What to put where? Extending the p-median problem to consider multiple facilities, multiple sizes and associated resource needs

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Abstract

This paper presents a spatial, hierarchical extension to the p-median problem in order to optimally locate multiple types and sizes of land based, biomass renewable energy facilities. The aim was 1) to ensure that the resource catchments required at selected locations did not overlap with other facility locations, and 2) to minimise transport distances (net energy gains). The problem is essentially a packing problem, where optimality was related to minimising distances to forest biomass. Some simple logics were applied in this initial piece of work and some further extensions are described.

Keywords: biomass, renewable energy, location-allocation, land use.

1 Introduction

Renewable energy has a critical role to play in meeting a whole host of national and international targets related to slowing the advances and impacts of climate change. Whilst there is an extensive body of research considering different aspects of off-shore and on-shore locations for wind turbines (visibility, physical suitability, facility location, service access etc), informed by governmental policy, the research and policy guidance are lacking for other land based renewable energy facilities such as those requiring biomass. As a result, the siting of anaerobic digesters, combined heat and power facilities, gasification units, etc has occurred on a piecemeal and *ad hoc* basis, with little overall planning. This is problematic: many kinds of land based renewable energy facilities require biomass as inputs, frequently from agricultural residues, slurry or woodland, as well as household food waste. Piecemeal and *ad hoc* siting of such facilities runs the risk of sub-optimal and even inappropriate locations being identified as *suitable* when considered at multiple scales such as national or community level. This problem is accentuated by the potential for multiple facilities of different sizes with no consideration of the geographic spread of the land resources resource needed to support such facilities.

A further issue relates to the using of increasingly available (and accessible) spatial technologies such as GIS, the latest incarnation of which include very powerful functionality such as location-allocation tools. These seek to match potential facility locations (supply) with the spatial distribution of demand. However a recent review of the renewable energy and energy policy literature [1] identified a dearth of correctly formulated methods in renewable energy facility planning. Specifically most of the approaches reported in the energy literature lacked the correct and appropriate selection and application of location-allocation models, failed to give robust consideration of the location of the feedstocks needed by biomass renewable energy facilities and failed to consider feedstock catchments for biomass and competition for them in an appropriate way: in many instances the result was inappropriate statistical methods and fallacious (mapped) results: the researchers had simply '*pressed the GIS button*' without fully understanding the tools being used nor their underlying assumptions.

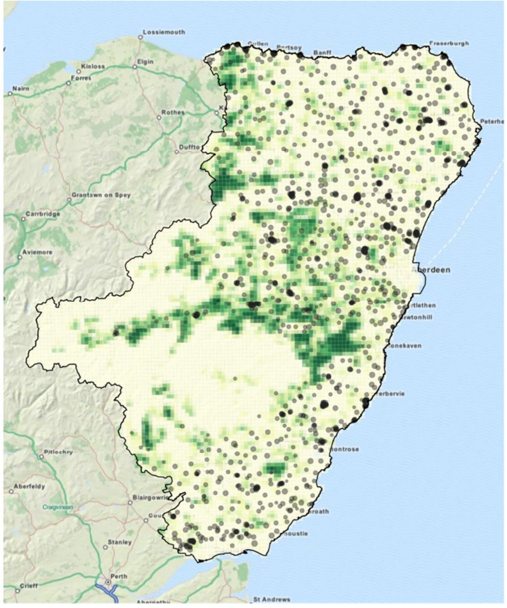
The p-median problem seeks to match the spatial distributions of supply and demand [2, 3]. Typically, potential sets of *n* locations are evaluated by the degree to which they minimise some objective function such as 'demand weighted distance' (for example, measured in person kilometres). Comber et al [1] extended the p-median to consider the biomass catchments required by *n* competing facility locations, such that the optimal subset of included locations that minimised demand weighted distance and did not have overlapping resource catchments. The case study developed by [1] considered only one size of facility, with a fixed biomass resource requirement. However, to support holistic planning of renewable energy and to maximise the potential of renewable energy, it is important for policy makers and planners to be able to consider multiple types and sizes of facility, with different resource requirements. As yet no research in the spatial planning literature has developed methods to optimally locate multiple sized facilities using robust, correctly formulated location-allocation methods. Typically, approaches undertake a suitability analysis but with no account of the specialities of demand [4] or use location-allocation approaches constrained by cost [5] or distance [6] and some research has identified sites one at a time sequentially [7]. None of these result in optimality. None fo the consider resource catchments and demand. None fo them consider these for different sized facilities. This paper presents a method for identifying the optimal locations of multiple renewable energy faculties, whilst considering their biomass requirements and associated catchments and the need to avoid competition for resources.

2 Case Study

A simplified case study was used to demonstrate the method extension. It seeks to determine the optimal location of a set of different sized renewable energy facilities all competing for forestry based biomass feedstocks in the North East Scotland region. Resource supply was a woodland 1km dataset derived using the method described in [8].

The harvestable biomass production from woodland is 12.9 t ha^{-1} yr^{-1} which equates to 1,290 t km^{-2} at 1km resolution (http://www.biomassenergycentre.org.uk). Demand was the population in census output areas classified as rural.

Figure 1: The study area in north east Scotland and the spatial distribution of wood biomass (green is more, yellow is less), and rural census areas with a transparency term added to the shading and an OpenStreetMap backdrop.



Three types of Combined Heat and Power (CHP) units were considered, with different capacities (energy outputs) and different feedstock or input demands.

- 1 MW, requiring 5,000 t yr^{-1} of feedstock;
- 4 MW, requiring 20,000 t yr^{-1} of feedstock;
- 20 MW, requiring 100,000 t yr^{-1} of feedstock.

In the study area the total potential amount of annual biomass from woodland is 1,895,677 t yr^{-1} and a mix of 3 20MW CHPs, 10 4MW CHPs and 30 1MW CHPs. This equates to a biomass supply of 650,000 t yr^{-1} or 34% of the available supply.

3 Algorithm

The algorithm has an objective function of minimising resource catchments sequentially for different sized facilities. Potential sites for the larger objects are identified first, followed by smaller objects which infill the gaps around the larger objects. In each stage, the algorithm proposed by Comber et al is applied. It applies the p-median problem, defined as:

$$\sum_{i}^{m} \sum_{j}^{n} a_i d_{ij} x_{ij} \quad \text{(Eqn 1)}$$

where i is the index of demand locations (1 to m) and j is the index of supply (1 to n), a_i represents the demand at demand location i, d_{ij} is the distance between i and j and x_{ij} is an allocation decision variable with a value of 1 if demand at location i, is served by a supply j and 0 if otherwise. In this way the p-median model accepts new potential locations if they reduce the overall demand weighted distance between supply and demand locations. The Comber et al (20150 extension constrains the interchange such that the catchments of the candidate locations do not spatially intersect (overlap) with catchments of the current set of locations, V. Formally then Equation 1 is *subject to*

$$x_{ij} \leq y_j; j \cap V = \emptyset \quad \text{(Eqn 2)}$$

The further extension proposed here applies this sequentially to different sets of differently sized facilities. In pseudocode this is:

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1. Use the algorithm to optimally locate the 20MW facilities
2. Remove these catchments from the search space
3. Use the algorithm to optimally locate the 4MW facilities
4. Remove these catchments from the search space
5. Use the algorithm to optimally locate the 1MW facilities
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The removal of already used catchments from the search space – that is, those whose resources have already been allocated to a facility – was done by not selecting new sites whose resource catchments overlap with those of already selected sites.

4 Initial Results and Discussion

The results in Figure 2 indicate the optimal locations for a mix of different sized CHP units, where optimality is defined on minimising feedstock distance and non-overlapping resource catchments for each facility. In this case the feedstock was biomass from woodlands. The algorithm is essentially a packing algorithm but rather than being in Euclidean space as many packing problems are (eg to optimally fill a container with different sized boxes), in this case the space is distorted by the availability of resources. The approach taken has been based on truck driver logic – optimally pack large items first because these for which there is less choice over where they could go and they will have largest impact on supply and demand. Potential locations are selected by distance as a proxy for transport, and therefore energy, costs.

The optimal selection of suitable sites for RE facilities is critical if land based biomass resources are to be efficiently and maximally used to support a diverse range of objectives including food and energy security as well as environmental protection. This paper proposes a hierarchical extension to the p-median problem in order to optimally locate different sizes of CHP units.

The method allows locations for multiple types and size of facilities to be evaluated. The algorithm could be applied to select optimal sites for multiple types and sizes of renewable energy facilities CHPs, anaerobic digesters, gasification units etc. It supports holistic, strategic regional planning and well as community level energy initiatives. The latter are increasingly being supported in Scotland (eg http://www.localenergyscotland.org/cares).

The next steps in this work are numerous. First, the algorithm at present may produce sub-optimal results because every possible spatial configuration of different numbers and sizes of facilities are not examined. This is an enormous search space: it requires consideration of every possible combination of zero to the maximum number of facilities constrained by the desired percentage of land resource to be used, for as many types and facilities under consideration. Grouping genetic algorithms have been shown to be particularly efficient at moving through such spaces: quicker and better than commonly used heuristics such as Teizt and Bart or standard genetic algorithms. Second, the evaluation function will be reformulated to net carbon gains. At the moment much of the research in this area is fixated with oil prices – essentially increases in price make renewable energy solutions more attractive. However this is to miss the point: the reason for need renewable energy is to reduce the carbon (not financial) costs of energy. Thus *energy robust* evaluations are needed that based on net carbon gains and not transport costs. Third, there is a large amount of political activity in Scotland promoting community level land reform and most proposals include a renewable energy proposal. The long term aims of this work are to develop a multi-scaled, energy robust planning tool to be used at community, regional and national scales. Fourth, there is also a need to consider the degree of community uptake and to this end energy aware geo-demographic classifications will be used to identify community receptiveness to renewable energy which may have considerable location implications for example relating to grid and infrastructure extensions, community participation supplying household waste to anaerobic digesters etc. Finally future work will consider network distances and net carbon gains in relation to resource transportation rather the Euclidean distances used here, to explore how asymmetric, amorphous catchments may be incorporated, allowing them to fill the available space between already selected sites and to consider different combinations of feedstocks – domestic, forest and agricultural. Household waste for ADs would locate sites nearer to higher population areas, for example.

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References

[1] A. Comber, Dickie J, Jarvis C, Phillips M and Tansey K. Locating bioenergy facilities using a modified GIS-based location-allocation-algorithm: considering the spatial distribution of resource supply. *Applied Energy*, 154: 309-316, 2015.

[2] Hakimi, S, (1964), Optimum Locations of Switching Centers and the Absolute Centers and Medians of a Graph. *Operations Research*, 12:450-459.

[3] ReVelle, CS and Swain, RW, (1970). Central facilities location. *Geographic Analysis*, 2: 30-42.

[4] Ma J, Scott NR, DeGloria SD, Lembo AJ (2005). Sitting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. *Biomass Bioenergy,* 28:591–600.

[5] Thompson E, Wang Q and Li M. (2013). Anaerobic digester systems (ADS) for multiple dairy farms: a GIS analysis for optimal site selection. *Energy Policy.* 61-124

[6] Panichelli L and Gnansounou E, (2008). GIS-based approach for defining bioenergy facilities location: A case study in Northern Spain based on marginal delivery costs and resources competition between facilities. *Biomass and Bioenergy*, 32: 289-300.

[7] Shi X, Elmore A, Li X, Gorence NJ, Jin H, Zhang X and Wang F (2008) Using spatial information technologies to select sites for biomass power plants: a case study in Guangdong Province, China. *Biomass Bioenergy*, 32: 35–43.

[8] A. Comber, AJ, Proctor, C and Anthony, S. The creation of a national agricultural land use dataset: combining pycnophylactic interpolation with dasymetric mapping techniques *Transactions in GIS,* 12(6): 775–791, 2008.

Figure 2: The locations selected locations and their catchments with the spatial distribution of forest biomass and the potential sites as context.