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Biomass and Bioenergy 20 (2001) 101–112

BIOMASS & BIOENERGY

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Assessment of biomass potential for power production: a GIS based method

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Received 3 February 1999; received in revised form 31 July 2000; accepted 28 September 2000

Abstract

A method is presented, which estimates the potential for power production from agriculture residues. A GIS decision support system (DSS) has been developed, which implements the method and provides the tools to identify the geographic distribution of the economically exploited biomass potential. The procedure introduces a four level analysis to determine the theoretical, available, technological and economically exploitable potential. The DSS handles all possible restrictions and candidate power plants are identified using an iterative procedure that locates bioenergy units and establishes the needed cultivated area for biomass collection. Electricity production cost is used as a criterion in the identification of the sites of economically exploited biomass potential. The island of Crete is used as an example of the decision-making analysis. A significant biomass potential exists that could be economically and competitively harvested. The main parameters that affect the location and number of bioenergy conversion facilities are plant capacity and spatial distribution of the available biomass potential. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Biomass energy potential; GIS; Biomass power plants; Agriculture residues

1. Introduction

Biomass is the most developed renewable energy source providing 35 and 3% of the primary energy needs of developing and industrialised countries, respectively. In spite of its flexibility as an energy resource, biomass share in regional energy balances is rather low. Biomass can be used for direct heating in industrial or domestic applications, in the production of steam for electricity generation or for production of gaseous or liquid fuels. Direct heating is the most widespread application but electricity production and biofuels are currently gaining considerable interest among energy policy makers [1,2].

Biomass resources can be grouped into wood residues, generated from wood products industries; agricultural residues, generated by crops, agro-industries and animal farms; energy crops, i.e. crops and trees dedicated to energy production; and municipal solid waste [3]. Given the numerous applications of biomass and the variety of sources it is not surprising that a wide array of biomass conversion technologies are commercially available or under development [4].

A significant part of recent research efforts have focused on the estimation of the biomass quantities

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PII: S0961-9534(00)00070-2

Nomenclature

a_n	biomass available for energy production from crop n (%)
A_n	cultivated area for crop n (ha)
A_{r}	area of the region under consideration (ha)
B_n	biomass theoretical potential for crop n (t of residue/year)
B_{av}	biomass available potential (kJ/ha/year)
B_{th}	total biomass theoretical potential (t of residue/year)
E_{w}	energy required for the evaporation of water (kJ/kg)
f_g	efficiency of the biomass collection procedure (%)
H_n	hydrogen content of residue from crop n (% wb)
HHV_n	higher heating value of the residue from crop n (kJ/dry kg)
LHV_n	lower heating value of the residue from crop n (kJ/kg)
$m_{\mathrm{H_2O}}$	water created (kg/kg)
W_n	humidity of residue from crop n (% wb)
Y_n	residue yield for crop n (t/ha/year)

from energy crops, the evaluation of biomass production yields as well as the determination of competitive prices for energy crops in order for such cultivations to substitute traditional agricultural crops [5–9]. The rather dispersed geographical distribution of biomass potential has raised the interest of researchers in using Geographical Information Systems (GIS) for the evaluation of the biomass supply and characteristics, the estimation of the transportation cost to existing power plants as well as the site selection for energy crop developments [9–14]. Moreover, the selection and design of biomass power plants has been the focal point of various optimization studies in relation to the availability of biomass within a certain distance from the plant site [15–21].

In the present work, the problem of identification and estimation of economically exploited biomass potential from agriculture wastes for power generation is tackled. Although energy crops have been extensively analysed from an economic point of view, the economical potential of agriculture residues has not been the focal point of similar analysis mainly because energy crops are considered the main contributor for energy production in the near future. The use of GIS as a site selection tool has focused to the identification of the optimal sites for energy crops development based on the expected biomass production yields or the allocation of biomass to existing power plants. GIS has not been used as a dynamic search engine for the selection of potential power plant locations taking into account geographic distribution of biomass potential and expected electricity production cost. The developed method introduces a set of sequential steps for the assessment of biomass potential as *theoretical*, *available*, *technological* and *economically exploitable*, respectively. At each level of the analysis, the spatial distribution of biomass potential is identified and is the basis for the evaluation of the availability of biomass for energy production and the economic appraisal of the new power plants. The method, finally, aims at the evaluation of the biomass potential that can be economically exploited for power production through the optimisation of power plants distribution taking into account the geographic spread of the available biomass and the plant characteristics. The whole procedure has been formulated as a GIS decision support tool, which is able to implement the developed method and provide consistent and reliable information for the potential contribution of biomass in the energy sector.

In Section 2 the method for the estimation of biomass potential is presented; in Section 3 the developed decision support tool is described and in Section 4 a case study is presented to highlight the features of the developed decision support tool and provide an estimation of the biomass potential of Crete, which is the largest island in Greece.

2. Methodology

The first step of the algorithm estimates the biomass quantities generated annually in the form of agricultural residues, on user-defined level of geographical analysis, making use of available statistical data stored in a GIS database. In the subsequent steps, the method

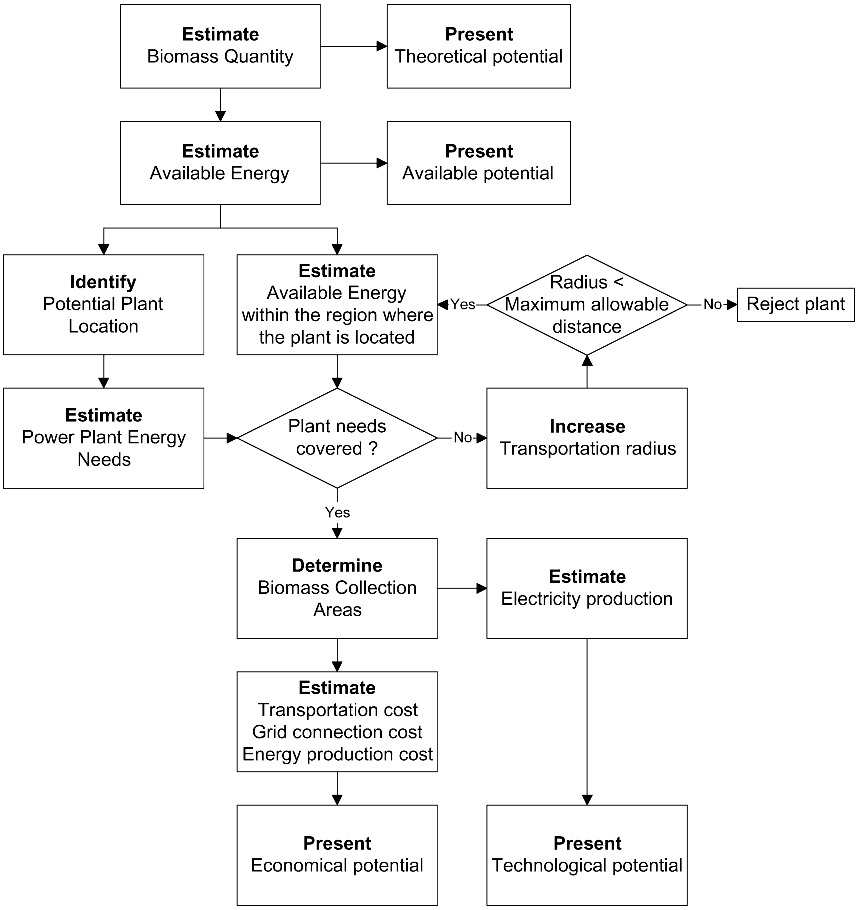

Fig. 1. Overview of the algorithm for the estimation of biomass potential.

estimates the biomass available for energy production taking into account the alternative uses of each biomass resource, the biomass conversion technology and the distribution of the available biomass to the identified power plants. Finally, the electricity production cost of the selected power plants is compared to that from conventional fossil fuel sources. The model structure for the estimation of the different biomass potential is presented in Fig. 1.

The appropriate GIS database structure has been dictated by the needed input data and the results to be obtained at each step of the method. Fig. 2 presents the geographical objects and the attributes used for the implementation of the method within the GIS environment. National census data on cultivated areas are initially related to region objects representing the finer possible administrative division of the area under consideration. Spatial aggregation and querying tools provided by the GIS are used to estimate and present the potential in any required spatial analysis. Candidate power plants are initially located at the centroids of the region objects and their technical characteristics are defined. The biomass collection area for each power plant is defined taking into account the maximum allowable biomass transportation distance and feasible power plants are identified. The electricity production cost for each of the identified plants is then estimated using the road and grid network. In the following paragraphs, the calculations in each step of the evaluation procedure are outlined, and the geographic objects, attributes and methods are described.

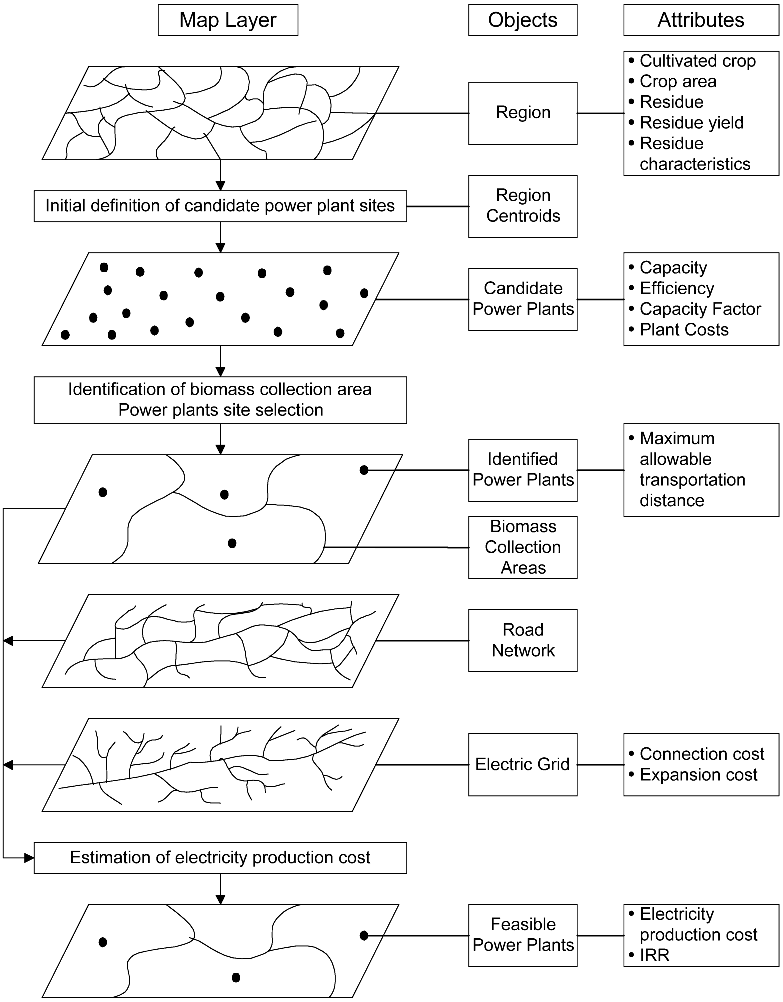

Fig. 2. Objects and attributes analysed within GIS.

2.1. Theoretical potential

The *theoretical biomass potential* is defined as the total annual production of agricultural, forestry and other residues in a region. This potential represents the total quantity of agriculture residues generated in a region, and can be considered as the upper bound of the bioenergy that can be actually derived from cultivated crops in the area. The main objective, in this step, is the formation of a GIS database of cultivated crops, which is used for the estimation and presentation of the biomass potential in any given geographic analysis. The theoretical biomass potential from agriculture residues, in a specific region, is a function of the cultivated area and the biomass production yield of each crop:

$$\begin{aligned} B_n &= \sum_n A_n Y_n, \\ B_{\text{th}} &= \sum_n B_n. \end{aligned} \tag{1}$$

Data on cultivated crop areas are available usually in the geographical analysis of administrative boundaries through national statistics [22]. The residue production yields for the most common cultivated crops are readily available in the literature [15–17]. Biomass production yields for energy crops can be estimated using parameters such as soil characteristics, climatic conditions and crop characteristics [5]. In the general case, where the desired analysis does not match the geographic analysis of the available database, spatial aggregation tools provided by the GIS are used to re-estimate the cultivated areas in the desired analysis and perform the necessary calculations.

Data for the cultivated crop areas constitute the attributes of geographical objects representing the boundaries of the regions defined by the user. Residue production yields depend mainly on harvesting practices and may have a significant variation from region to region. The method that implements Eq. (1) combines the available data, which refer to different spatial analysis and presents the quantity of the available biomass in the defined geographic regions.

2.2. *Available potential*

The theoretical biomass potential is subject to restrictions introduced by alternative uses of the agricultural residues, as well as efficiency of the residue collection procedure. The potential uses of the agricultural wastes are specific to the crop and residue, and when they are taken into account they determine the amount of residues available for energy production.

The *available biomass potential* is defined as the energy content of the biomass that can be technically and economically harvested and used for energy purposes. The energy content of the available biomass potential for each crop is evaluated using Eq. (2). The lower heating value is estimated from the higher heating value for each crop after excluding the energy required for evaporation of water content using Eq. (3) [15].

$$B_{\mathrm{av}} = \frac{f_g \sum_n B_n a_n LHV_n}{A_{\mathrm{r}}}, \tag{2}$$

$$LHV_n = HHV_n \frac{100 - W_n}{100} - E_{\mathrm{w}}(W_n + H_n m_{\mathrm{H_2O}}). \tag{3}$$

A database with the type of residues and their physical properties has been developed for each crop and is used for the estimation of the available biomass potential. Table 1 presents the characteristics of the main crops cultivated in Greece and their residues. The main residue from cereals cultivation is straw, which is currently used as fodder or fertilizer. The percentage of straw available for energy production, presented in Table 1, is derived from the residue that is currently not used. In the case of tree plantations, the main residues are branches, which are mainly used as firewood for space heating. The whole residue gathered from these plantations is available for energy production apart from a small fraction that is left on the field as fertilizer. The biomass collection efficiency depends on parameters such as farming and harvesting practices as well as efficiency of collection machinery and varies considerably from region to region. Available data on higher heating value and water content are used in the evaluation of the biomass energy content [23].

The database querying tools, provided by the GIS environment, are extensively used to implement the necessary calculations. The results are presented as a thematic map of the various ranges of available potential and constitute one of the criteria used in the next steps for the site selection of the bioenergy conversion facility.

2.3. *Technological potential*

The *technological biomass potential* for a certain biomass source and a specific energy form is defined as the energy that can be produced and is bounded by the characteristics of the selected energy production technology. There is a wide array of technologies making possible the use of biomass for energy production, and the most popular are direct firing for steam production, integrated gasification combined cycle, and co-firing with fossil fuels [24]. The technology selection to exploit the biomass from crop residues depends on the particular energy needs and the efficiency of the energy production process.

After the selection of the technology, the capacity of the power plant, the thermal efficiency and the capacity factor are defined. Then, the required quantities of appropriate agricultural residues that can be used as fuels in the plant are determined. Finally the area necessary for the collection of biomass is assessed taking into account the available potential of the neighbouring regions.

The technological biomass potential is assessed through the identification of all potential sites for installation of biomass power plants. The necessary

Table 1
Characteristics of cultivated crops and residues

Cultivation	Residue	Residue yield (t/ha)	Humidity (%)	Heating value (MJ/dry kg)	Biomass for energy (%)
Wheat soft	Straw	2.97	15	17.9	15
Wheat hard	Straw	2.82	15	17.9	15
Barley	Straw	2.12	15	17.5	15
Oats	Straw	1.26	15	17.4	15
Rye	Straw	1.26	15	17.4	15
Rice	Straw	4.52	25	16.8	25
Maize	Straw	7.17	55	18.4	30
Orange	Branches	7.41	40	17.7	90
Lemon	Branches	6.22	40	17.6	90
Mandarin	Branches	9.45	40	17.6	90
Apple	Branches	4.77	40	17.8	90
Pear	Branches	16.92	40	18.0	90
Peach	Branches	5.61	40	19.4	90
Apricot	Branches	6.23	40	19.3	90
Cherry	Branches	5.11	40	17.6	90
Almond	Branches	6.21	40	18.4	90
Olive	Branches	2.82	35	18.1	90
Olive	Kernels	64.0	60	15.7	50
Vines	Branches	4.97	45	18.9	90

inputs for the identification of power plant locations are the available biomass potential, the technical characteristics of the power plant and the maximum allowable distance for biomass collection, defined by the user. The potential sites are defined as the region objects representing the available biomass potential. In order to accept or reject a specific site, an iterative procedure is used. The available biomass potential of regions within an increasing radius is compared with the required energy input for the operation of the power plant. The site is accepted when the available potential is higher than the required energy input and the radius does not exceed the maximum allowable biomass collection distance. The site is rejected when the radius exceeds the maximum allowable distance and the available potential is lower than the required energy input for the operation of the biomass power plant. All available biomass in the regions within the specified radius is supplied to the power plant. The biomass that is still available in the area (i.e. is not used for the operation of any plant) is allocated to the next candidate plant. Taking into account that potential sites are more likely to be accepted when located into highly cultivated regions, the potential sites are initially ranked in descending order of available potential with the aim of speeding up the entire process.

The technological biomass potential is estimated as the sum of the energy production from all power plants that have been identified through the iterative procedure described above. It is clear that the technological potential has been assessed taking into account only technical restrictions on availability of biomass and efficiency of the selected technology.

2.4. Economical potential

The *economical biomass potential* is defined as the part of the energy that can be economically exploited with respect to alternative energy sources. The feasibility of the identified biomass power plants is determined using criteria such as the electricity production cost or the internal rate of return and net present value. The economical potential is determined by the capacity of the biomass plants with electricity production cost lower than the cost from conventional power plants. Alternatively, the economical potential can be determined by the profitability of the proposed investment using the net present value and internal rate of return as the main indicators to accept or reject an investment.

The energy production cost of the biomass-fired power plant is estimated taking into account the capital cost of the equipment, the grid connection cost, the cost for the construction of new power line, the operational and maintenance cost, the cost of biomass purchasing, and the transportation cost. Each identified biomass power plant is situated along the nearest road in order to avoid additional costs for road construction. The biomass transportation cost is a function of the quantity of available biomass in each region and the transportation distance. All potential paths connecting each biomass production site with the power plant are identified using the road network. The transportation distance is then identified as the length of the shortest route from the centre of each region to the power plant site.

3. Decision support system

GIS environments are used to create, store, retrieve, update and present geographical objects, attributes and methods. All possible geographical entities can be modelled within a GIS environment as point, line, or polygon objects. Attributes are stored in the form of database fields and are referenced to the corresponding geographical objects. Each geographic object and its attributes represent a database record. A set of records referring to objects with the same attributes represents a table, which can be presented either as a map (geographic objects) or a browser (data fields). The methods available in a GIS environment provide the tools to handle geographic operations, set a minimum connectivity between different sets of objects and perform database calculations with the aim to expand the interactions of objects. The user has the flexibility to create different sets of objects defined on the basis of common characteristics and develop models for extensive calculations using the built-in framework of object behaviours. It is obvious that GIS environments are not just extensions of the capabilities of conventional database systems but a dynamic environment able to accommodate and handle complicate geographic data structures and provide comprehensive information [25,26].

The DSS is built in a GIS environment with the objective to exploit its powerful features in handling all the parameters with geographic variability that influence biomass availability, site selection of the energy conversion facility and estimation of the performance and cost of the energy produced. The model for the estimation of biomass potential for power production has been developed in MAPINFO Professional, a GIS environment under WINDOWS 98. The procedure is based on the method described above and makes use of an extensive GIS database on geographic data related to all essential factors that affect the biomass potential. Fig. 2 presents the model structure for the estimation and presentation of the theoretical, available, technological and economical biomass potential.

The theoretical potential is evaluated using maps of administrative boundaries and statistical data. The initial step for this estimation is the definition by the user of the desired geographic analysis. Each geographic object, which is defined by the user, inherits the information contained on the initial region objects using built-in GIS spatial aggregation functions. The theoretical potential, is presented as a thematic map of the total amount of biomass available in each region. The information contained in such a map can be used to identify regions where extensive cultivation is sited and a more precise evaluation of the potential is justified.

For the estimation and presentation of available biomass potential, it is assumed that the biomass residue is uniformly spread over the entire area of the geographic objects and is expressed in terms of energy per unit area. This assumption does not affect the biomass potential estimation because the cultivated areas data stored in the GIS database are used in their original geographic analysis. The geographic analysis used in this step is the one defined during the estimation of theoretical biomass potential and the available potential is presented as a thematic map of energy per unit area.

The site selection of the power plants that could be installed in a certain region is the first step during the estimation of the technological potential. For each potential power plant site the necessary energy input and the radius defining the biomass-collection area are determined. If this radius exceeds the maximum acceptable level defined by the user, the power plant is rejected, otherwise the selected region is considered as the site for the specified power plant. When a region is partly within the circle defined by the biomass collection radius the biomass from the entire region is supplied to the plant.

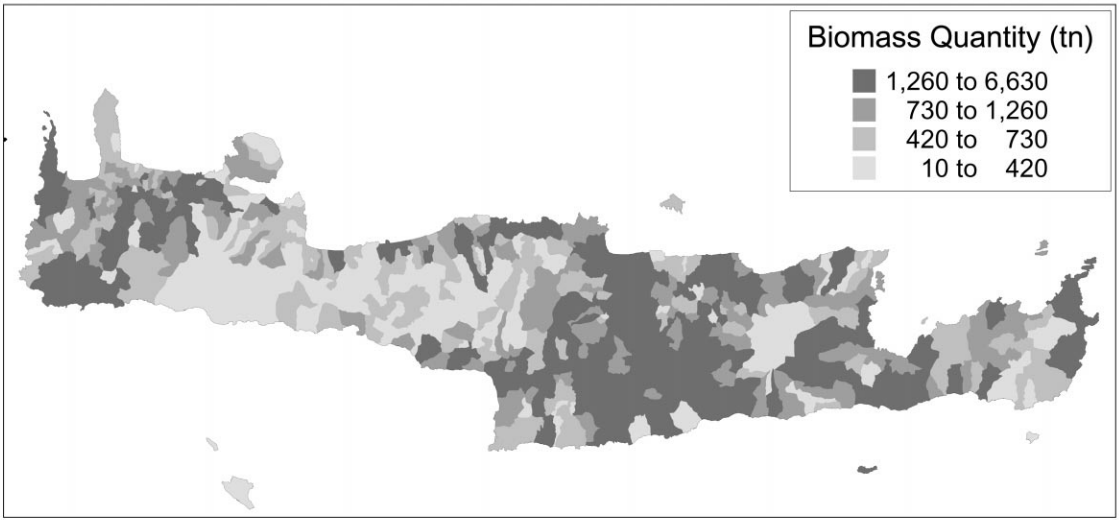

Fig. 3. Theoretical biomass potential.

During the estimation of the economic potential the distance of the plant from the nearest high-voltage grid line is estimated using built-in GIS methods since the cost of the grid extension is bared by the power plant owner. The biomass transportation cost is estimated on the basis of the quantity of biomass and the transportation distance. The energy production cost is estimated in terms of levelised electricity cost (LEC) and the results are presented as a thematic map that points out sites with low-energy production cost. This information represents the basic criterion for the selection and identification of the economically exploited biomass potential. Moreover, the GIS decision support tool allows the user to estimate the internal rate of return and the net present value in order to evaluate the profitability of proposed investments.

4. Case study: biomass potential in Crete

Crete is the largest Greek island with an autonomous energy system and relies heavily on energy supplies from the mainland. Crete has been identified as ideal region for the large-scale penetration of renewable energies into the energy system due to the high potential of wind and solar energy. Moreover, major parts of Crete are extensively cultivated and agriculture is one of the main economic activities of the island. The legislative framework concerning the exploitation of renewable energies in Greece indicates that in autonomous systems the power produced from renewable energy sources is paid a higher price form the utility compared to that in the mainland. This region has been selected for the aforementioned reasons as a case study to highlight the functions of the developed decision support tool.

The data for Crete used in the present case study are:

- Digital map of administrative boundaries.
- Digital map of town location and other demographic data.
- Digital map of the high-voltage grid network.
- Digital map of roads.
- Statistical data for cultivated areas and types of cultivation.
- Data on the characteristics of the residues produced from the major crops cultivated in Crete.

Fig. 3 presents the theoretical biomass potential in Crete, which has been defined as the total amount of biomass that can be produced in any region and provides a measure of the primary biomass resource. The crops and residues that have been taken into account are those in Table 1 and represent all the crops that could be used for energy production and

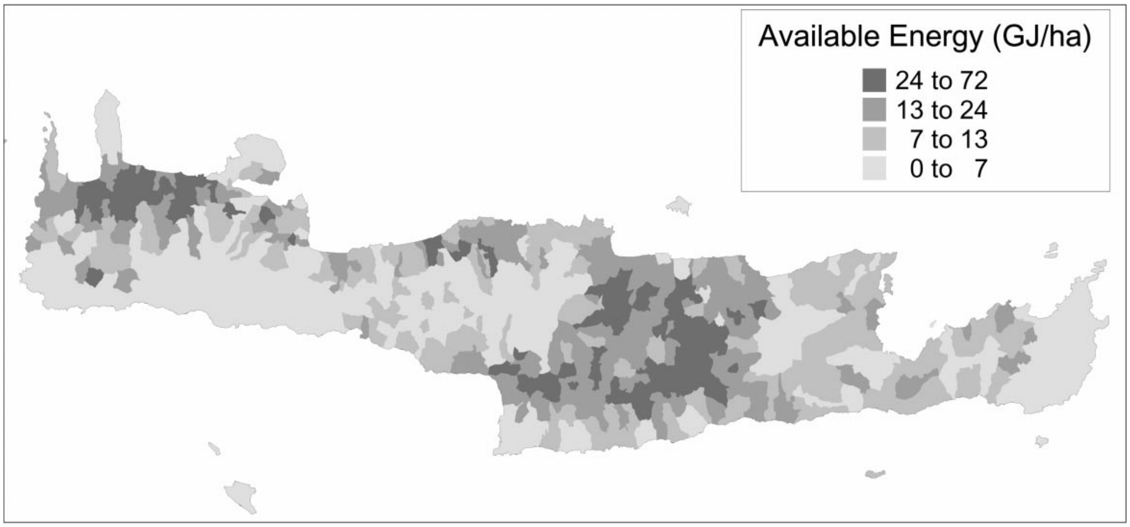

Fig. 4. Available biomass potential.

Table 2
Technical and economic parameters for biomass direct combustion power plants

	Scenario 1	Scenario 2
Capacity (MW)	20	10
Overall efficiency (%)	25	20
Capacity factor (%)	80	80
Investment cost (ECU/kW)	1700	2000
Operational and maintenance cost (% of investment cost)	5	5
Biomass price (ECU/t)	12	
Biomass transportation cost (ECU/t/km)	1	

are cultivated in Crete. The data on cultivated areas are taken from published records from the competent authorities [22].

Fig. 4 presents the available biomass potential in Crete is estimated on the basis of the crop characteristics of Table 1 using Eq. (2). The results indicate that there are two main regions where the energy content of the agricultural residues presents the higher concentration per unit area. These regions are indeed among the most cultivated plains in Greece and would be the ideal location of biomass-fired power plant for the additional reason that the major fraction of the island's population and consequently the electricity demand is located in the same areas.

The specifications for the power plant and the costs used for financial analysis are user-defined parameters. Table 2 presents the technical and economic parameters of two direct combustion technologies that have been analysed [27]. Fig. 5 presents the selected sites for the installation of power plants and the corresponding areas for the collection of the necessary biomass for the 20 MW power plant.

The economical biomass potential has been evaluated on the basis of the levelised electricity production cost. For the estimation of the electricity production cost the discount rate has been considered 8% and the investment life time 15 years. Fig. 6 presents the electricity production cost for the potential plants

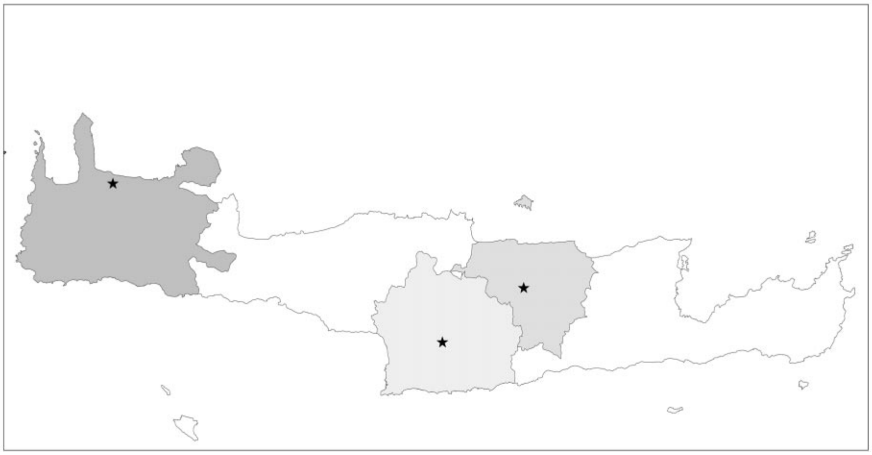

Fig. 5. Selected sites for 20 MW biomass power plants and size of areas for the collection of the necessary biomass.

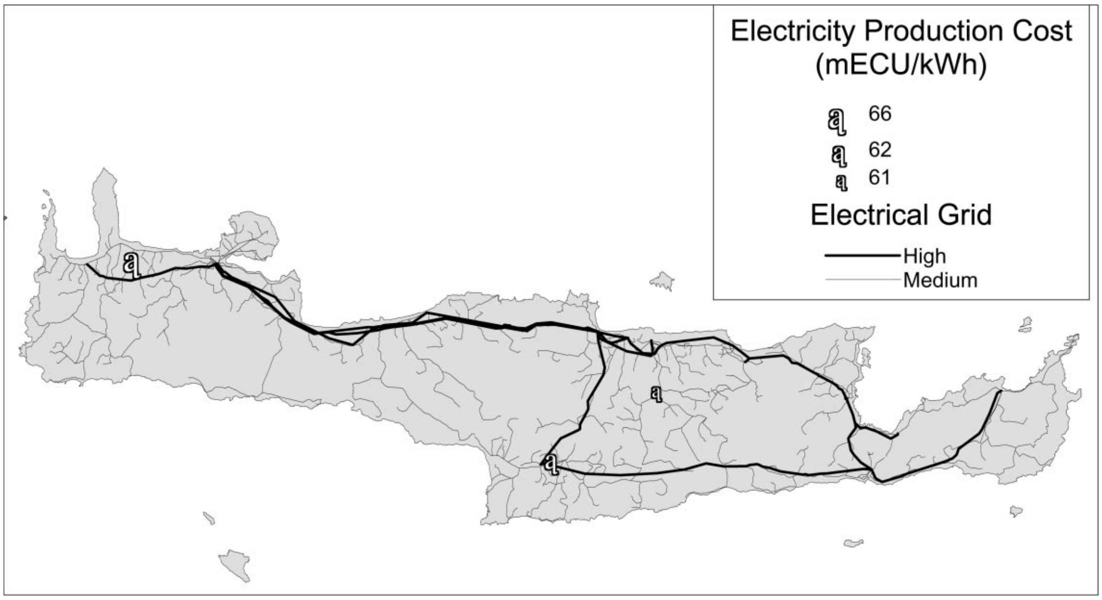

Fig. 6. Electricity production cost for 20 MW power plants.

identified using the 20 MW power plant. Taking into account that the utilitys average electricity production cost is 0.074 mECU/kWh, all of those plants could be considered viable if commissioned by the utility. The economical potential in this case is 60 MW. On the other hand, taking into account that the electricity-selling price from individual power producers to the utility is 0.064 mECU/kWh only two of the plants could be considered economically viable if commissioned by private investors. The economical potential in this case is 40 MW.

Fig. 7 presents the technological and economical potential for 10 MW power plants. It can be seen that in this scenario the number of possible power plants is increased, compared to the previous case, since there are more areas where the required biomass is within

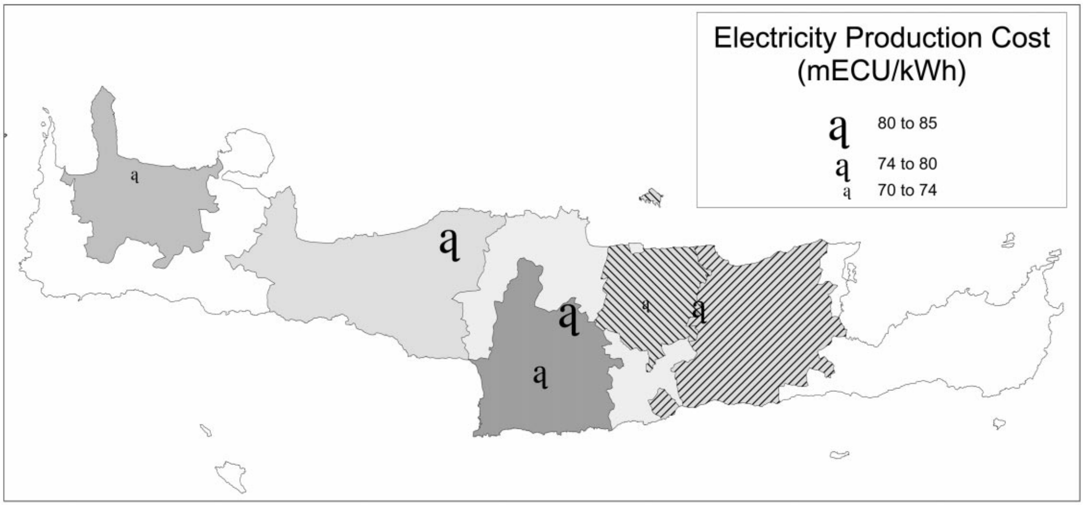

Fig. 7. Electricity production cost for 10 MW power plants and size of areas for the collection of necessary biomass for each plant.

the specified distance from the plant. The technological potential in the case of 10 MW power plants is 60 MW but the economical potential is reduced. Two of the identified power plants could be considered viable if commissioned by the utility while none of these plants can be viable for private investors with the current electricity-selling price.

5. Conclusions

The developed method aims at the evaluation of the geographical distribution of economically exploitable biomass potential. It introduces an integrated approach, which estimates the availability of biomass resource, the energy that can be extracted from it and finally the viability of specific investments. The spatial distribution of agriculture residues is analysed using a GIS and constitutes the basis for the estimation and presentation of the available biomass potential. The site selection procedure optimises the power plants distribution taking into account the capacity and performance of the plants and the geographical spread of the available potential. The electricity production cost is estimated taking into account the investment and operational plant costs as well as the biomass purchase and transportation cost. The proposed approach provides a framework able to host and analyse all potential restrictions for the optimal exploitation of agriculture residues for power production.

GIS is a useful tool and provides the means for identifying and quantifying all parameters that affect the available and technological biomass potential. In addition, it provides the flexibility to enrich the database, on which decisions are based, with spatial data of additional restrictions on biomass availability, or non-spatial data for other technology alternatives. The GIS is used as a dynamic environment for the analysis of the spatial distribution of biomass and the optimisation of power plants site selection in terms of biomass distribution and transportation cost. The use of readily available spatial and statistical data makes the GIS decision support system that implements the developed method applicable to different locations.

The financial framework for biomass exploitation in autonomous systems, the inefficiency of the existing electricity grid and the high RES potential establish Crete as the ideal region for RES investments. The case study in the island of Crete shows a significant economical potential that mainly depends on the type of investor. The developed model can provide valuable help towards the direction of the active involvement of energy actors in the definition of appropriate implementation plans for increasing the contribution of biomass to the energy system.

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