitability analysis.

3.3. Biomass Supply Chain Costs in Tasmania

Several scenarios were simulated with the location–allocation analysis to assess the impact of an increasing number of bioenergy power plants. From the location–allocation analysis, weighted unit transportation costs were calculated for an increasing number of bioenergy power plants. Figure 5 shows the four sites that were selected from the candidate locations (125 candidates) by solving the p-median problem using 15,322 biomass availability sources.

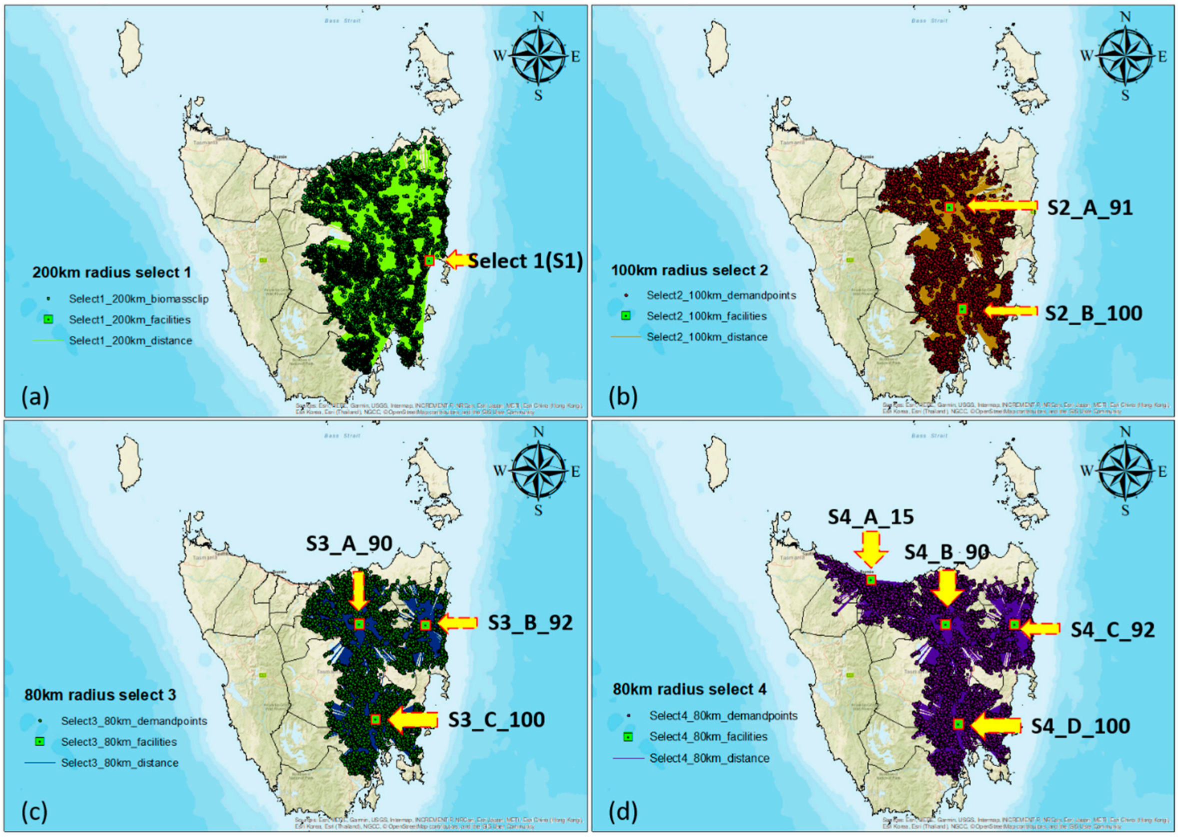


Figure 5. Optimal number and location of potential bioenergy plants. Lines show connections between origin and destinations; Tasmania road network was considered for the analysis; four scenarios were evaluated: (**a**) Scenario 1, 200 km radius selected one biomass facility (location code: Select 1), (**b**) Scenario 2, 100 km radius selected two biomass facilities (location code: S2_A_91 and S2_B_100), (**c**) Scenario 3, 80 km radius selected three biomass facilities (location code: S3_A_90, S3_B_92, and S3_C_100), and (**d**) Scenario 4, 80 km radius selected four biomass facilities (location code: S4_A_15, S4_B_90, S4_C_92, and S4_D_100).

The estimated supply chain costs for all identified locations are presented in Table 4. Harvesting, processing, and loading costs were not included in the supply chain cost calculations, as the primary focus of the study was on transportation costs. As expected, the total transportation cost was highly influenced by the distance between the biomass facility and the biomass feedstock available locations. Scenario 1, in which one biomass facility within a 200-km radius was selected, has the highest coverage rate (83.93%) among the identified biomass facility locations. However, the total transportation cost was very high due to the long distance between the selected facility and the biomass feedstock locations. When increasing the number of facilities, the transportation distance and total cost decreased rapidly compared with a single and long-distance biomass facility scenario. Scenario 2, in which two biomass facilities within a 100-km radius were selected, had a coverage rate that was approximately 74% of total biomass available locations. In Scenario 2, the average round distance was about 50% (97.22 km) of that calculated in Scenario 1 (189.66 km). The total transportation cost decreased substantially by increasing the number of biomass facilities. The results shown in Table 4 highlight the importance of optimizing the location of potential biomass facilities to reduce transportation costs. Based on the truck transportation cost scenario, the optimal number of biomass plants was 3 in the Tasmania region. As seen in Figure 6, there is an indication that transport costs start increasing when four or more biomass plants are built.

Table 4. Estimated transportation cost of biomass feedstock.

Facility Location [a]	Range (km) [b]	Demand (No.) [c]	Coverage Rate (%) [d]	Total Area	Biomass Availability (Green Metric Tons) [e]	Ave Distance (km) [f]	$/tonne/km [g]	Total Cost ($) [h]
S1	200	12,859	83.93	463,540	31,757,500	189.96	0.11	663,586,379
S2_A_91	100	5380	35.11	188,674	13,375,500	97.22	0.11	143,040,272
S2_B_100	100	5973	38.98	222,568	14,694,000	90.14	0.11	145,696,888
S3_A_90	80	1772	11.57	66,958	5,148,000	61.82	0.11	35,007,430
S3_B_92	80	3680	24.02	120,895	8,402,000	80.84	0.11	74,713,945
S3_C_100	80	4644	30.31	183,703	11,636,000	79.10	0.11	101,244,836
S4_A_15	80	1664	10.86	28,664	2,743,500	64.90	0.11	19,585,847
S4_B_90	80	1772	11.57	66,958	5,148,000	61.82	0.11	35,007,430
S4_C_92	80	3454	22.54	115,950	7,994,000	78.50	0.11	69,028,190
S4_D_100	80	4644	30.31	183,703	11,636,000	79.10	0.11	101,244,836

[a] selected number of biomass facilities and identified location ID (location information seen above Figure 5). [b] coverage radius distance from selected facilities. [c] total number of biomass availability locations to selected biomass facility. [d] coverage rate of selected biomass facilities (selected facility covered biomass demand location/total number of biomass availability locations) and sum of coverage rate in selected facility number is total coverage rate in each scenario. [e] sum of total biomass availability in allocated biomass demand locations. [f] average round distance between identified facility locations and biomass demand locations. [g] truck transportation cost assumed that MC (moisture content) = 55%, the chip van truck has a volume capacity of 83.4 m^3, a net payload of 29.2 tonnes, and transport chips with a basic density = 450 kg/m^3. [h] The cost estimation was based on average distance between identified biomass facilities and demand biomass availability locations.

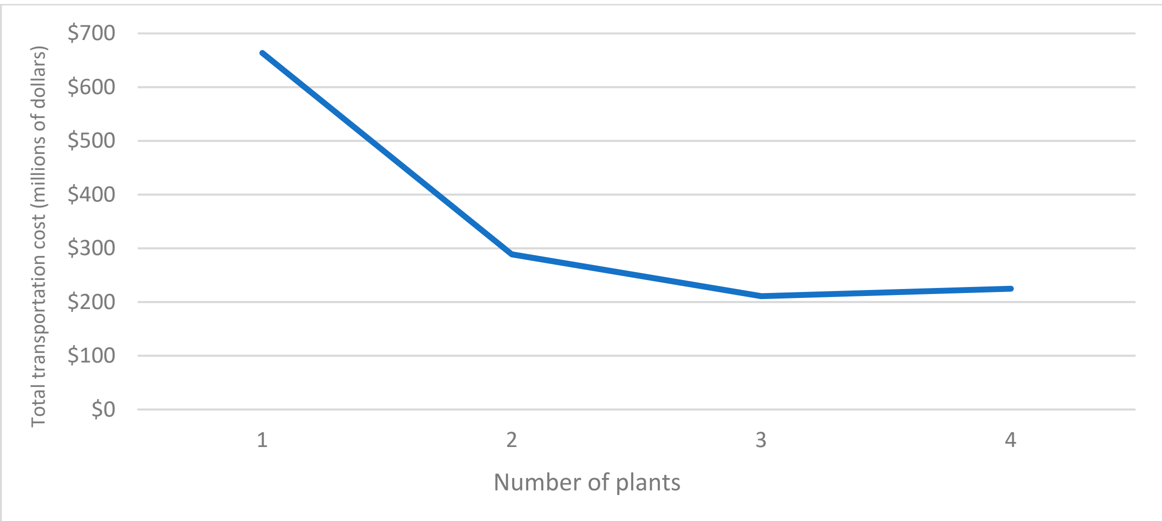


Figure 6. Variation of total transportation cost with number of plants.

Different MC levels (55%, 50%, 45%, and <40%) were used to simulate the impact of this parameter on biomass transportation costs. The assumed transport costs per tonne and kilometer were $0.11/tonne-km (MC = 55%), $0.10/tonne-km (MC = 50%), $0.09/tonne-km (MC = 45%), and \$0.08/tonne-km (MC < 45%), respectively. These costs were assumed based on a chip van truck with a volumetric capacity of 83.4 m^3 and 29.2 gmt of net payload that transports chips from residues with a basic density = 450 kg/m^3. Figure 7 shows the impact of MC on biomass transport costs. A fall in MC from 55% to 40% resulted in lower total transportation costs in all the biomass facility location scenarios analyzed. This confirms the results from previous studies, which have identified MC as one of the most important factors affecting the calorific value and transportation costs in biomass supply chains [49–55]. Thus, MC and transport distance constitute the factors with the major impacts on the biomass transportation efficiency from harvesting sites to biomass facilities [46,56].

Figure 7. Impact of moisture content (MC) on transport costs (for an explanation of the facility location codes, see Figure 5).

4. Conclusions

This study investigated the optimal location of potential biomass facilities in Tasmania, Australia, using a forest harvesting residue estimation procedure. In addition, an integrated multi-criteria analysis and Geographical Information System (GIS-AHP) model in conjunction with a supply chain cost analysis were developed to determine the best candidate locations. The estimated biomass availability indicated that Tasmania has an abundant biomass feedstock to operate biomass and energy facilities. After running several simulations on transportation cost scenarios, it was determined that three biomass plants within a radius of 80 km was the best option for Tasmania's future biomass energy plan. Considerable efforts in biomass supply chain research and life cycle analyses are still required to widely investigate the efficiency and total operation costs for the Tasmanian conditions [57,58]. From the supply chain costs analysis conducted in this study, the distance between biomass facilities and biomass feedstock locations, in addition to the MC of biomass feedstock, were the factors with the greatest impacts on transport costs. Previous biomass transportation studies in Australia have identified impact factors that have proved to be the most challenging issues in the forest biomass supply chain [52,55,59]. In future studies, other biomass supply chain costs including harvesting, processing, loading, and storage should be included so that the impacts of the location and size of biomass facilities in Tasmania on overall supply chain costs are properly quantified.

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