DEPARTMENT OF FOOD AND RESOURCE ECONOMICS
UNIVERSITY OF COPENHAGEN

IFRO Working Paper

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2014 / 03

IFRO Working Paper 2014 / 03

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JEL-classification: Q15, Q42, R12

March 2014

www.ifro.ku.dk/english/publications/foi_series/working_papers/

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Towards a sustainable capacity expansion of the Danish biogas sector

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Abstract

Promotion of bioenergy production is an important contemporary topic around the world. Vast amounts of research are allocated towards analysing and understanding bioenergy systems, which are by nature multi-faceted. Despite a focus on the deployment of multi-criteria decision-making (MCDM) methods for planning of bioenergy systems, only little research has addressed the location component of bioenergy facility planning. In this paper the authors develop a model for sustainable capacity expansion of the Danish biogas sector allowing for an identification and prioritization of suitable locations for biogas production. The model builds on a framework for spatial planning and decision making through the application of spatial multi-criteria evaluation (SMCE). The paper is structured around a case study including four Danish municipalities in order to demonstrate the power of the spatial multi-criteria evaluation model. The model allows a two level comparison of suitability, within municipalities as well as between municipalities. Criteria weights for generation of alternatives are obtained through an analytical hierarchy process (AHP), carried out among a group of Danish central governmental decision makers. We find that resource and production economic criteria are given highest priority followed by environmental and social criteria. In all four case study municipalities, the identified alternatives are compared through incorporating economic, environmental and social criteria. It is found that a sustainable facility location has the potential of reducing overall production costs by 3% as compared with current biogas plants. The results of this paper can provide support to central governmental decision makers, regarding regional allocation of subsidies in the country. Likewise local decision makers can obtain important information for planning and decision support, allowing for a more inclusive and transparent planning procedure.

1. **Introduction**

Bioenergy production is gaining increasing awareness among researchers as well as authorities and industries around the globe. Biogas production is a technology that has gained much attention in many agri-intensive countries, e.g. Denmark and Germany, for both agri-environmental reasons as well as economic and social reasons. One of the important aspects of biogas production for the farmers is that the degasified husbandry slurry reduces the leaching of nutrients from agricultural lands and to the aquatic environment, which in turn implies that a farmer engaging in biogas production has the potential to expand his husbandry production without increasing the emissions of nutrients. Also, biogas production contributes to the production of renewable and sustainable energy and work as a flexible and predictable fuel in the Danish wind-based renewable energy system. Last but not least bioenergy production systems, in general, are also found to facilitate job creation (Lavrencec 2010) and as biogas facilities normally are located in rural areas with fewer job opportunities, these jobs have a high social value (Al Seadi et al. 2008).

At the same time biogas production is concerned with a number of potential challenges, such as increased amounts of heavy transport, annoyances from high visibility of the plants in the agricultural landscape near local communities, where to access other biomasses than slurry, e.g. maize and potential environmental damages due to high concentration of nutrients from livestock manures.

As part of fulfilling its renewable energy obligations, Denmark has set a policy ambition to exploit 50% of all animal husbandry slurry by 2020, which in turn implies building approximately 20 new large centralised biogas plants (Bojesen et al. 2014). The location of these many new biogas facilities capture the dilemmas described above including economic, environmental and social factors and constraints resulting in a multi-criteria decision making problem, which needs to be resolved or tackled by authorities and other stakeholders. The trade-offs between the many concerns are experienced on a routine basis by planning officers at a local level when municipal plans are developed and project proposals evaluated; as well as at national level, when subsidies, in the form of project grants, are being distributed (Joensen and Mølgaard 2010).

In this paper we develop a value-driven spatial multi-criteria evaluation (SMCE) model in order to identify and prioritize suitable locations for biogas production, balancing the multiple regards needed for sustainable capacity expansion of the Danish biogas sector.

The paper is structured around a case study including four Danish municipalities with significant biogas potential in order to demonstrate the power of the spatial multi-criteria evaluation model. We adapt an existing multi-attribute decision making modelling framework in order to allow for comparisons of alternatives within as well as between municipalities.

1.1 Challenges in biogas planning and decision making

As part the Danish planning system all municipal plans and local plans must be sent to public hearings (Retsinformation 2013), as the ambition of the planning legislative framework is to include the general public as well as both private and public organisations and industries in the planning process. Establishment of biogas facilities is covered by this planning legislative framework and includes a requirement for environmental impact assessment (EIA) which underpins the need for public hearings. Further, public participation and local commitment or at least acceptance is seen as an important part of many biogas projects as this leads to a higher degree of social legitimacy (Daniels and Walker 2001). The absence of local commitment can lead to among other things local resistance against projects, which in turn leads to high transaction costs.

The need for local participation often leads to what Daniels and Walker (2001) term 'the fundamental paradox', which means that citizens and society as a whole demands technically sound decisions, but as situations become more complex fewer people have the technical background needed to either meaningfully contribute or critique the decisions. In effect planning processes easily get expert driven and public meetings and hearings concerning location of biogas facilities easily revolve around feelings such as the NIMBY (not-in-my-backyard) effect or specific interests instead of discussing how to balance the many tactical and strategic decision aspects and concerns. Ultimately such process characteristics may result in many undesired effects including increased transaction costs, prolonging project implementation, low levels of knowledge sharing between stakeholder groups and overall poorer decisions.

Appreciating the complex and multifaceted nature of biogas location planning, a participatory planning process may seem unrealistic and may not even lead to a better and more sustainable decision due to the high demands for technical understanding. Nevertheless the current planning situation calls for a planning process which can accommodate transparency and inclusion of multiple professional stakeholder viewpoints. Such a planning process is termed transactive planning (see e.g. Hudson 1979). The SMCE framework, as applied in this paper, follows the same logic as synoptic/ rational planning (see. e.g. Hudson 1979), which includes goal-setting, identification of alternatives, evaluation of means against ends and implementation of decisions. On the other hand, the SMCE framework has the potential to function as a transactive planning approach due to the strong communicative qualities of GIS (see e.g. Batty 2005), which in turn is also a core asset of the SMCE framework. Considering the need for definition and weighting of relevant criteria, SMCE models can also fulfil an important role as a platform for dialogue and mutual learning between professional stakeholders.

1.2 Literature review

There has been increasing awareness of the importance of location analysis throughout a number of industries including waste management, pulp and paper production as well as bioenergy production (Bojić et al. 2013, Braglia and Gabbrielli 2012, Sumanthi et al. 2008, Möller and Nielsen 2007). All these industries are highly concerned with minimizing production costs in general and transportation costs in particular as these, especially within bioenergy production systems are found to account for as much as 40% of the overall production costs (Jacobsen et al. 2013). Location analysis with regards to the production economic implications of different locations have proven to provide valuable decision support in a number of studies (e.g. Suárez-Vega et al. 2012, Clarke and Clarke 2001, Birkin and Culf 2001).

Bioenergy production systems include biomass production, conversion technology and energy distribution. These processes are embedded in multiple economic, environmental and social contexts. As a consequence these systems are highly complex and difficult to manage effectively, which in turn implies that location analysis within bioenergy production often focuses on only one or few components of the entire system. Relevant examples are provided by Höhn et al. (2014), Bojesen et al. (2014) and Panichelli and Gnansounou (2008) who use location-allocation models to determine the optimal location of bioenergy facilities minimizing transportation costs.

Romero and Rehman (1989) argue that when decision problems are characterized by a single criterion they should be regarded as technological, whereas when multiple criteria need to be considered, problems of decision making become economic. This shift from technological to economic decision making is caused by the trade-off between multiple attributes, which in turn fulfils multiple objectives.

In contrast to the single- or dual criterion models developed within the location analysis context, a rich literature has been established within multi-criteria decision making (MCDM) and multi-criteria evaluation (MCE) concerning both location studies (e.g. Gorsevski et al. 2012, Farahani et al. 2010, Zucca et al. 2008, Sharifi & Retsios 2003) and evaluation of bioenergy systems (e.g. Gebrezgabher et al. 2014, Theodorou et al 2010, Karagiannidis and Perkoulidis 2009, Buchholz et al. 2009, Beck et al. 2008, Rozakis 2001). However, the combination of the two is a rarity despite the valuable examples provided by e.g. Perpiña et al. (2013) and Ma et al. (2005). In these examples the authors perform a suitability analysis concerning location of a biomass plant, but do not address the formation and prioritization of suitable location alternatives.

In a literature review concerning more than 80 multi-criteria decision making studies within bioenergy systems Scott et al. (2012) concludes that less than 6% of the papers published between 2000 and 2010 address location issues. The difference between conventional a-spatial MCDM and spatial MCDM, which includes SMCE, lies in the spatial dimension of each criterion. Many of the factors relevant for managing bioenergy systems, such as production potentials, distribution possibilities, neighbouring effects, transportation issues have an important spatial dimension that will influence the suitability and subsequently capacity of a certain location.

Diakoulaki and Karangelis (2007) discuss the advantages and drawbacks of a Multi-Attribute Decision Making (MADM) approach and find that one of the main advantages of the MADM approach is that it provides a basis for normalization which is able to value both monetary and non-monetary measures against one another.

The aim of the present paper is to fill the knowledge gap addressed above and provide decision support to the real world decision problem of biogas installation allocations both at a regional and municipal level. This is done by developing a spatial multi-criteria location model for sustainable biogas production providing a case study on capacity expansion of the Danish biogas sector. In order to fulfil our aim we address the following during the remainder of the paper:

- First, we suggest a spatial multi-criteria evaluation (SMCE) suitability model for a sustainable site selection for biogas production in four Danish municipalities;
- Secondly, we investigate how the criterion weighting preferences of governmental decision makers can be modelled and will influence the site suitability degrees in four different municipalities;
- Thirdly, we develop a SMCE model for choosing between candidate sites in the four municipalities including both spatial and a-spatial criteria;
- Finally, we investigate how the defined alternatives rank under four different weights scenarios in order to explore rank reversal thresholds according to the SMCE model.

2. Theory

2.1 Value focused thinking and creation of alternatives

Decision problems are defined by Ackoff (1981) as problems in which a decision maker has alternative courses of action, the choice being made has a significant effect and the decision maker has doubt as to which alternative should be selected. The decision making process involves a sequence of activities that starts with recognition of a decision problem and ends with recommendation of courses of action (Ackoff 1981). The quality of the decision depends on the sequence and quality of the activities that are carried out. Depending on the situation, there are a number of ways in which the sequence of activities can be organized. According to Keeney (1996), two major ways of thought can be distinguished: alternative-focused, and value-focused. The alternative-focused approach begins with development of alternative options, followed by the specification of values and criteria and then concludes with evaluation and recommendation of an option. This is in effect an ex-post approach to the problem in question. In contrast, the value-focused way of thinking (an ex-ante approach), considers the values as the fundamental element in the decision analysis. It first focuses on the specification of values (value structure), then, considering these values, it develops feasible options to be evaluated according to the predefined value and criteria structure. This implies that decision alternatives are to be generated so that the values specified for a decision situation are best achieved. In turn this means that the order of thinking is focused on what is desired, rather than on the evaluation of alternatives. In fact alternatives are considered as means to achieve the more fundamental values, rather than being an end to themselves. In decision problems, in which alternative options need being developed and subsequently evaluated, the value-focused approach can be much more effective. However, if the decision problem begins with a choice of options, the alternative-focused approach seems more relevant.

Interestingly, when generating spatial options by means of a value-focused suitability analysis, different values apply than when the resulting options are evaluated for choice. For example, in suitability analysis, several more technical criteria could be considered, whereas in choice more political criteria could be considered. Hence different people, and their values, are relevant to design or choice. Moreover, from suitability analysis several possible location options result that are more suitable. Only after these possible locations are known, they can be evaluated for their impact to be considered in choice.

In this study a value-focused approach, guided by the framework for planning and decision making developed by Sharifi and Rodriguez (2002) is applied since this allows us to develop suitable alternatives based on national objectives and values and further compare the developed alternatives.

2.2 Intelligence, design and choice phase

The framework for planning and decision making has initially been described by Sharifi and Rodriguez (2002). This generic framework describing a planning and decision making process contains three phases: an intelligence phase building a process model; a design phase building a planning model; and last a choice phase building an evaluation model. This intelligence phase is concerned with understanding the system in question and formulating objectives.

The design phase has the purpose of generating alternative layouts of possibly suitable clusters of spatial objects, based on a set of selected criteria. In this case, clusters of spatial objects are groups of neighbouring pixels of a certain level of suitability. The partial outcome and the basis for designing of these alternatives is a suitability map indicating the degree of suitability according to the defined set of criteria. The model for obtaining the suitability map can be expressed as:

$$Design\ phase\ suitability\ degree;\ \widehat{X}_{\iota} = \sum_{j=1}^{m} w_j * x_{ij} \quad (1)$$

$\widehat{X}_{\iota}$is the suitability degree of the i'th pixel, in this paper measuring 100m x 100m, and w_j is the weight being assigned to the j'th criterion, which has a score value of x_i. Further w_j is characterised by:

$$1 \geq w_j \geq 0\ and\ \sum_{j=1}^{m} w_j\ = 1 \quad (2)$$

In the design phase only spatial criteria are included in the analysis. Each criterion is standardized according to an underlying value function specified by the decision maker. This standardization is a specification of how each criterion contributes to fulfilling an objective. For a further description of standardization methods see e.g. Sharifi et al. (2004).

In the choice phase the impact of the different alternatives are assessed, by the means of comparison between degrees of suitability, typically under multiple scenarios in order to explore how different criteria weights may influence the suitability of the alternatives in question an identify thresholds for rank reversal. This impact assessment will allow a decision as to which alternative should be chosen and why. The model for the choice phase suitability degree of each alternative can be expressed by:

$$Choice\ phase\ suitability\ degree;\ \hat{\hat{X}}_{kl}\ = \sum_{j=1}^{r} w_{jk} * x_{ijl} \quad (3)$$

$\hat{\hat{X}}_{kl}$ is the standardised suitability degree of each alternative under the k'th scenario. The score of each alternative x_i with respect to criterion j is evaluated in each municipality l, and weighted by w_j for each criterion under the k'th scenario. Through this mechanism the alternatives are evaluated by the same criteria under each scenario, but with a different weighting. The criteria in the design and choice phases are not the same but criteria used in the design phase may reoccur in the choice phase.

As part of the process of reaching a suitability degree for each alternative in the choice phase, the modeller must perform an MCA step and a spatial aggregation (SA) step. The implication of spatial aggregation is loss of spatial representation. In the choice phase it is possible to include both spatial and a-spatial criteria, which in effect means that one performs a hybrid of spatial and a-spatial multi-criteria evaluation. During this step spatial information is kept. Next step is spatial aggregation which implies as in the design phase that the spatial representation is lost. Instead the performance of each alternative is described by a maximum, minimum and average suitability score. A further description of the procedure is found in Herwijnen (1999).

The standardization procedure for the spatial criteria in the choice phase is the same as in the design phase. A-spatial criteria are measured at municipal level and are therefore standardized using the between municipality variation. This way of structuring the analysis constitutes an important part of the study since it allows us to compare dependant alternatives (within municipalities) and independent alternatives (between municipalities) simultaneously due to the global standardization. The way each criterion is standardized in this study is reported in the materials and methods section.

2.3 Estimation of criteria weights

As a representation of the importance of each criterion we assume the existence of a vector of weights w_j as specified in equation 2. These weights are essential to the overall aggregation of the criteria both in the design phase and choice phase, since it establishes a hierarchy between the different factors contributing in the planning and decision making process (see e.g. Saaty 1980, 2008). In this paper the AHP (analytical hierarchy process) which incorporates pairwise comparisons of criteria is used for obtaining the weights vectors. The AHP is a weight estimation technique used throughout the multi-criteria decision making literature (see e.g. Farahani et al.

2010, Saaty 2008, Sultana & Kumar 2012), where the purpose is to understand and aggregate different expert preferences. Such preferences are deducted by means of linguistic pairwise comparisons of the criteria of interest. This standard AHP makes use of a Likert valuation scale, where each linguistic label corresponds to a crisp value representing the importance of the specific criterion.

3. Materials and methods

The research presented here builds on a framework for spatial multi-criteria evaluation (SMCE), using the open source GIS ILWIS (Integrated Land and Water Information System) SMCE (52north 2010), for securing a sustainable capacity expansion of the Danish biogas sector through locating potential sites for new plants in four Danish municipalities. The geographical information for the model is compiled by using ArcGIS 10.1 (ESRI 2012). All spatial criteria are modelled as raster maps, with a cell size of 100 meters using WGS84 UTM zone N32 as spatial projection reference. The SMCE framework consists of three phases. The intelligence phase in which the decision making problem is formulated and objectives defined. Next is the design phase in which suitable locations and alternatives are identified. In the choice phase the comparison of the identified alternatives takes place and a final ranking is obtained.

3.1 Case study areas

As can be seen in figure 1 the four case study municipalities are all located in the western part of Denmark, where the biggest expansion of biogas production is expected to take place due to high concentration of livestock production and consequently large biogas production potentials. The four case study municipalities are Thisted, Ringkøbing-Skjern, Skanderborg and Aabenraa municipalities. Transport costs are a crucial cost factor in biogas production. To honour that, a location-allocation analysis of optimal location of future biogas plants was carried out. This analysis allows for a global minimization of the weighted transport distances of slurry input biomass from Danish pig and dairy cattle farms within a 40km driving radius (represented as the 'effect area' in figure 1) from each biogas plant(further description see e.g. Bojesen et al. (2014). This analysis was considered in choosing these four municipalities since each of them contain at least one transport economic optimal location. The geographical location of the four municipalities has also been taken into account in choosing case study sites, in order to explore regional differences in biogas plant location suitability degrees. The case study layout also represents an east-west, north-south gradient, which enables exploration of how different criteria weighing will cause a shift in which municipalities will be the most preferred. Finally, the selection of the four case study areas also rests on availability of planning restrictions data, as supplied by the Danish nature agency (Naturstyrelsen 2013c).

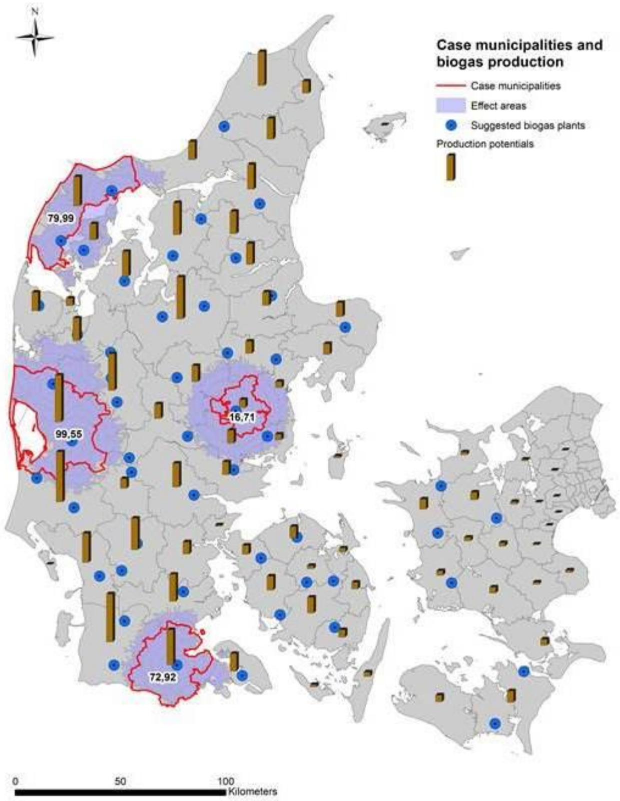

Figure 1 - Selection of case municipalities and representation of biogas production potential and effect areas around suggested biogas plants in case municipalities. Further the percentage of the household power consumption in each municipality that could be covered by biogas based power is included in the map. Source: Own calculations.

For the four case study municipalities, the SMCE is carried out during the design and choice phases as described above using the ILWIS SMCE software. In the design phase we model site suitability in the case study municipalities solely based on spatial criteria, which serves the purpose of identifying possible locations of future biogas facilities and by that, defining alternatives for further comparison. Subsequently, in the choice phase, we model the performance of the identified alternatives based on both spatial and a-spatial criteria. The outcome of the choice phase, and by that the entire analysis will be an evaluation of rankings of the different possible locations under different scenarios, which ultimately can serve as decision support for locating future biogas plants.

3.2 Intelligence phase – defining modelling objectives

To identify the main objective of locations of future biogas plants we must consider the implications of the Danish governmental agreement on green growth (Grøn vækst 2009). This agreement forms the basis for a number of initiatives allowing the realization of the vision of a society in which green behaviour and green technologies are emphasized in order to tackle environmental and climatic challenges and at the same time stimulating a green economy. Hence, the main objective of locations for future biogas plants is to facilitate the best possible implementation of a predefined technology, meaning biogas and facilitate a predefined measure of success, i.e. 50% of the produced slurry.

Consequently, the main objective of biogas plant location, is to be considered sustainable. This guides the model building in the sense that we seek to construct a model allowing for a sustainable capacity expansion of the Danish biogas sector and by that the inclusion of the three sub-objectives: economic feasibility, environmental suitability and social acceptability

3.3 Design phase - suitability modelling and design of alternatives

The design phase includes a suitability model from which a suitability map is obtained showing to which degree each pixel in the raster is suitable or not. In contrast to the major part of the existing MCDM location literature, the design phase is not the end, merely a means, since it provides the basis for the design of alternatives which can further be compared.

The objective and sub-objective formulation from the intelligence phase, section 3.2, steers the choice of criteria for the suitability analysis, in the design phase, which are based on a review of criteria used in facility location problems (Farahani et al. 2010) and discussions with central governmental decision makers (Naturstyrelsen 2013a). This approach of using literature studies and decision maker interviews is supported by Malczewski (1999).The suitability model formulation is presented in figure 2 below and describes how we adopt the findings of the literature review and discussions with decision makers. Together with the sustainability objectives described above these findings serve as input for the suitability analysis and identification of alternatives.

Standardization is a crucial part of the suitability analysis as this is a means of representing the value functions underlying each map entering the analysis. Standardization allows different utilities to be attached to each criterion, which consequently can provide diverse manifestations of the same criteria according to the values of different decision makers or different planning contexts. The standardizations and criteria weights according to the AHP analysis are reported in table 1 in section 3.3.6. These weights and standardizations are reflected in the criteria measures and implemented in the SMCE analysis as specified in figure 2.

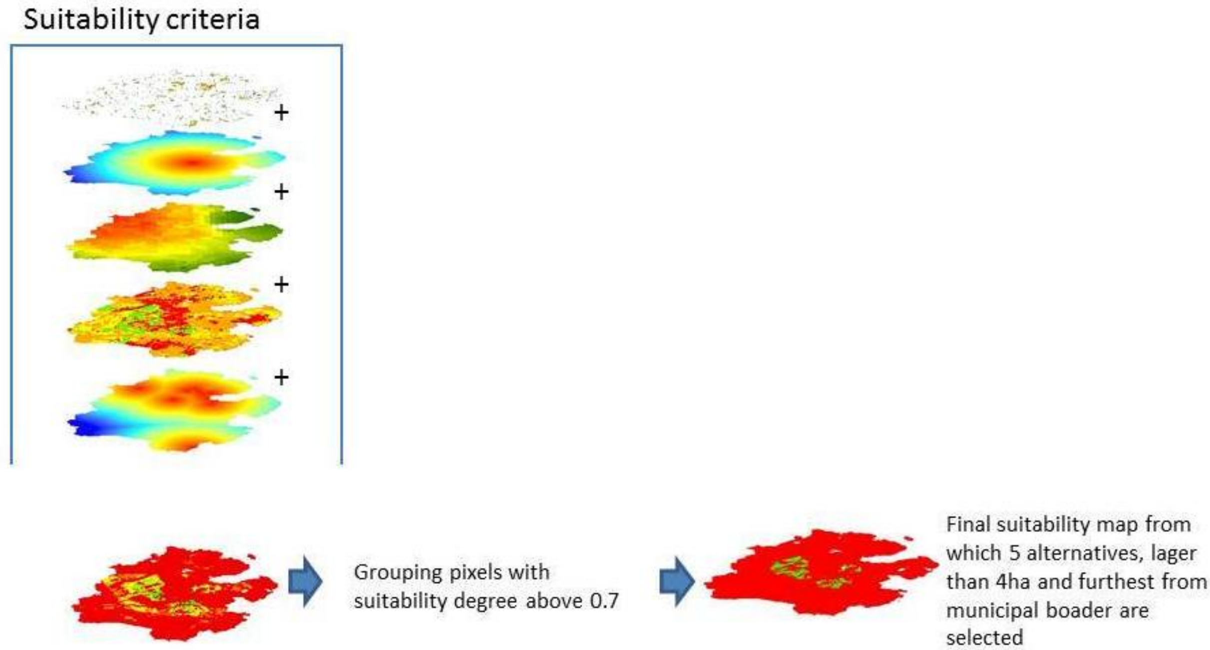

Figure 2 – Suitability model from the design phase. Source: own calculations developed on the basis of Farahani et al. 2010.

The suitability degree threshold is chosen as largest value where all case municipalities contain feasible solutions, i.e. 0.7. The size of each alternative is set at 4 ha as this is the average land area used by large centralised biogas plants in Denmark. The suitability considerations are based on criteria regarding population density, production potential, distance to transport economic optimal points, planning zone suitability, and distance to heat plants and combined heat and power plants. We elaborate on each of them in the following.

3.3.1 Population density

Data for the population densities are obtained from Statistics Denmark and is based on the Danish central person register at January 1st 2012. This data has been aggregated by a 100m x 100m grid in order to match the scale of the current analysis. The fewer people living in the vicinity of a biogas plant, the fewer will be exposed to the potential annoyances of the plant, such as increased transportation, noise and the perceived risk of smell. Through standardization higher utility values are assigned the lower the population density is.

3.3.2 Production potential

The production potentials are estimated based on Bojesen et al. (2013) by summing the slurry production at farms larger than 30 animal units in 40km travel distance service areas. These areas are calculated from the centroids of $1km^2$ grid cells in the case municipalities. Subsequently these $1km^2$ grid cells are disaggregated into the 100m x 100m cell size of the raster map. Issues of spatial autocorrelation are considered as ruled out as slurry supplies are reported at the possible finest scale available ($1km^2$).

The utility of a certain location increases with increasing production potential. The marginal benefits of increasing production potential is though decreasing, resulting in a concave utility function, reaching a utiliy value of 0,75 at a potential production level of 7 mill. m^3 methane, since this is the average size of new biogas plants being built in Denmark today (Bojesen et al. 2014).

3.3.3 Distance to transport economic optimal points

As transportation of slurry accounts for 33% of the overall biogas production costs, transport minimization is regarded as a crucial cost criterion for a suitable location. In the suitability analysis the distances to these transport economic optimal points are considered through a Locate-allocated analysis, using ArcGIS 10.1, Network Analyst (ESRI 2012). The optimal set of 20 locations is found based on solving the p-median problem (Daskin 1995) considering the slurry supply weighted minimum transport distance. The figure of 20 new biogas plants is found based on the Danish national biogas ambitions, saying that by 2020, 50% of the slurry should be utilized for biogas production. It is subsequently found that the average capacity at each plant is 7mill. m^3 methane, which is the average capacity of the new plants being built today (Bojesen et al. 2014). It is further assumed that biogas plants operate within a 40 km driving radius from the plant.

The distance to transport economic optimal points is considered a cost which implies that the shorter distance the higher utility will that location result in. Standardization assumes a linear downwards sloping utility function as distance increases.

3.3.4 Planning zone suitability

Data for the planning zones suitability criterion is based on data from the Danish nature agency (the national planning authority) and has been developed in cooperation with Danish municipalities. These planning zone maps show where favourable and unfavourable locations are according to legislative restrictions. Planning zone suitability includes a number of environmental regards and planning legislative restrictions. The areas where biogas production has a favourable status or may be approved after closer assessment are both treated as factors in the spatial multi-criteria evaluation. Favourable zones are considered twice as attractive as the assessment zones. Restricted areas, where biogas is not possible due to restrictions in the planning legislation and ambiguity areas, where restricted and assessment areas overlap are treated as constraints.

Standardization of planning zone suitability gives the maximum utility to the areas in a favorable zone and 50% utility to areas in an assessment zone.

3.3.5 Distance to heat plants and combined heat and power plants (CHPs)

The distances to heat plants and CHPs are calculated as Euclidian distances within the municipal boundaries. Data is obtained from PlansystemDK, a Danish municipal planning database (Naturstyrelsen 2013b). This criterion is considered in the design phase since the expansion of district heat networks are very costly, whereas biogas pipelines from the actual biogas plant to heat plant or CHP are relatively cheap in comparison. Consequently the vicinity to existing district heat producing plants is considered important from the perspective of both production economics and market access.

Distance to heat plants and CHPs is considered as beneficial within the interval 0-10km. The most beneficial location, resulting in the highest utility value, is at a distance of 5km. This is due to the fact that the biogas needs to be cooled off before being incinerated in a gas engine.

3.3.6 Criteria weights for the suitability model

In order to obtain criteria weights for the suitability model we apply the AHP methodology (Saaty 1980) by conducting a survey on criteria preferences among a group of Danish governmental biogas planners (Naturstyrelsen 2013a). The AHP methodology is a commonly used MCDM technique applied in a number of spatial multi-criteria studies (see e.g. Braglia and Gabrielli 2012, Wang et al. 2009, Malczewski 1999). Saaty and Vargas (1991) argue that one of the advantages of the AHP methodology over e.g. cost benefit analysis (CBA) is that the AHP does not need monetary unit conversion of all criteria and preferences, which is not always possible nor favorable as the human perception is not always monetary. Further, Vaidya and Kumar (2006) argue that the AHP draws attention to the objectives. A central part of the AHP procedure is pairwise comparison which is applied in both the suitability model and the evaluation model in order to match the ILWIS SMCE terminology.

The weights obtained via the AHP analysis survey among a group of Danish governmental planners are seen in table 1 below. With a consistency ratio (CR) at 0.05 preferences are found to be consistent among the governmental planners. Since the Danish government has set clear goals with regards to expansion of biogas production and local implementation is supported through state agencies, governmental planners are important stakeholders.

Indicator and criteria	Weights
1. Population density. The lower density the better.	0.12
2. Local slurry production. The higher the production the better it is.	0.26
3. Distance to transport economic optimal points. The shorter the distance the better it is.	0.38
4. Degree of planning zone suitability. The higher suitability degree the better it is.	0.17
5. Distance to heat plants and CHPs. The closer to 5km the better it is.	0.08

Table 1 - Indicator weights based on an AHP survey among Danish governmental planners and standardization of indicators, Source: Own calculations based on personal communications (Danish Nature Agency 2013a).

In order to validate the consistency of the pairwise comparisons as carried out by the Danish Nature Agency a consistency ratio (CR) was calculated based on the procedure described by e.g. Malczewski (1999), where

$$CR = \frac{CI}{RI} \quad (4)$$

CI is a consistency index calculated from a consistency vector and RI is a random index generated by a random pairwise comparison matrix. If CR < 0.1 the ratio indicates a reasonable level of consistency in the pairwise comparisons, meaning that the decision makers' answers given in the survey are consistent and hence not arbitrarily.

3.4 Choice phase - evaluation of alternatives

In the choice phase we compare for each municipality the five suitable locations ($\widehat{X_i}$> 0.7, c.f. equation 1) larger than 4ha furthest away from the municipal boundary. This final selection of location alternatives is done to lower the probability of spill over effects from one municipality to another. Such effects could be that the additional jobs created should benefit citizens in the same municipality as the biogas plant is located. Another effect could be the increased amount of traffic to and from the biogas plant. If it is located at the municipal boarder a large proportion of the increased traffic will affect the citizens of the neighbouring municipality as well. Since the level of analysis is within municipalities we wanted to avoid the boarder spill over effects, since it would diminish the quality of the choice analysis.

For the comparison of alternatives we build an evaluation model consisting of both spatial and a-spatial factors with the purpose of comparing alternatives within the municipality as well as between the municipalities. The evaluation criteria are chosen based on discussions with central governmental biogas officers (Naturstyrelsen 2013a) bearing the results of the intelligence phase in mind. In figure 3, the base model is presented in which both spatial and a-spatial criteria are incorporated covering economic, environmental and social areas of concern. These criteria will be discussed in the following.

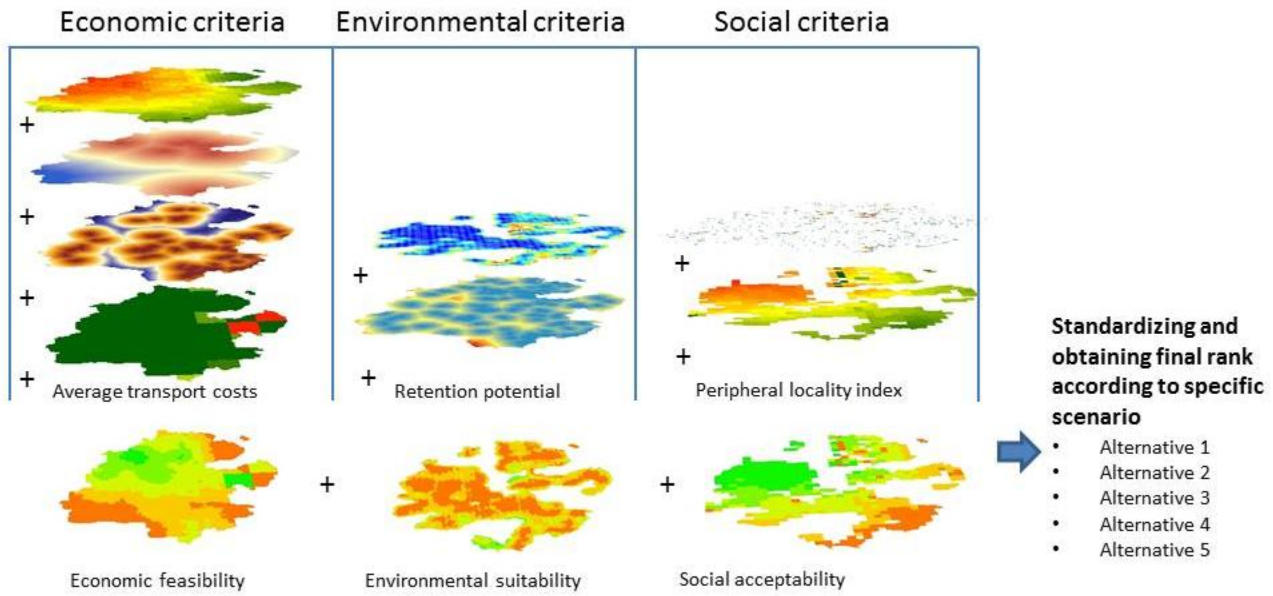

Figure 3 - Representation of the evaluation model applied to all alternatives incorporating economic, environmental and social criteria. Source: Own calculations.

3.4.1 Production potential

Production potential is also included in the evaluation model as a spatial criterion and evaluated such that the larger production potential the better it is. This will allow a distinction between alternatives within each municipality as well as across municipalities. The largest differences are expected to be found between municipalities due to regional differences in production potentials. Data occur in the interval [0;14.8] mill. m^3 methane. Data for this criterion is the same as mentioned in section 3.3.2.

3.4.2 Distance to heat plants and CHPs

Distance to heat plants and CHPs (combined heat and power plants) is treated as a spatial criterion also in the evaluation model and evaluated such that the shorter distance the better it is. This evaluation is different from that in the suitability model, since the latter will give preference to the locations closest to the lower half of the interval 0-10km as specified in the suitability model (see section 3.3.5). The justification for this criterion in the evaluation model is that if conventional biogas production is chosen the biogas produced should be transported via pipelines to a CHP/ heat plant to be incinerated. Data source is the same as reported in section 3.3.5.

3.4.3 Distance to natural gas grid

Distance to the natural gas grid is included in the evaluation model as a spatial criterion, and evaluated such that the shorter distance to the natural gas grid the better it is. The distance is calculated as Euclidian distances to the existing distribution gas grid. Grid location information is obtained from plansystem.dk (Naturstyrelsen 2013b). The inclusion of this criterion is justified because if upgrading of biogas to biomethane is the preferred choice of technology then the costs for establishing access via pipelines to the natural gas grid are minimized.

3.4.4 Potential stock of alternative biomass

The larger the potential stock of alternative biomass, the more feasible the location, since other biomass is needed in the biogas production in order to increase the dry matter content in the biogas reactor. This criterion is a spatial criterion which is motivated by the fact that the higher the proportion of pigs are in an area, the higher is the degree of freedom regarding choice of crops on agricultural areas, since these areas are not reserved for fodder production. Data for this criterion is obtained from Bojesen et al. (2013) and occurs in the interval [0.73; 2.6] (mill. AU pigs/AU cows/25km^2). The assessment scale 25km^2 is chosen in order to accommodate an estimated area need to produce enough biomass for the biogas plant.

3.4.5 Average transport costs

Average transport costs are an important driver in location of biogas plants and are found to account for 33% of the overall production costs (Jacobsen et al. 2013) or approximately 25% of the earnings per. 1000m^3 methane sold. The average transport costs range between [0.86; 0.96] (DKK/1000m^3 methane) and evaluated so that the smaller these costs are, the more economic feasible is the location. Average transport costs are included as an a-spatial criterion since one value is calculated for each alternative measuring at least 4 ha. In order to be able to compare across alternatives and municipalities a plant size of 7 mill. m^3 methane is assumed. Data for this criterion originates from Bojesen et al. (2013) and Jacobsen et al. (2013), who provide an investment analysis of biogas production including a model for transportation costs.

3.4.6 Visibility

Visibility is included as a spatial criterion with environmental relevance. The lower the visibility of the plant the more suitable the location. With low visibility the plant will have lower visual impact on the surroundings and may even prevent triggering the potential perceived risk of odors in the local environment. Data for the visibility is based on a digital elevation model combined with land use data in a view shed analysis carried out in ArcGIS 10.1. This model analysis is conducted at a 250m grid scale and computes the number of vantage points (grid cell centroids) that can see the location in question, within a 1000m radius. To mimic visibility from a person's perspective a vantage point height of 2 meters was applied. The fewer points that can see the location in question, the better it is. The location in question is assumed to have a height of 20m, which is assumed to be the highest point of the biogas plant (e.g. the top of the chimney). Values for this criterion represent the number of points from which the location in question can be observed and range between [0; 48].

3.4.7 Sensitivity to noise and smell

The model is designed to favour biogas locations which are remote from areas which are sensitive to noise and smell; hence for example recreative areas, mixed business and dwelling areas and summer allotment areas are included in the evaluation model as a spatial criterion in order to give preference to the alternatives which influence the surrounding environments the least in these terms.

Proximity is measured by Euclidian distance Using data which originates from the Danish TOP10DK dataset, hosted by the Danish geodata agency (Geodatastyrelsen 2013).

3.4.8 Retention potential

The retention potential indicates a soils ability to adsorb nutrients and by that prevent leaching into the aquatic environment measured by kg N/ha. The higher the retention potential the higher the adsorbtion ability. Retention potentials are calculated for large waterways, which may cover several municipalities, since they are delineated by topological rather than administrative boundaries. An area with low retention potential will in terms of retaining nutrients, benefit more from these advantages of a biogas plant than an area with high retention potential since degassed slurry is more easily adsorbed in the soil. Data for the criterion is obtained from Jacobsen (2012) and ranges between [78.55; 701.33](kg N/ha).

3.4.9 Population density

Population density is included as a spatial factor also in the evaluation model since this criterion measures the potential social impact of a given alternative location. Data for the population densities are obtained from Statistics Denmark which is based on the Danish central person register January 1st 2012 and was obtained as household point data ranging between [0; 2767](inhab./km^2). This data has been aggregated by a 1km^2 grid in order to accommodate not only the exact location of a biogas plant but also its immediate vicinity. The fewer people living in the vicinity of a biogas plant, the fewer will be exposed to the potential annoyances of the plant, such as increased transports and the risk of odours.

3.4.10 Job creation potential

Job creation potential is included in the evaluation model as a spatial criterion since one of the arguments in the Danish debate for the justification of biogas production is that it contributes to the creation of more “green” jobs and in that way also has a social impact. Lavrencec (2010) suggested a formula for estimating the job creation potential from biogas production as a function of the production capacity of a given biogas plant, which is why we calculate the job creation potential as a function of the production potential. This results in a data set ranging between [0; 63.7](number of fulltime jobs). The more jobs created the better is the location.

3.4.11 Importance of jobs – peripheral index

Job creation potential is one thing but the social impact of more jobs is also important. In deprived areas one additional job may have a higher social impact than one additional job in a more affluent area with more opportunities. In order to include such complex information in the evaluation model peripheral index values as calculated by the Danish Chamber of Commerce (2013) are utilised. Higher index values for a municipality imply both a higher level of affluence and a lower degree of peripherality. Consequently, the lower the peripheral index value is, the higher is the impact of the biogas plant. This index includes elements such as unemployment rate, crime rate, mean educational level etc. all calculated at a municipal level. Index values exist for all Danish municipalities and within this case study the peripheral index values range between [332.15; 626.2]. Since the index does not vary within a municipality this criterion is a-spatial.

3.4.12 Criteria weights for the evaluation model

For the evaluation model (i.e. in the choice phase) weights are assigned using the pairwise comparison techniques embedded in the ILWIS SMCE software. In order to explore the variability of the 20 alternatives, 5 in each of the 4 municipalities, three scenarios are built, giving priority to the economic factors, the environmental factors and the social factors respectively. A fourth scenario is also built assuming equal importance of all criteria.

4. Results and discussion

4.1 Suitability within the four case municipalities

Based on the criteria weights (table 1) and standardizations stated above, suitability maps are obtained, as illustrated in figure 4. Suitability zones are formed when four or more pixels (i.e. 100m x 100m cells) share edges and have equal suitability. By comparing the suitability zone patterns of the four case municipalities we are able to describe the suitability landscapes of these four municipalities and on that basis select the five most suitable alternatives in each municipality for further comparison.

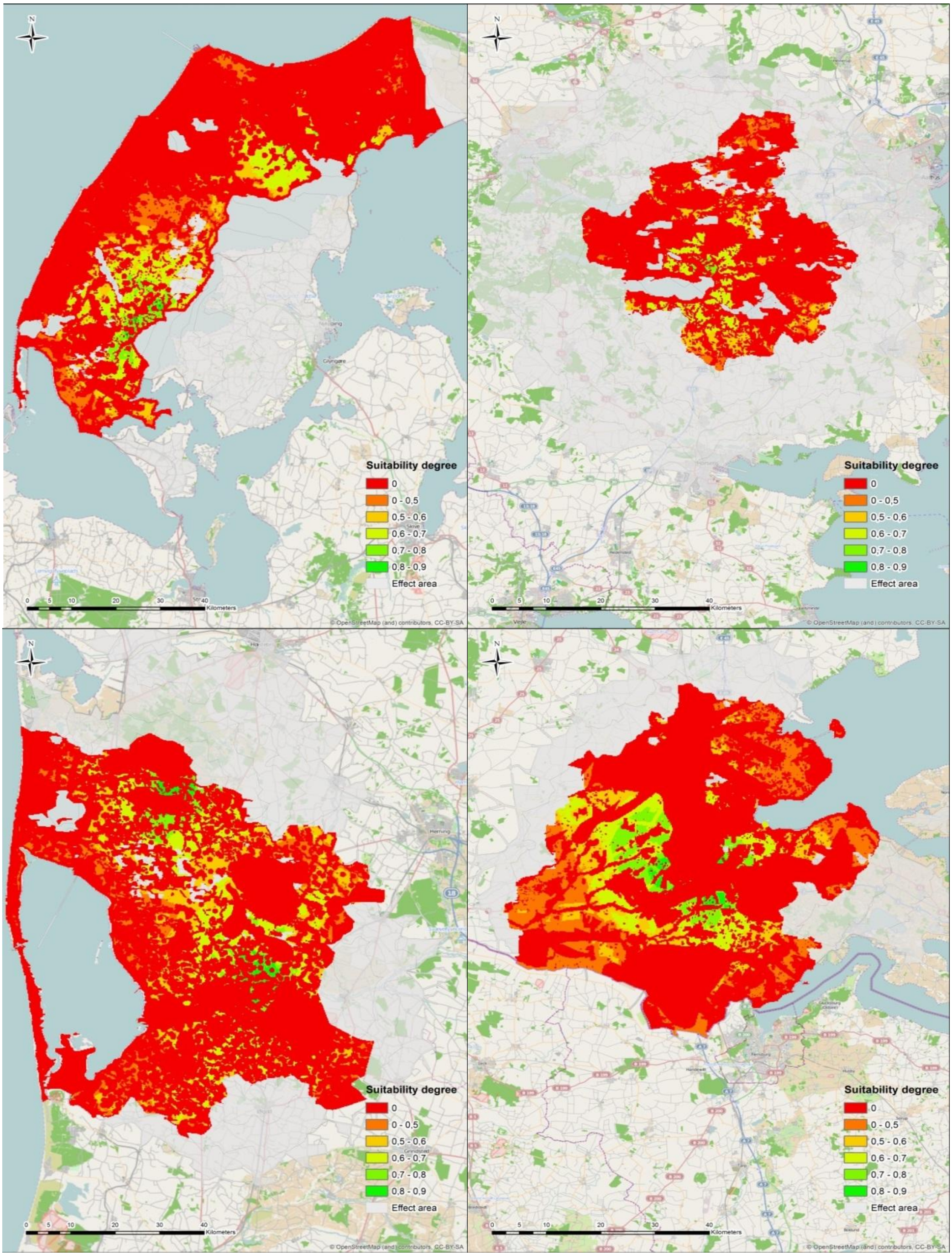

Figure 4 - Suitability maps for each of the four case municipalities Thisted, Skanderborg, Ringkøbing-Skjern and Aabenraa. Shaded grey areas are the effect areas within which the biogas plant will deliver and receive resources to and from. Source: OpenStreetMap and Own calculations.

Considering figure 4, we see that large parts of the four case municipalities are unsuitable for location of biogas plants (red areas). These areas are unsuitable mainly due to certain land use type (eg. Dwelling and urban areas) and planning legislative restrictions (e.g. Natura 2000 areas, habitat areas, ground water interest areas, low land areas etc.). The suitability patterns of the four municipalities vary so that Aabenraa is characterized by larger coherent suitable zones, whereas Ringkøbing-Skjern is characterised by smaller and more scattered suitable zones. In Thisted and Skanderborg large parts of the municipal fringes are unsuitable. Despite these different suitability patterns the proportion of areas with a suitability degree above 0.7 is rather similar [3.67; 6.13] % (table 2). Despite the similar relative suitable areas the absolute figures vary substantially due to large differences in the size of the four case study municipalities approx. [39000; 142000] ha.

Area in relation to suitability degrees	Ringkøbing-Skjern	Skanderborg	Thisted	Aabenraa
Total area (1000ha)	142.91	39.19	104.32	92.51
% of area > 0.5	17.02	15.58	16.20	21.42
% of area > 0.6	12.27	10.86	11.48	13.03
% of area > 0.7	4.58	3.67	4.64	6.13
% of area > 0.8	1.34	0.00	0.96	1.77
% of area > 0.9	0.06	0.00	0.00	0.03

Table 2 - Total area in suitability intervals in the four case municipalities – Source: Own calculations

4.2 Final suitability and identification of alternatives

In order to produce the final suitability map, which serves as a basis for identifying alternatives to compare, a suitability threshold value is set for how suitable an area needs to be in order to be included.

From table 2 we see that the suitability threshold degree where all municipalities have suitable areas are at > 0.7. In order to calculate suitable zones all coherent clusters of pixels with suitability degree above 0.7 are grouped into one suitability zone. The zone size is further evaluated and zones above 4 ha (4 pixels) are accepted, since the average land area use of existing biogas plants is 4 ha. In table 3 the result of the suitability zoning is found. Setting the suitability threshold to 0.7 implies that the four sets of suitable zones to choose from range between 24 zones in Skanderborg and 196 zones in Ringkøbing-Skjern.

# zones in relation to suitability degrees	Ringkøbing-Skjern	Skanderborg	Thisted	Aabenraa
# zones ≥ 0.5	217	44	140	140
# zones ≥ 0.6	207	34	130	130
# zones ≥ 0.7	196	24	120	120
# zones ≥ 0.8	102	0	55	52
# zones ≥ 0.9	5	0	0	2

Table 3 - Number of zones above 4ha in suitability intervals – Source: Own calculations.

The alternatives for the evaluation model are chosen as the 5 zones, with a suitability degree above 0.7 and with a minimum size of 4ha lying furthest away from the municipal boundary, measured by Euclidian distance. This distance selection criterion is chosen in order to minimize spill over effects, e.g. contracting farmers not living in the municipality; jobs creation for citizens from neighbouring municipalities; visibility issues exported to the neighbouring municipality etc. In figure 5 we see the final suitability map with the five alternatives for each of the four case municipalities.

4.3 Standardization of the evaluation model criteria

All spatial criteria are standardized according to the maximum standardization procedure (for further description see e.g. Sharifi et al. 2004) distinguishing between benefit and cost criteria. The a-spatial criteria are standardized so that the maximum input value receives the utility value 1 and the minimum input value receives the utility value 0.2. This is done to give priority to the locations municipalities with high attribute values and simultaneously not exclude locations in municipalities with lowest attribute values.

4.4 Weighting of the evaluation model criteria

The evaluation model consists of one reference scenario adopting even weights both between sustainability areas and the criteria within each sustainability area. Another 3 scenarios are considered, giving priority to the economic, environmental and social criteria respectively in order to explore the sensitivity of the evaluation model.

In all scenarios even weights are applied within each sustainability area but between sustainability areas the weights vary so that in the economic scenario the economic sustainability area is weighted by 0.82 and the other two areas 0.09 each. In the environmental weights scenario the environmental sustainability area is weighted by 0.82 and the other two 0.09. Likewise in the social weights scenario the social sustainability area receives a weight of 0.82 and the other two areas receive 0.09 each.

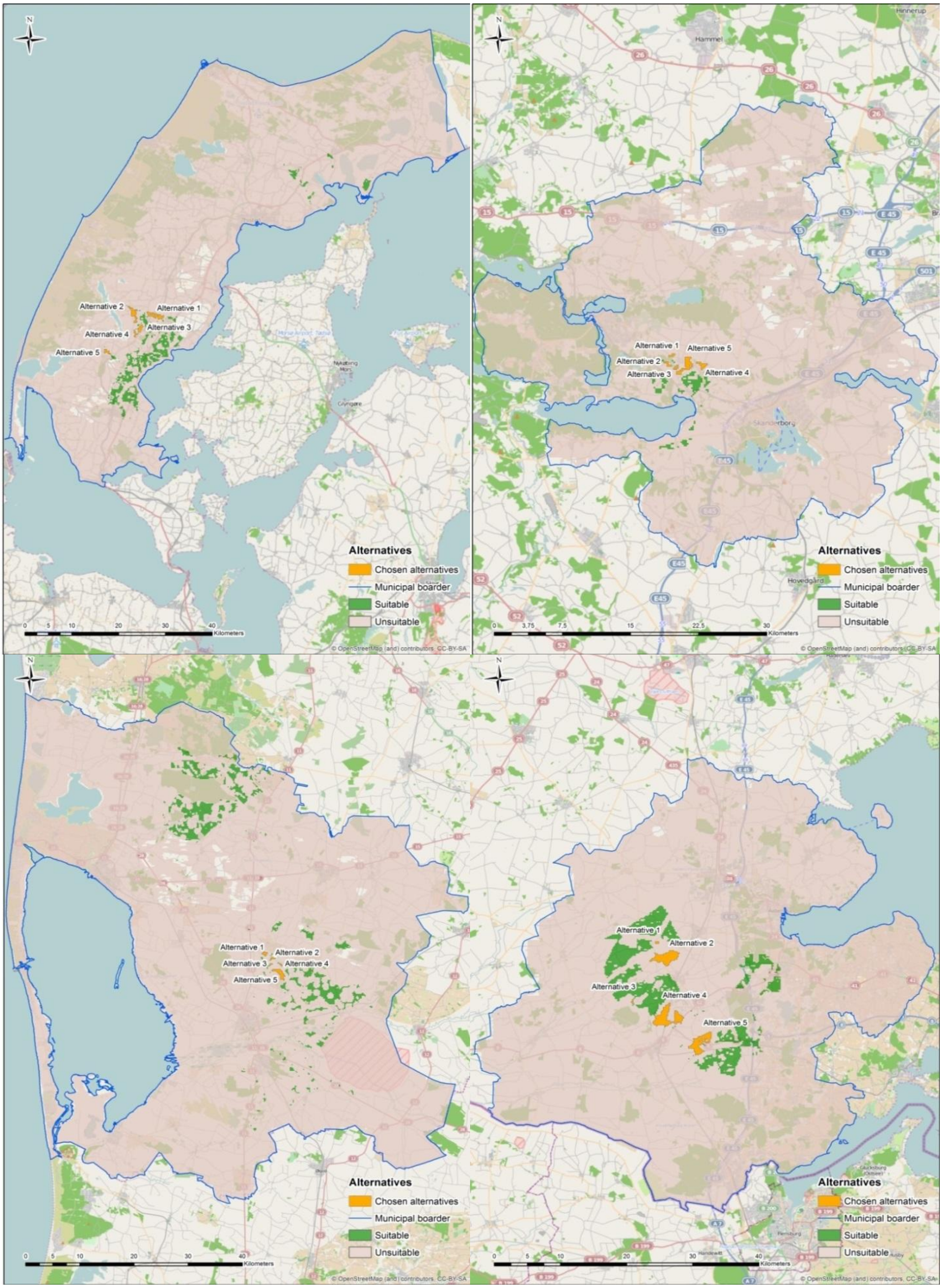

Figure 5 – Potential alternatives (i.e. suitability >0,7 zone area ≥ 4ha) are all marked with green. Chosen alternatives for the evaluation model in the four case municipalities are marked with orange. Source: OpenStreetMaps and Own calculations.

4.5 Ranking of municipalities and alternatives

The results of the average scores within each municipality under each of the four scenarios are shown in figure 6. Under all four scenarios Aabenraa has the highest average suitability and may thus be considered to be the dominant municipality. This result is to a large extent driven by a high production potential, which results in lower transportation costs when considering a biogas plant producing 7 mill. m^3 of methane, as well as higher job creation potential. Aabenraa is also the municipality with the highest peripheral index, which implies that jobs created in Aabenraa will have a higher social impact than jobs in e.g. Skanderborg, since this is a much more affluent municipality and therefore has a much lower peripheral index value.

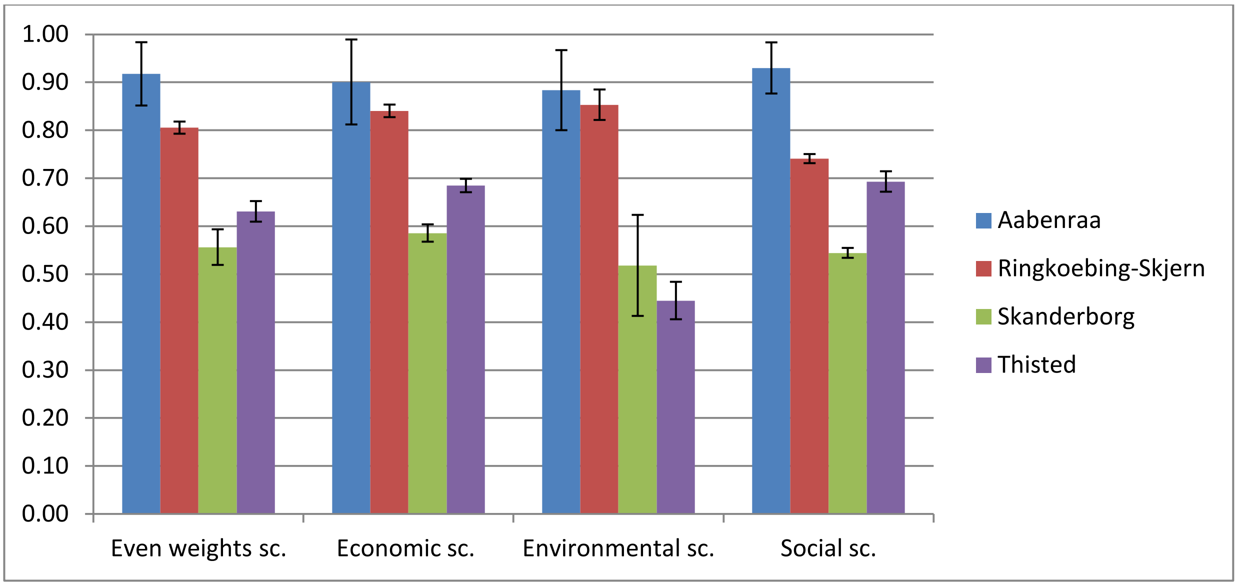

Figure 6 – average suitability scores in the 4 case municipalities under four scenarios including indication score variability. Source: Own calculations.

When considering the variability within municipalities of the suitability degrees under the even weights scenario, see figure 6, we see that the best alternatives in Ringkøbing-Skjern performs worse than the lowest scoring alternative in Aabenraa. Hence Aabenraa is the dominant municipality under the even weights scenario, though with a higher variability than the other municipalities. Also Ringkøbing-Skjern dominates Skanderborg and Thisted both on average and considering any of the 5 alternatives. This dominance of the Aabenraa and Ringkøbing-Skjern over Skanderborg and Thisted is due to economic and environmental factors, such as production potential which in turn influences the transport costs. High production potentials and low transport costs are caused by high density of large farms and have an indirect impact on the distance to noise and smell sensitive areas as well, since these areas indicate human activity such as recreational and summer residential areas. By that production potentials and noise and smell sensitive areas indicate two different land-use types, which are mutually exclusive.

Scenario	Municipality	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Average score
Even weights	Aab	**0.99**	**0.96**	**0.94**	**0.86**	**0.83**	0.92
	RkSk	0.79	0.81	0.82	0.81	0.79	0.81
Economic	Aab	**0.98**	**0.99**	**0.90**	**0.86**	0.77	0.90
	RkSk	0.83	0.85	**0.86**	0.83	0.83	0.84
Environmental	Aab	**0.99**	0.84	**0.95**	0.80	0.84	0.88
	RkSk	0.82	**0.85**	**0.89**	**0.88**	0.82	0.85
Social	Aab	**0.99**	**0.97**	**0.94**	**0.89**	**0.86**	0.93
	RkSk	0.74	0.75	0.74	0.75	0.73	0.74

Table 4 - Scores of 5 alternatives in the dominant municipality Aabenraa (Aab) and in the second highest scoring municipality Ringkøbing-Skjern (RkSk). Source: Own calculations.

Considering The 5 alternatives in the two dominating municipalities Aabenraa and Ringkøbing-Skjern, table 4 above, we see that Aabenraa has the highest score (indicated by bold numbers) in 15 out of 20 comparisons and considering average suitability scores dominates Ringkøbing-Skjern under all scenarios. Considering all alternatives under the even weights scenario and the social scenario Aabenraa dominates Ringkøbing-Skjern. Despite this dominance, we see in table 4 a larger variation in the degree of suitability among the alternatives in Aabenraa (0.77-0.99 in the economic scenario) than in Ringkøbing-Skjern (0.82-0.89 in the environmental scenario).

This variation is also found in table 5 below, where the exact attribute values for Aabenraa and Ringkøbing-Skjern are presented. Here we see that the attribute intervals in Ringkøbing-Skjern are more narrow and in more cases, e.g. 'Distance to heat plants and CHPs' are within the attribute interval boundaries from Aabenraa. This implies that choice of location in Ringkøbing-Skjern is more flexible than in Aabenraa due to the smaller variation, but the cost of that is a decrease in overall utility as found in table 4.

Criterion	Unit	Aabenraa	Ringkøbing-Skjern
Production potential	Mill. m3 methane	[7.8;13.05]	[7.49;8.59]
Distance to heat plants and CHPs	Kilometres	[2.76;11.12]	[4.99;7.28]
Distance to natural gas grid	Kilometres	[0.2;3.79]	[0.22;1.82]
Potential stock of alternative biomass	Mill. AU pigs/ mill. AU cows pr. 25km2	[0.06;2.21]	[1.07;2.39]
Average transportation costs	DKK/1000 m3 methane	[0.86;0.91]	[0.88;0.89]
Visibility	Number of vantage points	[29;48]	[42;48]
Sensitivity to noise and smell	Kilometres	[0.1;3.0]	[0.36;1.84]
Retention potential	Kg N/ha	[182.53]	[78.55]
Population density	Inhab./km2	[0;106]	[5;20]
Job creation potential	Number of fulltime jobs	[29.3;54.8]	[41;46.7]
Importance of jobs - peripheral index	Index value	[626.2]	[446.7]

Table 5 - Attribute intervals for evaluation model criteria in Aabenraa and Ringkøbing-Skjern municipalities. Source: Own calculations.

An exception from this general trend in found under the economic and environmental scenarios, where at least one of the highest scoring alternatives are found in Ringkøbing-Skjern (marked with bold in table 4). This implies that municipal dominance is dependent on which criteria are given priority. So depending on how many sites should be chosen and which scenario is given priority the preferred alternative will change.

Based on table 5 above we are further able to evaluate the implications of implementing biogas projects in the two dominating case municipalities. Compared to Jacobsen et al. (2013) we are able to reduce the average transport costs by 7% (0.86 DKK/1000m^3 methane), which in turn means that the overall production costs can be reduced by approx. 3% (Jacobsen et al. 2013). This reduction in transport costs is further associated with a stable slurry biomass resource availability above 7 mill. m^3 methane equivalents and the generation of more than 30 full time jobs.

5. Conclusion and perspectives

In this paper we add to the scarce literature on the use of spatial multi-criteria evaluation (SMCE) within bioenergy facility location. Through a value-focused approach we set up a model consisting of three phases (intelligence, design and choice) for selecting and prioritizing suitable areas for biogas facility location in Denmark. This in turn provides decision support to how a sustainable capacity expansion of the Danish biogas sector can take place. We adapt the existing framework for planning and decision making as embedded in the ILWIS SMCE software in order to accommodate a comparison of identified alternatives within and between municipalities.

By adopting the ILWIS SMCE methodology we achieve a flexible model that has the potential to make biogas planning more transparent and in this way to facilitate knowledge sharing and focusing the debate on criteria formulation and prioritization.

Based on the case study we conclude that the across all case municipalities approximately 4-6% of the land surface area is suitable for biogas production. The capacity expansion of the Danish biogas sector could take place in any of these locations. Among central governmental decision makers we find that highest priority is given to the economic criteria in the suitability model.

Based on this study we conclude that an SMCE location analysis as presented here resting on sustainability measures and provision of performance data holds large potentials of increasing the knowledge base in an inclusive biogas facility location decision making process. Further it increases the level of transparency in the final decision as it becomes clearer what trade-offs are being made.

In terms of policy implementation and distribution of scarce subsidies priorities must be established and resources should be allocated to the regions where the highest utility is achieved. In the case study comparison on how the identified alternatives perform, the Western (Ringkøbing-Skjern) and Southern (Aabenraa) municipalities perform better than the eastern (Skanderborg) and the north-western (Thisted) parts of the country. The areas with high suitability are found in Aabenraa, but depending on which criteria are given priority, areas with high suitability can also be found in Ringkøbing-Skjern, which in turn has the lowest variation in suitability.

The suggested methodology could be expanded to other Danish municipalities, which in turn would provide decision support at a national level as to which municipalities to prioritize in terms of supporting the development of biogas projects. The methodology followed in this paper could also be applied in other countries than Denmark, but depending on the required level of accuracy substantial work would be needed in order to provide data on e.g. biogas potentials. Additionally, high resolution data would be required, which is available in a Danish context, and necessary given Danish intense land use. Irrespective of the level of data accuracy the process of working with the SMCE problem will provide valuable decision support since this will shed light on the structure and content of the decision problem and emphasise relevant trade-offs.

6. Directions of future research

Despite the flexibility of the ILWIS SMCE software and its ability to incorporate flexible criteria weightings it is not able to appreciate the often non-linear relationship of criteria trade-offs. Such an inclusion of non-linear trade-off relationships would enable the inclusion of preference studies and thus provide a means to incorporate behavioural economics into the spatial multi-criteria evaluation model. This would especially be relevant in the Choice phase, as this is often more political oriented than the design phase. An example is how much visual annoyance will citizens accept in order to gain access to one additional job in their own municipality? This is how to balance environmental suitability and social acceptability. Such a relationship would very seldom be linear.

Even though the majority of the indicators in this study are designed to capture spatial variability, the attribute values do not address the inherent fuzziness of many of the attributes, which leads to loss of information. An example hereof is that planning suitability on one hand is also associated with planning rejectability on the other hand. Future work concerning SMCE in relation to location of biogas facilities could therefore benefit from appreciating the interval nature of many of the indicators in the SMCE model suggested in this paper.

Finally, the municipalities in this study have been treated in isolation and only four of the Danish municipalities with potential for biogas installations have been studied. Interactions between all municipalities with such potential could be studies for e.g. carry-over and efficiency effects.

Acknowledgements

The authors would like to thank Professor Mark Birkin, University of Leeds for a valuable commenting of the paper.

References

1. Ackoff, R. L. 1981. The art and science of mess management. Interfaces, Vol 11 (1).
2. Batty M. 2005. Approaches to Modeling in GIS: Spatial Representation and Temporal Dynamics - in Maguire, D. J.; Batty, M.; Goodchild, M. F. (Eds.) 2005. GIS, Spatial Analysis and modeling. ESRI Press, Redlands California.

3. Beck, J.; Kempener, R.; Cohen, B.; Petrie, J. 2008. A comlpex systems approach to planning, optimization and decision making for energy networks. Energy Policy, 36, 2795-2805.

4. Birkin, M. and Culf, R. 2001. Optimal distribution strategies. In Clarke, G. and Madden, M. (Eds.) 2001. Regional science in business. Advances in spatial science, Springer-Verlag.

5. Bojesen, M.; Birkin, M.; Clarke, G. 2014. Spatial competition for biogas production using insights from retail location planning. Energy, accepted for publication. Available online 24 January 2014

6. Bojesen, M.; Skov-Petersen, H.; Gylling, M. 2013. Forecasting the potential of Danish biogas production – spatial representation of Markov chains. IFRO Working paper 2013/16.

7. Bojić, S.; Đatkov, Đ.; Brcanov, D.; Georgijević, M.; Martinov, M. 2013. Location allocation of solid biomass power plants: Case study of Vojvodina. RenewableandSustainableEnergyReviews26, 769–775.

8. Braglia, M. and Gabrielli, R. 2012. A decision support system for locational analysis in paper industry. Int. J. Logistics Systems and Management, Vol. 11 (1).

9. Buchholz, T.; Rametsteiner, E.; Volk, T. A.; Luzadis, V. A. 2009. Multi Criteria Analysis for bioenergy systems assessments. Energy Policy 37, 484–495.

10. Clarke, M and Clarke, G. 2001. In Clarke, G. and Madden, M. (Eds.) 2001. Regional science in business. Advances in spatial science, Springer-Verlag.

11. Daniels, S. E. and Walker, G. B. 2001 Working through environmental conflict, the collaborative learning approach. Praeger Publishers, Westport, Connecticut.

12. Danish Chamber of Commerce, 2013. Dansk Erhvervs Kommuneindeks. Available online: [http://www.danskerhverv.dk/Nyheder/Documents/2013%20bilag/Dansk-Erhvervs-Kommuneindeks-2013.pdf], Cited 20.08.2013.

13. Daskin, M. S. 1995. Network and discrete location: Models, algorithms and applications. J. Wiley and Sons, inc., New York.

14. Diakoulaki, D. and Karangelis, F. 2007. Multi-criteria decision analysis and cost–benefit analysis of alternative scenarios for the power generation sector in Greece. Renewable and Sustainable Energy Reviews, 11, 716–727.

15. Eckenrode, R. 1965. Weighting multiple criteria, Journal of Management Science 12 (3) 180–192.

16. ESRI (Environmental Systems Resource Institute). 2012. ArcMap 10.1. ESRI, Redlands, California.

17. Farahani R. Z.; SteadieSeifi, M.; Asgari, N. 2010. Multiple criteria facility location problems: A survey. Applied Mathematical Modelling, 34, 1689-1709.

18. Gebrezgabher, S. A.; Meuwissen, M. P. M.; Lansink, A. G. J. M. O. 2014. A multiple criteria decision making approach to manure management systems in the Netherlands. European Journal of Operational Research 232, 643–653.

19. Geodatastyrelsen 2013. Available online: [http://www.geodata-info.dk/Portal/List.aspx] accessed 02.01.2013.

20. Gorsevski, P. V.; Donevska, K. R.; Mitrovski, C. D.; Frizado, J. P. 2012. Integrating multi-criteria evaluation techniques with geographic information systems for landfill site selection: A case study using ordered weighted average. Waste Management 32, 287-296.

21. Grøn vækst. 2009. Available online: [https://www.landbrugsinfo.dk/ Planteavl/Filer/PL_aktuelt_09_369b2.pdf], cited 10.10.2013.

22. Herwijnen, M. 1999. Spatial decision support for environmental management. Free University Amsterdam, The Netherlands.

23. Hudson, B. M. 1979. Comparisons of current planning theories: counterpart and contridictions. Journal of the American Planning Association 45(4) pp. 387–398.

24. Höhn J, Lehtonen E, Rasi S, Rintala J. 2014. A Geographical Information System (GIS) based methodology for determination of potential biomasses and sites for biogas plants in southern Finland. Applied Energy, 113, 1-10.

25. Islas, J.; Manzini, F.; Martinez, F. 2003. Cost-benefit analysis of energy scenarios for the Mexican power sector. Energy, 28, 979–92.

26. Jacobsen, B. H.; Laugesen, F. M.; Dubgaard, A.; Bojesen, M. 2013. Biogas produktion i Danmark - Vurderinger af drifts- og samfundsøkonomi. IFRO rapport 220.

27. Jacobsen, B. H. 2012. "Analyse af omkostningerne ved en yderligere reduktion af N-tabet fra landbruget med 10.000 tons N". FOI udredning 2012/26.

28. Joensen, J. W. and Mølgaard, J. 2010. Biogasanlæg – udpegning af mulige placeringer. Afgangsprojekt, Landinspektøruddannelsen, 138p., Aalborg universitet.

29. Karagiannidis, A. and Perkoulidis, G. 2009. A multi-criteria ranking of different technologies for the anaerobic digestion for energy recovery of the organic fraction of municipal solid wastes. Bioresource Technology 100, 2355-2360.

30. Keeney, R. L. 1996. Value-focused thinking: Identifying decision opportunities and creating alternatives. European Journal of Operational Research. 92, 537-549.

31. Lavrencec, L., 2010. Highlights of socio-economic impacts from biogas in 28 target regions. Available online: [http://www.biogasin.org/files/pdf/Highlights_of_socio-economic%20issues.pdf], cited 07.08.2013.

32. Lemvig biogas, 2013. Gylle fra blot én ko dækker dit el-forbrug. Available online: [http://www.lemvigbiogas.com/biogas.htm]. Accessed 20.08.2013.

33. Ma, J.; Scott, N. R.; DeGloria, S. D.; Lembo, A. J. 2005. Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. Biomass and Bioenergy 28, pp. 591–600.

34. Malczewski, J., 1999. GIS and Multicriteria Decision Analysis. Wiley, New York, 392pp.

35. Möller, B and Nielsen, P. S. 2007. Analysing transport costs of Danish forest wood chip resources by means of continous cost surfaces. Biomass and Bioenergy, 31, 291-298.

36. Naturstyrelsen 2013a. Meeting with the Danish Nature Agency 05.02.2013. Jensen, L., email: lajen@nst.dk

37. Naturstyrelsen 2013b. Plansystem.dk. Available online: [http://www.plansystemdk.dk/]. Accessed 28.10.2013.

38. Naturstyrelsen 2013c. Personal communication. Steffensen, H., email: halst@nst.dk.

39. Nijkamp, P.; Rietveld, P.; Voogd, H.; 1990. Multicriteria Evaluation in Physical Planning, Elsevier Science Publishers, Amsterdam.

40. 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.

41. Perpiña, C.A.; Martínez-Llario, J.C.B.; Pérez-Navarro, Á.a. 2013. Multicriteria assessment in GIS environments for siting biomass plants, Land Use Policy, 31, 326-335.

42. Retsinformation 2013. Consolidations act LBK nr 587 af 27/05/2013. Available online: [https://www.retsinformation.dk/Forms/R0710.aspx?id=144425#Kap4], cited 13.09.2013.

43. Romeo, C. and Rehman, T. 1989. Multiple criteria analysis for agricultural decisions. Elsevier, The Netherlands.

44. Rozakis, S.; Soldatos, P.G.; Kallivroussis, L.; Nicolaou, I. 2001. Multiple Criteria Analysis of Bio-energy Projects: Evaluation of Bio-Electricity Production in Farsala Plain, Journal of Geographic Information and Decision Analysis. Vol. 5 (1), 49-64.

45. Saaty, T. L. 2008. Decision making with the analytic hierarchy process. International Journal of Services Sciences, 1, 83-98.

46. Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, Inc., New York.

47. Saaty, T. L. and Vargas, L. G. 1991. Prediction, Projection and forecasting – Applications of the analytical hierarchy process in economics, finance, politics, games and sport. Kluwer Academic publishers.

48. Scott, J. A.; Ho, W.; Dey, P. K. 2012. A review of multi-criteria decision-making methods for bioenergy systems. Energy 42, 146-156.

49. Sharifi, M. A.; Herwijnen, M.; Torn, W. 2004. Spatial decision support systems. ITC lecture notes. ITC, Enschede, The Netherlands.

50. Sharifi, M.A., Retsios, V., 2003. Site selection for waste disposal through spatial multiple criteria decision analysis. Journal of Telecommunications and Information Technology 3, 28–38.

51. Sharifi, M. A. and Rodriguez, E. 2002. Design and development of a planning support system for policy formulation in water resources rehabilitation: the case of Alca´ zar De San Juan District in Aquifer 23, La Mancha, Spain. Journal of Hydroinformatics 4(3).

52. Sharifi, M.A., van den Toorn, W., Rico, A., Emmanuel, M., 2002. Application of GIS and multicriteria evaluation in locating sustainable boundary between the Tunari National Park and Cochabamba City (Bolivia). Journal of Multi-Criteria Decision Analysis 11, 151–164.

53. Statistics Denmark, RASU33. Befolkningen efter område, uddannelse, socio-økonomisk status, alder og køn, 2013. available online: [http://www.statistikbanken.dk/statbank5a/default.asp?w=1680], cited 07.08.2013.

54. Suárez-Vega, R.; Santos-Peñate, D. R.; Dorta-González. P. 2012. Location models and GIS tools for retail site location. Applied Geography 35, 12-22.

55. Sultana A, Kumar A. 2012. Optimal siting and size of bioenergy facilities using geographic information system. Applied Energy, 94, 192-201.

56. Sumathi, V. R.; Natesan, U.; Sarkar, C. 2008. GIS-based approach for optimized siting of municipal solid waste landfill. Waste Management 28, 2146–2160.

57. Teodorita Al Seadi, Dominik Rutz, Heinz Prassl, Michael Köttner, Tobias Finsterwalder, Silke Volk, Rainer Janssen. 2008. Biogas handbook. ISBN 978-87-992962-0-0, University of Southern Denmark Esbjerg, Niels Bohrs Vej 9-10, DK-6700 Esbjerg, Denmark.

58. Theodorou, S.; Florides, G.; Tassou, S. 2010. The use of multiple criteria decision making methodologies for the promotion of RES through funding schemes in Cyprus, A review. Energy Policy 38, 7783–7792.

59. Vaidya, O.S.; Kumar, S. 2006. Analytic hierarchy process: An overview of applications. European Journal of Operational Research 169, 1–29.

60. Wang, G.; Qin, L.; Li, G.; Chen, L. 2009. Landfill site selection using spatial information technologies and AHP: A case study in Beijing, China. Journal of Environmental Management. Volume 90, Issue 8, pp. 2414–2421.

61. Zucca, A.; Sharifi, A. M.; Fabbri, A. G. 2008. Application of spatial multi-criteria analysis to site selection for a local park: A case study in the Bergamo Province, Italy.Journal of Environmental Management 88, pp. 752–769.

62. 52north.org. 2009. ILWIS (Integrated Land and Water Information System) 3.6. Available online: [http://52north.org/communities/ilwis/]. Accessed 01.02.2013.