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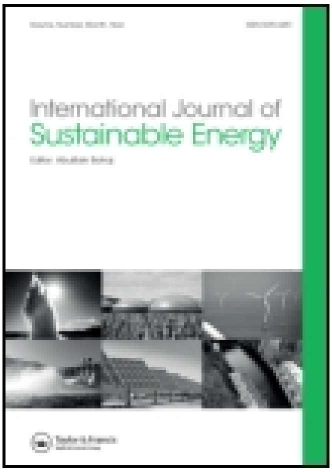

International Journal of Sustainable Energy
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gsol20

Optimisation of the regional energy supply network: a multi-objective analysis in the province of Florence (Italy)

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Published online: 25 Jun 2013.

To cite this article: I. Bernetti, S. Sacchelli, V. Alampi Sottini, N. Marinelli, E. Marone & S. Menghini (2014) Optimisation of the regional energy supply network: a multi-objective analysis in the province of Florence (Italy), International Journal of Sustainable Energy, 33:6, 1076-1089, DOI: 10.1080/14786451.2013.811412

To link to this article: http://dx.doi.org/10.1080/14786451.2013.811412

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International Journal of Sustainable Energy, 2014
Vol. 33, No. 6, 1076–1089, http://dx.doi.org/10.1080/14786451.2013.811412

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(*Received 31 January 2013; final version received 24 May 2013*)

This work presents an integrated method for the optimisation of a regional wood-energy supply network. The model is based on a scalar system that comprises a demand point (district heating plants (DHP)) and bio-energy sources (supply basin (SB)), each of which is related to a biomass terminal. The objective of optimisation is based on both technical-logistics and environmental parameters. An SB is defined by the anisotropic weighted Voronoi tessellation methodology. The parameters are then aggregated to a multi-objective analysis that includes the optimisation of variables and compromise programming approach. Results permit the identification of the best supply chain organisation and the determination of the agro-forest energy districts where rural policy and intervention could be applied. The model was tested in the province of Florence (central Italy) to depict efficient scenarios for the fuelling of DHPs.

Keywords: biomass logistic; Voronoi tessellation; multi-objective programming; agro-forestry districts

1. Introduction

According to European policies, biomass can be considered one of the key renewable energy sources (European Commission 2012) as its use to generate heat reduces emissions of greenhouse gases compared to the use of fossil fuels. However, the dispersed nature of biomass resource involves complex transportation problems within the supply chain (Williams and Larson 1993; Zhang, Johnson, and Sutherland 2011). In this framework, a practical and efficient regional energy supply network (RESN), which could be defined as the whole logistics of the bio-energy chain in a specific area, is needed. The design of an efficient RESN is a difficult task, as it must jointly consider logistic, economic, social and environmental aspects. In this work, the organisation of RESN is based on a scalar system that comprises the demand point (district heating plants – DHPs) and bio-energy sources (supply basins – SBs). In addition, a methodology able to aggregate SBs to define regional energy clusters (RECs) suitable for the implementation of biomass terminals (BTs) was defined. In fact, a literature analysis highlights that to meet the increasing bio-energy demand and to ensure its continuous supply, it is necessary to optimise the wood-energy chain by including BTs (Kanzian et al. 2009) (Figure 1). The main aims of BTs are the storage and the processing of woody biomass for energy purposes (De Mol et al. 1997). In particular, in mountainous areas and in central and northern European countries, BTs serve as stock reserves

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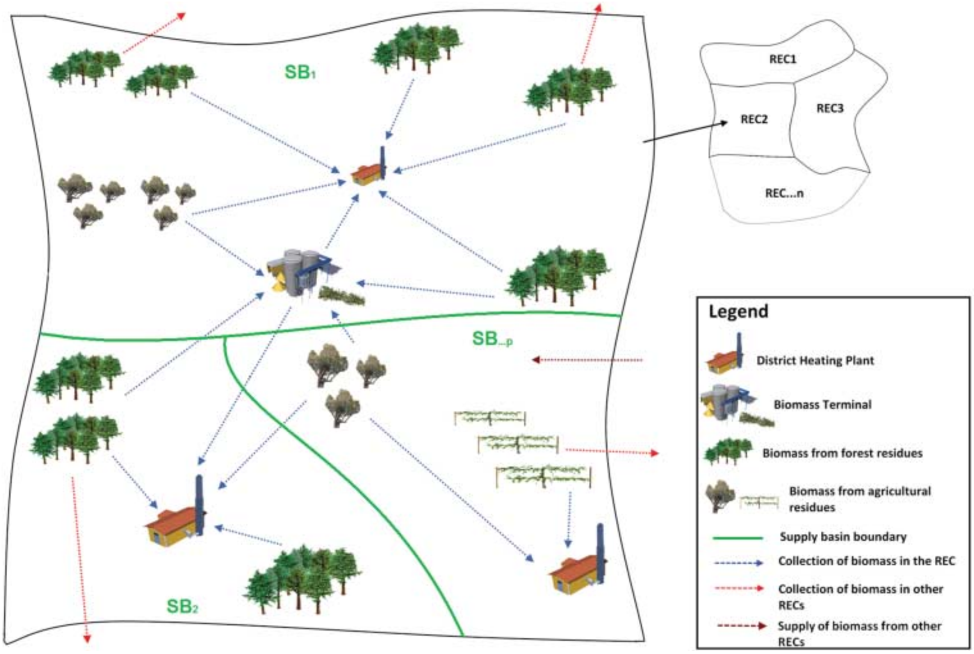

Figure 1. Example of RESN.

of biomass during winter and spring seasons (Gronalt and Rauch 2007). In general, BTs could (i) provide fuel wood, woodchips, other biomass fuels and energy services, (ii) safeguard the supply security and quality standards (fuel quality, provision of services, etc.) and (iii) improve the logistic of the RESN (Loibnegger and Metschina 2010).

Mathematical models and operational research have been largely adopted in the design of efficient bio-energy chains with respect to the optimisation of biomass transport. A first typology of research, based on simulation models (Hall, Gigler, and Sims 2001; Sokhansanj, Kumar, and Turhollow 2006; Mobini, Sowlati, and Sokhansanj 2011), aimed at the design and management of the biomass supply chain. Other researchers developed optimisation models to determine the optimal material flow, transportation, storage and chipping location of energy systems, mainly heating plants (Eriksson and Björheden 1989; Möller 2003; Freppaz et al. 2004; Gunnarsson, Rönnqvist, and Lundgren 2004; Kanzian et al. 2009; Van Dyken, Bakken, and Skjelbred 2010). Eriksson and Björheden developed a model with decision variables related to storage and chipping location for a heating plant. Gunnarsson, Rönnqvist, and Lundgren (2004) developed a mixed integer programming model for the tactical-strategic supply chain management of forest fuel used in a heating plant in Sweden by focusing on supply procurement decisions rather than on the production process. The authors also introduce a multitemporal model of the bio-energy chain. The model developed by Kanzian et al. (2009) included 16 combined heat and power plants and eight BTs in Austria.

Several scientific contributions show a series of analyses based on the geographic information system (GIS) and related to the optimal allocation of biomass. Moller and Nielsen (2007) consider the optimal allocation of wood chips in relation to the minimisation of the transportation costs of the wood fuel from the forest areas to the end users (district heating systems or individual households for the production of thermal energy or cogeneration). Panichelli and Gnansounou (2008) developed the BIOAL analysis algorithm to simulate the allocation of forest biomass into two roasting plants. In the paper, the algorithm allowed for the definition of a logistics of the chain that was able to minimise the transportation costs through the detection of the optimal demand localisation up to its saturation. A similar logistics of the chain can be found in a paper by Frombo et al. (2009) where a model for the allocation of biomass in plants for the production of thermal energy through a mixed nonlinear programming methodology, which was able to introduce environmental constraints, was developed.

Optimum locations of bio-energy plants were studied in Schmidt et al. (2010) with a case study in Austria. Sultana and Kumar (2012) use the GIS to determine optimal locations, sizes and number of bio-energy facilities (pellet plants) in Alberta (Canada) while optimising the transportation cost.

Lam, Varbanov, and Klemes (2010a, 2010b, 2011) address the problem of minimising the carbon footprint (CFP) generated by the production processes related to agro-energy supply chains using a P-graph algorithm capable of identifying the interconnections among supply, demand and optimal allocation of by-products of the energy supply chain in such a way that the CO2 emissions in the production processes are minimised. The methodology is developed on a model of mixed integer linear programming – (MILP), which is capable of evaluating the cost-effectiveness of different decision alternatives (construction of new roads, changes in fuel prices, etc.). Bernetti, Ciampi, and Sacchelli (2011), through the use of the MILP technique, identify a methodology for minimising the CFP in the wood energy chain in an area of central Italy.

Within this context, regarding the optimal allocation of bio-energy resources, the examined literature shows that the following issues are still unsolved. First, with respect to the energetic-environmental perspective, an efficient methodology is not provided for the definition of SBs (Figure 1). Recently, though Yu et al. (2012) used Thiessen polygons (Voronoi diagram) for the definition of biomass sub-collection regions, these regions are designed in an anisotropic geographical space that does not take into account the critical geo-morphological characteristics for minimising the costs of both the collection and the carbon emissions related to the transport of biomass. In addition, according to the knowledge of these authors, multiple objectives models (considering jointly logistic, socio-economic and environmental aspects) for the optimisation of the wood energy chain in a spatially explicit area have not yet been used because the presence of multiple objectives and spatialised variables implies highly nonlinear models whose solutions are difficult to ascertain from a computational perspective. Recently, genetic/evolutionary algorithms (GAs/EAs) and biological evolution-based heuristic approaches have been deemed suitable for tackling the problem (Aerts, Van Herwijnen, and Stewart 2003). Additionally, non-classical heuristic approaches have also been found applicable to this problem.

In consideration of the discussed background, this paper aims to (i) implement a spatial model able to depict environmentally and logistically efficient SBs, taking into consideration the geo-morphological characteristics of the territory and (ii) apply a multi-objective (MO) RESN optimisation that is able to satisfy DHP bio-energy demand, based on technical-logistic and environmental parameters and on the GAs/EAs approaches.

The approach adopted in this paper, which is described in detail in Section 2, is developed in two phases. In the first phase, efficient SBs are depicted. SB efficiency is quantified in terms of the biomass transport distance required to minimise carbon dioxide emission from the woodchip source to DHP. In the second phase, a geo-referenced MO redistricting model is applied to generate several REC plans based on different sets of management and environmental objectives. Each REC plan evaluation is conducted taking into account the optimisation of a set of criteria.

In Section 3, the proposed methods are implemented in a case study (the province of Florence, located in central Italy) for the design of a RESN serving 282 new DHPs that are distributed in a scattered manner throughout the territory. The best RESN was evaluated using a pay-off matrix approach (Sumpsi, Amador, and Romero 1997). In the final section, the strengths and limits of the work are discussed, as well as the application phases for the implementation of the RECs.

2. Methods and material

The geographical formulation of the methodology requires the creation of a dedicated GIS based on the following maps: biomass inventory map, slope map, road network, and future DHPs map. The structure of the model is described in Figure 2. The first phase of the methodology aims to identify efficient SBs for each DHP in terms of minimisation of emissions from processing to biomass transportation. The accurate estimation of emissions at the local level is modelled through a raster map in which each cell is associated with the unit cost of crossing in terms of carbon emissions. The SB of the single biomass plant is identified through a tessellation algorithm, weighed on carbon emissions. In the second phase, the different SBs are aggregated to create RECs that are efficient from the logistic, environmental and economic perspective and suitable for the implementation of BTs. This phase is realised through an MO geographical planning model. The objectives of the models are:

(a) the optimisation of the size of the BT, identified on the basis of technical parameters that allow for the management of the BT by an economically efficient enterprise;
(b) the minimisation of the supply distances;
(c) the maximisation of the compactness of the RECs;
(d) the optimisation of the supply-demand balance within each RECs.

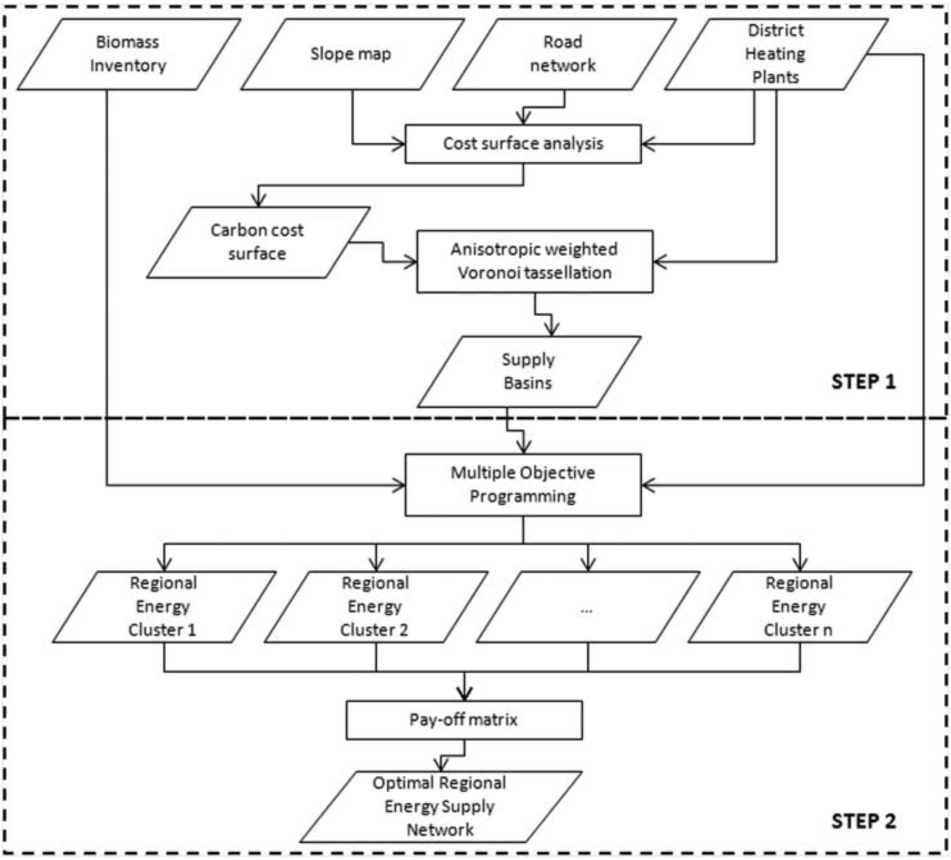

Figure 2. Flow chart of applied methodology.

Because the objectives are mutually conflicting, the most satisfactory RESN is identified through a multistep process based on the pay-off matrix technique (Sumpsi, Amador, and Romero 1997).

2.1. *Model description*

2.1.1. *Step 1: identification of the SBs*

The SBs for each DHP are defined to minimise CFP transport. Based on Thiessen polygons approach and to minimise total CFP, the area of influence around the biomass demand points is computed by Xtent algorithm (Renfrew and Level 1979), which implements anisotropic weighted Voronoi diagrams.

Following the notation of Renfrew and Level (1979) and Aichholzer et al. (1999), let a be a single pixel on a raster map representing the whole study area. S is a set of p points (DHPs) on anisotropic region T with $a \in T$. An anisotropic weighted Voronoi diagram associates each site $p \in \mathrm{S}$ with the SB_p (Equation (1)).

$$\begin{aligned} \mathrm{SB}_p &= \{a | I_p(a) > I_q(a) \quad \forall q \in S\} \\ I_p(a) &= w_{p^z} - k \cdot d_a, \end{aligned} \tag{1}$$

where q is a further DHP and I_p is the strength of influence that each p DHP has on any given location a in the current SB_p. The basic idea is that each a cell will be allocated to the p point that scores the highest I for that cell. The magnitude of I is determined by two terms, the centre weight (or size) w_p and the distance d_a. Obviously, a large DHP in close proximity will have the best chance to score the highest I (i.e. 'dominate' a cell). However, a very large DHP can also be dominant, even if it is farther away. The distance function on T is obtained by taking, for points p and a, the cumulative cost of transition (d_a) from a to p. The two coefficients z and k determine the balance between the size and distance of the DHP. The importance of distance increases in a linear manner while the importance of size increases exponentially (Aichholzer et al. 1999). Thus, a larger DHP will be competitively stronger in relation to smaller ones, even at an increased distance.

To obtain efficient SBs from an environmental perspective, the CFP is calculated as the total carbon dioxide emissions due to extraction and transport phases. The emitted CO_2 is computed as the sum of emission for each crossed a cell throughout a friction surface.

2.1.2. *Step 2: the MO model*

The aggregate of SBs depicts an optimal area (REC) for the possible implementation of BTs.

REC is defined as follows. Let SB_i represent ith SB and t_j represent the jth REC. A REC is a set of SBs:

$$t_j = \{\mathrm{SB}_{j'}, \mathrm{SB}_{j''}, \mathrm{SB}_{j'''}, \ldots\}. \tag{2}$$

The RESN plan R_p is a separation of the set of all SBs into a disjoined set of RECs of an exogenously given size as follows:

$$R_p = \{t_{j'}, t_{j''}, t_{j'''}, \ldots\}. \tag{3}$$

The MO optimisation depends on several criteria (technical-logistics and environmental ones) where criterion c_l of plan R_p can be defined as

$$c_l(R_p) = \mathrm{Crit}(t_j) \quad \forall t_j \in R_p \tag{4}$$

and where $\mathrm{Crit}(t_j)$ is the specific function of the criterion.

The examined objectives are described as follows:

(a) To create RECs as consistent as possible in terms of energy demand, thus making each REC as close as possible to the optimal size:

$$\begin{aligned} c_{\text{demand}}(R_p) &= \max[\text{demand}(t_j)] - \min[\text{demand}(t_j)] \quad \forall\, t_j \in R_p \\ \text{where} \quad \text{demand}(t_j) &= \sum \text{demand}(p_j). \end{aligned} \tag{5}$$

(b) To minimise the distance x_i between the biomass SB and the demand p, thus allowing the transport of woodchips to be as efficient as possible with respect to carbon emissions:

$$\begin{aligned} c_{\text{distance}}(R_p) &= \min[\text{distance}(t_j)] \quad \forall\, t_j \in R_p \\ \text{where} \quad \text{distance}(t_j) &= \sum \text{distance}(x_i) \quad \forall\, (SB, p) \in t_j. \end{aligned} \tag{6}$$

(c) To maximise the compactness of the RECs such that the transport of the biomass from the BT towards any DHP efficiently minimises the CFP. On a first analysis, the location of the BT has been determined to be in a barycentric position within the corresponding REC as follows:

$$\begin{aligned} c_{\text{compactness}}(R_p) &= \text{MAX}[\text{compactness}(t_j)] \quad \forall\, t_j \in R_p \\ \text{where} \quad \text{compactness}(t_j) &= 1 - \frac{\{\max[\text{lat}(t_j)] - \min[\text{lat}(t_j)]\}}{\{\max[\text{long}(t_j)] - \min[\text{long}(t_j)]\}} \cdot e \end{aligned} \tag{7}$$

with lat and long being latitude and longitude, respectively, and e representing the matrix contiguity of the SB. The mandatory contiguity among the SB in the same REC is expressed as

$$\sum_{\text{SB}_j} e(\text{SB}_{j'}, \text{SB}_{j^n}) = 1. \tag{8}$$

(d) To equalise the energy demand as much as possible with the energy supply within the REC, thus minimising the exchange of biomass among the different RECs:

$$\begin{aligned} c_{\text{balance}}(R_p) &= \min[\text{balance}(t_j)] \quad \forall\, t_j \in R_p \\ \text{where} \quad \text{balance}(t_j) &= \min\left[\sum \text{demand}(p_j) - \sum \text{supply}(\text{SB}_j)\right]. \end{aligned} \tag{9}$$

Additionally, to optimise each objective, the method of compromise programming (CP) (Zeleny 1973), which is based on the concept of trade-off compensation among the various objectives, was implemented to aggregate the different criteria. A compensatory and a non-compensatory approach were applied. Using the compensatory aggregation, the low level of an objective can be compensated by the high level of another objective. One of the most common compensatory operators is the sum of the normalised value of the objectives (Zimmermann 1996):

$$v(R_p) = \sum\nolimits_{\forall l} \overline{c_l(R_p)}, \tag{10}$$

where $\overline{c_l(R_p)}$ is the normalised value of the criterion 'evaluation of the plan'.

With the so-called 'non-compensatory' aggregation, the worst score among all of the criteria is taken into account and is considered as limiting. The most commonly used operator is the minmax (Flavell 1976):

$$v(R_p) = \max\{\min[\overline{c_l(R_p)}]\}. \tag{11}$$

Given the high nonlinearity of the model, the MO programming has been solved by applying the GAs/EAs-based metaheuristic method greedy randomised adaptive search (Mladenović et al. 2007) method, implemented in the BARD library (Altman and McDonald 2011) of the R-cran open-source environment.

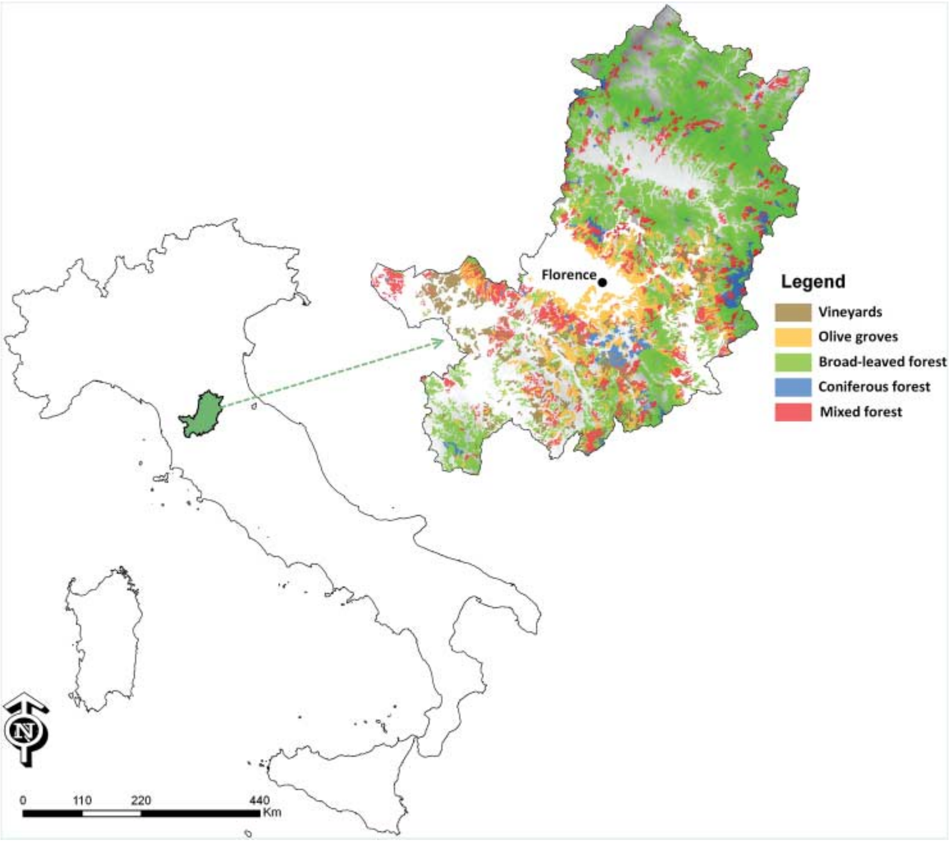

Figure 3. Study area.

2.2. *The study area and the data preparation*

The province of Florence covers an area of 3514 km^2 and has a population of 985,273 inhabitants. The agro-forest environment of the province is characterised by 1640 km^2 of forest area, mainly covered by deciduous broad-leaf. The presence of agricultural land cultivated with permanent crops is relevant. The olive growing areas reach 278 km^2, while in the Florentine Chianti the vineyards cover 166 km^2 (Figure 3). As a consequence, the potential supply of economically viable woodchips in the province of Florence comes from two main sources (i) forest residues from both deciduous (203,326 tons of dry matter) and high forests (52,300 tons of dry matter) and (ii) the residues from the pruning of vineyards and olive groves (103,600 tons of dry matter) (Bernetti, Fagarazzi, and Fratini 2004).

With respect to the demand for woodchips in the study area, a research conducted by Bernetti, Ciampi, and Sacchelli (2011) led to the identification of 282 potential new DHPs, which were selected through a multi-attribute analysis that identified the eligibility criteria for the installation of the plants (biomass supply, distance from roads, house density).

The territorial informative system realised for the development of the model is composed of the following databases: (a) biomass availability inventory for the province of Florence (vectorial format); (b) digital terrain model (raster format); (c) road system (vectorial format); (d) administrative boundaries (vectorial format); (e) geo-databases of proposed DHPs inclusive of the annual bio-energy demand; (f) Corine Land Cover Map (raster format).

In applying the model, the number (exogenous) of RECs to be identified was determined by dividing the total supply of available biomass with the optimal size of a BT, given the local operating conditions (Francescato et al. 2010). Using this procedure, it was possible to obtain a RESN consisting of 20 RECs.

For the application of a weighted anisotropic tessellation model, a friction raster map for the cost of crossing, with respect to carbon emissions and with a resolution of 100 m, was first calculated by combining the geo-databases of the biomass inventory, the road network and the DTM (Bernetti, Fagarazzi, and Fratini 2004). By using the map of friction, 282 maps of cumulative carbonic cost of transport (one for each DHP) were calculated. Once the tessellation was achieved, the biomass requirements of the DHP and the potential energy available inside the SB are associated with the polygons using a map overlay.

The resulting database was used for the formulation of the MO model and is suitable for the creation of RESN scenarios.

3. Results and discussion

Figure 4 shows the 282 DHPs and the relative SBs obtained using the Voronoi tessellation model. In the background, the map of friction is shown. As evident from an analysis of Figure 4, the basins' boundaries follow in a rather efficient way the points of maximisation of carbonic cost.

The various RESN scenarios were obtained by separately maximising each objective function from (a) to (d) (see Section 2.1.2) and by calculating the MO plans using the two methods of aggregation (compensatory and non-compensatory). Figure 5 shows the identified RESN scenarios.

Following the approach applied in Sumpsi, Amador, and Romero (1997), an efficient method for the analysis of the results of an MO model is represented by the pay-off matrix. Each row of the pay-off matrix shows the value (normalised) that is obtained for the different objective

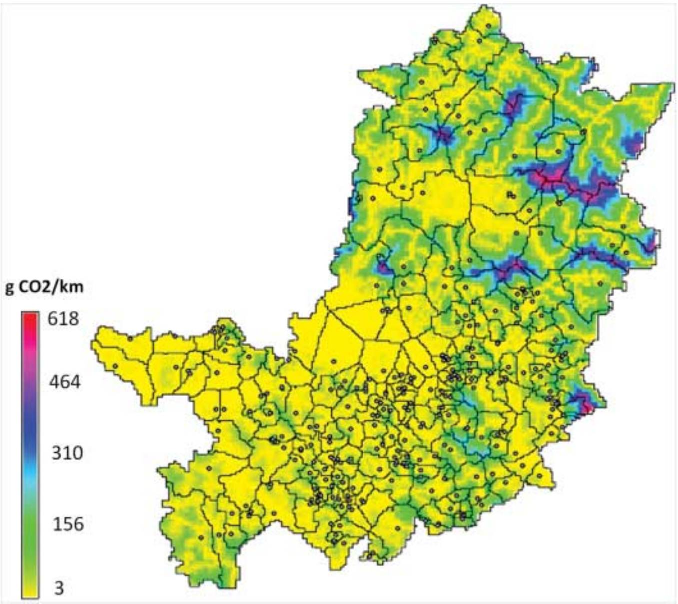

Figure 4. DHP localisation and delimitation of SBs.

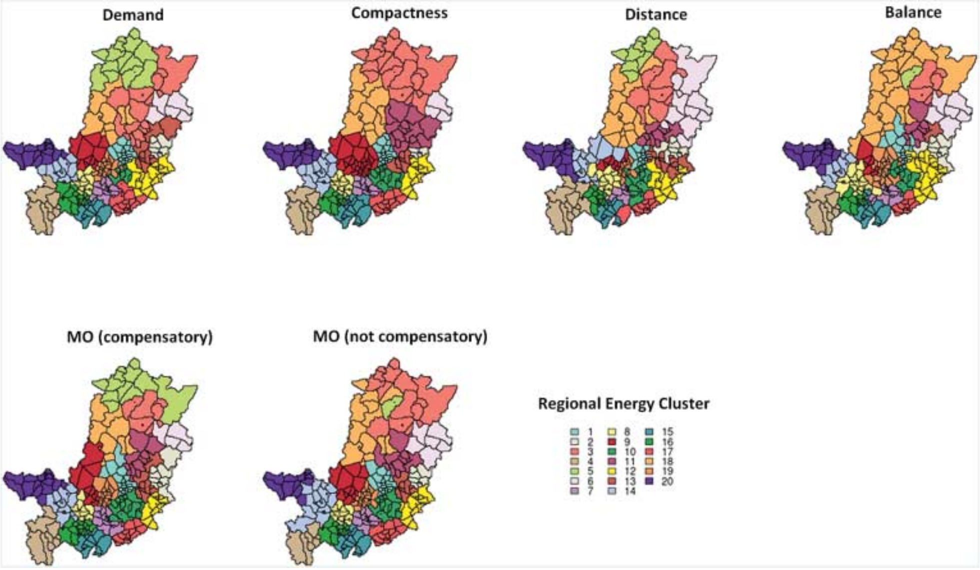

Figure 5. RESN scenarios.

Table 1. Normalised pay-off matrix.

R_p	Demand	Compactness	Distances	Balance
Demand	1.00	0.45	0.76	0.90
Compactness	0.08	1.00	0.70	0.00
Distance	0.69	0.00	1.00	0.82
Balance	0.00	0.19	0.00	1.00
MO (compensatory)	1.00	0.39	0.36	0.99
MO (not compensatory)	0.82	0.45	0.42	0.91

functions and the different criteria considered. Thus, through the matrix, it is possible to analyse the trade-off among the various objectives. Table 1 shows the pay-off matrix normalised in the interval [0,1] for the calculated R_p scenarios.

Table 1 highlights that the greater conflicts are those resulting from the objective of balancing supply and demand (balance) because the maximisation of this balance leads to higher penalties among other criteria, in particular, demand and distance. These two criteria, in fact, reach the minimum value for the set of calculated scenarios. On the other hand, the compactness criterion seems in contrast with the minimisation of the difference in demand size and in the balance of supply and demand. Finally, the minimisation of transport distances among the different SBs achieves the worst result with respect to compactness. The results of the pay-off matrix appear to be confirmed by a visual analysis of the solutions in the model (Figure 5). The conflicting structure of the model is attenuated in the solutions of compensatory and especially non-compensatory CP (Table 1 and Figure 5). Both solutions represent more balanced RESN scenarios and show that by sacrificing balance and demand criteria to a non-significant degree, important progress toward achieving the other goals can be obtained. The results further show that, on the whole, the criteria for choosing the best RESN are in stark contrast to each other. When excluding the optimisation scenario for energy balance while penalising the achieved results for the other criteria, it becomes crucial to analyse the different scenarios in detail. To do so, it is useful to consider that the evaluation criteria for the plans can be divided into two subsets as the two goals of balance and

Table 2. Analysis of the technical and logistic criteria in the various REC.

	Demand		Compactness		Distance	
REC (n°)	Demand (GJ year^1)	Suppy/demand	Demand (GJ year^1)	Suppy/demand	Demand (GJ year^1)	Suppy/demand
1	98,276	1.67	78,656	0.58	82,773	0.99
2	26,570	0.54	39,912	1.14	45,787	1.02
3	26,675	0.43	33,322	2.21	28,121	1.00
4	25,693	0.50	32,688	2.15	23,401	1.93
5	57,916	0.97	37,425	0.31	5676	0.83
6	39,792	0.74	53,312	2.16	42,226	1.67
7	82,724	1.39	38,848	0.90	54,971	1.02
8	106,228	1.81	117,376	0.66	107,292	0.76
9	38,907	0.67	32,110	1.01	58,884	0.66
10	37,617	2.49	88,378	0.66	45,480	0.76
11	33,074	0.54	47,963	1.23	31,805	1.43
12	113,994	1.95	81,692	0.68	168,349	0.62
13	72,536	1.20	106,089	0.50	15,427	1.14
14	49,848	0.86	62,591	1.28	36,109	1.25
15	54,647	0.93	60,501	0.76	61,898	0.99
16	53,730	0.91	45,976	0.89	43,072	0.99
17	64,390	0.91	35,945	1.28	33,042	0.95
18	38,717	0.43	52,316	2.33	89,899	1.87
19	89,378	1.53	68,372	0.46	140,190	0.68
20	35,192	0.49	32,435	2.26	31,503	2.32
Mean	57,295	1.05	57,295	1.17	57,295	1.14
Max	113,994	2.49	117,376	2.33	168,349	2.32
Min	25,693	0.43	32,110	0.31	5676	0.62

	MO (compensatory)		MO (not compensatory)	
REC (n°)	Demand (GJ year^1)	Suppy/demand	Demand (GJ year^1)	Suppy/demand
1	91,780	0.96	101,143	0.77
2	40,420	1.27	24,136	1.33
3	33,797	0.97	66,827	1.47
4	25,693	1.99	20,978	1.71
5	45,485	1.53	5,676	0.83
6	38,709	1.02	42,226	1.67
7	79,516	0.90	81,623	0.66
8	62,835	0.79	83,620	0.65
9	72,753	1.10	67,837	1.00
10	93,600	0.59	71,323	0.60
11	42,581	1.53	48,501	1.61
12	76,305	0.52	97,284	0.45
13	72,536	0.84	57,109	0.75
14	59,560	1.11	62,098	1.53
15	54,647	1.08	55,748	1.15
16	58,629	1.00	47,887	0.97
17	44,893	0.95	50,631	1.19
18	38,596	1.64	47,939	1.88
19	75,807	0.71	86,141	0.64
20	37,764	1.98	27,178	2.11
Mean	57,295	1.12	57,295	1.15
Max	93,600	1.99	101,143	2.11
Min	25,693	0.52	5,676	0.45

optimum size have a technical-logistic nature while the maximisation of the compactness and the minimisation of the distances have an environmental nature. The first, therefore, can lead to inefficiencies that impair the functionality of the RESN and, accordingly, the two goals must be analysed in detail in the various districts. Table 2 shows the details of the technical and logistic

Table 3. Unbundled pay-off matrix.

R_p	Compactness	Distance
Demand	0.45	0.76
Distance	0.00	1.00
MO (compensatory)	0.39	0.36
MO (not compensatory)	0.45	0.42

parameters for each REC in the case of RESN optimisation according to the criteria of demand, compactness, distance, MO compensatory and MO non-compensatory.

Considering the minimum and maximum values of the energy dimension and of the relationship between supply and demand, none of the five solutions shows unsolvable critical problems from the technical or economic perspective (Francescato et al. 2010). In fact, the maximum and minimum sizes fall within the parameters of design feasibility of a BT. With regard to the supply/demand budget; these limits may be listed as approximate deficits (up to 50%) or surpluses (not more than 200%) as shown by the underlined values in Table 2.

With regard to the budget deficits in the management of an REC (demand greater than supply), different strategies can be implemented such as (i) importing from an REC in budget surplus, (ii) using firewood currently intended for plants with low energy and environmental efficiency (fireplaces and traditional stoves), (iii) developing energy crops, (iv) designing district heating systems that require less energy. For the satisfaction of point (ii), the potential trade-offs at the local level regarding the different sources of wood for energy use should be analysed (Sacchelli, Fagarazzi, and Bernetti 2013). Point (iii) should be assessed according to the presence of suitable areas for the cultivation of short rotation forestry (Tenerelli and Carver 2012). The REC in budget surplus (supply greater than demand) may allocate the surplus for (i) export to deficit REC, (ii) non-energy uses of biomass (compost, wood-based panels), (iii) non-collection of biomass surplus.

By analysing Table 2, it is possible to highlight that the scenario maximising the compactness has 7 critical RECs out of 20 and may, therefore, be problematic. By deepening the analysis and excluding the scenario related to the maximisation of compactness, the two environmental parameters (compactness and transport distance) must instead be considered globally. Limiting the pay-off matrix to technically efficient solutions and to only environmental objectives (Table 3), it is evident that minimising the difference among the dimensions of RECs (demand) dominates (in a Pareto way) the other three solutions and that it, therefore, can be considered as the reference scenario for the design of an RESN plan.

4. Conclusions

The paper proposes a new model for the optimisation of the RESNs, developing an approach based on the technical-logistic and environmental optimisation of a scalar system consisting of demand points (bio-energy plants) and bio-energy resources (SBs) organised through a network of logistics infrastructure (BTs).

The optimisation model is applied in two stages. In the first stage, the SBs of the demand points are identified on the basis of CFP minimisation. This step was conducted by applying a Voronoi tessellation approach. The second phase is represented by a geographical MO model of regionalisation for the identification of RECs based on GAs/EAs approaches. Each scenario has been assessed according to the optimisation of the evaluation criteria and according to CP.

The model was applied to a real case in the province of Florence to create a RESN that served 282 DHPs in its design. The application showed that the methods used can efficiently identify geographical areas of biomass supply from the perspective of the minimisation of carbon emissions. In addition, the morphological characteristics of the territory and the road network can be considered. In the second phase, the SBs were aggregated to achieve efficient energy districts for the creation of BTs. In the province of Florence, the optimal size of a BT leads to the demand for 20 BTs and, thus, the need for 20 RECs. The perimeters of the 20 RECs were determined considering the objectives of optimum size, maximisation of compactness, minimisation of transport distance within the REC and optimisation of the supply–demand balance. Using pay-off matrix analysis, six different RESN scenarios were identified. The most satisfactory scenario in terms of compromise among the different objectives was the minimisation of the difference among RECs (demand). From the perspective of the operational management of the different BTs, it will be necessary to realise a detailed energy plan for each REC that takes into account (i) the operational steps for the implementation of the plan, (ii) the optimal localisation of the BTs, (iii) the analysis of the transport infrastructure required and (iv) the economic planning of the management company of the BTs. Some useful decision-making insights can be drawn from this study. First, the optimisation of the management of the RESN can occur using the GIS, which consider geographical, technical and logistic variables of the territory under analysis. Furthermore, the technical and environmental efficiency of the RESN is a complex matter as it depends on numerous objectives that must be considered simultaneously. The application of the implemented model allows for the quantification of the value of these objectives and the trade-off among them. The application has shown that, through sequential steps, the proposed method provides efficient information for the rational selection of the optimal scenario. Moreover, according to the geographical and logistic peculiarities of the studied area, policies and initiatives in the agro-energy sector can be calibrated for each REC. Another advantage of the proposed model is related to the possibility of the geo-visualisation of the achieved results. This last aspect may also facilitate the transfer of information to policy-makers and local stakeholders (Guo et al. 2005). Based on these insights, policy-makers may move forward in renewable energy policy formulation and evaluation.

The limits highlighted by the application are related instead to the static nature of the approach, which does not permit the assessment of possible increases in demand (e.g. new DHPs) and supply (e.g. new sources of biomass from dedicated crops). Moreover, further criteria and goals that address the social and environmental aspects (minimisation of the impact on the environmental multifunctionality related to the extraction of biomass that includes the effects on the local economy, changes in employment, etc.) should be considered. Finally, a possible future research study could address the identification of the most efficient locations of BTs within each REC.

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