Applied Energy 87 (2010) 2551-2560

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal

H. Viana[a,*], Warren B. Cohen[b], D. Lopes[c], J. Aranha[c]

[a] Forestry Sciences, Agrarian Superior School, Polytechnic Institute of Viseu, Quinta da Alagoa, Estrada de Nelas, 3500-606 Viseu, Portugal
[b] USDA Forest Service, 3200 SW Jefferson Way, Corvallis, OR 97331, USA
[c] Forestry Department, University of Trás-os-Montes e Alto Douro, 5000-911 Vila Real, Portugal

ARTICLE INFO

Article history:
Received 20 April 2009
Received in revised form 5 February 2010
Accepted 5 February 2010
Available online 1 March 2010

Keywords:
Bioenergy
Biomass
Wood fuel
Logging residues
Mapping
Combined heat and power plant
Power generation

ABSTRACT

Following the European Union strategy concerning renewable energy (RE), Portugal established in their national policy programmes that the production of electrical energy from RE should reach 45% of the total supply by 2010. Since Portugal has large forest biomass resources, a significant part of this energy will be obtained from this source. In addition to the two existing electric power plants, with 22 MW of power capacity, 13 new power plants having a total of 86.4 MW capacity are in construction. Together these could generate a combination of electrical and thermal energy, known as combined heat and power (CHP) production. As these power plants will significantly increase the exploitation of forests resources, this article evaluates the potential quantities of available forest biomass residue for that purpose. In addition to examining the feasibility of producing both types of energy, we also examine the potential for producing only electric energy. Results show that if only electricity is generated some regions will need to have alternative fuel sources to fulfil the demand. However, if cogeneration is implemented the wood fuel resource will be sufficient to fulfill the required capacity demand.

1. Introduction

There is an emerging consensus on the need to reverse the trend of global warming associated with climate change. The main goal is to quickly reduce emissions of greenhouse gases.

The European Union (EU) is resolved to reduce member country greenhouse gas emissions (GGE) and is promoting the development of new energy policies as one important means to that end. These policies should lead both to the development of new and more secure energy sources and contribute to a reduction in the growing dependency of EU member states on imported fossil fuels.

1.1. Renewable energy strategy and policy

To implement its renewable energy (RE) strategy, in March 2007 [1] the EU formally committed to the "20-20-20" initiative, which set as target and objectives for 2020 [2,3]. These include (i) reducing greenhouse gas emissions by at least 20% of 1990 levels (30% if other developed countries commit to comparable cuts), (ii) increasing the share of RE (wind, solar, biomass, etc.) consumption to 20% compared to 8.5% today, and (iii) cutting energy consumption by 20% of projected 2020 levels by improving energy efficiency.

* Corresponding author. Tel.: +351 232 446 600; fax: +351 232 426 536.
E-mail address: hviana@esav.ipv.pt (H. Viana).

0306-2619/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2010.02.007

Renewable energy has gained greater importance over the years, and is today considered the solution to the energy future in Europe. Since 1990, the EU has been engaged in an ambitious and successful plan to become a world leader in RE production and use. The strategic energy plans and policies of the EU, as well as those individual member states, established concrete targets for exploitation of indigenous renewable energy sources (RES), and for bioenergy in particular. As a first step towards a strategy for RE the Commission adopted a Green Paper on 20 November 1996 [4]. The most ambitious strategic goals were defined in 1997 in a European Commission White Paper [5], where the EU set the target to increase the share of renewable up to 12% by 2010. The White Paper also contains a comprehensive Strategy and Action Plan setting out the means to reach this objective.

After the order Green Paper (2000) on security of energy supply [6], diverse and concrete proposals were made. One of these proposals, directive 2001/77/EC [7] on electricity production from renewable sources, was adopted in 2001. Under this directive 22% of the electricity consumed in the EU by 2010 should be produced from renewable energy sources.

According to the national targets for future consumption of electricity produced from renewable energy sources, defined for each member state, Portugal committed to 39% (including large hydro). These goals were also stated in the National E4 Programme (Energy Efficiency and Endogenous Energies) launched in 2001 [8], and subsequently in the National Strategy for the energy launched in 2003 [9] and 2005 [10]. In 2007 Portugal established a more ambitious strategic target in its National Strategy of Sustainable Development [11]. This new National Strategy for the energy establishes that 45% of the national energy consumption in 2010 should be exclusively produced from renewable energy sources. In this way Portugal intends to set an example in the fulfilment of the EU objectives to reduce emissions of greenhouse gases.

1.2. Biomass energy policy

Amongst renewable resources, paramount importance has been given to the bioenergy because it has low negative environmental impact in terms of CO_2 emissions for the entire fuel cycle and zero CO_2 emissions from fossil fuels during operation.

The European Commission White Paper [10] recognized bioenergy as the most promising areas within the biomass sector for several reasons. First, because it would increase the amount of people working in the forestry sector. Second, because the combined use of heat and power (CHP) has the greatest potential per unit volume among all renewable energy sources. They also issued the opinion that the contribution of biomass-derived energy to the primary energy mix should reach 10% by 2010. The European Commission's Green report (2000) [12]. also recognized that biomass is a versatile energy resource, with a widespread availability through forest and agricultural residues that has so far not been fully exploited. Consistent with the Green report [13]. emphasis is given to the electricity generation from biomass energy plants, and some successfully examples of implementation in some member states are presented.

The strongest incentive of the EU towards development of biomass energy was given in 2005 with the Biomass Action Plan [14]. In this plan, the EU stated that the increased use of renewable energy is essential for environmental and competitiveness reasons, and recognized that "biomass has many advantages over conventional energy sources, as well as over some other renewable energies, in particular, relatively low costs, less dependence on short-term weather changes, promotion of regional economic structures and provision of alternative sources of income for farmers" [14]. This action plan established several measures to promote biomass in heating, electricity and transport, followed by crosscutting measures affecting biomass supply, financing and research [14,15].

According to this EU strategy, the goal of reaching 45% of national energy consumption in 2010 from renewable energy sources will be achieved in part from biomass energy production. Hence, the Portuguese government decided to extend the current installed power (two electric power plants, with 22 MW of power) to 250 MW by 2010 [11]. Therefore, in 2006, fifteen new power plant (90 MW) exploration licenses were made available to achieve this aim. However, because only 13 licenses were applied for, presently new power plants will only provide 86.4 MW of additional power. These new power plants will be capable of generating both electrical and thermal energy, or CHP.

The new power plants locations were defined by the Portuguese government with the double objective of increasing the quota of renewable energy in the global production of electricity and to promote the development of forest residues harvesting. This will also serve to remove shrub competition in forest groves and reduce wildfire hazard [16].

These power plants will have variable power generation capabilities and combine different technologies, as appropriate to local circumstances. Two power plant models are planed: small units, with power production ranging from 1.8 to 4.5 MW, and large ones with power production ranging from 9 to 9.9 MW. Considering that wood-fuel demand will increase significantly and will be variable across regions, it will be necessary to apply rational resource exploitation actions associated with regional and local needs. For example, there may be significant competition in some areas due to the presence of pulp mills or other biomass consuming industries. In these cases special solutions and compromises will be needed, or it may not be feasible to construct a power plant in such a location. As stated in the 2005 EU's report *'The support of electricity from renewable energy sources'* [17] the future development of RES projects in a specific area must taken into account spatial aspects of planning. This is especially fundamental for projects in the field of wind and biomass.

In this context the objectives of this paper are to: (1) assess Portugal's current forest biomass resource potential for commercial generation of electricity at regional and national levels, (2) assess the spatial distribution of biomass availability, and (3) evaluate the suitability of existing and proposed wood-fired power plant locations in Portugal.

2. Study area

Portugal is located between the latitudes of 36° 57' 23" and 42° 09' 15"N and the longitudes of 09° 30' 40" and 06° 10' 45" W. This area includes two distinctive bioclimatic regions: a Mediterranean bioclimate in everywhere except a small area in the North with a temperate bioclimate [18]. With four distinct weather seasons, the average annual temperatures range from about 7 °C in the highlands of the interior north and center and about 18°C in the south coast. Average annual precipitation is more than 3000 mm in the north and <600 mm in the south.

With complex topography and elevations ranging from the sea level to 2000 m, and a small amount of suitable soils for agriculture, Portuguese land is well-suited for forest growth. Forest activity is a direct source of income for a vast forest products industry, which employs a significant part of the population.

3. Methodology

The framework of this study followed four main steps. The first step consisted of forest cover classification and mapping, within Portugal. In a second step, we estimated the available forest biomass and annual growth at national and regional levels. In the third step, the geographical location of existing power plants was evaluated, and a GIS-based analysis was applied to examine the relationship between existing biomass and the power plants wood-fuel demand. Finally, based on the available quantities of biomass and growth we compared the maximum theoretical potential of energy production for two scenarios (fully condensing plants and cogeneration plants).

3.1. Forest land cover of study area

To calculate woody biomass, it was necessary to identify and classify forest cover, as well as to characterize forest stand structure. In Portugal, forests cover approximately 3.4 million hectares [19] and represents 38% of the national territory.

The main trees species, which are widely planted for commercial purposes and capable of providing a regular supply to meet fuel demand, are *Pinus pinaster* (maritime pine) and *Eucalyptus globulus* (eucalyptus). Thus, only these stands (710.300 hectares of maritime pine and 646.700 hectares of eucalyptus, according to the National Forestry Inventory [19]) were considered in the calculations of potential biomass.

The spatial distribution of forested land cover was made at regional level, using a so-called NUT III sub-regions (Nomenclature of Territorial Units for Statistics) boundaries (Fig. 1). The pine and eucalyptus stands occur mainly in the north and center of Por-

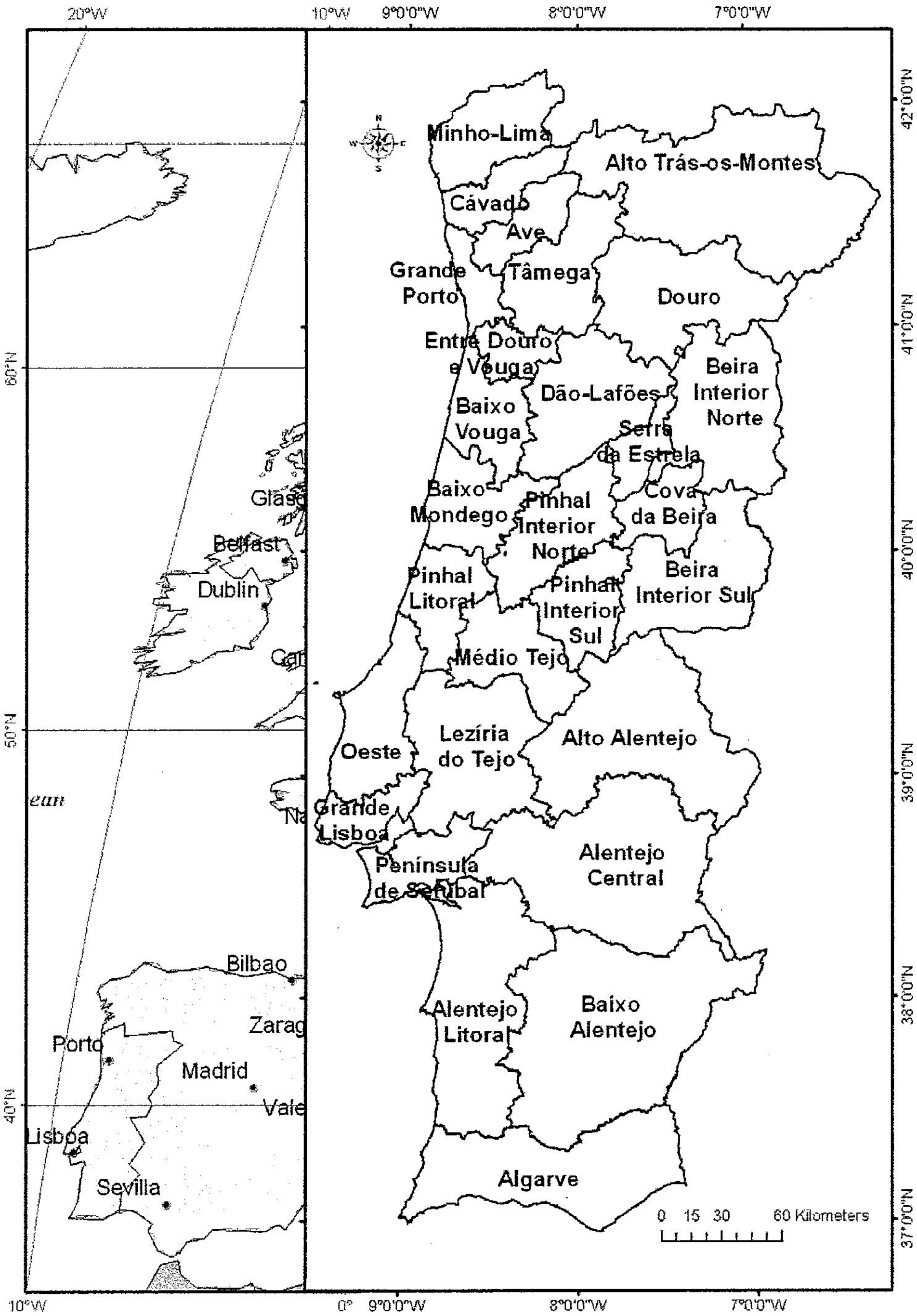

Fig. 1. NUT III sub-regions.

tugal as ecological conditions limit their growth in the south part of Portugal.

3.2. Forest biomass calculation

The biomass potentially suitable for energy use is commonly classified into primary residues, secondary residues, tertiary residues and energy crops [20-26].

Portuguese political strategy to implement the new power plants states that the main source of fuel should come from the residual biomass generated by forest activity. Because of this policy, only primary residues availability (parts of trees, unsuitable for saw timber such us branches and tops [20-26]) were used in the calculations. Also industrial byproducts, such us sawdust and woodchips, could constitute an alternative source of fuel; however, as they are widely used by plywood and fibreboard industries, this could result in a restriction of biomass supply.

The potential supply of woody biomass resources was achieved through different calculation processes based on pine and eucalyptus stands dendrometric data, of each considered region. In North and Center regions the data was collected by field inventory, within maritime pine and blue-gum eucalyptus stands. For the other re-

Table 1
Allometric equations used in the evaluation of the residual forest biomass of maritime pine.

Source	Allometric equation (kg/tree)	
[29]	$B = 0.656\ \text{dbh}^{2.364}\ \text{h}^{-0.977}$	(1)
[30]	$B = 0.463\ \text{dbh}^{1.604}$	(2)
[31]	$\text{Log}(B_d) = 2.911 + 2.130\log(\text{dbh})$	(3)
[32]	$y_{ijt} = \beta_{0ij \times y11t}^{\beta_{1ij}}$ Leaves: $\beta_{021} = (-30.760406 + 0.58157013 \times y_{1110} - 2.50380386\text{E}-04 \times y_{1110}^2 + 3.07544565\text{E}-08 \times y_{1110}^3)/10{,}000$ $\beta_{121} = 2.013$ Live branches: $\beta_{022} = (-59.521553 + 1.068209 \times y_{1110} - 4.5891371\text{E}-04 \times y_{1110}^2 + 5.62875901\text{E}-08 \times y_{1110}^3)/10{,}000$ $\beta_{122} = 2.013$ Dead branches: $\beta_{023} = (-17.410039 + 0.262031 \times y_{1110} - 1.1243324\text{E}-04 \times y_{1110}^2 + 1.38169184\text{E}-08 \times y_{1110}^3)/10{,}000$ $\beta_{123} = 2.013$	(4)

Table 2
Allometric equations used in the evaluation of the residual forest biomass of blue-gum eucalyptus.

Source	Allometric equation (kg/tree)	
[29]	$B = 8.54 - 1.537\ \text{dbh} + 0.163\ \text{dbh}^2$ (North and Center) $B = 7.615 + 0.102\ \text{dbh}^2$ (South)	(5)
[30]	$B = 0.1785\ \text{dbh}^{1.756}$	(6)
[33]	$B_d = \text{Wbr} + \text{Wl}$ $\text{Ln (Wbr)} = -6.989 + 3.157\ln(\text{dbh})$ $\text{Ln (Wl)} = -4.902 + 2.524\ln(\text{dbh})$	(7)
[34]	$B_d = \text{Wbr} + \text{Wl}$ $\text{Wbr} = 0.0956\ \text{dbh}^{1.6746} \times \text{h}^{-0.8507}$ $\text{Wl} = 0.2490\ \text{dbh}^{1.2640} \times \text{h}^{-0.7121}$	(8)

Where B is the total weight of biomass (tops and branches). Bd the total weight of dry biomass. dbh the diameter breast height. h the total height of the tree. Wbr the weight of branches. Wl the weight of leaves. Y_{IJt} the diameter breast height at the age t, and Y_{ijt} is the weight of each component of the crown biomass.

gions the data were collected in the NFI 2005/2006 [19] and in some previous published studies [27,28]. Several specific allometric equations for maritime pine (Table 1) and for eucalyptus (Table 2) were used to calculate residual biomass quantities for all the regions (Eqs. (1)-(8)) [29-34]. The total available biomass for the whole country, which can be transformed into energy, is the sum of the estimates for each region.

3.3. Spatial distribution of forest biomass and geographical location of power plants

After the wood fuel quannties were calculated, the spatial assessment of forest biomass availability by region was mapped. As the data provided by forest inventories [19] did not include the sample plot coordinates, and because no accurate map existed of forest land cover distribution, it was not possible to modulate biomass spatial distribution using real data. Hence, the resultant map expresses the theoretical biomass quantities per year, assuming that they are uniformly distributed all over the region.

As previously presented. this case study analysis was carried out considering the existence of the two actual power plants (Mortagua - M. with 9 MW, and Vila Velha de Rodao - WR, with 13 MW), and the anticipated location of 13 new power plants (86.4 MW), to the Portuguese electric network (Fig. 2). The spatial forest biomass availability and the anticipated geographical locations of new power plants were recorded in a GIS database. Spatial and query tools, provided by the GIS, were used to analyse the available wood fuel in each power plant's influence area.

3.4. Comparison of fully condensing and cogeneration plants scenarios

To analyse the maximum potential of energy production, based on power plant geographical locations and according to their fuel demands, we compared two scenarios: fully condensing plants and cogeneration plants.

The conversion of residual forestry biomass into electrical power, heating power. or both ((HP) is made typically through simple combustion, but alternative processes such as co-firing, in particular coal-fired, or gasification are often used in some EU countries. Conversion process efficiency depends upon the resultant final products. In stand alone plants, the efficiency of biomass combustion for electricity production typically varies between 25% and 30% [35,36], but if the electrical production is combined with heat production ((HP), the efficiency can rise to 80-100%, in power plants having capacities ranging between 1 and 10 MW [35,36]. The technical parameters used in this study, adopted from [37-40] are presented in Table 3.

At this point, it is important to clarify that our results are related to *theoretical biomass potential;* e.g. the annual production of forest residues in a region. However. since the theoretical biomass potential is subject to restrictions [41], e.g. the efficiency of the residues collection procedure, the amount of biomass that can be technically and economically harvested and is suitable to be used for energy purposes, is defined as *available biomass potential.* In this research, the biomass calculation was made assuming that the *available biomass potential* is only limited by the distance from collection area to the power plant. No other technical, ecological or economical restrictions were considered in this evaluation, which obviously differs from the reality. Thus, two approaches were considered:

- the *theoretical forest biomass potential* of each region. the *maximum theoretical power plant capacity,* optimum thermal boiler load - Q_B (MW_{th}) and the electricity output (f) that can be calculated, e.g. if all the biomass is collected across the region and used into energy production, the possible maximum size of power plant(s) (non considering any restriction of exploitation of fuel) is obtained [37,38] (Eqs. (9) and (10)).
- the *available biomass potential,* where the viable fuel collection area for each power plant, is a circular area with a radius of R km, being the power plant located at the center. After calculation of R_o (optimum radius), is possible to obtain the *available power plant capacity,* Q_B (MW_{th}) and respective maximum energy production potential (f).

The optimum radius is calculated as a function of the cost of wood waste and density of wood fuel availability, Y (t/h/year), as described in Eqs. (11) and (12), for fully condensing plant and cogeneration plant, respectively [37-39].

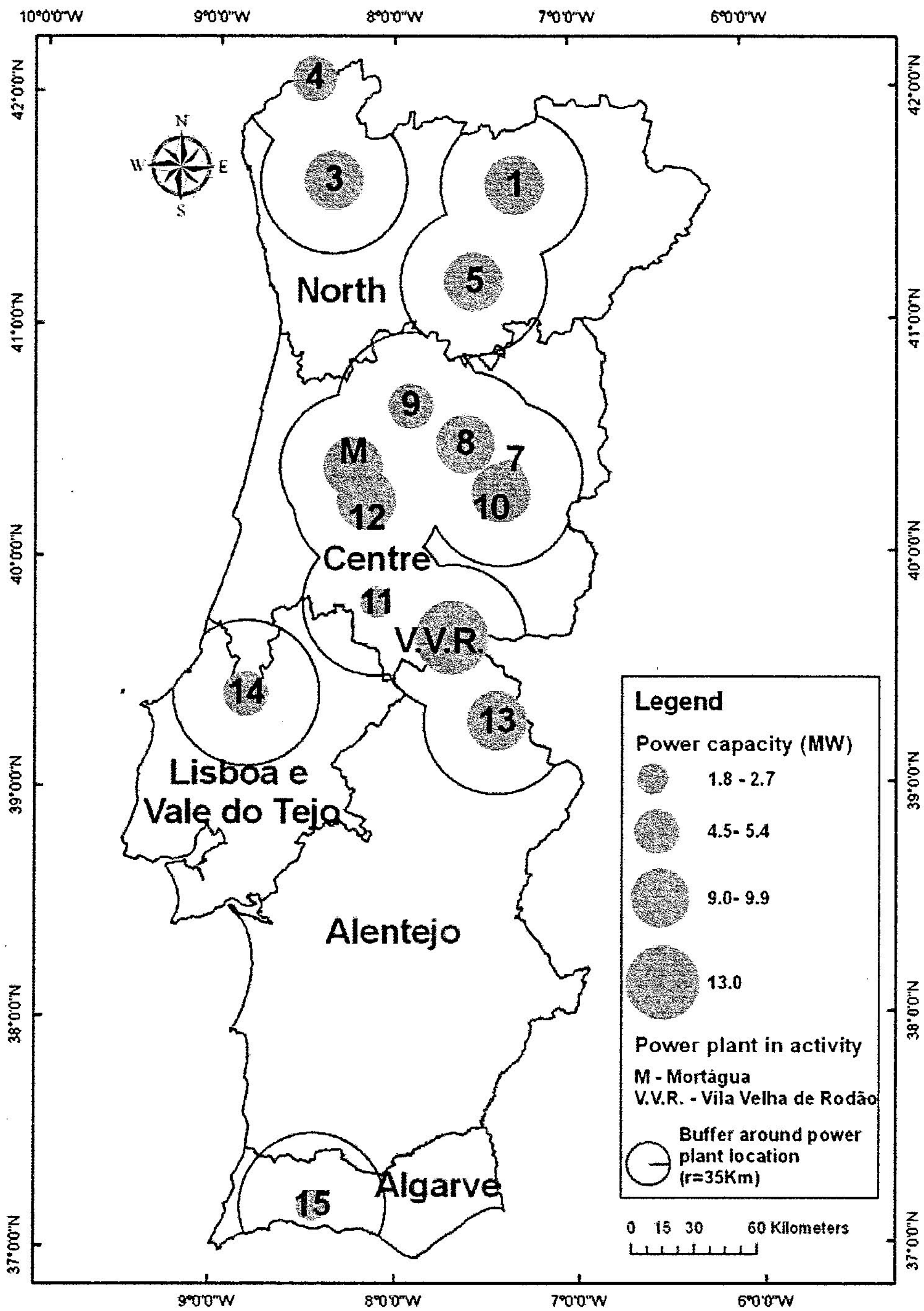

Fig. 2. Power plants location with the identification of the NUT II sub-regions boundaries, and the optimum biomass supply area (R = 35 km).

$$Q_B = \frac{\psi\pi R^2 (LHV)\eta_B}{t} \tag{9}$$

$$E = \frac{\psi\pi R^2 (LHV)\eta_B\eta_{CO}}{t} - Q_D \tag{10}$$

$$R_O = \left(\frac{3(C_{ls}N)}{\psi\pi C_{ts}}\right)^{\frac{1}{3}} \tag{11}$$

$$R_O = \left(\frac{2\alpha}{\beta}\right)^{\frac{1}{3}} \tag{12}$$

Thus, the optimal cost of wood waste at source $(C_{WS})_O$ (maximum affordable fuel cost obtained at the expense of a fixed capacity of the power plant, fixed by a radius R_O), is obtainable by substituting R_O into:

$$(C_{ws})_O = \alpha R_O^{-2} + \beta R_O + \gamma \tag{13}$$

Being:

$$\alpha = \frac{1}{\psi\pi}\left\{tQ_D p_d - tQ_D\left(f_e p_{ee} + f_e p_{ec}\frac{m}{t} - \frac{I_s[K_m f_a + 1]}{tf_a}\right) - (C_{ls}N)\right\},$$

$$\beta = -\frac{2C_{ts}}{3},$$

$$\gamma = (LHV)\eta_B\eta_{CO}\left\{f_e p_{ee} + \frac{m f_e p_{ec}}{t} - \frac{I_s[K_m f_a + 1]}{tf_a}\right\},$$

$$f_a = \frac{(1+i)^n - 1}{i(1+i)^n},$$

Table 3
Technical parameters for a wood fired plant.

Parameters			Unit
Power plant			
Running time	t	8000	h/year
Process steam demand (fully condensing plant)	Q_D	0	MW_{th}
Process steam demand (cogeneration plant)	Q_D	27.2	MW_{th}
Overall efficiency (fully condensing plant)	η	25	%
Overall efficiency (cogeneration plant)	η_{CO}	60	%
Boiler efficiency	η_B	80	%
Electrical export factor	*fe*	90	%
Biomass			
Nominal higher heating value	*LHV*	13.8	MJ/kg
Moisture content (wet basis)	*MCwet*	30	%

where *fe*, is the electricity export factor (% or decimal), *(Cws)o* the optimal unit cost of wood wastes (€ Cent/t). C_{is} the specific wage per capita of labour cost (€/person/year), C_{is} the unit cost of transportation (€/t/km), C_{WS} the unit cost of wood wastes (at the site of source) (e Cent/t), E the electricity output (MW_e) K_m the discount rate (%), *Is* the specific cogeneration investment (€/MW_e), Km the maintenance coefficient (% or decimal), *LHV* the lower heating value of fuel (MJ/kg), m the number of months (month), n the economic cogeneration lifetime (year), *N* the number of workers (person), pd the price of thermal energy (€ Cent/kWh), *pee* the price of electricity capacity, (€ Cent/MW/month), *pec* the price of electricity energy (€ Cent/kWh), Q_B the boiler thermal load (MW_{th}), Q_D the process heat demand (MW_{th}), *R* the radius of biomass supply area (km), R_0 the optimal radius of biomass supply area (km), t the annual cogeneration operating time (h), N_B the boiler efficiency (%), $O_{n_{co}}$ the cogeneration efficiency (%) and *Y* is the annual specific wood waste availability (t/ha/year).

The size of a power plant is directly influenced by the biomass availability, *Y* (t/ha/year) and the boiler efficiency (n_B) (Eq. (9)), which prescribes the biomass demanding area, with a radius of *R* km.

The optimum collection area (with radius *R*) depends on biomass-associated costs. According to [42,43] biomass-associated costs could be summarized by four major factors: harvesting, transportation, biomass origin (pure and dense stands, burnt areas, shrub areas with scattered trees) and characteristics (e.g. coniferous or hardwood, logs or branches). These factors can also vary according to several variables as:

Machinery: harvester, forwarder, crane, chainsaw; Transportation: tractor and trailer; lorry (2,4 or 6 wheel drive); Terrain morphology: slope, presence of rocks; Stands types - area, number of trees per hectare, age, species; Operation: tillage, final cut; Man-labour - cutter qualification, driver qualification, operation time; Biomass format: slash, wood and wood parts, chips, bundles, round wood.

This analysis is comprehensively presented by [42-44] in Pinus and Eucalyptus stands, at a local scale. Different methodologies and cost calculation models to calculate the different biomass-associated costs (feeling, bucking, forwarding, transport and chips) can be found in [45,46].

Given the impossibly of implementing a detailed analysis throughout the entire study area, the achieved optimum radius results from the knowledge of the general exploitation existent in Portugal. The considered biomass costs were calculated [42,43] for Eucalyptus stands at final harvest (1200 trees per hectare in average [31]) using a harvester and a forwarder for cutting and loading and a tractor and trailer for transportation, and Pinus stands at final harvest (600 trees per hectare in average [31]), using a chainsaw and manual loading and a lorry (two wheel drives) for transportation.

Based in the abovementioned studies [42-44] and on the available knowledge about the existent power plants in Portugal [40], the achieved R_0 was approximately 35 km for a 9 MW power plant.

After superimposing within a GIS the projected power plant locations with a land cover map, such as Carine Land Cover (CLC2006) [47], it was possible to realise that the biggest power plants are locate within forested areas. They require a large amount of biomass but they are surrounded by large amounts of biomass. Small power plants are located within less forested areas. They require small amount of biomass but biomass could be far way from the power plant location. Therefore, for the purpose of this study, a radius of 35 km for all the power plants was considered optimum (Fig. 2). Given the resource competition that will exist, we can assume that, independently of power plant size, the collection area will be the same for all power plants. On the other hand, as the goal of this work is to know the maximum power

Table 4
Total amount of theoretical and available residual biomass from maritime pine and eucalyptus, by NUT II sub-region.

NUT II Sub-region	Area (ha)	Forest area (ha)	B_d total (tonnes)	B_d (ton/year)	B_d (ton/ha)	B_d available (tonnes) (R = 35 km)	B_d available (ton/year) (R = 35 km)
Mean values achieved							
North	2128898.8	314400.0	4844028.5	273045.2	27.7	2610138.4	147126.7
Center	2367489.4	668000.0	11313251.0	569601.1	28.2	7693256.4	387341.1
L.V.T.	1170004.6	211100.0	2657602.4	190005.1	32.7	882065.7	63063.2
Alentejo	2727597.4	146100.0	836241.9	55658.5	14.0	116367.3	7745.2
Algarve	499487.9	17400.0	88337.3	8829.1	13.6	38929.7	3890.9
Total	8893478.1	1357000.0	19739461.0	1097139.0	23.2	8312368.8	609167.1
Maximum values achieved							
North	2128898.8	314400.0	6016987.5	342774.1	34.5	3242171.3	184699.1
Center	2367489.4	668000.0	13450714.0	723436.6	34.2	9146777.7	491952.6
L.V.T.	1170004.6	211100.0	3238889.0	247294.1	38.7	1074996.4	82077.6
Alentejo	2727597.4	146100.0	1197319.7	85551.2	18.3	166613.1	11904.9
Algarve	499487.9	17400.0	111278.6	11510.5	16.3	49039.8	5072.6
Total	8893478.1	1357000.0	24015188.8	1410566.5	28.4	10112895.4	775706.8
Minimum values achieved							
North	2128898.8	314400.0	3935660.0	224821.6	22.8	2120676.5	121142.0
Center	2367489.4	668000.0	9220289.3	461185.8	22.8	6269997.0	313616.4
L.V.T.	1170004.6	211100.0	2182931.3	156861.2	26.8	724521.1	52062.7
Alentejo	2727597.4	146100.0	479470.0	25795.8	9.8	66720.7	3589.6
Algarve	499487.9	17400.0	64777.9	5994.4	10.8	28547.3	2641.7
Total	8893478.1	1357000.0	15883128.5	874658.7	18.6	6688451.2	493052.4

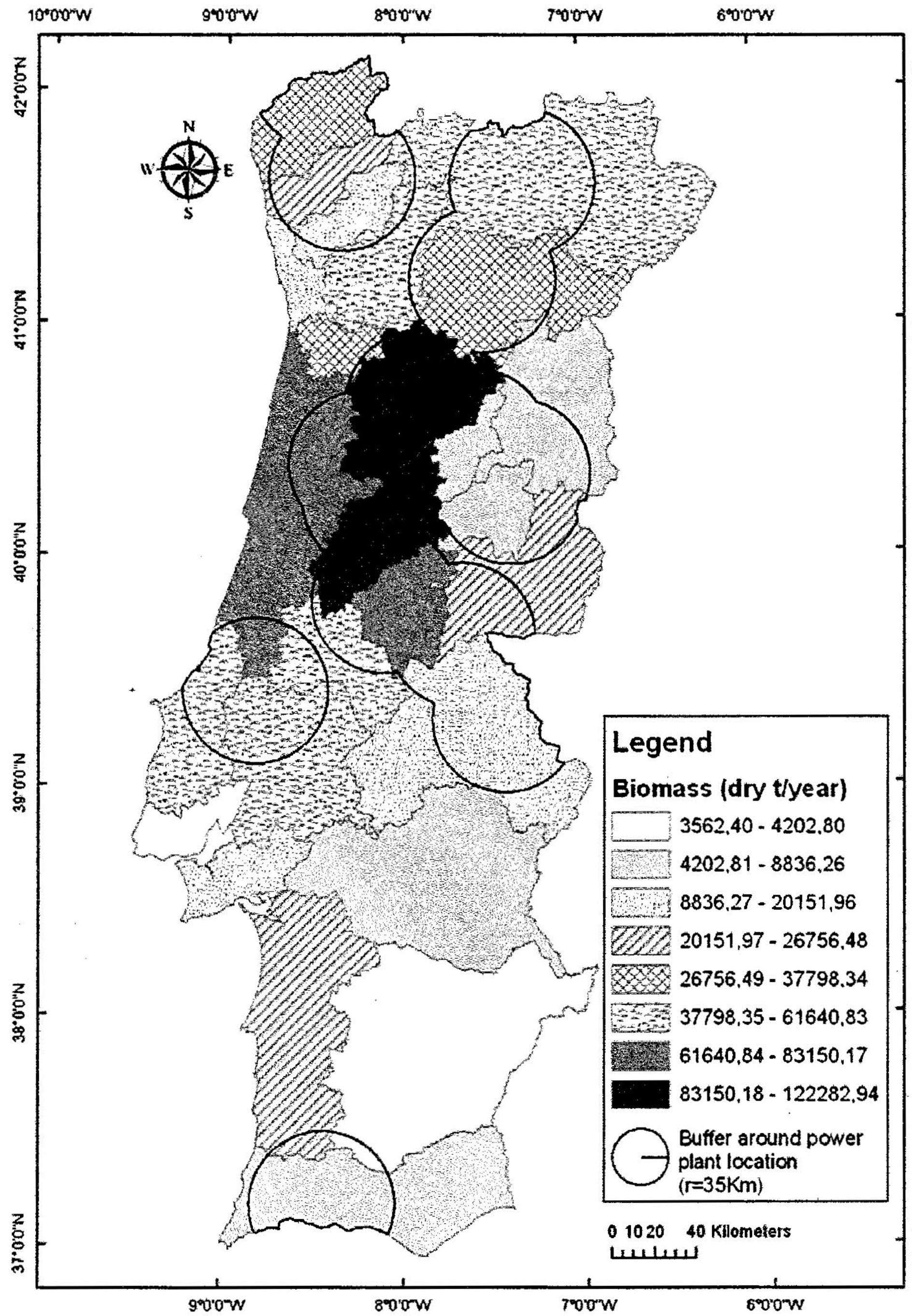

Fig. 3. Logging residues availability at regional scale (t/year). The biomass supply area (exploitable radius of 35 km) is identified.

capacity which should be installed in the best case, we consider the same optimum radius (35 km).

4. Results and discussion

The estimated total amount of biomass averages around 1.097 million dry t/year, with 579.91 thousand dry t/year from maritime pine and 517.23 thousand dry t/year from eucalyptus. However, these values range from 874.66 thousand dry t/year (473.70 thousand dry t/year of pine and 400.96 thousand dry t/year of eucalyptus) to 1.41 million dry t/year (673.54 thousand dry t/year from pine and 737.03 thousand dry t/year from eucalyptus). These results are presented in Table 4, grouped by NUT II regions (see Fig. 2).

When considering only an area of 35 km radius circle around each power plant (installed and planned), the exploitable biomass is considerably less. The estimated total amount of biomass averages 609.17 thousand dry t/year, and the maximum and minimum values are 775.71 thousand dry t/year and 493.05 thousand dry t/year, respectively.

The differences among estimates are due to the use of different biomass allometric equations (Tables 1 and 2). As the growth of trees varies among regions of Portugal with differences in environmental conditions, region-specific equations were required. Furthermore, some equations directly quantify dry biomass and others quantify wet biomass, which then has to be converted by a multiplicative dry factor.

The biomass availability maps, presented in Figs. 3 and 4, show the spatial distribution of biomass by the *NUT* III regions. The higher quantities of logging residues generated per year of maritime pine and eucalyptus are located at the northern and central regions. In the southern regions (Alentejo and Algarve) the biomass amount is significantly lower. This was expected since, in north and central Portugal. pinus and eucalyptus species are dominant, while in the south cork oak and holly oak are the most abundant species.

A GIS-based analysis allowed for assessment of both the theoretical maximum and the available potential power installation. In a future, the 15 power plants' (two installed and 13 planed) total power capability will be 108.4 MW (Table 5). Our results illustrated that the theoretical maximum power potential (Q_B) of fully condensing power plants is 131.4 MW. However, when calculation is performed using logging residue availability, for the maximum transport distance of 35 km, the real maximum power potential is just 73.0 MW. This means that the power plant capacity to be installed in the country (108.4 MW) is very high even if only logging residues from maritime pine and eucalyptus will be used as fuel source. However, only the region of LVT (see Fig. 2)

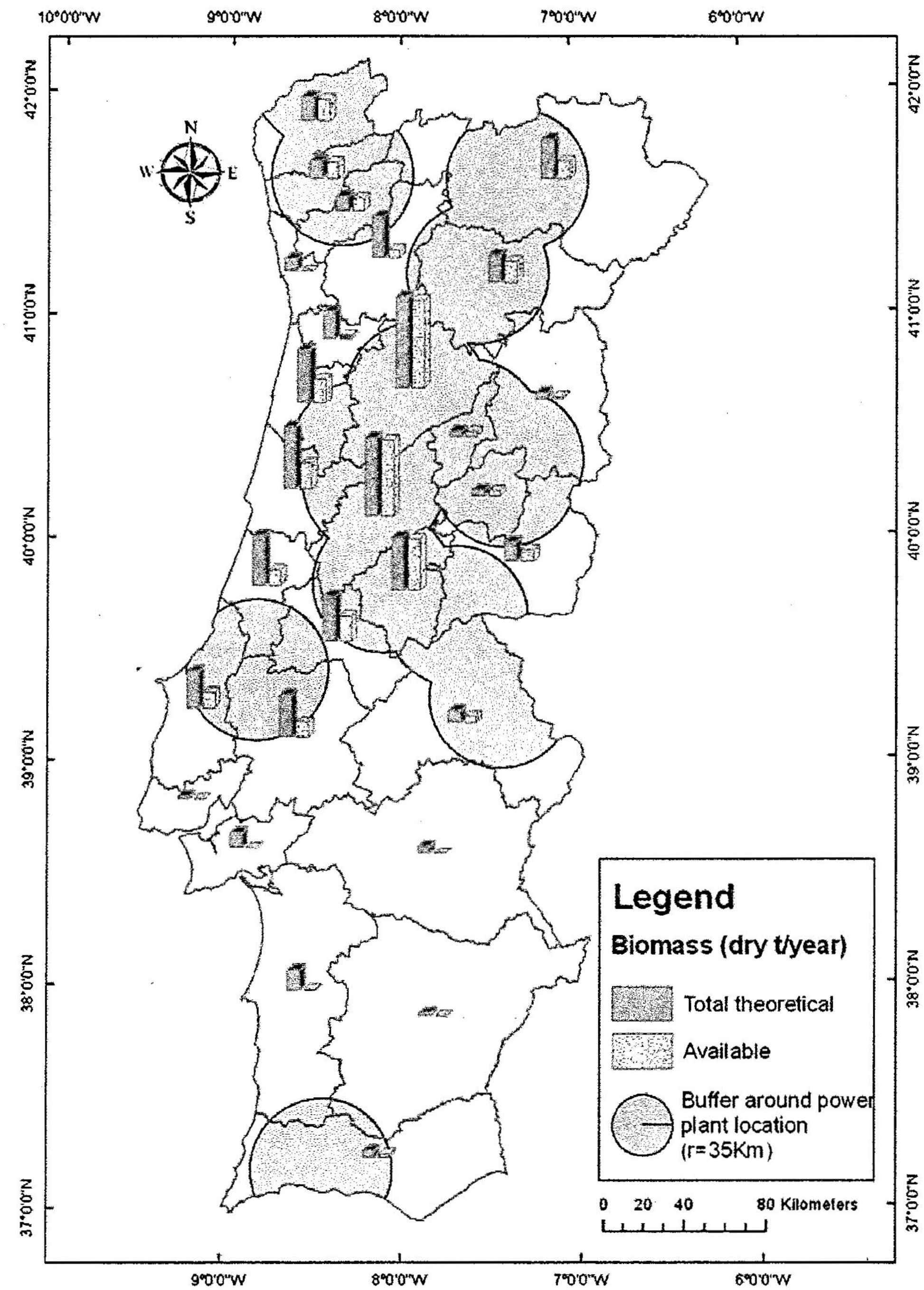

Fig. 4. Total theoretical and available (within a radius of 35 km) biomass potential supply.

Table 5
Potential power production of fully condensing plants and cogeneration plants.

Power plant	Installed capacity (MW)	Theoretical biomass (t/year)	Available biomass (t/year) ($R = 35$ km)	Fully condensing plant		Cogeneration plant	
				Maximum theoretical potential, Q_B (MW)	Maximum available potential ($R = 35$ km), Q_B (MW)	Maximum theoretical potential, Q_B (MW_{th})	Maximum available potential ($R = 35$ km), Q_B (MW_{th})
1	9.9						
3	9.0						
4	4.5						
5	9.9						
North	33.3	273045.24	147126.69	32.7	17.6	78.5	42.3
7	1.8						
8	9.0						
9	4.5						
10	9.0						
11	2.7						
12	9.0						
M	9.0						
VVR	13.0						
Center	58.0	569601.1	387341.1	68.2	46.4	163.8	111.4
13							
Alentejo	9.0	55658.5	7745.2	6.7	0.9	16.0	2.2
14							
LVT	5.4	190005.1	63063.2	22.8	7.6	54.6	18.1
15							
Algarve	2.7	8829.1	3890.9	1.1	0.5	2.5	1.1
	108.4	1097139.0	609167.1	131.4	73.0	315.4	175.1

could possibly supply the demand (7.6 MW) using only this fuel source.

This problem could be overcome by the use of second-generation power plants that use cogeneration. Results from GIS-based analysis enabled us to estimate a theoretical maximum and a real maximum power potential of 315.4 and 175.1 MW_{th}, respectively. However, even using second-generation power plants the Alentejo and Algarve regions do not produce enough forest biomass and will need other fuel source to supply their biomass needs.

5. Conclusions

Our results, regarding logging residues availability and future demand of biomass for energy production, enabled identification of the most suitable regions for increasing forest fuel usage.

In this study, biomass available quantities were estimated with respect to the optimum transport allocation areas. However, it is important to take in account that this biomass would not be fully used, as there exist technical limitations (e.g. slope) which limit the collection process. Although this study quantified logging residues existence, the annual biomass availability will depend on forest management, such as tree thinning and pruning, applied to a forest stand during its life cycle. Furthermore, because logging residue supplies depend on harvest activity (e.g. the exploitable residues are different for manual or mechanised harvesting), annual variation in residue amount must also be expected.

The present analysis was made for all power plants as a whole, considering the same collecting area (35 km radius) for all, but removing the overlapping areas. However, as the power plants will have different power capability and different ownership, in practice the biomass needs calculation must be made for each one separately. Furthermore, according to competition rules, the collection area radius will overlap, in particularly in the central region. As a consequence, competition for resources within an area, will affect biomass acquisition costs, leading to enlarged collection area radii. Even considering the best estimates, amounts of biomass will strongly limit the potential energy conversions, as the demand of installed power is very high.

Power plant location was not designed according to local needs of energy or according to local biomass availability, but according to energy transformers' station location, were energy could be injected in Portuguese energy network. Following [48] the resolution of an optimization model, addressing constrains (cost for supply of biomass, operation of production plants, investment in plants, and transportation of biomass) would have been essential to generate the optimal locations of power plants.

In this research we did not explore other vegetation biomass sources, which could have a strong contribute to biomass supply. These other sources are: the biomass from stands under grove bush, shrub land and shrubs growing in burnt areas. These types of biofuel are very significant and cannot be discarded, as 1.8 million hectares are shrub land [19] and 3.1 million hectares [49] are burnt areas (1.5 million hectares from shrub land and 1.6 million hectares from stands), just in the 2001-2006 period, which can generate millions of dry tonnes of biomass each year. A third important biomass source is the agricultural sector, where the residues from vineyard thinning, wine industry, olive groves and fruit trees orchard pruning, olive pulp remaining from olive oil production, etc., can have a considerable exploratory interest.

Portugal has a high biomass potential which can be used in energy production, although it is already used by pulp, plywood and fibreboard industry. The use and probable competition for the same biomass resource requires special concern, to avoid the excess of exploitation, and consequent disequilibrium of ecosystems.

This case study does not end here, as it continues to undergo new surveys and computer calculations, which will be reported in due course.

References

[1] Council of the European Union. Presidency conclusions of the Brussels European Council 8/9 March 2007. Brussels; 2 May 2007.
[2] Commission of the European Communities. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - 2020 by 2020 - Europe's climate change opportunity. COM(2008)30 final. Brussels; 23 January 2008.
[3] Commission of the European Communities. Communication from the Commission to the European Parliament, the Council, the European

Economic and Social Committee and the Committee of the Regions. Second strategic energy review - an EU energy security and solidarity action plan. COM(2008) 781 final. Brussels; 13 November 2008.

[4] Commission of the European Communities. Communication from the Commission. Energy for the Future: Renewable Sources of Energy. Green Paper for a Community Strategy. COM(96) 576 final. Brussels; 20 November 1996.

[5] European Commission. Communication from the Commission. Energy for the future: renewable sources of energy. white paper for a community strategy and action plan: COM(97)599 final. Brussels, Belgium; 1997.

[6] European Commission. Green Paper: Towards a European strategy for the security of energy supply. COM(2000)769 final, Brussels; 2001.

[7] European Commission. Directive of the European Parliament and the Council on the promotion of electricity produced from renewable energy sources in the internal electricity market, Directive 2001/77/EC, Brussels, Belgium; 2001.

[8] Resolucao do Conselho de Ministros no. 154/2001 de 27 de Setembro. Programa E4. Eficiencia Energetica e Energias Endogenas. Ministerio Da Economia. Lisboa; 2001.

[9] Resolucao do Conselho de Ministros no 63/2003. Diario da Republica - l Serie-B, No 98, 28 de Abril de; 2003.

[10] Resolucao do Conselho de Ministros no 169/2005. Diario da Republica - l Serie - B No 204 - 24 de Outubro de; 2005.

[11] Energia e Alteracoes Clirnaticas, Mais investimento, melhor ambiente. Ministerio da Economia e da Inovacao. Lisboa; 2007. p. 32.

[12] Resolucao da Assernbleia da Republica no 40/2007. Diario da Republica, 1.a serie - No.159 - 20 de Agosto de; 2007.

[13] European Commission. Green Paper: Towards a European strategy for the security of energy supply. Technical Document, Brussels; 2002. p. 68.

[14] Commission of the European Communities. Communication from the Commission. Biomass action pian. COM(2005) 628 final. Brussels; 2005.

[15] European Commission. Commission staff working document Annex to the Communication from the Commission. Biomass action plan. Impact Assessment COM(2005) 628 final; 2005.

[16] DGGE. Estrategia National para a Energia. A criacao de uma rede de Centrais de Biomassa dedicadas. Direccao Geral de Geologia e Energia: 2006.

[17] Commission of the European Communities. Communication from the Commission. The support of electricity from renewable energy sources. COM(2005) 627 final. Brussels; 7 December 2005.

[18] Rivas-Martinez, Diaz S, Penas A Bioclimatic map of Europe. Bioclimates. Cartographic service. Spain: University of Leon; 2004.

[19] DGRF. Resultados do Inventario Florestal Nacional 2005/06. Planeamento e Estatistica. Direccao Geral dos Recursos Florestais. Ministerio da Agricultura do Desenvolvimento Rural e das Pescas. lis boa; 2007.

[20] Berndes Coran, Hoogwijk Monique, *van* den Broek Richard. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenergy 2003;25:1-28.

[21] Hoogwijk M, Faaij A, Van den Broek R. Berndes G, Gielen D, Turkenburg W. Exploration of the ranges of the global potential of biomass for energy. Biomass Bioenergy 2003;25:119-33.

[22] European Commission. BIOMASS - Green energy for Europe. Luxembourg: Office for Official Publications of the European Communities; 2005. p. 46.

[23] WESST. Wood Energy Resources. Module 5. Wood energy supply system training; 2008. <http://www.wesst.com/> (verified 17.09.08).

[24] BFIN. Biomass Resources. Bioenergy feedstock information network; 2008. <http.jjbioenergy.ornl.gov/> (verified 17.09.08).

[25] Easterly James L, Burnham Margo. Overview of biomass and waste fuel resources for power production. Biomass Bioenergy 1996;10(2-3).

[26] European Commission. BIOMASS: an energy resource for the European Union. European Communities, Programme "energy, environment and sustainable development". Office for Official Publications of the European Communities, Luxembourg. EUR 19424; 2000. p. 17.

[27] ADIV. Avaliacao da sustentabilidade do recurso florestal para avaliacao da viabilidade da insralacao de centrals terrnoelectncas a biomassa florestal na regiao Centro. ADIV-IPV, Viseu: 2006.

[28] UTAD. Avaliacao da sustentabilidade do recurso florestal para avaliacao da viabilidade da instalacao de centrais termoelectricas a biomassa florestal na regiao Norte. UTAD, Vila Real; 2006.

[29] Arthur D. Little International, Inc. Residues florestais para producao de energia em Portugal. Ed. Tecninvest, SARL; 1985.

[30] Silva R. Tavares M Pascoa F. Residual Biomass of Forest Stands. *Pinus pinaster* Ait. *and Eucaliptus globulus* Labill. Aetas n 5, 10 Congresso Florestal Mundial, Paris; 1991.

[31] Domingos L Estimating net primary production in *Eucalyptus globulus* and *Pinus* pinaster ecosystems in Portugal. PhD thesis, England: Kingston University; 2005.

[32] Barreto L.s. Pinhais Bravos. Ecologia e Gestao. Lisboa: Departamento de Engenharia Florestal, Universidade Tecnica de Lisboa, Instituto Superior de Agronomia; 1995.

[33] Fabiao AM. Contribuicao para o estudo da dinamica da biornassa e produtividade prima ria Iiquida em eucaliptais, lis boa, Portugal: Tese de Doutoramento. Universidade Tecnica de lisboa, Instituto Superior de Agronomia; 1986.

[34] Tome M. lnventariacao de recursos florestais. Caracterizacao e rnomtorizacao de povoamentos florestais e mates. Publicacoes GIMREF, TP 2/2007, vol. n. lisboa: Universidade Tecnica de lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais; 2007.

[35] Faaij, Andre Pc. Bio-energy in Europe: changing technology choices. Energy Policy 2006;34:322-42.

[36] Breeze P. The future of global biomass power generation. The technology, economics and impact of biomass power generation. london: Business Insights ltd.; 2004.

[37] Prasertsanb S, Krukanonta P. Implications of fuel moisture content and distribution on the fuel purchasing strategy of biomass cogeneration power plants. Biomass Bioenergy 2003;24:13-25.

[38] Krukanonta P, Prasertsanb S. Geographical distribution of biomass and potential sites of rubber wood fired power plants in Southern Thailand. Biomass Bioenergy 2004;26:47-59.

[39] Fiala M, Pellizzi G, Riva G. A model for the optimal dimensioning of biomass-fuelled electric power plants.J Agr Eng 1997;67:17-25.

[40] Central de Biomassa de Mortagua: 2009. <http://www.energiasrenovaveis.com/DetalheEstados.asp?lD_conteudo=22&ID_area=2&lD_sub_area=37> (Veritied 05.11.2009).

[41] Voivontas D, Assimacopoulos D, Koukios EG. Assessment of biomass potential for power production: a GIS based method. Biomass Bioenergy 2001 ;20:101-12.

[42] Carinhas,Joana CV. A study on eucalyptus residual biomass exploitation. MPhii thesis, Portugal: UTAD, Vila Real; 2006.

[43] CBE - Portuguese Centre for Biomass and Energy. Evaluation of associated costs to forest residual biomass economic exploitation; 2009. <http://www.drapc.min-agricultura.pt/base/geral/files/avaliacao_custos_ap roy _biomassa.pdf>.

[44] Spinelli Raffaele. A Decision support system for assisting harvesting system choice in eucaliptus spp fast growing short rotation plantations. PhD College of life Sciences, University College Dublin, National University of Ireland, Dublin; 2006. 115p.

[45] Leduc S, Lundgren J, Franklin 0, Dotzauer E. Location of a biomass based methanol production plant: a dynamic problem in northern Sweden. Appl Energy 2010;87:68-75.

[46] Kinoshita Tsuguki, Inoue Keisuke, Iwao Koki, Kagemoto Hiroshi, Yamagata Yoshiki. A spatial evaluation of forest biomass usage using GIS. Appl Energy 2009;86:1-8.

[47] IGP, 2009, CLC2006 - Cartogratia CORINE Land *Cover* 2006 para Portugal Continental; 2009. <http://www.igeo.pt/gdr/projectos/c1c2006/> (verified 15.99.09).

[48] Leduc S, Natarajan K, Dotzauer E, McCallum I, Obersteiner M. Optimizing biodiesel production in India. Appl Energy 2009;86:125-31.

[49] DGRF. Estatisticas dos incendios florestais, Totais Nacionais (1980-2006). Direccao geral dos Recursos Florestais. Ministerio da Agricultura do Desenvolvimento Rural e das Pescas: 2007.