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Geographical analyses of wood chip potentials, costs and supply for sustainable energy production in Denmark

Sustainable energies; tools for managing sustainability

Abstract

The biomass resource from forests is geographically distributed. In Denmark, as well as other countries, these resources are utilised for sustainable energy production. Supply and demand varies by energy plant location and size. Typically a bioenergy plant is located at a heat demand site. This results in a significant need for transportation of biomass resource, which has impact on the way bioenergy markets operate, and how the targets of sustainable development are met. Therefore an optimal transportation pattern is desired. The presented study uses a practical application of raster-based geographical information systems (GIS) to perform cost-supply analysis of wood chip resources for energy production. Recoverable potentials are mapped using forest statistics, production forecasts and land use data. For bioenergy-plant sites the transportation costs for wood chips from the forests are analysed using cost distance analysis, which allows for the production of continuous transport cost surfaces. A geographical model of distributed resources and cost surfaces facilitates the production of cost-supply curves. These curves constitute an effective way to assess the costs of delivered biomass dependent on amount and location, and to analyse discrepancies in the way biomass markets operate. Results show that energy plants in areas with sparse forest cultivation and energy plants with a large consumption of biomass fuels have higher fuel costs in average $/tonnes. Therefore the results of this study may be used to select fuels by regional availability, and to assess the economic advantages of decentralised energy production. Cost-supply curves could also be used for sensitivity analyses at specific sites for managing economic risk of bioenergy plants, for sensitivity analysis of biomass recovering of different forest harvest management systems and for sensitivity analysis of different transportation management options.

Introduction

Sustainable energy production and sustainable forestry are not necessarily contradictions. Common for both is the need to develop socio-economically sound solutions (Mæng et al., 1999). A sustainable energy system utilises forest resources in a way that minimises societal costs and environmental impacts. One area where the demand of wood fuel is economically interlinked with forest production is the transport of wood chip fuels from forests to energy plants.

This study presents a method to determine the transport costs of wood chips from forests to locations of energy plants in Denmark. In this study, wood chip is used as a common word for forest residues, from both cutovers and thinnings. Spanning from forestry to transportation logistics and the energy sector, a multidisciplinary study is required to perform cost-supply analyses of biomass resources for sustainable energy production. The term cost-supply covers information about how demand can be covered with different forms of supply, and at which costs. Cost-supply problems are of a geographical nature, as both supply from distributed resources and costs for transportation are determined by location and distance. The sensitivity of costs against location and size of a bioenergy plant can be analysed by establishing a spatial relation between supply, transportation and costs (Downing and Graham, 1996; Talbot and Nord-Larsen, 2003). In this study the spatial relation is being established using a raster-based geographical information system (GIS) as a common geographical reference for all data input. A geographical model is used for the exploration, explanation and determination of logistical costs. With the methods available in a raster GIS, an innovative methodology to carry out cost-supply analysis has been developed.

First the theoretical nature of the research is addressed through a discussion of least cost transport modelling and resource distribution modelling using raster-GIS. Secondly, the necessary data sets are discussed, seeking to utilize existing data to the highest possible extent. Thirdly a cost distance model for wood chips logistics is described, which is used to produce information on cost supply curves for selected bioenergy plants. Finally, the implications of the findings are discussed in a socio-economic perspective for sustainable development.

Biomass in the Danish energy system

Wood for energy production, including wood chips, pellets and industrial wood waste, covered 3.5% of the Danish primary fuel consumption of 823 PJ in the year 2002. Forest wood chips are used in approximately 80 energy plants across the country, ranging from small district heating schemes to central coal-fired power stations. In the year 2002 the consumption of wood chips for energy purposes was 3.7 PJ, of which 2.9 PJ or 79% were used in district heating schemes, producing heat for local communities (Danish Energy Authority, 2003). Most of these energy plants have a heat output in the order of 1-10 MJ/s. The total amount of wood chips equalled about 1.4 million m^3, of which more than 90% were produced domestically. The average properties of wood chips as fuel for bioenergy plants are as follows: specific heat value, 2.6 GJ/m^3; 0.25 wet tons per m^3; and 1.4 wet tons per tons of dry matter, at a moisture content of 40% (Danish Energy Authority, 2002).

It is often less costly to import biomass fuels but the fact that wood chips are difficult to store and bulky might explain the absence of large scale wood chip import so far, except a limited import of logs for wood chip production (Nicolaisen, 2000). Several studies (Lind, 1994; Nord-Larsen and Heding, 2003) foresee a stable domestic supply of forest wood chips for the next decade, which will be sufficient to cover domestic consumption, unless demand increases significantly.

From this it can be concluded that the wood chip market in Denmark is saturated and mature, leaving only few domestic resources unused under present economic circumstances. Therefore the problem addressed here for the Danish case is not the exploration of new resources or potential new consumers, but the allocation of domestic wood chips in a cost efficient way.

The fact that the biomass resources are CO_2 neutral releases them from CO_2- and energy taxation, and they are therefore approx. 50% cheaper than fossil fuels for heat producing schemes. A survey of 22 district heating stations (Danish District Heating Association, 2004) which use wood chips as their primary fuel source shows that their average fuel costs are 8.96 US$/GJ (standard deviation 2.65 US$/GJ), which is roughly 23 US$/m3 (DKK to US$ conversion as of March 2004). This can be compared to gas prices including taxes in the order of 16-22 US$/GJ, depending on consumption (DONG, 2002). Nevertheless many of the mostly consumer-owned bioenergy plants are on a tight budget. They share a strong interest in making domestic wood chip supply more cost efficient. With transportation taking up 20 to 40% of the delivered fuel costs, it is an important contributor to the delivered costs of wood chips from the forest. Reasons for this are the low production density of biomass fuels, the scattered and small forests in Denmark, and the low bulk density of most biomass fuels. Therefore improved cost efficiency is related to efficient logistics and resource allocation. Transport over long distances, which is caused by a mismatch between local availability and demand, should be avoided.

Biomass from forests

Forestry in Denmark is characterized by a rather inhomogeneous distribution of forests, of which most are small and scattered across the country. The total forest area is 486.000 ha, equal to 11.3% forest cover (Ministry of Environment, 2003). About 20% of forests are smaller than 5 ha, and 50% smaller than 50 ha (Statistics Denmark, 2003). This makes forestry operations costly compared to other countries, and increases the demand for carefully conducted wood logistics (Kofman et al., 1994). Another important factor is that many forests are utilized for other purposes than producing timber, typically recreation, ground water and coastal protection, and some forests are the subject for natural protection.

Forest statistics show that the average annual biomass increment is about 11 m^3/ha, whereas the average annual felling rate is only at 4 m^3/ha (Ministry of Environment, 2003). This means for the assessment of wood chip resources that, theoretically, the potential is steadily increasing. Also, national forest plans seek to double the forest coverage during the 80-100 years (Ministry of Environment, 1994). A recent prognosis foresees a constant supply of wood chips in the next two decades, given that fuel prices and thus demand do not change significantly (Nord-Larsen and Heding, 2003). Log prices, in particular conifers, have seen a steady decrease in recent years, resulting in less felling and thinning operations. From this it can be concluded that an assessment of wood chip supplies can rely on conservative production forecasts, as near future production will be close to the utilised amount rather than the theoretical potential. Alternatively, the potential could be assessed from standing volumes, predicted yield and harvest methods as suggested in other sources (Lind, 1994; Börjesson and Gustavsson, 1996; Downing and Graham, 1996; Hall et al. 2001).

Wood chips are produced from deciduous as well as coniferous species, either by chipping summer dried logs or by chipping during thinning operations. In both cases drying decreases the moisture content to the 40 – 55% required by most of the combustion processes employed.

Usually there is access to forest wood chips from the nearest road side accessible by road trucks, where either a chipper-forwarder empties its bin into containers or a stationary chipper is located while chipping is going on (Danish Energy Agency, 2002).

Transportation of wood chips

Wood chip transportation is a quite straightforward logistical enterprise, linking forest resources to the consumer locations. The typical means of transportation from forest road to energy plant are road trucks with trailer, carrying two removable bin containers with a volume of 40 m^3 each. These containers are left at the forest roads while loading. It can be assumed that the volume of the containers corresponds to the allowed maximal load of the vehicle (Bøllehus et al., 1994). Trucks and trailers are usually standard configurations. The cost of transportation is highly dependant on travel time, which is a function of distance and road properties.

The means of wood chip transportation leaves room for improvement (Bøllehus et al., 1994); the most important issues, besides vehicles with higher payloads, are better planning, route optimisation and scheduling of personnel and vehicles. Better transport economy can also be achieved through improved utilisation of vehicles and personnel, reducing the hourly costs of a truck.

The study seeks to calculate location variable costs generated by transportation to and from a forest site, whereas factors such as terminal time for loading, unloading and moving, chipping, storage and further processing are considered independent from location. Costs of biomass delivered to a bio-energy plant do not include the revenue a forest owner might receive. Also, decisions on whether to produce wood chips for energy or fibre are entirely based on empirical data and forecasts. Therefore, the delivered costs calculated here neither reflects the wood chip market price, nor do they include the forest owners' profit and long term interest.

Methods and model building

A GIS comprises of a number of tools to manage geographical data, produces digital maps and visualises results. It also has a generic set of functions which can be applied to a raster or grid. Local, focal, zonal and global functions help to understand the neighbourhood, overlay or increment of cellular representations of the real world. A GIS model generally returns output as derivatives of base maps, and can comprise whole hierarchical trees of data and functions. A GIS model is built up from data and handling software. The GIS model described here was implemented using ArcGIS 8.3 software by ESRI, including Spatial Analyst for grid analysis. The geographical data base used as input were basically a raster of forest cells, a road vector network and point locations of energy plants. The database was completed with additional attribute data. Where it was appropriate, vector data were converted to raster themes in the ArcInfo grid format in order to enable the model to perform map algebra and other raster functions.

A generic method used for modelling distance-induced costs is cost-weighted distance analysis, which, based on modelling friction across cost surfaces, returns a least cost travel path and cumulative costs of transport from source to target. This method can be used for solving a range of problems, where friction, distance and allocation have influence on the result. In order to accept this kind of research, deterministic models based on logic must be granted. It must be understood that the choice of travel path is determined by least cost route, rather than preference.

The study area includes the entire land mass of Denmark except the island of Bornholm, represented through a reference grid resolution of 25 m, based on UTM zone 32N and the European Datum 1950 (ED50).

Biomass resource mapping

In order to model the geographical origin of wood chip amounts it is necessary to know forest location, preferably by species and type, and specific production for each species and forest type. Biomass resources should be mapped with a spatial resolution as high as possible. It is, however, impossible to model the exact location and amount of the future biomass potential from forestry, and even present forest production can rarely be related to precise location. Digital forest inventories, which would allow for precise modelling of stands and their productivity, so far only exist for a few Danish forests (Ministry of Environment, 2003). A less ambitious approach must be chosen that would still allow for mapping resources in space and time within acceptable error margins.

The location of forests can be derived either from vector land use maps, where forests are mapped as discrete objects, or by using raster maps, derived from remotely sensed data. Interpreted Landsat 5 TM satellite imagery is available through the Land Cover Plus (LCP) theme, produced in 1995 and distributed through the Area Information System (AIS) of the Ministry of Environment. At a first glance, the vector land use maps, also available through the AIS, have the advantage of a better topographical representation of forest shapes and areas (NERI, 2000). Although containing less accurate spatial information, the LCP data set distinguishes between more forest type classes and species than the vector land use data set. The resolution of 25 m is very detailed for the purpose, and can be maintained for the remaining data themes. For accuracy and economic reasons the study uses LCP grids until better data is developed.

To calculate a likely distribution of recoverable resources in raster-GIS, the LCP land use theme was reclassified to hold forest cells only. A number of 11 different forest types, from bushes to beech forest, represents the Danish forests with reasonable spatial accuracy, see Table 1. A comparison between the LCP data and the national statistics of actually recorded forest areas (Statistics Denmark, 2003) show that the total forest area was found to be just 6% less in the LCP theme, probably because of misinterpretation, spatial resolution and its age.

LCP code	Description	Comments	Total area [ha]	% of forest area
14	Shrub / forest	No wood chip production	83,534	16.8
15	Deciduous forest	Tops and large branches from felling	137,718	27.8
16	Coniferous forest	Tops and large branches from felling	71,404	14.4
26	Beech forest	Tops and large branches from felling	49,011	9.9
27	Young trees	Thinning	14,688	3.0
28	Spruce plantation	Tops and large branches from felling	60,587	12.2
29	Mixed forest	Assumed 35% deciduous, 65% coniferous	8,511	1.7
30	Mountain pine woodland	Wood chips from whole trees	32,433	6.5
32	Larch forest	Tops and large branches from felling	2,037	0.4
33	Recently felled forest	No wood chip production	2,394	0.5
34	Thin coniferous forest	No wood chip production	33,564	6.8

Table 1: 11 different types of forests were extracted from the LCP data set, which has been converted to a grid with the LCP code as a grid value.

The study uses a regional wood chip supply forecast derived from (Lind, 1994), updated by means of a more recent but not geographically related forecast (Nord-Larsen and Heding, 2003). The forecast data used are for the period 2000-2009, and a conservative scenario in which wood chips are produced from tops and large branches from felling; whole trees from thinning operations with a thinning diameter of 12 cm; and whole trees from replacing old mountain pine plantations. The production forecasts used only include forests larger than 0.5 hectares, as regular forest operations are only feasible in forests of minimum size. Hedges, large single trees and other small non-forest objects are not included in the model. A minimal forest size in the forest grid was established by excluding coherent forests smaller than 0.5 ha through grouping the LCP data into regions with the same grid value, representing coherent forests or forest compartments. Their area was calculated using a zonal geometry function, and thereafter all regions with an area less than 0.5 ha were then removed from the grid.

The forecast used include annual wood chip volumes, specified by forest class, on the regional level. These were related to the physically mapped forest cells. The method used for biomass modelling therefore is a combination of physical mapping and empirical modelling, which is assumed to be sufficient until nationwide forest inventory maps do exist. The result is a grid which holds values for annually recoverable amounts of wood chip wastes which can be collected in each forest cell, given in kg dry matter per cell (625 m^2), see Fig. 1. The resulting annually recoverable wood chip resources are 225,000 tons dry matter.

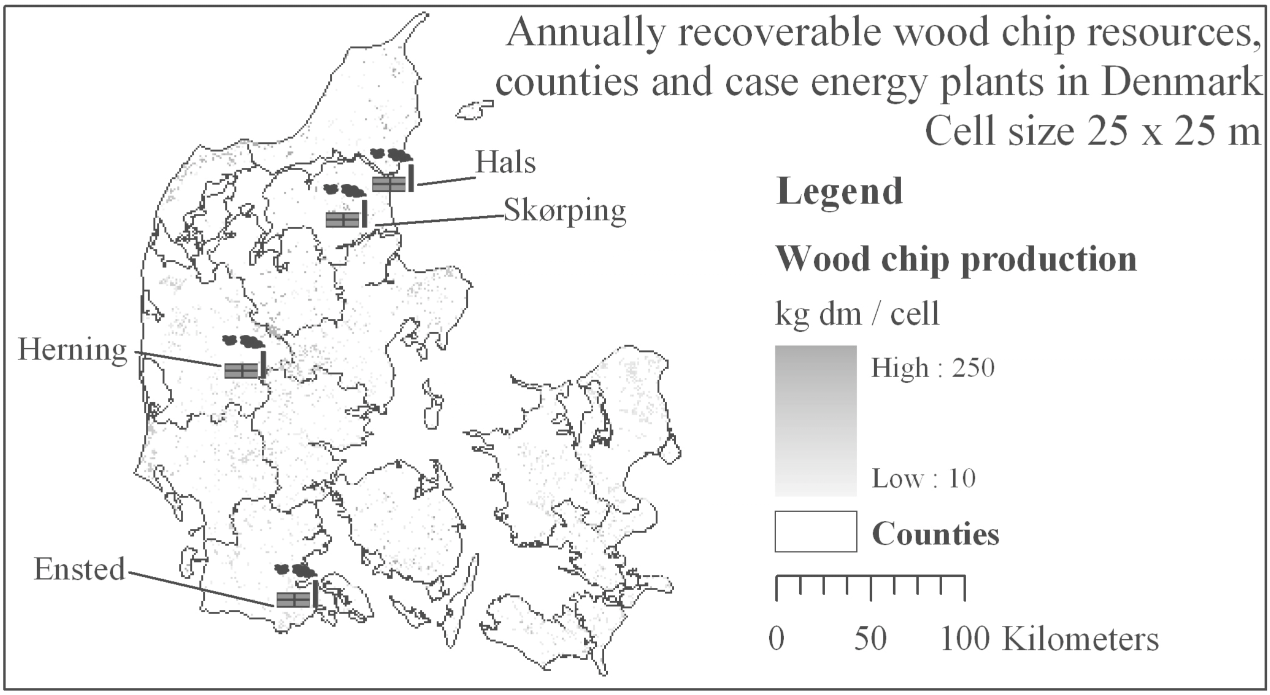

Figure 1: The distribution of annual wood chip production in kg dry matter per cell area of 625 m^2 in Denmark has been calculated from interpreted satellite images and a production forecast.

Energy plants selected as cases

Out of the total number of approximately 80 energy plants using wood chips as primary or secondary fuel, four energy plants have been selected. All of them are located in Jutland, the western part of Denmark. The bioenergy plants in Hals, Herning and Skørping and the mainly coal-fired plant in Ensted were selected on the following basis: they should be of different size and annual wood chip consumption; be located in different areas; and have different locations in relation to the primary road network and forests. All selected energy plants use biomass for co-firing or as a primary fuel. Table 2 contains the main data of the energy plants chosen as case studies. The figures of annual wood chip consumption were derived from annual statistics (Danish District Heating Association, 2003) and general information material (ELSAM, 2003 a/b).

Plant name	Plant type	Composition of fuel consumption	Rated power and heat output	Annual wood chip consumption
Hals	District heating	64% wood, 31% straw, 5% oil	0 MW, 8 MJ/s	5,500 tons dry matter
Skørping	District heating	95% wood, 5% oil	0 MW, 7 MJ/s	9,000 tons dry matter
Ensted	Power plant	93% coal, 5% straw, 1% wood, 1% oil	600 MW, 80 MJ/s	15,000 tons dry matter
Herning	Cogeneration	55% wood, 45% natural gas	89 MW, 174 MJ/s	50,000 tons dry matter

Table 2: The main properties of the bioenergy plant case studies. Fuels used and wood chip consumption were as recorded for the heating period 2002-2003 (Danish District Heating Association, 2003), except for Herning and Ensted, where these data were derived from (ELSAM, 2003 a/b).

Transport costs modelling

The model described here uses travel time across a road network with the average travel speed for trucks as friction values for producing least cost travel paths between forest cells and plant locations. Travel speed is limited because of allowed speed, traffic, slope and curves, as well as the type of vehicle, and, in extreme situation, weather conditions. Another type of friction occurs at intersections with traffic lights and roundabouts, at ferry or road toll terminals, or through intermediate construction work. The calculation of transportation time by cost-distance analysis uses a polyline theme from a Danish road network database called VejnetDK, a detailed, topological, vector-based road network database (KMS, 2000), which was converted to a linear raster of 25 m cell size. Because a national road database with precise truck travel speed does not exist, only allowed and average travel speed is available for each road section. These speed values were reclassified to lower values for trucks, based on measurements conducted by (Bøllehus et al., 1994).

The possible locations of least cost travel paths are limited to the existing road network, meaning that the cost or friction grid is a linear grid representation of the road network, the friction being the allowed or reached travel speed in each cell. Some topological information from the original vector road theme is lost through this process. Wherever grid representations of roads do cross, the model assumes interconnection. This does not cause error in most cases (smaller roads usually connect to arterial roads), but causes errors in the connection of motorways to the remaining road network.

The cost weighted distance functions available in ArcGIS calculate travel time between two neighbouring grid cells as the product of the linear distance between the centroids of the cells and the average friction values of both cells. The cumulative travel time along a path is the sum of all these path sections across the grid mesh.

In-forest transportation is difficult to model, because locations of wood chip storage areas or container depots are impossible to predict. In-forest transportation, typically by chipper-forwarder, is more likely defined by harvest patterns than distance. Therefore this study uses a Euclidean allocation of the cost values for forest locations from the nearest access road.

Transport costs are calculated using truck costs per time. The employment time of a truck is assumed to be twice the time needed to travel the lead distance plus the terminal times (Bøllehus et al., 1994). This neglects the costs of driving a truck from a truck depot, and possible savings by visiting several forest locations during one trip. These uncertainties are sought to be levelled out using actually recorded travel time for a few forest locations to adjust travel speed for several types of roads (Bøllehus et al., 1994). This results in a continuous cost surface, including the optimal routes from all forest locations to the bioenergy plant, for which a cost-supply curve can be calculated. The expressions for the ArcGIS RasterCalculator functions used are given in Table 3.

The transport cost calculations are site specific and have to be repeated for each new site. The result of a site-specific transport cost calculation is a continuous grid, which holds values for transport costs per ton dry matter, given as integer values in US cents/t, see Figure 2. An integer grid is required for the zonal statistics operations described next.

Function	Input	Output	Map algebra expression
Cost distance	Truck speed grid (km/h)	Cumulative Travel time along road network (minutes)	costdistance([dhstation],((Pow([truckspeed],-1))*3,6/60))
Euclidean allocation	Travel time along road network (minutes)	Continuous travel time surface (minutes)	eucallocation(Int([Costdistance of truckspeed]))
Arithmetic calculation	Travel time (minutes)	Travel costs (US$)	((([traveltime] * 2) + TermTime) * (Truckcost_hour) / Payload
Zonal sum	Zone grid: travel costs Value grid: biomass amounts	Table with sum of biomass for each instance of travel costs	zonalsum([travelcost], [biomass])

Table 3: Map algebra functions, their in-and output and the Raster Calculator expressions used to model transport costs.

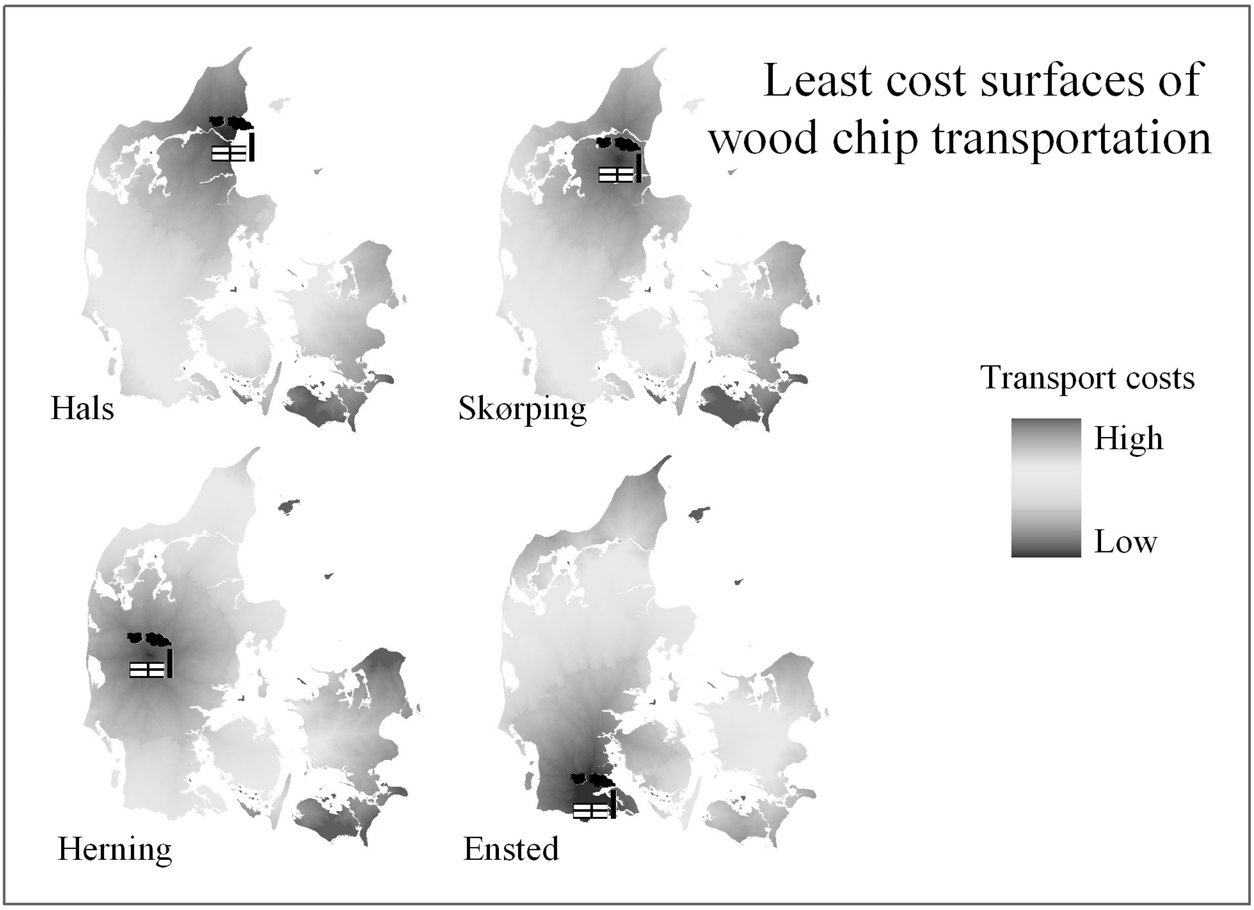

Figure 2: Least cost surfaces of wood chip transportation to the four case studies. Local and regional accessibility determines costs of transportation. The lowest costs are found in the neighbourhood of plants.

Production of cost-supply curves

Cost-supply curves are derived through zonal statistics, where transportation costs are the zone theme and biomass resources are the theme to be summarized. With a known biomass distribution over the underlying transport cost surface, for each forest cell the amounts and the transportation costs are known. With the zonal statistics function in ArcGIS Spatial Analyst, summarising the amounts for each instance of transportation costs returns a site-specific frequency distribution of costs and amounts; see Figure 2. The average costs for accumulated amounts of wood chips are then calculated in a spreadsheet. The result is a cost-supply curve for a specific site, see Figure 3. From the cost-supply curve the average price for a chosen amount of wood chips can be read and used for assessment of fuel price sensitivity. Cost-supply curves can be statistically described by regression analysis. The resulting regression functions can be used to calculate site specific fuel costs depending on local demand.

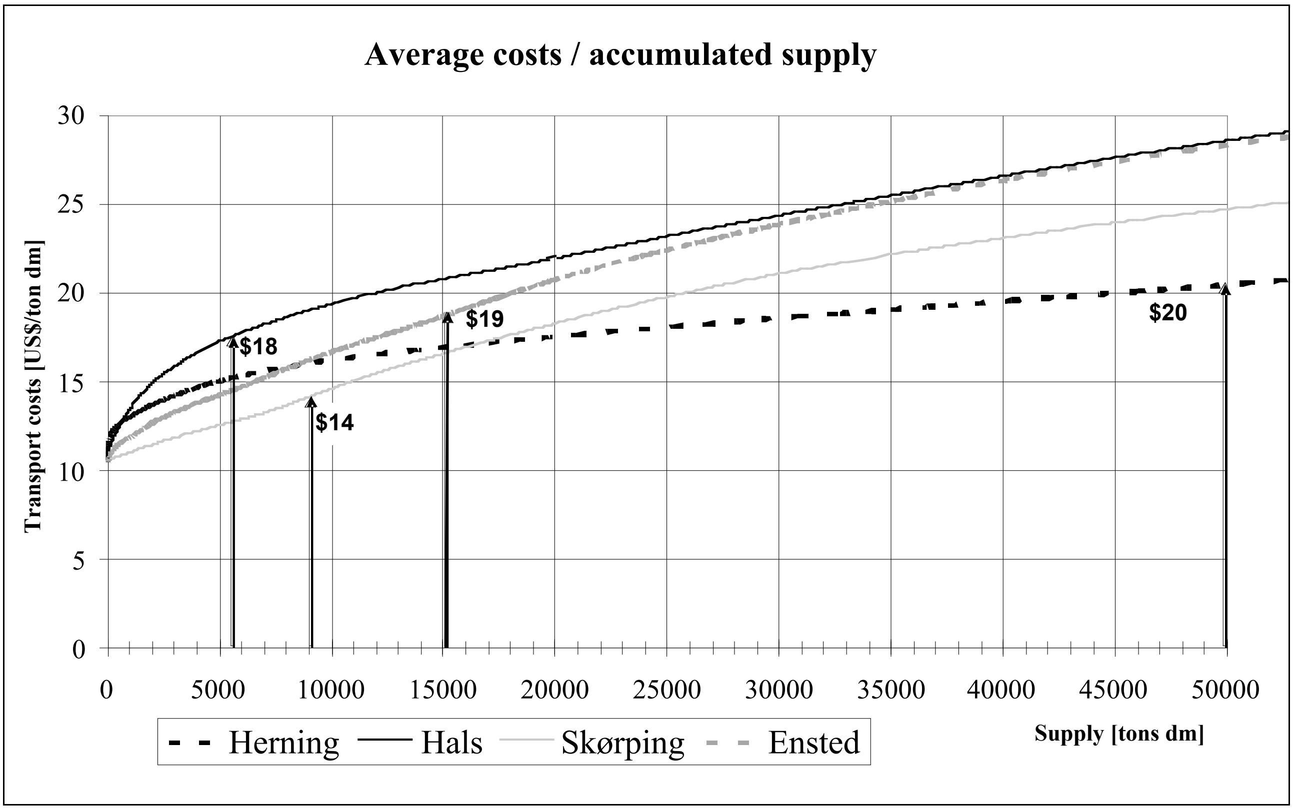

Figure 3: Cost supply curves for the four case studies. Shape and slope of the curves are indicators for local wood ship accessibility. The cost values are the average costs for transport if the annual fuel supply is met.

Interpretation of results

With the methodology presented above, cost supply curves have been calculated for the locations of four energy plants which use wood chips as their main source of fuel of for co-firing, see Figure 3. The diagram shows average costs of biomass over accumulated amounts. When comparing the cases the effects of local forest distribution become quite clear. The wood chip demand has great influence on the delivered costs, simply because wood chips need to be transported from further away. What can be seen from the shape of the curves, as well as the point where annual fuel demand is met is that cost-supply conditions depend on location. For a given annual fuel demand the model returns different costs. The plant in Skørping is surrounded by forests, which is why the cost supply curve is very flat initially. On the other hand, the plant in Hals has worse road connections and fewer forests in its neighbourhood, resulting in high costs of supply. The large plant in Herning has good access to regional resources and also a better road connection, which keeps the costs of fuel supply substantially lower than for the other locations, given they had the same fuel consumption. The effects of road connection can also be read from the cost supply curves, as high initial transport costs are calculated for those energy plants which need to travel along secondary roads first. This fits very well with the initial assumptions.

The slope of the curves indicates the sensitivity of costs against the biomass amounts. The more scattered and heterogenic biomass resources are, the more inclined is the cost-supply curve. By varying annual demand, e.g. as a function of heat demand or the plant efficiency, the margin for fuel cost elasticity is returned. A comparison of transport cost sensitivity is shown for the four cases in Figure 4. A location such as Ensted is more sensitive towards transport costs than the location of Herning. This indicates that wood chip logistics have to be carried out more carefully for sensitive locations, as the transport costs can vary by 10% for a variation of fuel demand of plus-minus 20%.

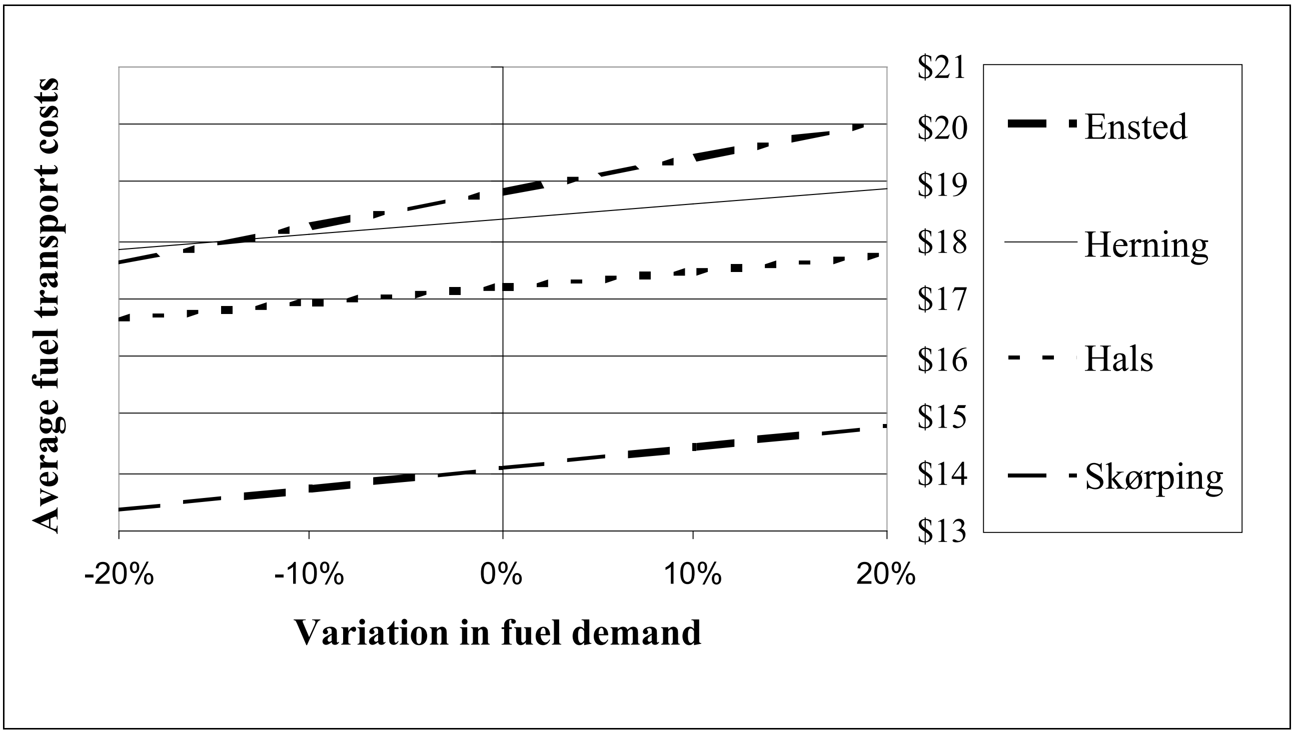

Figure 4: Average transport costs and their sensitivity to fuel demand for the selected case studies.

For a known wood chip demand the least cost fuel supply areas can be found in the GIS by looking up the maximal transport costs at which the accumulated demand is met. A query of the transport cost map returns the resource trade area from which the wood resources should be delivered from at least costs.

Discussion of results

The delivered fuel costs and their sensitivity to location and amount for a chosen bioenergy plant is very important information when locating and dimensioning a plant. Some locations are less costly and cost-sensitive to supply with wood chips than others. In particular decisions on whether to install a cogeneration unit with a significantly higher fuel demand and higher investment costs can benefit from this information.

The results indicate that even large energy plants with optimal road connection have higher costs of fuel supply. The reason for this is, besides larger resource trade areas around large energy plants, is that all bioenergy plants produce district heat and therefore are located near towns, away from large forests. Traditionally, the larger cities have been supplied with heat from power stations, fired with coal landed at low costs at the cities' harbours. If coal is replaced with wood chips, the fuel logistics may not fit to the new type of fuel. It is therefore obvious that small, distributed energy plants have a lower fuel cost structure than larger energy plants, and be more efficient in socio-economical terms.

In a country like Denmark, where experiences with wood chip supply chains have been made since the 1980's, and one must assume that information on secure and cost-efficient wood chip supply does exist, cost supply analysis can still help to solve one or the other problem, in particular because the market is saturated and demand is increasingly covered by import of wood logs. By proper allocation of the domestic fuel resources to those energy plants with the lowest overall costs, including transport costs, socio-economic costs for the overall system can be kept down. Also a study of this kind allows finding the difference of costs of delivered fuel and the market price. Leaving out the income of forest owners, this difference is mainly caused by the income a wood chip logistics company can create. Larger logging operators and logistic companies are likely to have lower costs (Van Belle et al., 2003).

This study only calculated cost supply curves for one plant at a time. In the real world energy plants will compete for the resources from a given forest cell. The plant with the lowest overall cost structure will, theoretically, be the receiver. To incorporate this behaviour in a GIS model either requires an allocation procedure, or an optimization model. An improvement of the model presented here will be to use the network analysis methods in ArcInfo, which allow among others to allocate resources to energy plants, using least cost allocation based on fuel demand.

Among the known errors of the modelling approach are the missing topology of a raster-based road network representation; missing information about ferry tariffs for the many inter-island ferries; potential errors in least cost routing, such as routes preferred by driver preference; and, most importantly, the lack of a wood chip resource map of sufficiently high spatial resolution. These errors have so far not been qualified and measured.

Conclusions

In this study, the transportation costs for wood chips from forests were analysed for selected bioenergy plant sites in Denmark using geographical resource mapping and cost distance analysis. A modelling methodology has been developed, which allows producing cost-supply curves.

The results of this study may be used to select fuels by regional availability, and to assess the fuel supply economy and its sensitivity for distributed energy plants using various sources of locally distributed fuels.

Looking at the geographical distribution and high transportation costs of biomass fuels, it is obvious to consider them as local fuels, which, in contrast to solid and liquid fossil energy carriers, are to be produced and used within local regions. Transportation needs should be restricted to a minimum and energy production distributed to locations close to energy sources. In other words, a socio-economically sound biomass fuel supply shall seek to meet demands at least costs. However, experience shows that the normative model used here often does not reflect reality. Large amounts of biomass are transported along long distances in the country. The reason for this can be found in both the relatively low costs of transportation, and problems of allocating wood chips within the many energy plants. Wood chips are harvested in intervals of one or more decades; they need to be stored in the forest for drying; and the price calculation of local hauling companies does not follow a strict set of rules.

From the first positive results of the modelling approach presented here it can be concluded that least cost modelling of wood chip supply can contribute to decision making in several areas of the forest-to-energy chain. Forest owners can assess the value of their often unused forest residues. Hauling companies could use least cost modelling to improve transport efficiency. Energy plants which use wood chips, consider doing so, or think about conversion to cogeneration and thereby higher fuel demand can use a least cost resource and transportation model to answer costs of supply and sensitivity questions. Finally, policy makers can use a least cost supply model to assess both environmental and socio-economic aspects of the development towards increased use of local wood resources. Regulations of tariffs, taxes etc. require information about which development is the most environmentally benign and the socio-economically least costly alternative of using renewable energy sources.

Regarding the insufficiencies of the model presented here, it could be improved in many aspects, the most important probably being better data on forest production. It should be possible to utilise forest stand records of at least the most important forests, containing valuable data for wood chip production forecasts. Regarding the model itself, a solution must be found to take into account the many competing bioenergy plants. So-called cost-sheds, an analogy to hydrology, could be used to map the boundaries of resource trading areas, which could supply biomass to a given plant at least costs. Another important addition is the dimension of time. Forests in Denmark are changing. Will the remaining old mountain pine plantations be replaced with new forests within one or two decades? The many deciduous forests planted for ground water protection during the last decade will require thinning. Will the planned establishment of national parks restrict wood production in a few areas? The final conclusion must be that a system, which is intended to link the many factors of the forest-to-energy chain, heavily relies on an improved information flow from and to each of these factors in order to create common knowledge, from which then all factors would benefit.

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