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Optimal location of centralized biodigesters for small dairy farms: A case study from the United States

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ABSTRACT

Anaerobic digestion technology is available for converting livestock waste to bio-energy, but its potential is far from fully exploited in the United States because the technology has a scale effect. Utilization of centralized anaerobic digesters (CADs) could make the technology economically feasible for smaller dairy farms. An interdisciplinary methodology to determine the cost minimizing location, size, and number of CAD facilities in a rural dairy region with mostly small farms is described. This study employs land suitability analysis, operations research methodology and Geographical Information System (GIS) tools to select appropriate sites for CADs in Windham County, Connecticut. Results indicate that overall costs are lower if the CADs are of larger size and are smaller in number.

Keywords:

Dairy;
Methane;
Biodigester;
Fixed-charge location problem

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Abbreviations:

CAD	=	Centralized or Community Anaerobic Digester
GIS	=	Geographical Information System
US	=	United States
GHG	=	Greenhouse gases
CO_2e	=	Carbon dioxide equivalent
USEPA	=	The United States Environmental Protection Agency
USDA	=	The United States Department of Agriculture
MIP	=	Mixed Integer Programming

1. Introduction

Improved planning and management of earth's energy resources is highly desirable to ensure a sustainable energy future [1] in view of climate change induced from anthropogenic activity and fossil fuel depletion. Agriculture is increasingly gaining policy attention for its dual role in climate change. On the one hand, a substantial portion of global greenhouse gas (GHG) emissions come from agriculture related activities such as fertilizer use, livestock production, rice cultivation, and biomass burning, while on the other hand the sector has potential to contribute towards attaining a sustainable energy future. Although the demand for livestock products might double by 2050 and enhancing livestock farming could be a developmental strategy for rural economies, growth of livestock farming poses a trade-off between development and the environment and hence it has been in the focus of public policy debate [2]. Among the negative externalities of the sector, the most global one is its contribution to climate change. According to most recent estimates released by the Food and Agriculture Organization, the world's livestock sector contributes approximately 14.5% of total global anthropogenic GHG emissions [3]. Averaged over the period 2001–2010, China, United States (US), and India

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are top three emitters of methane and nitrous oxide produced from manure management activities [3].

The global dairy sector contributes 4.0% [±26%] to the total world-wide anthropogenic GHG emissions [4]. Methane emission from dairy farms in the US has risen steadily over the last two decades. In 2009 the agricultural sector was responsible for 6% of total US GHG emissions [5] in CO_2e units, and methane from dairy farms contributed around 14% of that total. The US Environmental Protection Agency (USEPA) also reported that the share of manure management relative to enteric fermentation has also gone up in the last two decades, accounting for approximately 42% of dairy methane in 2009.

These facts and figures provide clear evidence of the importance of manure management in global warming mitigation and in making dairy farming environmentally sustainable. The international dairy community is under pressure from policymakers around the world to reduce its carbon footprint. Under these circumstances, the International Dairy Federation – an organization that represents the dairy sector globally, places high priority on handling the environmental challenges at the farm level. In the first ‘Dairy Farming Summit’ of the International Dairy Federation, a consensus was reached that dairy farmers need to address the environmental sustainability issue while promoting output growth [6]. The summit identified that two of the best available solutions at present are anaerobic digesters (AD) or biodigesters and energy audits [6]. Anaerobic digestion technology has been used widely in many countries over the past decades to convert manure to heat and/or energy with other side benefits. Biogas produced in anaerobic digesters consists of methane (50% to 80%), carbon dioxide (50% to 20%) and small amounts of other gases (such as carbon monoxide). The methane produced is then burned off or used to power an engine that produces electricity and heat. Technical details of waste to bio-energy generation opportunities and types of digesters are available in the published literature [7].

Of late, the US has seen some growth in biodigester operations. New technical designs and business models are being put forward, but a huge potential remains untapped [8]. The USEPA in conjunction with the US Department of Agriculture (USDA) runs the ‘AgSTAR’ program to promote ADs for green energy generation and cut down on methane emission. A recent study models the potential contribution of ADs towards this aim [9]. According to results of that study, by 2050 ADs could contribute 5.5% of the total domestic energy generation while mitigating 151 million metric tons of CO_2e, mostly from methane abatement [9].

One obstacle faced by this ‘cow to power’ GHG mitigation strategy is the required scale of operation. Only a small percentage of dairies with potential for bioenergy generation are currently utilizing ADs probably due to the associated high capital cost and size economies embedded in the technology. Small and medium sized dairies may not find it profitable to set up individual ADs due to high capital costs and long payback periods. According to the USEPA calculations, an AD may be profitable only for the larger farms (e.g. for dairy farms milking more than 500 cows) as it involves scale economies [10]. Other researchers also report a similar size threshold requirement for an economically viable AD [11]. With utilization of centralized or community anaerobic digester (CAD) systems, however, more farms can be brought under the umbrella of a large AD plant and economies of scale can be achieved. Such a solution could be a win-win situation, as farmers would stand to benefit by earning extra money and not be burdened by future taxes that might be imposed on them, while society at large would also enjoy better environmental quality. Yet, only a few dairy based CADs are either proposed or operational in the US. Since 2000, however, several CAD feasibility studies for commercial dairies in the US have been conducted, showing increasing appeal of the CAD model (see [12] for a review). For instance, researchers from the Cornell University have conducted a couple of feasibility studies for CAD in the New York State: one for a group of 10 dairy farms with a total of 3,700 cows [13]; and one for a group of 25 dairy farms with a total of 4,199 cows [14].

Quite surprisingly, most available feasibility studies concerning the location of a CAD ignore spatial optimization criteria. Very few researchers have addressed the location component of bioenergy facility planning, even though biomass transportation is the main operating cost [15, 16]. One should expect the siting decision to be based on several criteria and use of an economic optimization framework should improve its financial viability. Therefore, this paper attempts to make an empirical contribution to that aspect of the literature. Our specific objectives are to:

1. Conduct a resource mapping of dairy manure and other possible sources of bio-wastes that are useful for co-digestation, in a region dominated by small dairy farms;

2. Find suitable locations for placing CAD plants; and
3. Select the optimal number, size, and location of CAD plants in the region.

The remainder of this chapter is structured as follows: section 2 provides information on the case study area for which the empirical investigation is carried out; section 3 presents the optimization model and other methods used in the research; section 4 discusses the data sources and results from a Geographical Information System (GIS) analysis; section 5 describes numerical optimization models and results; and section 6 concludes.

2. Area of study

As this paper focuses on the siting of CAD(s) for small sized dairy operations, the State of Connecticut is chosen for an empirical application of the proposed model. Despite a constant decline in farm and cow numbers, dairy farming remains an integral part of the Connecticut State economy and the dairy industry contributes approximately 40% of Connecticut's manure [17]. Due to rapid farmland loss in the state, there is no longer sufficient land available for sustainable agronomic application of manure and Connecticut currently faces a nutrient surplus problem [17]. Biodigesters can be a solution to the manure management issues. However, the smaller size of Connecticut dairy farms, in comparison to the national average, can be a major obstacle for having ADs in individual farms. For example, the average number of milk cows per Connecticut farm was 85 in 2002 and 84 in 2007 [18]. Although, the USEPA list [19] shows that the state has two operational ADs, personal communication reveals that one has been shut down and the other is malfunctioning.

On the other hand, there is rising demand for manure management and renewable energy in the state. The Connecticut Climate Change Action Plan (2005) notes that manure, though it contributes less than 0.5% of the state's annual GHG emission, can be utilized through CADs for energy generation. Although, the plan calls for building at least one CAD by 2010 and two by 2015, no such plant exists in Connecticut to date. Some initiative has been taken, however, and a feasibility study – to assess the possibility of alternative manure management technologies including biodigesters is now available. That feasibility study observes that there are four clusters of farms in the state with a high density of dairy cattle. The identified areas are located in Litchfield, Tolland, Windham, and New London counties [17]. However, the study does not carry out a formal location analysis to set up CAD plants. Thus, our study aims to fill that knowledge gap. Windham County is chosen as the focal area of study, as it is the most important dairy county in the state based on dairy sales [18], and it also houses the highest number of dairy cows in the state [18]. Furthermore, a recent study examines the economic feasibility of a farm based AD business center plan in the town of Woodstock [20], which reveals that local stakeholders are also interested in this issue.

3. Methodology and related literature

This work draws from models developed for the classic plant location problem, which has been studied for decades. In summary, a model developed to analyze plant location decision would optimize one or more objectives subject to various constraints in a static framework. The objective of conventional private sector location models is to minimize cost which has two components: (i) transportation; and (ii) the cost of building and operating plants, known as 'fixed charge' in the operations research literature.

Location models find their use in the field of waste management [21, 22, 23] among others. A more complex approach is used to model annual manure flow logistics (transport, storage, treatment, and processing) and locations of landfills and municipal solid waste facilities in [24] and [25], respectively. Another variety of mathematical optimization model to address the questions related to our stated research objective (3) has been developed for Italian farming districts [26]. The optimization problem in that work is presented as a net present value maximization problem, while plant capacities and presence or absence of a plant in particular locations are treated as auxiliary variables in the model. Values of these two auxiliary variables can be determined from optimal values of decision variables, which are the fractions of biomass at some source assigned to a destination plant. Two more recent applications of location-allocation models in the context of bio-energy facility location planning are found in [27] and [28].

The methodology of this study is based on location-allocation modeling frameworks following recent literature [27, 28]. It addresses the four fundamental questions listed by location geographers [29]: (i) How many plants should be built? (ii) Where should they be located? (iii) Which farms should they serve? and (iv) What should be their size? What follows next is a description of the modeling steps.

Suppose a private agency is willing to set up a system of CAD(s) to utilize the dairy waste generated in a defined region. Also suppose that there are *M* sources of manure and *P* potential locations to choose from for siting one or more CAD plants. Assume that for each chosen site, *S* possible sizes of biodigesters are available. The private digester firm wants to minimize the daily cost of operation by trading off transportation cost against fixed charge. The problem is defined as follows:

$$Min\ \ C = \sum_{i=1}^{P}\sum_{j=1}^{M}\left(T \times d_{ji} \times m \times X_{ji}\right) + \sum_{i=1}^{P}\sum_{k=1}^{S} F_k Y_{ik} \quad ...\ (1)$$

$$\sum_{j=1}^{M} X_{ji} \leq \sum_{k=1}^{S} a_{ik} Y_{ik}\ \forall\, i = 1,...,P \quad ...\ (2)$$

$$\sum_{j=1}^{M} X_{ji} \geq a_{\min} \sum_{k=1}^{S} Y_{ik}\ \ \forall\, i = 1,...,P \quad ...\ (3)$$

$$\sum_{k=1}^{S} Y_{ik} \leq 1\ \forall\, i = 1,...,P \quad ...\ (4)$$

$$\sum_{i=1}^{P} X_{ji} = b_j\ \forall\, j = 1,...,M \quad ...\ (5)$$

$$X_{ji} \geq 0, \quad Y_{ik}\ are \quad binary\ (0,1) \quad ...\ (6)$$

All symbols are defined in Table 1.

Eq. (1) presents the objective function to be minimized. Equations (2)–(5) represent various constraints. Eq. (2) specifies the capacity constraint of the CAD if opened at site *i*. The total number of cows allocated from M sources to the *i*-th CAD site must not exceed the capacity of the plant (a_{ik}), defined in terms of the number of cows. Eq. (3) characterizes a threshold constraint suggesting that only if the total number of cows to be served at any site *i* is greater than $a_{\min}$ (i.e. the minimum size which is chosen to be 1,000 cows), a CAD could be opened there. Eq. (4) imposes another restraint stating that only one size is permitted in a given site. Eq. (5) constrains the optimization by requiring that all cows at M sources must be allocated to any of P possible CAD sites.

Here the above model is solved using a mixed integer programming (MIP) formulation. To solve the model, it is necessary to find out the number of manure sources *(M)* and the number of potential locations *(P)* to site CADs. Regarding potential sites, two strategies can be pursued: (A) CADs can be sited in suitable places outside dairy farms; and (B) CADs can be placed in large dairy farms so that transportation of large volumes of manure could be avoided. Thus, before undertaking the optimization exercise it is essential to carry out resource mapping and land suitability analysis.

Advanced GIS tools are becoming increasingly useful to undertake the resource mapping and land suitability analysis. For example, researchers have employed spatial modeling techniques using GIS software to assess solar energy potential [30, 31], which will be of great help in energy planning and policy. Researchers have also utilized the versatility of GIS to design web-

Table 1: Nomenclature of model symbols

Variable	Definition
C	Total cost of biodigester operation for a day
T	Unit transportation cost
d_{ji}	Distance between manure source point *j* and plant location *i*
m	Volume of daily manure generation per cow
X_{ji}	Number of cows from manure source *j* assigned to a plant at location *i*
F_k	Cost of building, machineries, installation, and operating a plant of size *k* for a day
Y_{ik}	Whether a plant of size *k* is opened (= 1 if yes) or not at location *i* (= 0 if no)
a_{ik}	Capacity (in terms of number of cows) of plant size *k* at location *i*
$a_{\min}$	Minimum size (in terms of the number of cows) of a biodigester
b_j	Number of cows at manure source point *j*

based spatial decision support systems that map the sources of biomass available in a region and suggest potential locations of digesters [e.g. 11, 32, 33]. These tasks are done in a number of steps as described below. The first step is to create a geo-spatial database to identify and locate the sources of organic waste. Recent research shows that a higher volume of biogas generation and greater profits are obtained if food wastes are added to dairy manure [34]. Therefore not only information on locations of dairy farms but also food waste sources is to be collected. The locations of these potential contributors to a CAD in the targeted region have to be geocoded in the ArcGIS 10.0 software using their addresses and a layer of roads in that region.

The second step is to create a land suitability map for potential sites to set up CAD plants. As researchers in this field suggest, locating potential sites is a complex task involving many environmental, economic, and social constraints. For example, suppose an energy company building a new biodigester is looking for potential sites. It will take into consideration distance to major highways and the grid system, and combine such information with physical characteristics of the land, land use, livestock density, and regulatory data to decide on the best site for that plant.

Land suitability analysis is the methodology to be used here. This methodology has its root in multi-criteria evaluation (MCE), which is later integrated with GIS [35]. Suitability analysis is a GIS based process used to evaluate the appropriateness of a given piece of land for a particular use, given some factors and/or constraints. In this case, a set of criteria to assess suitability of CAD at a given site is developed following previous literature [e.g. 11, 33, 36]. Table 2 provides the list of criteria used in this research. Each criterion could be modeled as either a factor in which suitability values vary continuously over the landscape or constraints in which there is a zero/one dichotomization of the landscape [37]. For factors each location has a degree of suitability whereas for a constraint each location is either suitable or not suitable. The choice of how to model a criterion has additional considerations. From a GIS modeling perspective, factors are most easily implemented in a raster based system whereas constraints are as easily implemented in a vector system as in a raster system. A more important modeling difference is that in an MCE, each factor has an associated weight so that factor trade-offs can be evaluated whereas constraints have no weights because they are absolute - either yes or no. Factor weights are always subjective and can be determined by different schemes involving expert opinion [37]. A constraint does not have this problem but its cut-off value (a distance value or thematic value) used to determine whether a location is suitable or not is also subjective unless there is a specific mandated value such as a zoning setback. The analyst makes a choice based on the information available.

In our case, no expert opinions regarding factor weights were available. More importantly, the suitability analysis is used here to determine a set of potential discrete sites rather than the final sites. Each potential site also has a requirement that it must be larger than a certain area. In the continuous factor approach an arbitrary suitability cut-off value would be needed in order to determine the area of any potential site. This research therefore follows a constraint and thus a vector data based approach to GIS suitability analysis rather than a raster based, factor approach. The ESRI Spatial Analyst toolbox in ArcGIS 10.0 is utilized to combine the different buffer layers associated with the constraint criteria of the suitability analysis. What follows is a brief explanation of some of the constraint criteria used in land suitability studies for biodigesters and listed in Table 2.

In CAD siting analysis it is a convention to assume that the plant needs to be sited within close proximity of the farms to reduce transportation cost. Previous studies report that in the United Kingdom and Denmark dairy slurry is transported from within a 10 km radius of the site [33]. For the CAD in California, manure is trucked to the plant from farms within a six mile (~9.65 km) radius. Another concern is objection from the public if this type of facility is to be built near residential areas. Evidence exists for community objections against siting such plants in close proximity of residential areas [38]. As transportation of manure is a critical component of CAD operations, and construction of new roads is expensive, proximity to an existing main road network is preferred. If the main output of the CAD is bio-energy, it has to find potential buyers such as energy companies so the plant has to be connected to the grid. Such connection can be costly so it is also prudent to consider locations as close as possible to existing transmission lines or grid substations [33]. The buffer tool in ArcToolbox has been used to demarcate the area that is within some distance of the input features. However, it must be mentioned that choices for radius to draw buffers are subjective.

Table 2: A list of criteria to evaluate land suitability

Attribute	Specification
Dairy farms	Sites falling outside 7 km buffer zone to be avoided
Developed land	Sites falling within developed land and 200 m buffer zone to be avoided
Airport	Sites falling within such areas and 500 m buffer zone to be avoided
Aquifer	Sites falling on aquifer tables and within 100 m buffer zone to be avoided
Water	Sites falling within such areas and 100 m buffer zone to be avoided
Private open space	Sites falling within such areas and 200 m buffer zone to be avoided
Federal open space	Sites falling within such areas and 200 m buffer zone to be avoided
Protected area	Sites falling within such areas and 200 m buffer zone to be avoided
Agricultural area	Sites falling within such areas and 100 m buffer zone to be avoided
Railway track	Sites falling within such areas and 100 m buffer zone to be avoided
Roads	Sites falling within 30 m and outside 300 m buffer zone to be avoided
Transmission lines	Sites falling within 200 m and outside 1 km buffer zone to be avoided

4. Data and GIS analysis

The first task is to collect data on biomass availability in the study region and location of other waste sources. The Connecticut Farms Database is the most useful resource for the purpose of locating and obtaining information on the farms in the state. This search starts with a list of 132 operating dairy farms in 2009, obtained from the Connecticut Department of Agriculture through personal communication. This data set contains names and addresses of these farms, and approximate number of dairy cattle as reported by farmers. Thirty-one dairy farms in the Windham County are found. The farm population, as expected, is dominated by small herds with an average of 254 dairy cows per farm and a range going from 10 to 800. Four farms (IDs: F_{10}, F_{16}, F_{19}, F_{24}) are big enough that they satisfy the minimum herd size requirement for an economically viable AD, as set by the EPA.

For this research, only academic institutions and health facilities are considered as co-digestable biomass sources. They generate much less waste than dairy farms, but constitute a steady source of food waste, which can be utilized as a complement input in digesters. Address information on public schools, colleges, universities, hospitals, and nursing homes are collected from various online sources. To derive coordinates from addresses, the geocoding tool in ArcGIS 10.0 software is used. Addresses of three dairy farms cannot be matched and hence they are dropped from the analysis. To match with the other GIS data files, the coordinate system of these geocoded points are converted to a projected coordinate system (North American Datum of 1983 Connecticut State Plane, unit: feet).

None of the waste sources identified and mapped, have any measured and reported data for waste generation. Hence, other published information have been utilized to construct proxies for actual waste generation. Estimates are available on manure generation by a mature dairy cow. An EPA report says that on an average a 1,400 lbs Holstein dairy cow produces 112 lbs of manure per day [39] while another study reports an average of 115 lbs or 13.8 gal from the Midwest US [40]. This latter figure is used here as the value for m in Eq. (1). Daily food waste volumes are calculated using formulae shown in a previous study [41]. However, the generated food waste volumes are small and also not much is known about its transport. Thus, food waste is not utilized in the modeling exercise.

It is assumed that tanker trucks are to be used for hauling manure from farms to CAD(s). Assuming 35 miles per hour speed for a 5,000 gal truck to transport manure, and custom hauling charges for such a vehicle based on Pennsylvania figures [42], the per gallon per mile transportation cost T is estimated. The distances d_{ji} between waste sources and potential digester locations are computed as Euclidian distances.

Capital cost of the fixed charge component can be in millions of dollars depending on the capacity or size of the AD unit. There are several figures available on the web for the capital cost, but most of them are not suitable for this study. However, the 'AgSTAR' program has collected data on various types of digesters and modeled the relationship between capital cost (cost of the digester, the engine-generator set, engineering design, and installation) and size (number of dairy cows) through linear regression [43]. A Plug-flow digester type is chosen as this is the most widely used AD technology in the US [8], and the most technically suitable for Connecticut conditions according to a feasibility study [17].

The regression equation *capital cost* ($) = 566006 + 617 × *number of cows* (N = 19, R^2 *not reported*) is used to compute approximate capital costs for several digester sizes [43]. The other part of fixed charge – annual operating cost - is assumed to have five components (opportunity cost of land, repairs/maintenance, property tax, insurance, and salary of an operator/manager). Average rental rate for cropland in New York State for the year 2009 [44] is used to compute opportunity cost of three acres of land that will host a digester. The other components are estimated using the guidelines of a recent feasibility study conducted for a Windham County based dairy digester business plan [20]. As the optimization model is set for a day, first the capital cost is annualized using an annuity factor and then expressed in per day basis. For conversion to annualized cost: (i) the life of the digester is assumed to be 15 years (16 years in [20]; 20 years in [13]); and (ii) a 7% rate of discount is assumed as advised in the federal guidelines for a cost-benefit analysis [45]. All monetary variables are expressed in 2009 constant US dollars.

The most recent land use map of Connecticut (for the year 2006) is available from the website of the Center for Land Use Education and Research at the University of Connecticut [46]. This raster data-based map illustrates 12 land cover categories. The categories utilized in this research are: (i) developed (commercial, industrial, residential, and transportation routes); (ii) agricultural field (crop and/or pasture land); and (iii) utility rights-of-way. County and town boundary and road maps are obtained from the website of the University of Connecticut's Map and Geographic Information Center [47]. The maps on other environmental attributes are collected from the GIS data repository of the Connecticut State Department of Energy and Environmental Protection [48].

Buffers of a 7 km radius are drawn around geocoded waste sources (dairy farms) to put a first round of constraint on plant location. Figure 1 depicts the union of buffer zones (area with long dash shade), which provides the initial set of feasible locations. Then various overlay tools in ArcGIS are utilized to impose other location constraints (listed in Table 1) one at a time on this initial set and reduce the number of potential sites. Figure 1 also illustrates an intermediate stage of this location search task. Imposing all constraints but the last one (proximity to transmission line), results in a much smaller subset (black polygons) than the initial set of locations. Then, the transmission line constraint is imposed and only those sites that fall within the buffer (shaded with gray in Figure 2), are considered for further search. The final overlay analysis ended with 68 polygons as potential sites.

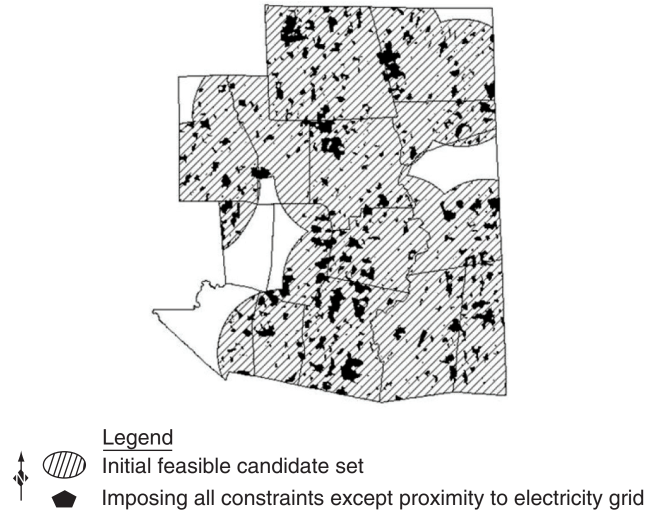

Figure 1: An intermediate look of the land suitability map

However, siting a CAD plant requires a minimum land area. Personal communication with the Hooley digester (at Tillamook Bay, Oregon) guides us to choose

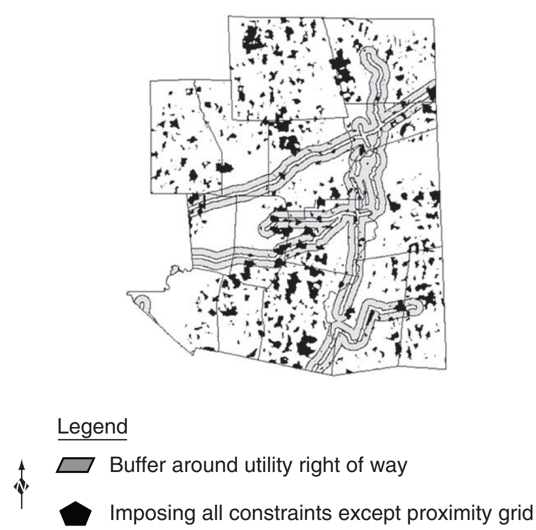

Figure 2: Imposing the transmission line constraint

three acres as a threshold so only polygons exceeding three acres are considered. After imposing this threshold area constraint, the candidate set is further reduced to 22. Figure 3 shows these 22 candidate locations along with the dairy farms. However, six of these sites are extremely close to other locations (within one-third of a mile) and hence discarded in the final analysis. The final set of feasible digester locations is {d-1, ..., d-16}.

Most of the dairy farms are so small that it is not cost effective to send a truck to collect manure individually. It would be more cost effective if the nearby farms can be thought of as a cluster and a big truck is sent to collect manure from each farm within a cluster. Waste management type location-allocation models used a similar aggregation concept to reduce the dimensions of the model [24]. Our research considers a farm to be a potential member of a cluster, if that farm is located within a 5 km radius of the focal farm of that cluster. The 28 dairy farms are grouped in various clusters as shown in Table 2. These clusters are slightly different under the two location strategies. In strategy A, digester location(s) would be chosen from the 16 off-farm candidate sites {d-1, ..., d-16}. Under strategy B, digester locations will be selected from four large farms. Similar strategy is followed in a feasibility study for regional digesters in California, where it is assumed that a CAD would be located on one of the participating dairies' site [49]. In our case, farm F_{24} is one such candidate to have a CAD and hence it is appropriate to separate it out from fellow farms in the same cluster. Thus, cluster c-13 under strategy A is broken down to two clusters, C_{13} and C_{14}, under strategy B. The farm clusters contain 6,820 cows for the modeling exercise. Thus, this study finally covers approximately 96% of dairy cattle population of Windham County.

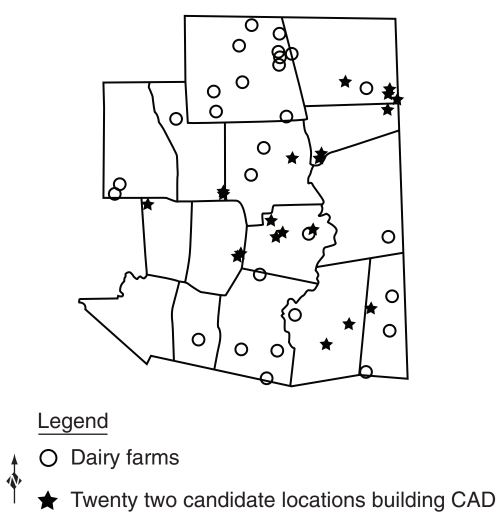

Figure 3: Set of candidate locations which satisfy all criteria for CAD(s)

5. Numerical models and results

Several variations of the MIP model are formulated and solved. Table 3 describes all the modeling scenarios. Scenarios I-III are linked with strategy A. In scenario I, a small size CAD (with capacity to handle manure from 2,000 cows) is considered. Scenarios II and III are more flexible as they allow the model to choose from two sizes (small and medium) and three sizes (small, medium, and large with capacities to handle 2,000, 3,500, and 7,000 cows) respectively. Scenarios IV-VI, on the other hand, refer to strategy B, i.e. on-farm CADs. In scenario IV the model is asked to choose from two CAD sizes (small and medium) and four farm locations. Scenario V forces all four large farms to have a CAD and allows the MIP to decide which farm clusters would support each of these CADs. This Scenario allows seven size possibilities ranging from 1,000 to 7,000 cows to choose from. Scenario VI relaxes the constraint imposed on the location in scenario V, and allows the MIP to choose the optimal location.

Eight more scenarios are also considered, for the purpose of sensitivity analysis. These scenarios examine the impact of 25% and 50% increases in unit transportation cost (T), and a 10% higher or lower volume for manure generation (m). All scenarios/models are executed using GAMS software and CPLEX solver. Tables 4 and 5 display the MIP optimization results for the various off-farm digester location scenarios. There d-i represents i-th off-farm candidate location for CAD, c-j and Cj denote j-th farm cluster, Fi symbolizes i-th on-farm candidate location for CAD, and the numbers in italics are number of cows. What follows next is a discussion of the MIP results and sensitivity analysis.

Scenario I results in opening four 2,000 cow digesters to handle all the cows in the sample. Under scenario II, when the model is allowed to choose between the same size and a medium one (3,500 cows), it chooses two medium size CADs. Scenario III further supports the notion that due to a large margin between low transportation costs and high fixed charges, fewer

Table 3: Farm clusters and scenarios explored in location analysis

Scenarios	Specification
Scenario I:	Farm clusters c-1 ... c-13; Locations to choose from: d-1 ... d-16; CAD size: 2000 cows
Scenario II:	Same clusters and locations as in I; CAD sizes: 2000 & 3500 cows
Scenario III:	Same clusters and locations as in I; CAD sizes: 2000, 3500 & 7000 cows
Scenario IV:	Farm clusters C_1 ... C_{14}; Locations to choose from farms: F_{10}, F_{16}, F_{19}, F_{24} ; CAD sizes: 2000 & 3500 cows
Scenario V:	Farm clusters C_1 ... C_{14}; Locations to choose from farms: F_{10}, F_{16}, F_{19}, F_{24}; CAD sizes: 1000, 2000, 3000, 4000, 5000, 6000 & 7000 cows
Scenario VI:	Farm clusters C_1 ... C_{14}; Locations to choose from farms: F_{10}, F_{16}, F_{19}, F_{24} ; CAD sizes: 1000, 2000, 3000, 4000, 5000, 6000 & 7000 cows
	Sensitivity analysis
Scenario III/VI - A:	Unit transportation cost is 25% higher
Scenario III/VI - B:	Unit transportation cost is 50% higher
Scenario III/VI - C:	Manure generation is 10% higher
Scenario III/VI - D:	Manure generation is 10% lower

Table 4: Optimized results for alternative location scenarios (I-III)

Scenario I:

	c-1	c-2	c-3	c-4	c-5	c-6	c-7	c-8	c-9	c-10	c-11	c-12	c-13	Capacity utilization
d-1			145		658				342				855	2,000
d-6			315				460	715				510		2,000
d-13						350				500		290		1,140
d-16	450	160		370							700			1,680

Minimized cost/day: $ 3,940

Fixed charge/day: $ 3,488 Transportation cost/day: $ 452

Scenario II:

	c-1	c-2	c-3	c-4	c-5	c-6	c-7	c-8	c-9	c-10	c-11	c-12	c-13	Capacity utilization
d-1			460		658		460	715	342			10	855	3,500
d-12	450	160		370		350				500	700	790		3,320

Minimized cost/day: $ 3,090

Fixed charge/day: $ 2,530 Transportation cost/day: $560

Scenario III:

	c-1	c-2	c-3	c-4	c-5	c-6	c-7	c-8	c-9	c-10	c-11	c-12	c-13	Capacity utilization
d-6	450	160	460	370	658	350	460	715	342	500	700	800	855	6,820

Minimized cost/day: $ 2,849

Fixed charge/day: $ 2,181 Transportation cost/day: $ 668

numbers of plants with higher capacities are always cost effective compared to a relatively decentralized CAD network. Scenario III results in the minimum cost under strategy A, although transportation cost is higher compared to scenarios I-II.

Very similar results are also obtained for scenarios those are under strategy B. Scenario IV replicates the results for scenario II. When the model is allowed to choose between a small size and a medium size, it chooses two medium size CADs. When, the model is forced to set up CADs at all four farms (Scenario V) and three size choices are allowed for (1,000 cows, 2,000 cows, and 3,000 cows), transportation cost falls but the rise in the fixed charge component is high enough to negate that

Table 5: Optimized results for alternative location scenarios (IV-VI)

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	**Capacity utilization**
Scenario IV:	F16	450	160		370		350		715	75	500	700				3,320
	F24			460		658		460		267			800	225	630	3,500
	Minimized cost/day:				$ 2,888											
	Fixed charge/day:				$ 2,530			Transportation cost/day:					$ 358			
Scenario V:	F10	150	30				350		670				800			2,000
	F16		130		370						500					1,000
	F19	300										700				1,000
	F24			460		658		460	45	342				225	630	2,820
	Minimized cost/day:				$ 3,419											
	Fixed charge/day:				$ 3,228			Transportation cost/day:					$ 191			
Scenario VI:	F10	450	160	460	370	658	350	460	715	342	500	700	800	225	630	6,820
	Minimized cost/day:				$ 2,745											
	Fixed charge/day:				$ 2,181			Transportation cost/day:					$ 564			

benefit and the net impact is a higher cost. When the locational restriction is withdrawn from scenario V, the new scenario VI delivers the minimum cost under strategy B. The largest size CAD (capacity: 7,000 cows) is chosen to handle all manure at one place. Again, transportation cost rises, but not enough to dominate the gains arising from a much lower fixed charge.

These results on size and location of CADs, and allocation of cows to CADs are robust to small changes in objective function parameter values. Eight sensitivity scenarios examine the effect of such changes in parameters T and m on location-allocation results. Only the minimized cost and transportation cost figures change from scenario III and scenario VI results. The GAMS output also gives information on the sensitivity of the optimal solution, C^*, to changes in the right-hand side (RHS) coefficients.

Marginals ($\partial C^*/\partial a_{ik}$, $\partial C^*/\partial b_j$) are reported for the capacity constraint set (Eq. 2) and the waste utilization constraint set (Eq. 5) in the GAMS output. A marginal represents a shadow cost, which quantifies the impact of a one unit change in the RHS of the constraint on the optimal value of the objective function. The shadow cost of capacity constraints are either negative or zero, implying that relaxing the size constraint would further reduce C^* in most of the cases due to economies of size. On the contrary, all the shadow costs of waste utilization constraints are positive, implying that an increase in number of cows in the cluster would raise C^* due to increased transportation cost.

A final question that arises is: which scenario/strategy is to be chosen for the sample of farms at hand? The results show that one big CAD will be the cost minimizing solution whether it is built within a farm (strategy B) or on other suitable sites (strategy A). Interestingly, the results also indicate that in this case siting the CADs at the farm is preferred, as C^* in scenario VI is significantly lower than C^* in scenario III. In the absence of uncertainty or risk, scenario VI is clearly the optimal choice. However, shipping and storing a large volume of manure in one place may be risky. Although the degree of risk cannot be quantified at present, a failure of such large manure storage could cause havoc in the local environment [50]. With that consideration in mind, scenario IV (two medium sizes) may be more desirable to a social planner, depending on the extent of risk and the planner's degree of risk aversion.

6. Concluding remarks

The dairy community in many parts of the world is under pressure from policy makers to improve manure management and make dairy farming more sustainable. Anaerobic digestion (AD) is a tried and tested technology available to convert manure (a bad) to energy (a good). However, to exploit this technology in an economically viable way, a minimum scale of operation (often defined in terms of the herd size supplying manure for the AD facility) is required. European countries (Denmark, Germany, and United Kingdom) have shown how centralized anaerobic digesters (CAD) can be a solution to this problem.

A thorough review of the feasibility analysis literature on CAD reveals that most of the time CAD locations are chosen based on non-economic considerations. This study integrates GIS based resource mapping and land suitability analysis with an already existing rich class of facility location models. Four fundamental location-allocation questions are addressed in the context of a given region: (i) How many CADs should be built? (ii) Where should they be located? (iii) Which farms should supply manure to them? and (iv) What is the optimal size of each CAD?

A location-allocation model (a.k.a. fixed charge transportation model) is applied in this study to small and medium sized dairy farms in Windham County, Connecticut. Several mixed integer programming type location-allocation models under different assumptions are solved. Model results suggest that one big CAD facility handling all the manure would be the cost minimizing solution. However, these results need to be interpreted with caution because they are dependent on the criteria used to determine suitable locations for the CADs. Modification of these criteria would change the set of possible sites. The choice of Euclidean distance rather than the road network distance and use of fixed constraint buffers (instead of a continuous, factor approach) are other methodological limitations of our exercise (although the factor approach has its own limitations as previously discussed). Use of other GIS techniques may yield better solutions to these problems and a comparative analysis deserves attention in future work. Also, the mathematical model relies mostly on synthetic data, whereas the collection of actual farm data would be desirable.

Keeping in mind the dearth of CAD related economic analysis and growing business and policy interests in such green energy and pollution abatement activities, the economic optimization exercises presented in this article should also be developed further conceptually before deriving policy recommendations. The conceptual advances needed are along two dimensions. First, some of the simplifying assumptions made in the cost minimization model could be relaxed. For example, a more realistic scenario could be assumed in transporting the manure to the CAD by bringing additional constraints on the capacity of the manure hauling vehicles. Similarly, partial allocation of manure to one of the CADs is another way to achieve an optimum as farmers do apply manure on cropland as well. Second, the modeling could be transformed from a cost minimization to a profit maximization framework. That transformation would allow one to carry out a broader benefit-cost analysis to determine the optimal CAD capacity (and locations) for any given region. Such an analysis would involve the comparison of benefits and costs (farm level, local, regional, and global) associated with pollution controls, thereby helping to determine the socio-economic contribution of CADs to a region.

We conclude the paper by highlighting the role of local town management bodies and municipalities as facilitators and consumers, creating a local market for biogas based energy [51].

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