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MINIMIZING CARBON FOOTPRINT OF BIOMASS ENERGY SUPPLY CHAIN IN THE PROVINCE OF FLORENCE

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Abstract: The paper presents an approach for optimal planning of biomass energy system based on carbon footprint minimization. A geographical spatial demand driven approach is applied to assess the feasible ways for transferring energy from renewable sources to district heating plants in the Province of Florence (Italy). The proposed approach has been developed on three levels. In the first one, the Province of Florence is partitioned into a number of Regional Energy Cluster (REC) using a multidimensional algorithm of regionalization called SKATER. The variables used in SKATER model are related in order to realize sustainable policy for forest and agriculture biomass productions. In the second step a geographical fuzzy multiple attribute decision making model was applied to the selection of biomass district heating localization. Finally, in the third step a geo-referenced Mixed Integer Linear Programming model based on resource-supply-demand structure for carbon-minimization energy planning has been applied.

Keywords: carbon footprint, biomass, MILP, fuzzy MADM, regionalization, spatial analysis, GIS.

INTRODUCTION

Biomass is one of the key renewable energy sources. Using biomass to generate heat reduces emissions of greenhouse gases compared to the emissions of fossil fuel use. However, the dispersed nature of biomass resource involves complex transportation (and also environmental) problems within the supply chain. As a result, the environmental efficiency of a regional energy supply chain has the characteristics of spatial and geographical planning problem.

Several indicators for evaluating environmental impact of biomass supply process have been proposed. Carbon FootPrint (CFP) is defined as the total amount of CO_2 emitted over the full life cycle of biomass production process (Lam et al. 2010a). The CFP of a biomass supply chain is the total CO_2 amount emitted throughout the supply chain life cycle (Perry et al., 2008). Energy supplied from biomass cannot be considered truly carbon-neutral even though the direct carbon emissions from combustion have been offset by carbon fixation during feedstock photosynthesis (Anderson and Fergusson, 2006). The net CFP is mainly caused by the indirect carbon emissions generated along the supply chain, especially by harvesting, transportation and burning which release emissions. Especially transportation activities could contribute to the greater part of the CFP in the supply chain (Forsberg, 2000). The typical locations of biomass sources (farms, forest, etc.), the relatively low energy density and the distributed nature of the sources require extensive infrastructures and huge transport capacities for implementing the biomass supply networks. A solution to this problem is the utilization of biomass for heating houses, because this demand source is also dispersed in territory. District heating (less commonly called tele-heating) is an efficient system for distributing heat generated in a centralized location for residential and commercial heating requirements.

The paper presents an approach for optimal planning of biomass energy system based on CFP minimization in district-heating planning. A geographical spatial demand driven approach is applied to assess the feasible ways for transferring energy from renewable sources to district heating plants in the Province of Florence (Italy).

Section 2 presents the case study, Section 3 describes the methodological approach concerning how to minimize CFP in district heating planning at regional level. In Section 4 results are discussed.

THE CASE STUDY: DESCRIPTION OF THE PROVINCE OF FLORENCE

The territory of the Province of Florence covers an area of 3,514 km^2, with a population of 985,273 inhabitants (ISTAT, 2008) and a density of population of about 280 inhabitants/km^2, which sensitively increases to 1,644 inhabitants/km^2 in the urban area. The total surface covered by urban area is 183 km^2. The settlement morphology varies from the conurbation formed by Florence and by the others towns of the plain, with a higher urbanization, to the system of the small historical villages, farms, villas and parishes which are the evidence of the strong relationships which, in the past, described the rural organization of the countryside of Florence and, nowadays, “outline” the Chianti landscape.

The agro-forest environment of the Province is characterized by 1,640 km^2 of forest area, mainly covered by deciduous broad-leaf. The presence of agricultural land cultivated with permanent crops is relevant mainly in the hills surrounding the town of Florence, where the olive growing areas reach 278 km^2, while in the Florentine Chianti the vineyards reach 166 km^2.

METHODOLOGY

Biomass to energy projects are highly geographical dependent and the supply chain efficiency can be strongly influenced by location of district-heating, particularly in terms of CFP minimizations. The key element is to obtain sufficient biomass quantities in order to satisfy the energy plant demand, at least the carbon emission cost paid for transportation.

The problem of choosing the best locations for energy facilities is commonly assessed using a specific application based on the geographic informative system (GIS). Noon and Daly (1996), Bernetti et al. (2004) and Noon et al. (2002) used GIS, in order to identify the sites for only one facility, but without assessing site competition. However, when resources in the region are scarce, the district heating plants have to compete in order to meet their own demand. This leads to a location-allocation problem. Nord-Larsen and Talbot (2004) and Ranta (2005) applied linear programming in order to minimize transportation cost to detected units. Finally Panichelli and Gnansounou (2008) used a GIS based linear programming approach for selecting least cost bio-energy location.

Minimizing CFP in district heating issues requires the optimization both of demand location and of biomass network transfer links by the coupling of linear programming model and Geographic Information System. The main problem of this methodology regards the size of the model that, for a global optimization, can rise also to about several trillion of decision variables.

To face up to this problem Lam et al. (2010b) proposed a Regional Energy Clustering approach. The region under consideration is modeled as a collection of zones. The zones are smaller areas within the region, accounting for administrative or economic boundaries, which are considered atomic (i.e. non-divisible). For each zone corresponding rates of energy demands and biomass resource availability are specified.

In this paper, in order to obtain an environmentally efficient local optimization, the proposed approach has been developed on three levels.

In the first level, the region is partitioned into a number of Regional Energy Cluster (REC) using a multidimensional algorithm of regionalization called SKATER. The variables used in SKATER model are related in order to realize sustainable policy for forest and agriculture biomass productions. In the second step, a geographical fuzzy multiple attribute decision making model (FMADM) is applied to the selection of efficient biomass district heating localization. Finally, in the third step a geo-referenced Mixed Integer Linear Programming (MILP) model based on resource-supply-demand structure for carbon-minimization energy planning has been applied for each Regional Energy Cluster (Fig. 1).

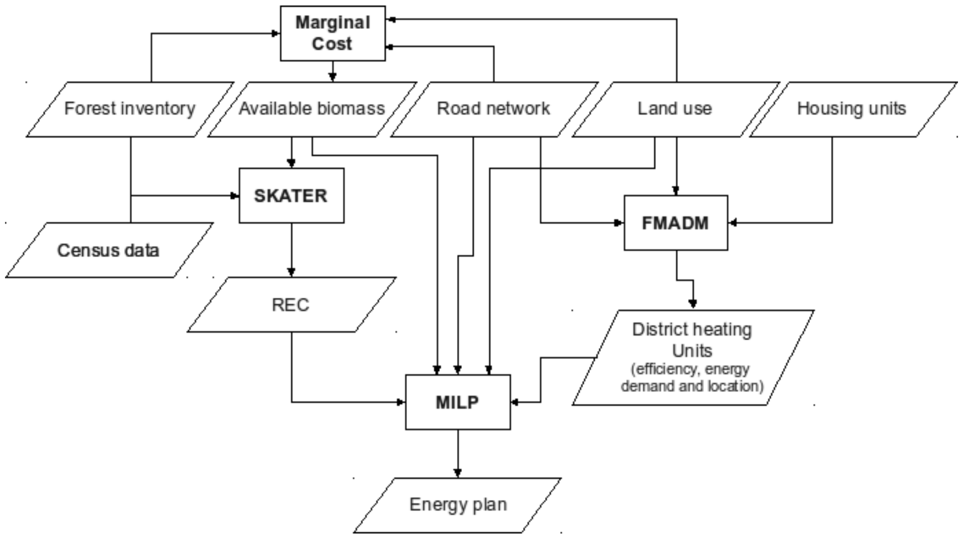


Figure 1. Methodology overview

As explained in figure 1, the GIS realized for the development of the model is composed by the following data bases: *a)* Forest Inventory of the Province of Florence, extracted by Tuscany's Inventory (vectorial format); *b)* Digital Terrain Model (raster format); *c)* Road system (vectorial format); *d)* Administrative boundaries (vectorial format); *e)* Housing units (vectorial format); *f)* Corine Land Cover land use map (raster format); *g)* Census data on Industry and Services (numerical format).

The REC step

In our approach the cluster combines smaller zone to assure efficient biomass energy policy. The zones are the smallest administrative units within the Province of Florence. Regionalization is to divide this large set of zones into a number of spatially contiguous regions while optimizing an objective function, which is a homogeneity intra-zones/heterogeneity inter-zones measure of the derived regions (Gou, 2008). In our model homogeneity/heterogeneity is related to indicators of sustainability of biomass harvest and supply chain logistics that are the characteristics of the agro-forest land and the potential supply of agro-energies and traditional timber assortments for each of the minimum administrative units.

The used sustainability indicators are the following ones:

- *land agro-forest characteristics,* defined through the quantification of the percentages of arable land areas, of permanent crops and forest areas;

- *biomass products,* including both the bio-fuel deriving from the agricultural crops and forest cultivations and from the traditional timber assortments (calculated with the methodology proposed by Bernetti et al., 2004);

- agricultural specialization index: it quantifies the importance of the agricultural sector, at municipal level, through the percentage of the workers involved in the same sector in relation to the total number of workers and in relation to the Region (Tuscany).

Given a set of spatial objects (e.g. administrative units) with a set of multivariate information a regionalization method aggregates the spatial objects into a number of spatially contiguous regions while optimizing an objective function, which is normally a measure of the attribute similarity in each region. With SKATER (Spatial 'K'luster Analysis by Tree Edge Removal) method a connectivity graph to capture the adjacency relations between objects is used. Figure 2 shows the connectivity graph for Province of Florence.

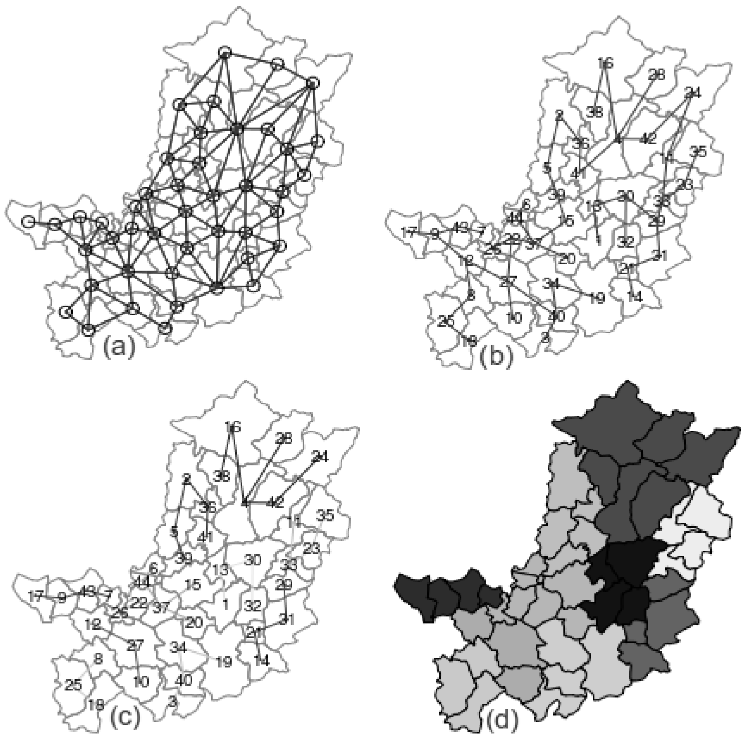


Figure 2. SKATER process

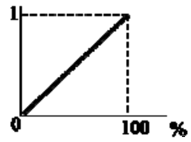
The cost of each edge is proportional to the dissimilarity between the objects it joins, where the dissimilarity is measured using the values of the attributes of the neighboring pair. It is possible to limit the complexity of the graph pruning the edge with high dissimilarity. An efficient method for pruning the graph is the so called "minimum spanning tree". A minimum spanning tree is a spanning tree with minimum cost, where the cost is measured as the sum of the dissimilarities over all the edges of the tree (Figure 2.b). By cutting the graph at suitable places, connected clusters (Figure 2.c and 2.d) are obtained (for further details see Assunçao et al. 2006).

The fuzzy FMADM step

District heating efficient location has been evaluated by the application of a model of decisional analysis based on a multi-attribute fuzzy approach (FMADM; Munda, 1995). The evaluation was done on the basis of the suitability to installing wood biomass plants for three different settlement typologies (ISTAT, 2001), which are: *i)* towns: aggregation of contiguous or nearby houses separated by roads, squares or similar; *ii)* residential complexes: aggregation of contiguous houses with the absence of squares or similar; *iii)* scattered houses: buildings scattered in the municipal territory having a distance such as neither creating a residential complex.

The indexes implemented in the model FMADM were elaborated on a GIS platform and then they were normalized with fuzzy functions (Cox, 1993; Zimmermann, 1987) on the basis of the information given by experts of the agro-energetic sector (table 1).

Table 1. Utilized Indicators in the model FMADM

Indicator	Description	Elaboration	Membership functions
Rurality Index (R)	It defines the potential easiness of wood bio-fuel supplying at a local scale.	It is calculated as the percentage of the agro-forest land with a *Density index* having a radius of 175 m around the settlement element.	
House density (Hd)	It defines the economic-logistic suitability for the creation of a district-heating plant.	It is calculated with a *Density index* having a radius from the buildings of 75 m, around the settlement element.	
Road distance (Rd)	It defines the access suitability to the plant, in terms of supplying costs of the raw material and of the CFP of the productive process.	It is calculated with a *distance* from the major and minor roads.	

The aggregation of the fuzzy criteria was done on the basis of two different techniques: one for the towns and the residential complexes and one for the scattered houses.

The following aggregation was applied for the towns and the residential complexes:

$$I_{tr}^{j} = \frac{1+R^{j}}{2} \tag{1}$$

with I_{tr} being the suitability for the localization of the district heating plant j within the town or the residential complex and R being the rural index.

The following formula was applied for the scattered houses:

$$I_{sh}^{j} = \frac{min\left(Hd^{j}, Rd^{j}\right) + R^{j}}{2} \tag{2}$$

with I_{sh} being the suitability for the localization of the district heating plant j within the house cluster, Hd is the house density, Rd being road distance and R is the rural index.

The MILP step

The objective of MILP model is to minimize CFP within the boundary of each REC. The model structure is the following:

$$MIN \sum_{j=1}^{m} \sum_{i=1}^{n} t_{i,j} X_{i,j} \tag{3}$$

s.t

$$\begin{aligned} &\sum_{j=1}^{m} \sum_{i=1}^{n} p_i X_{i,j} \geq d_i Y_i \quad \forall j \\ &\sum_{j=1}^{m} X_{i,j} \leq 1 \quad \forall i,j \\ &Y_j = [0,1] \quad \forall j \end{aligned} \tag{4}$$

with: Y_j, being the district heating location; $X_{i,j}$, being the raster location of biomass source obtained from the regional forest inventory as data point representing 1 Km^2 of land and allocated to district heating j; d_j, being demand of biomass from district heating j; p_i being the supply of biomass from source i; $t_{i,j}$, being the carbon emission in full life cycle of biomass process (harvest + transportation) from source i to district heating j, calculated through a GIS cost surface procedure.

RESULTS AND DISCUSSION

The SKATER step

Figure 3 shows the results of the SKATER procedure in terms of the average value of the utilized indicators. From the analysis of the figure, it is possible to highlight that, among the ten obtained regions (R1, R2, …R10), the allocation of the agro-forest land shows greater values than the average value for the Province of Florence for: *a)* the arable land area in the R1, R5, R6, R8 and R10; *b)* the permanent crops in the R1, R3, R4, R7 and R10 and *c)* the woods in the R2, R5, R8 and R9. The availability of traditional timber assortments (other biomass) is directly linked with the wood area, while the wood splinter productive potentiality shows a tight correlation with the permanent crops areas. Thus, thanks to the clustering deriving from the SKATER analysis, it is possible to distinguish the territorial peculiarities of each region; for instance, the areas characterized by a high forest relevance (R9) and the ones in which the permanent crops are important, both in terms of cultivated area (R3 e R4) and of employment linked to the sector (R4).

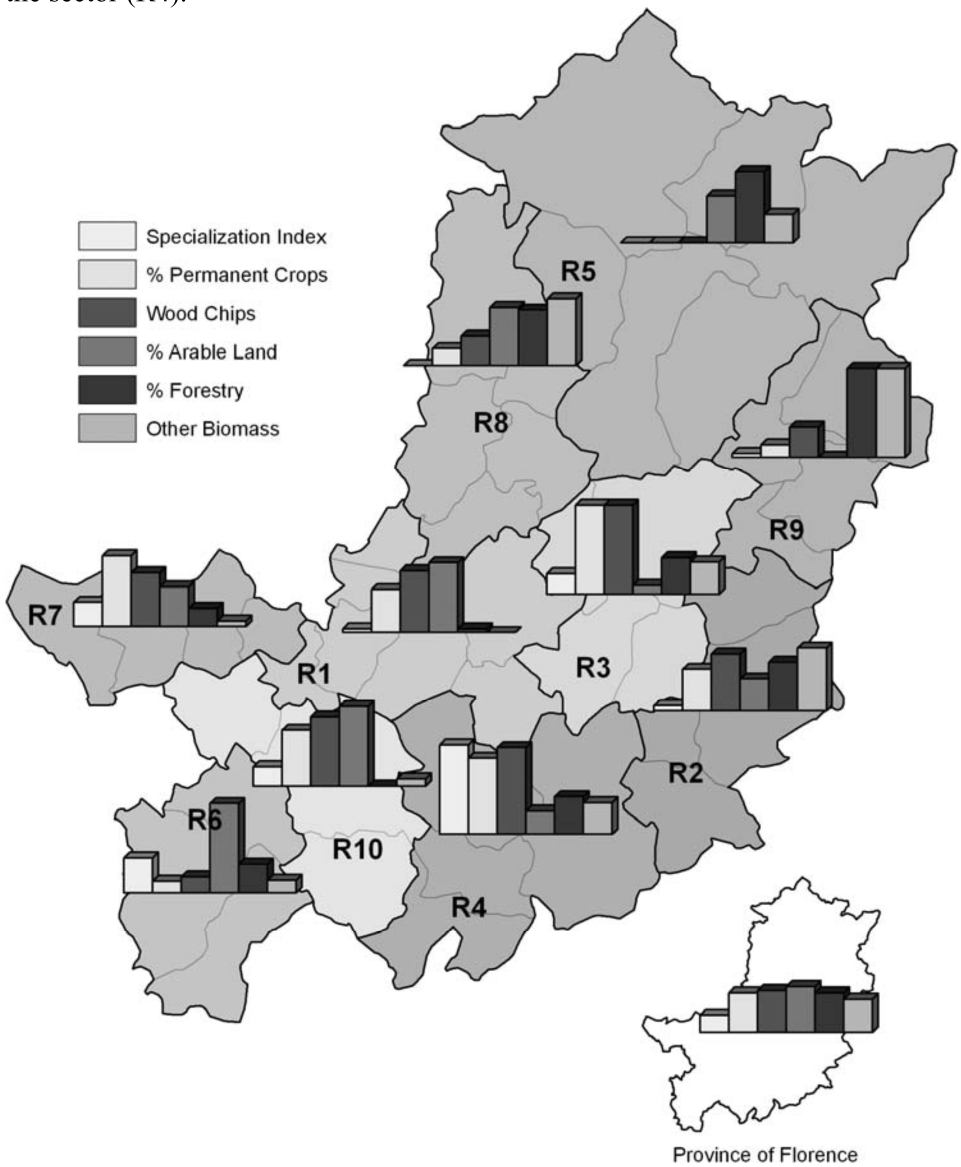


Figure 3. SKATER results

The FMADM step

The application of the FMADM model allowed the evaluation of the efficiency of the possible localizations of new plants. From the analysis of table 2, it is possible to highlight how the greater number of plants belongs to the medium-low, zero and low classes; these turn to be mainly the scattered houses, which is the least suitable settlement typology for the installation of district heating plants. For this reason, in order to optimize the agro-energetic planning process linked to the minimization of the CFP, the selected plants for the development of the MILP models are the ones with a highest possible efficiency.

Table 2. FMADM results

Efficiency class	Total plants	% scattered houses	% Towns and residential complexes	Total energetic requirement (MWh/year)	Potential installing power (MW)
0	5,887	90.8	9.2	7,876,097	4,653
0.01 - 0.25	2,441	97.5	2.5	554,842	267
0.26 - 0.5	7,454	99.5	0.5	1,245,963	619
0.51 - 0.75	33	3	97	98,656	28
0.76 - 1	187	0	100	302,612	156

In order to identify the localizations of new district-heating plants for the planning of the supply chain in every single REC, the district-heating localization in each REC has been ranked. Then, the localizations have been selected in order of decreasing efficiency until the biomass requirement (demand) came out to be equal to the annual yield (supply), considering also the sustainability of a wood ecological conservation. The results of the selection of each REC are showed in figure 4.

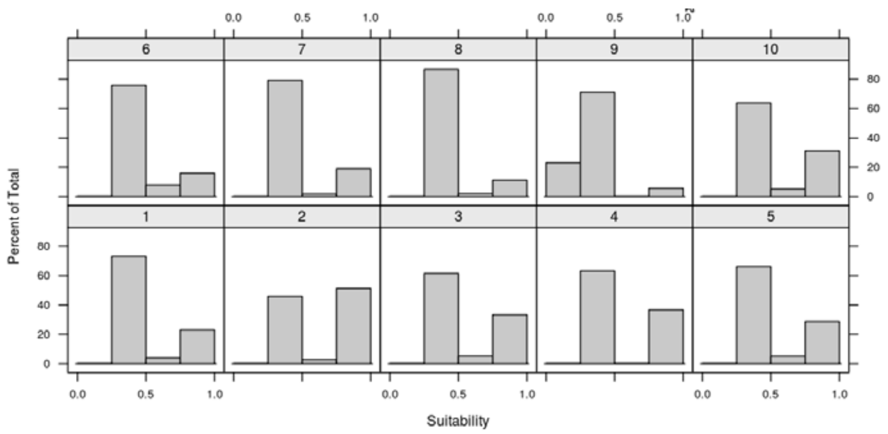
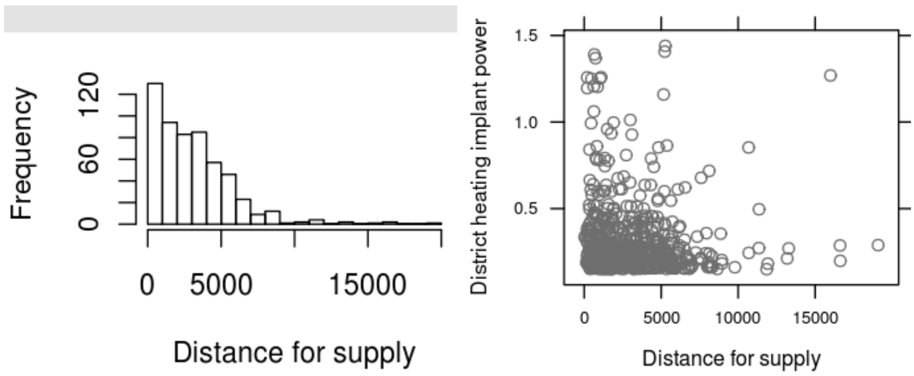


Figure 4. FMADM selection results

The MILP step

The most direct and immediate result of the adopted procedure is the possibility of planning with an high territorial degree an energetic supplying of the district heating plants in the REC, thus minimizing the environmental impact in terms of carbon dioxide emission.

By aggregating the results obtained from the 10 MILP models, it is possible to evaluate the global impact of the district-heating energy plan in the Province of Florence. As it is showed in figure 5, the optimization of the supply chain with the use of operational research methods allows the achievement of moderate CFP. In fact (see table in figure 5), the median of the transport distance is about 3 kilometers, with an interval between the first and the fourth quartile included between 2.7 and 4.5. The distribution of the frequency shows how values grater than 10 kilometers are rare. In addition, by examining the scatter plot between carbon footprint and power of district heating plant, it is possible to notice how the adopted procedure allows the achievement of limited distance of transportation values, also in the case of high power installations.



Mean Distance for supply (m)				
1st Qu.	Median	Mean	3rd Qu.	Max.
1053	2661	3124	4500	19090

Figure 5. CFP data by district-heating implant

By examining figure 6, which shows the previously explained elaboration for each REC, it is possible to notice how the lower CFP is obtained in REC 1 (Florence), 2 (Fiesole and the hills surrounding Florence), 6, 7 (hills of Vinci) and 10, corresponding to localizations characterized by a supplying based on the vineyards and olive growing pruning, which are generally close to the most suitable localizations for the rural district-heating plants. Worse results are evident for REC 5 and 9, characterized by a supplying based on forest resources often far from the towns.

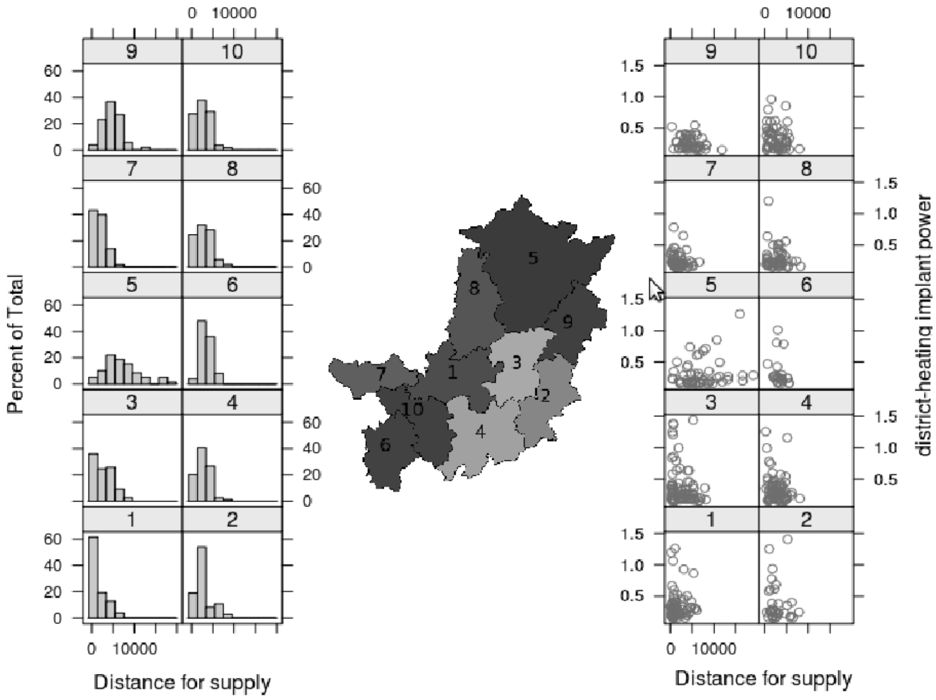


Figure 6. Carbon footprint by district-heating plant and by REC

CONCLUSIONS

When assessing simultaneous potential locations for energy facilities the location–allocation problem has to be solved in order to tackle resources competition among facilities. A multi-step procedure combined with GIS-based approach seems to be effective for selecting suitable energy facilities location. Addressing the problem through a convenient approach is fundamental to define facilities location as the optimal sites can vary in function of resources competition and environmental impact, evaluated through the carbon footprint concept.

The quantity and heterogeneity of the input data and the need for a structured analysis of the information make essential the need of integrated tools to assess the problem.

Further efforts have to be done to integrate software tools and data processing. The developed approach allows the planning of district-heating supply chain and select best energy facilities locations based on minimization of carbon footprint. Nevertheless, other models belonging to the logistic structure are being investigated, considering not only carbon footprint minimization but also environmental and social constraints.

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