Politecnico di Milano
Corso di Laurea Specialistica in Ingegneria per l’ambiente e il territorio
A.A. 2009 – 2010

IEE BioEnerGis project: planning biomass thermal conversion plants in Lombardy

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"Take care of the earth and of the water.

They have not been given us by our fathers,

but lent by our sons"

Kenyan nomad shepherds proverb

Introduction

Biomass represents a renewable energy source present in good quantity on European territory and national levels, particularly in Lombardy region. Their appropriate energy use could contribute positively to achieve the objectives set by the Kyoto Protocol, in Italy as in all the other nations of the European Union, and to contrast global warming and climatic changes, since the balance of GHGs production, typically CO_2, may be considered almost neutral. Furthermore, their local presence provides an opportunity to reduce energy dependence from non-European countries.

This work is part of the wider IEE (Intelligent Energy Europe) BioenerGIS project, promoted by European Union. This project intends to assess and coordinate the exploitation of biomass energy contribution in 4 sample regions within the Community: Lombardy, Northern Ireland, Slovenia and Wallonia.

In particular, the methodology exposed in this work was applied to Lombardy region in order to provide a good model sharable with all the other regions, whose peculiarities could be adapted case by case without substantially modifying the common method, with the goal to locate most suitable sites and to accommodate biomass energy conversion facilities. Through the realization of localization maps of new possible thermal or cogenerative plants, serving district heating networks, it will be possible to involve both the interest of public administrations and of private operators into a common action program, able to take into account the necessities of all the different stakeholders and all the possible financial and normative instruments. So, the attempt to introduce energy planning in the biomass exploitation is another main goal of this project, in order to avoid the realization of plants without any prior study to evaluate the actual availability of biomass on the territory and its energy need. Moreover the valorization of biomass use could start a process of environmental and social-economic improvement, such as the culture diversification, the recovery of abandoned soils, the maintenance of forests and job creation.

The whole European project is organized into 8 work packages (Figure 0.1) to be concluded within the end of 2011. More precisely, the work packages regard:

- WP1- Project management
- WP2- Potential biomass system
- WP3- Estimate of heat demand
- WP4- Identification of the configuration of the plants
- WP5- Development of a DSS (Decision Support System) with a GIS interface geared to define the areas suitable to the realization of biomass plants
- WP6- Support to the stipulation of local agreement through public and private partnership
- WP7- Dissemination of the results
- WP8- Activity of common dissemination

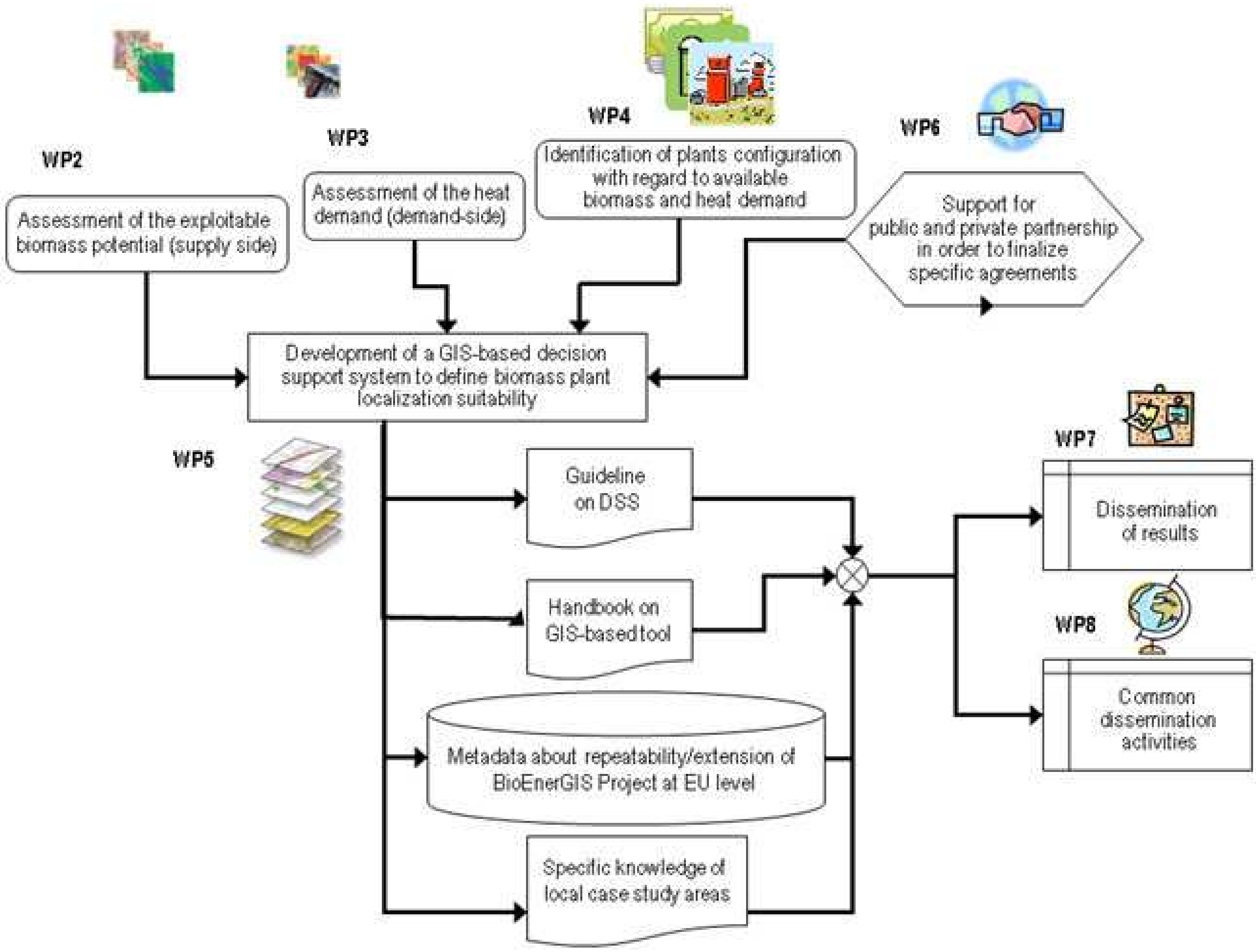

Figure 0.1. General scheme of IEE BioEnerGIS work projects.

The greatest part of the work described here and performed within Terraria srl belongs to WP5, while data referring to potential biomass (WP2), heat demand (WP3) and possible configuration of the plants (WP4) have been provided by

BioEnerGIS project partners. This work can be thought as divided into 4 subsequent operative steps (Figure 0.2). Raw data of biomass availability and heat demand referring to each municipality have been elaborated and assign to each single cell belonging to a grid that discretize the territory of Lombardy Region. Once data of biomass availability and of heat demand have been discretized and assigned, it has been possible to individualize suitable cells to the realization of a biomass conversion facility and to determinate its nominal thermal power. All the feasible plants have been later rated forming three several rankings adopting three different criteria: the supplying certainty criteria, the global pollutant emission criteria and the local one. In comparison with this greedy solution, several globally optimal solutions have been proposed in the hypothesis of short distribution chain of biomass, in order to underline possible similarities between the two different approaches or, on the contrary, the potential differences.

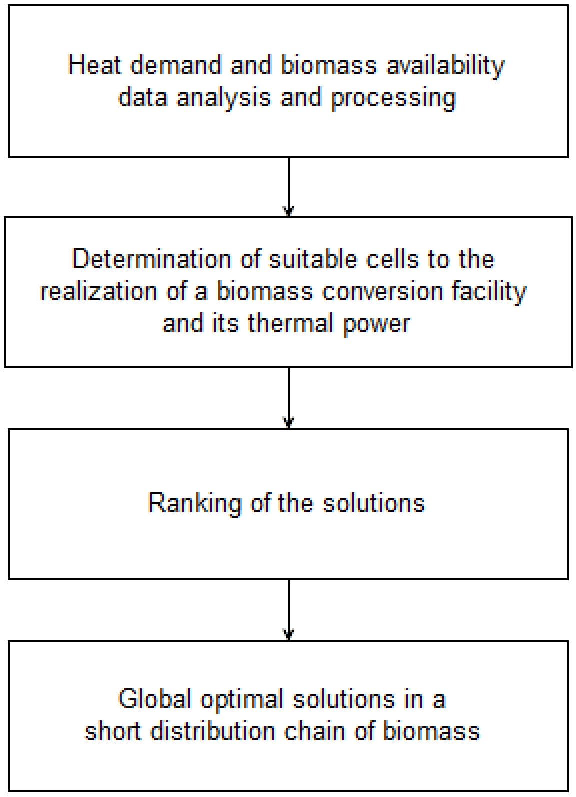

Figure 0.2. General scheme of the performed operative steps.

To reach BioenerGIS WP5 purpose three software instruments have been utilized: ArcGIS® tool was mainly used to elaborate heat demand and biomass offer data, while Fortran® was used in the following phase to individualize the suitable cells for the realization of conversion facilities and DH networks. In the last phase *What'sBest®* optimizer by Lindo Systems provided global optimal theoretical solutions to the problem in the hypothesis of short distribution chain of biomass.

In the specific, chapter 1 describes the heat demand and the biomass offer data, with a deepening to their specific categories, their characteristics and the period they refer; chapter 2 explains the ArcGis® elaboration data, necessary to dispose the data into the same territorial unit (i.e. cell of a grid). Chapter 3 initially introduces the method and the parameters used to identify all possible localizations of biomass conversion facilities and the corresponding HD network at regional level; then it shows the solution deriving from the implementation into a Fortran® executable file (i.e. Biopole) of the described method, exposing three different classification of the feasible plants and their localization deriving from the adoption of three different criteria. Chapter 4 reports several optimal solutions obtained through the use of an optimizer and different constraints on the minimal thermal power to be installed in a suitable cell, with a description of the domain, the variables and the parameters formalizing the problem of the localization. Finally Chapter 5 exposes the conclusion that could be drawn from the whole work, suggestions to possible deepening and further elaboration of the topic.

1. Data

The fundamental idea at the basis of the whole methodology behind IEE BioEnerGIS is the comparison between the presence of some heat demand within a limited area and the availability of enough biomass able to satisfy it, partially or completed, with its relative energy contents. This process is called agricultural-energy chain, and involves 3 important steps: to find the biomass, to transform it and to use its energy contents within the considered system (Figure 1.1).

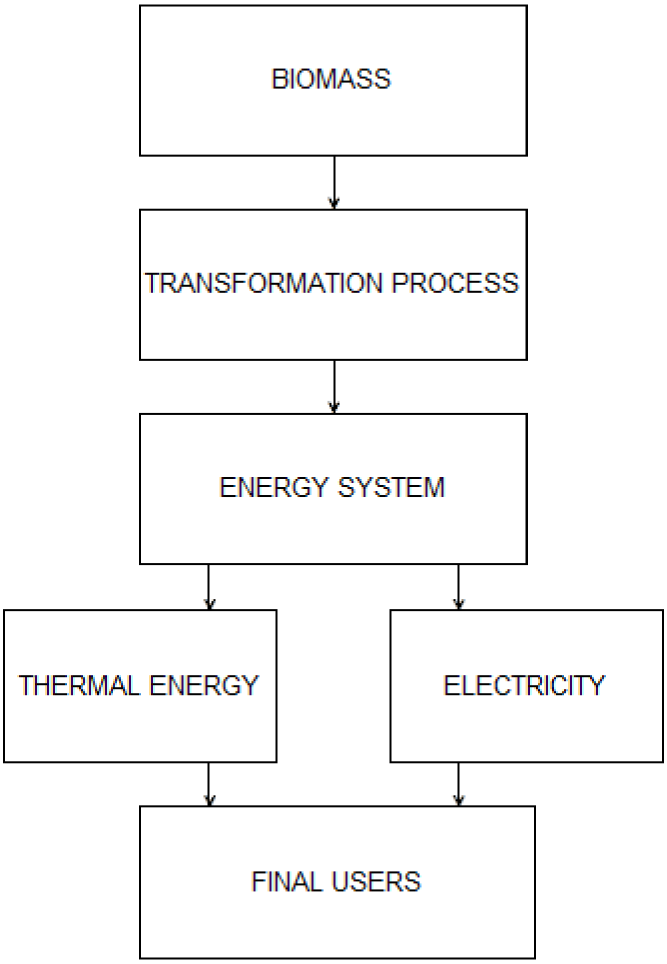

Figure 1.1. Biomass agricultural-energy chain.

Biomass availability assessment is the starting point of the whole chain, and it precedes the design of conversion facilities for thermal or cogenerative energy production. Biomass is not homogenously spread on the territory, and their availability is not continuing and constant during the year, so an economical and efficient conversion facility could be realized only in concurrent presence of both heat demand and biomass availability.
The biomass conversion takes place in specific plants, whose characteristics are identified by the biomass type they are designed to manage. So, in order to identify the suitability of a certain area for the realization of a biomass conversion facility and of a district heating network it is necessary to have 3 kinds of data:

1) biomass availability data
2) heat demand data
3) typologies of conversion facility

1.1 Biomass availability data

Biomass availability data on Lombardy Region are updated to 2009 (CRASL 2010, Estimation of biomass potentials in Lombardy. Forest, agriculture, zootechnics and waste sectors: adopted methodologies and main results). Several type of biomass is considered suitable to energy conversion, and they have been subdivided in 4 macro-categories, 13 categories and 21 sub-categories (47 if we consider separately all industrial residuals forming each sub-category):

1) Forest
    1.1) Forests
    1.2) Poplar plantations
2) Agriculture
    2.1) Cereals
    2.2) Rice
    2.3) Maize
    2.4) Primary and Secondary Arboreous
3) Zootechnics
    3.1) Bovine
        3.1.1) Liquid manures
        3.1.2) Solid manures
    3.2) Chicken

        - 3.2.1) Liquid manures
        - 3.2.2) Solid manures
    - 3.3) Suine
        - 3.3.1) Liquid manures
        - 3.3.2) Solid manures

4) Wastes
    - 4.1) Urban wastes
        - 4.1.1) Organic
        - 4.1.2) Green
        - 4.1.3) Wood
    - 4.2) Industrial
        - 4.2.1) Agricultural industry
        - 4.2.2) Meat industry
        - 4.2.3) Fruit and vegetable industry
        - 4.2.4) Sugar processing
        - 4.2.5) Dairy industry
        - 4.2.6) Baking industry
        - 4.2.7) Alcoholic and non-alcoholic beverages
        - 4.2.8) Wood processing and production of panels and furniture
        - 4.2.9) Pulp, paper and cardboard production and processing
    - 4.3) By products
        - 4.3.1) Industrial slaughtering (bovine, suine and chicken)
        - 4.3.2) Whey
        - 4.3.3) Various (fruit and vegetables processing, vegetable preserves, exhausted march from distilleries, fresh march and olive residues from oil production)

The biomasses quantities are related to the municipality within they are produced, and the regional total amount given by literature is the sum of each municipal contribution. Each municipal biomass amount has been later assigned to the land cover producing it, and then partitioned into square cells of dimension 1 km covering all the regional territory in a uniform grid. On the contrary, wastes have been assigned to the barycentric cell of the municipality producing them, since wastes are usually collected within a specific place (i.e. ecological platform). These operations of assignment have been performed through ArcGis®, as more precisely exposed in Chapter 2. The units of measurement, the territorial unit biomass data refer to and the adopted land cover for the assignment of each biomass category are summarized in Table 1.1.

Table 1.1. Unit of measurement and territorial unit of biomass data.

	BIOMASS CATEGORY	UNIT OF MEASUREMENT	TERRITORIAL UNIT	LAND COVER
1	Forest	m^3	Municipality	DUSAF
2	Agriculture	t	Municipality	SIARL
3	Zootechnics	m^3	Municipality	DUSAF
4	Wastes	t	Municipality	-

1.2 Heat demand data

Heat demand data identifies the areal heat demand divided into 3 sectors of interest: residential sector, tertiary sector and industrial sector. The choice to keep the heat demand divided by sector primarily follows the consideration that each sector is characterized by a specific annual amount of full load hours: for example, the industrial sector requires thermal energy for a greater number of full load hours per year than the other sectors, estimable in a fix value of 4000 h/y (BioEnergy2020+). An estimation of the amount of full load hours per year per sector is provided in Table 1.2.

Table 1.2. Full load hours per year per sector to be considered for a conversion plant (BioEnergy2020+).

Sector	$h_s[h/y]$
Residential	2000
Industrial	4000
Tertiary	2000

Moreover each heat demand sector requires thermal energy within specific periods of time during the day; for example, residential sector typically requires thermal energy in the earlier morning and in the evening, following the most common working day. On the contrary, industrial heat demand for space heating and low enthalpy process does not show peaks during the day, since required thermal energy is sometimes constant also during the night, if the productive process does not stop at all. Finally, the heat demand of the tertiary sector coincides with the length of a typical working day, since thermal energy is required in agreement with the duration of the activities within offices, law courts, libraries, schools, leisure centers, etc. These different amounts of full load hours, the necessity of a factor of simultaneity to take in account the concurrent presence of these heat demands and the knowledge of their specific distribution during the day are fundamental to estimate the power of the facility to be installed within a certain area (Chapter 3). Heat demand data used in this work are gathered from SIRENA (*Sistema Informativo Regionale ENergia Ambiente*, regional informative system for energy and environment), an informative regional territorial system arranged by Lombardy Region to collect, within a single instrument, the updated knowledge about the regional energy system (e.g. energy demand and offer, infrastructure of energy production and transport); as a function of these regional energy flows, SIRENA is able to report a quantification of their impact on the environment and on the quality of the air in the atmosphere. Energy data are divided by sector consumptions, and SIRENA also reports the energy vectors (i.e. natural gas, electric energy, diesel, oil, biomass, etc.) utilized to satisfy the energy demand. In SIRENA the administrative subdivision energy data refers to is the municipality; Lombardy Region is composed by 1546 municipalities, whose energy consumptions are identified by their unique Istat code. Several energy consumption data have been attached to each Istat code, expressed in TOE (*Tons of Oil Equivalent*, or TEP), one for each sector considered (i.e. residential, industrial and tertiary); so data format can be thought as illustrated in Table 1.3.

Table 1.3. Municipal heat demand format (SIRENA).

COD_ISTAT	Municipality	Residential HD [TOE]	Industrial HD [TOE]	Tertiary HD [TOE]
12001	Agra	406.8756	28.2967	18.5802
...	...	...	...	...
108055	Roncello	2085.691	147.0759	805.5943
...	...	...	...	...

The heat demand data currently available in SIRENA refer to 2007.

1.3 Typologies of conversion facility

The choice of the most suitable process of transformation depends on the biomass characteristics, such as moisture content, composition, etc., and the nature of the process is various:

1) Thermo chemical (i.e. direct combustion)
2) Biochemical (i.e. anaerobic digestion)

3) Physical-chemical (i.e. mechanic extraction of oil from oleaginous plants)

In this work only options 1 and 2 have been considered. With regard to biomass energy systems, the same technology of no-renewable fuels is utilized: alternated endothermic engines, external combustion Stirling engines, gas micro-turbines and ORC (Organic Rankine Cycle) (LISEA).

1.3.1 Direct combustion

Direct combustion of woody biomass is the most spread technology for biomass conversion: combustion happens within a boiler, where the conversion of the biomass generates the necessary energy to the production of steam or organic fluid, whose successive expansion moves a turbine and causes electrical generation. The biomass suitable for direct combustion have to be characterized by a moisture contents lower than 30% in weight, and by a ratio carbon-nitrogen greater than 30 (LISEA). Examples of such biomass are forest residuals, poplars, willows, eucalyptus and miscanthus, agricultural residues such as straw, hay, stems of maize, etc. or agro-industrial residues such as olive residues, rice hulls, seeds, shells or kernels. The principal problem of this technology is the uncertainty about biomass availability, since 1-10 MW power plants need of an high quantity of fuel; this fact can be avoided realizing organic fluid small plants with a size of about 200 kW, whose biomass supply can be easily managed (BioEnergy2020+). Furthermore biomass plants based on direct combustion produced, besides smokes, ashes estimable in 2% of the weight of the entering total mass. Italian law classifies ashes resultant from biomass combustion process as “not dangerous special wastes”, that could be disposed through simplified procedures (TUA, art.214 and D.M. 5 February 1998) as the production of cement conglomerates, the use in cement factors or in bricks and expanded clay industry, the employment in the formation of road embankments or the production of fertilizers. Although promising experimentations have taken place, such as Biocen project, a study promoted by Lombardy Region in 2004 regarding the management and the valorization of combustion ashes in wood-energy chain, and the disposal of ashes as fertilizer is a common practice in other countries; in Italy the agronomical use of combustion ashes has been not yet allowed.

1.3.2 Anaerobic digestion

Anaerobic digestion is a biochemical process of transformation of biomass into a particular biofuel (i.e. biogas, a mixture of carbon dioxide and methane) that can be used as energy source in alternate endothermic engines and gas micro-turbines. The process of transformation takes place within a reactor, a simple silo called digester, by several populations of symbiotic bacteria; the biogas is later purified, dehumidified and desulfurizated, in order to allow its combustion within energy system (Figure 1.2). Suitable biomass for this kind of process is characterized by a moisture contents greater than 30% in weight, and a ratio carbon-nitrogen smaller than 30 (LISEA); zootechnics (i.e. slurry and manure from chicken, bovine and suine breeding), dedicated cultures (i.e. triticale, etc.), agricultural (i.e. leaves and beetroot residuals) and agro-industrial residuals (i.e. residuals of the industrial processing of tomatoes, wood, sugar, dairy, baking, confectionery, alcoholic, fruit and vegetable industries, slaughtering, etc.) are generally used in anaerobic digestion process.

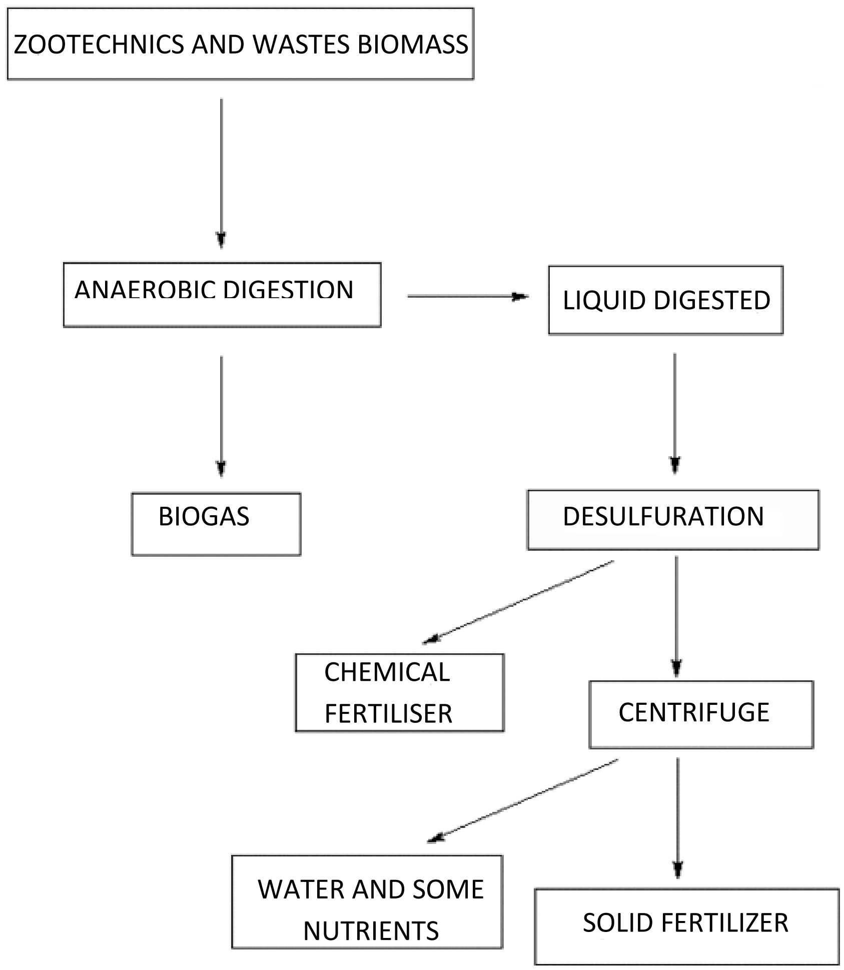

Figure 1.2. Process of biomass anaerobic digestion and production of fertilizers.

The dimension of this kind of plants allows them to be well integrated in agricultural realities, especially in breeding farm, where there is abundant biomass at zero cost. The use of digested materials, where it is allowed by"Nitrates Directive", represents the most efficient solution in the disposal of the discards of anaerobic digestion process.
Direct combustion allows 4 types of plants, characterized by the combination of use of herbaceous or woody biomass as fuel, and by only thermal or CHP (*Combined Heat and Power*) production; anaerobic digestion, instead, identifies only CHP production possibility. So in this work we totally consider 3 typologies of conversion facilities: thermal or CHP production from woody biomass, thermal or CHP production from herbaceous biomass, CHP from anaerobic digestion (Table 1.4).

Table 1.4. Considered types of conversion facility.

k	Thermal conversion facility	k	CHP conversion facility
1	Woody Biomass	3	CHP woody Biomass
		4	CHP Herbaceous Biomass
2	Herbaceous Biomass	5	CHP Biogas

In Table 1.5 biomass categories and their relative typologies of conversion facility are reported, while the NCV (Net Calorific Value) of each biomass sub-categories are summarized in Annex 1. Industrial wastes sub-categories are identified by EWC (*European Waste Catalogue*) codes, identifying several industrial sectors that produce biomass residuals:

- 0201 – Agricultural industry
- 0202 – Meat industry
- 0203 – Fruit and vegetable industry
- 0204 – Wastes from sugar processing
- 0205 – Wastes from the dairy products industry
- 0206 – Wastes from the baking and confectionery industry
- 0207 – Wastes from the production of alcoholic and non-alcoholic beverages
- 0301– Wastes from wood processing and the production of panels and furniture
- 0303 – Wastes from pulp, paper and cardboard production and processing

By products wastes sub-categories are instead identified by CRASL acronyms:

- FR_VEG – residues from fruit and vegetables processing industry

- VEG_PRES – residues from vegetable preserves industry
- WINE_MARCH – fresh march from oil production
- OLIVE_RES – olive residues from oil production

Table 1.5. Biomass categories and relative typologies of conversion facility.

BIOMASS MACRO-CATEGORY	BIOMASS CATEGORY	BIOMASS SUB-CATEGORY	COMBUSTION PLANT	ANAEROBIC DIGESTION
1_FOREST	Forest residues		YES	NO
	Poplars		YES	NO
2_AGRICULTURE	Cereals		YES	NO
	Rice		YES	NO
	Maize		YES	NO
	Arboreous(p&s)		YES	NO
3_ZOOTECHNICS	Bovine	Solid	NO	YES
		Liquid	NO	YES
	Chicken	Solid	NO	YES
		Liquid	NO	YES
	Suine	Solid	NO	YES
		Liquid	NO	YES
4_WASTES	Urban	Organic	NO	YES
		Green	NO	YES
		Wood	YES	NO
	Industrial	CER_0201	NO	YES
		CER_0202	NO	YES
		CER_0203	NO	YES
		CER_0204	NO	YES
		CER_0205	NO	YES
		CER_0206	NO	YES
		CER_0207	NO	YES
		CER_0301	NO	YES
		CER_0303	NO	YES
	By products	Bovine	NO	YES
		suine	NO	YES
		chicken	NO	YES
		whey	NO	YES
		FR_VEG	NO	YES
		VEG_PRES	NO	YES
		WINE_MARCH	NO	YES
		OLIVE_RES	NO	YES

1.4 Grid and cartography

The cartographic basis and the territorial subdivision of Lombardy Region, used to elaborate and reassign biomass quantities in ArcGis®, are represented by the following shapefile format:

- the grid of square cells, 1 km ground resolution
- the borders of Lombardy municipalities
- the borders of Lombardy provinces
- the borders of Lombardy Region

In Figure 1.3 the Lombardy Region shapefile is represented at municipal level, covered by the grid 1 km ground resolution.

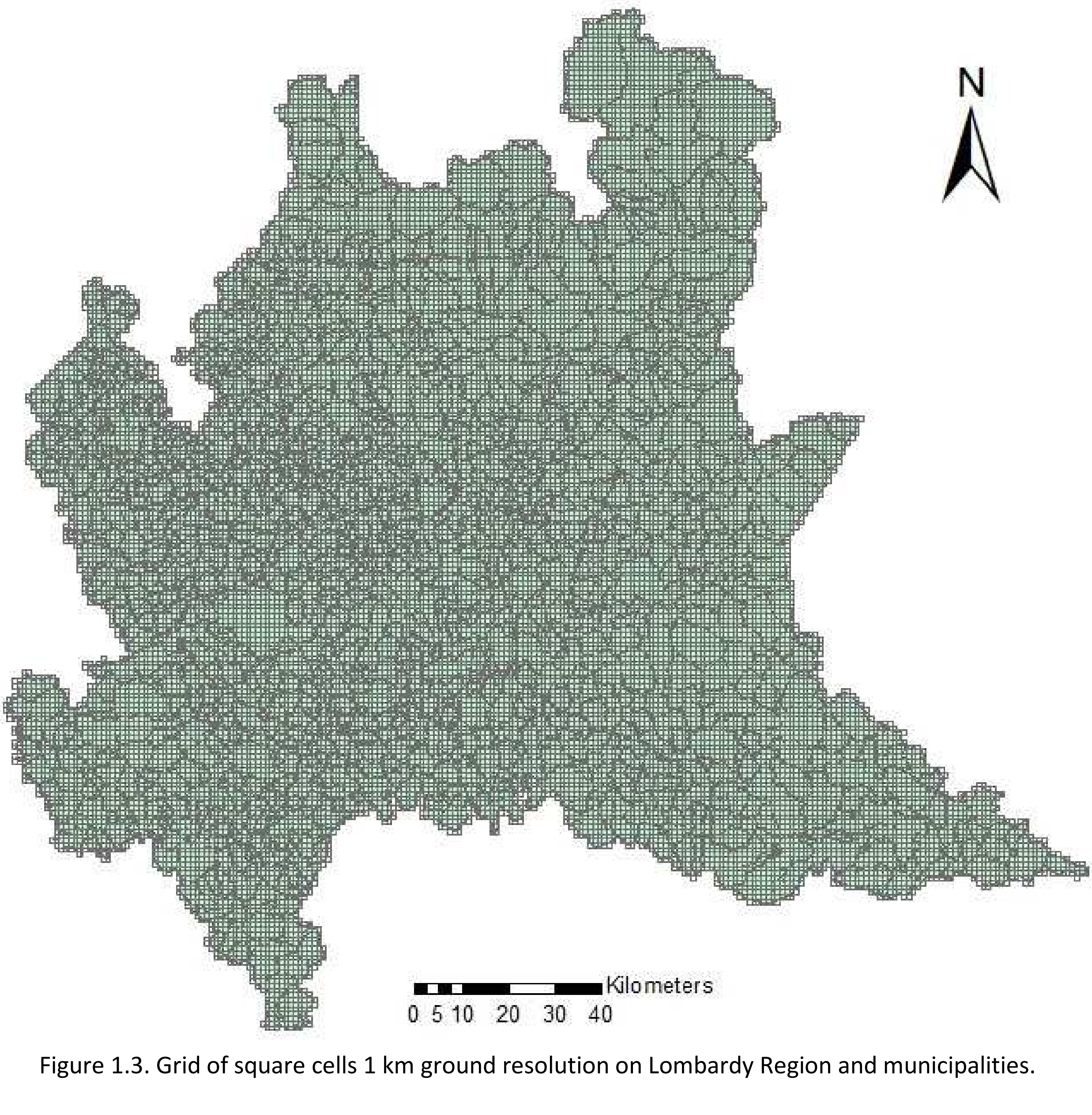

Figure 1.3. Grid of square cells 1 km ground resolution on Lombardy Region and municipalities.

Regarding projected coordinate system and geographic coordinate system all data and parameters characterizing the shape files are summarized in Table 1.6.

Table 1.6. Projected coordinate system and geographic coordinate system parameters.

Projected Coordinate System	Monte_Mario_Rome_Italy_1
Projection	Transverse Mercator
False Easting	1500000
False Northing	0
Central Meridian	-3.45233333
Scale Factor	0.9996
Latitude Of Origin	0
Linear Unit	Meter
Geographic Coordinate System	GCS_Monte_Mario_Rome
Datum	D_Monte_Mario
Prime Meridian	Rome
Angular Unit	Degree

Following the proposed method, the total regional area has been made discrete by the grid of square cells, for a total of 24727 cells 1 km ground resolution. The choice to use a grid and to discretize data in relation to it derives from a simple and arbitrary consideration: according to the dimension decided for the cell, a grid allows the analysis to be led at different levels of spatial resolution, varying from a very detailed one (i.e. 500 m) to a medium detailed (i.e. 2 km). From this point of view a grid of 1 km resolution guarantees more flexibility than the administrative subdivision of the territory (i.e. municipality), whose dimension could be very different case by case, and it allows us to localize a possible plant with much more precision. Moreover, a district heating network privileges short length of the pipe network, in order to keep the loss of heat due to transport at the minimum level, and so we can hypothesize that its total length, for an economical operation, could be completely contained within a cell (BioEnergy2020+); in this way the adoption of the grid is useful to localize also the district heating network with great precision. However, this choice is heavier from a computational point of view, since the system has to consider heat demand and biomass data not referring to Lombardy municipalities (1546), but to a domain one order of magnitude greater (24727), that is the number of cells of the grid; furthermore their meaning, in reference to the territorial reality, is not so immediate.

2. ArcGis® processing

This chapter exposes the process of elaboration adopted within this work for the biomass and heat demand data described in Chapter 1. Data have been considered by category, and they have been assigned to the territorial unit they refer to (i.e. municipality and then cell). In order to be assigned per cell, forest, poplar, agricultural, zootechnics data and heat demand data have been assigned to the corresponding land cover within the municipal territory they belong to; for forest, poplar and zootechnics data DUSAF (*Destinazione d'Uso dei Suoli Agricoli e Forestali*, use destination of forest and agricultural soil) land cover by ERSAF (*Ente Regionale per i Servizi all'Agricultura e alle Foreste*, regional agency for forest and agricultural services) has been used, while for agricultural data SIARL 08 has been regarded as more detailed and suitable. SIARL is an integrated part of DUSAF. Data processing has been realized with ArcGis® tools.

2.1 Forest biomass

Forest biomass is represented by forest and poplar category (Chapter 1), and the total quantities of available biomass on the whole regional territory are summarized in Table 2.1.

Table 2.1. Forest biomass categories, DUSAF code and total quantity.

Biomass category	DUSAF code	Quantity [m^3/y]	Density [t/m^3]
Forest	31	139482	0.5
Poplar	2241	196236	0.5

Forest biomass defines the potential volume of fresh matter, expressed in m^3, as annual sum of residues from actual forest tree logging and residues from complementary forest tree felling, deriving from the annual allowed cut approach (CRASL, 2010); the density of the fresh matter has been supposed equal to 0.5 t/m^3. Forest biomass quantity is spread on the corresponding DUSAF land cover (i.e. code 31), identifying broad-leaved (code 311), conifer (code 312) and mixed forests (code 313). The result per cell is showed in Figure 2.1.

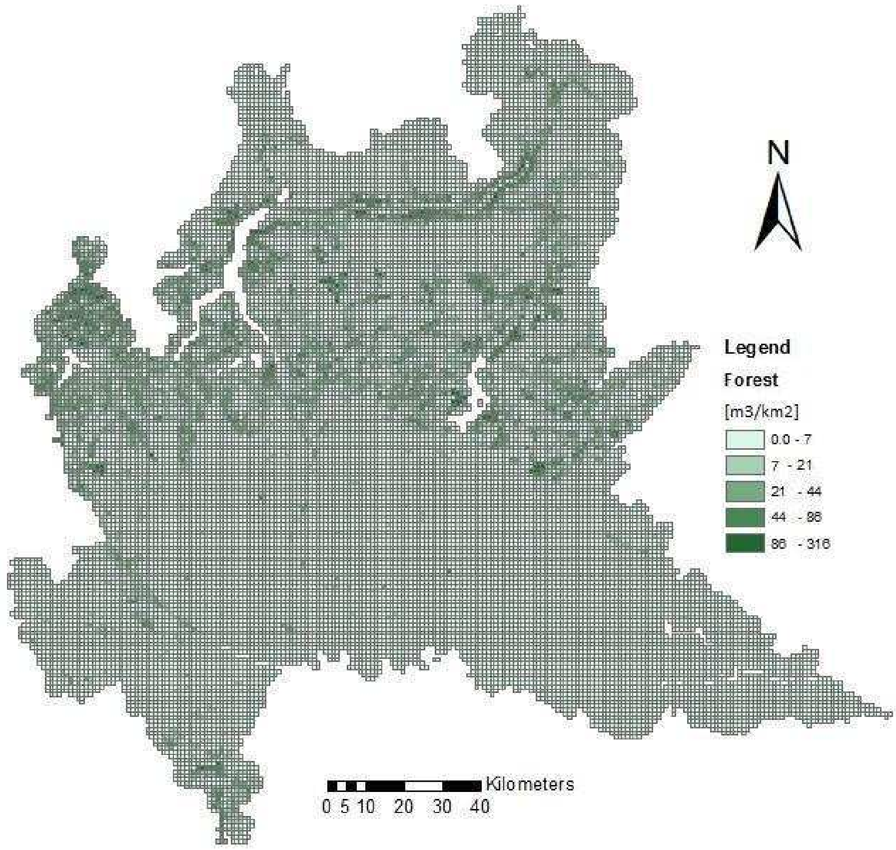

Figure 2.1. Forest biomass availability per cell.

Poplar biomass, instead, is represented by a separated sub-category, since poplar high density growing belongs to SRF (*Short Rotation Forestry*), an acronym that identifies the growing of wood species (e.g. poplar, willow, alder and elm) characterized by high rate of growth and destined to the energy conversion. DUSAF land cover provides a specific code (i.e. 2241) to poplar plantations; so municipal poplar data of production, expressed in tons, have been spread on those areas, and finally gridded as showed in Figure 2.2.

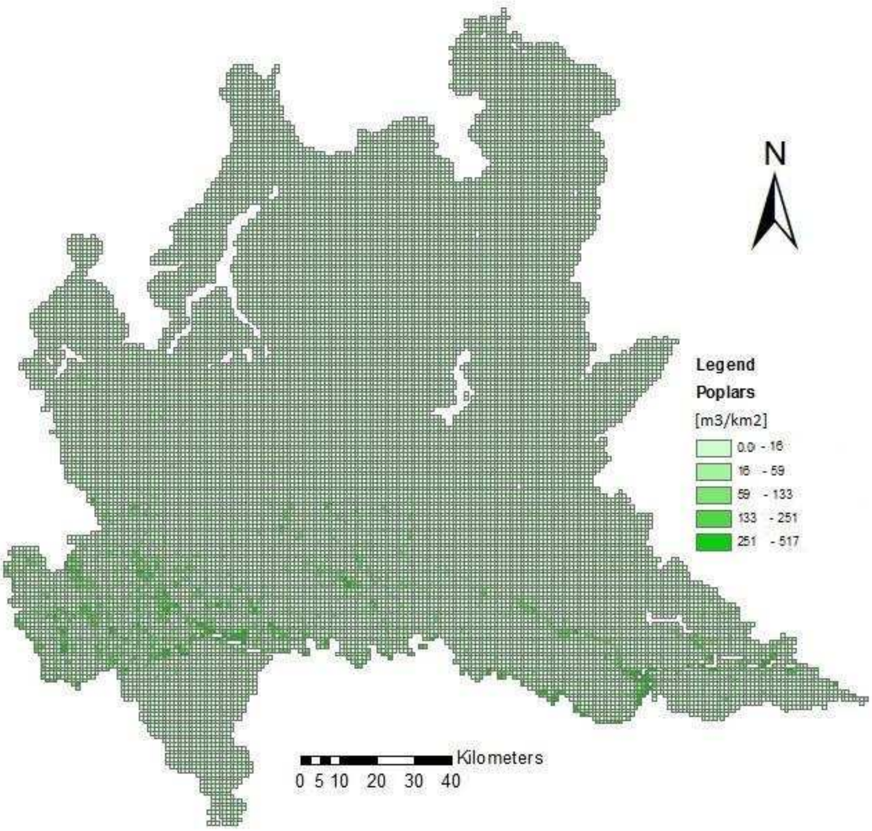

Figure 2.2. Poplar biomass availability per cell.

Observing Figure 2.1 and Figure 2.2 it is possible to notice the different localization of forest and poplar biomass: if forest biomass is principally provided by the northern mountainous part of Lombardy, on the contrary poplar biomass is produced only in the plain part of the region, especially along Po, Adda and Oglio river southern part.

2.2 Agricultural biomass

Agricultural activities generate large amounts of biomass residues. While most crop residues are usually left in the field to reduce erosion and recycle nutrients back into the soil, some could be used to produce energy. Agricultural biomass is a relatively broad category of biomass that includes the food-based portion of crops (such as corn, sugarcane, and beets), the nonfood-based portion of crops (such as maize and corn leaves, stalks, and cobs, orchard trimmings and rice husks), perennial grasses, and animal waste. In this work, agricultural biomass only considers the nonfood-based portion, divided into 4 categories: cereals, rice, maize and pruning. Each category corresponds to a specific code in SIARL 08 land cover, as summarized in Table 2.2.

Table 2.2. Agricultural biomass categories, total quantity and SIARL 08 code.

Biomass category	SIARL 08 code	Agricultural use	Quantity [t/y]
Cereals	1	Other	57116
Rice	4	Rice	237996
Maize	5	Maize	564844
Prunings	3	Forest and woody cultivation	42365

In order to obtain biomass quantities referring to each cell the method used consists of operating an intersection, with ArcGis® toolbox, between municipal biomass data and relative agricultural land cover, obtaining an area specific production of agricultural biomass. This quantity is an average value of production, since the whole municipal biomass quantity is equally spread on the specific land cover within the municipality, and no difference of productivity is considered. Then, operating an union with the grid, we are able to derive the biomass quantity per year available within each single cell. In Figure 2.3 rice biomass availability per cell is represented.

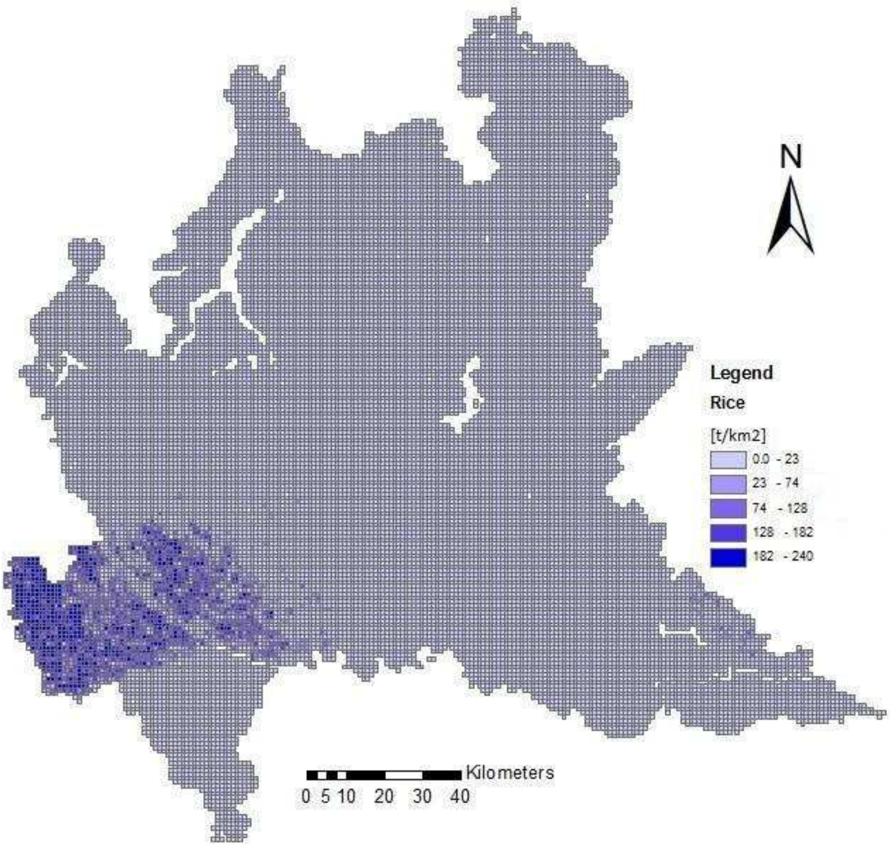

Figure 2.3. Rice biomass availability per cell.

According to Figure 2.3 we can notice that rice production is concentrated in province of Pavia, where the rice straw availability reaches the highest levels. Other areas providing rice biomass suitable for energy conversion are exclusively in province of Mantova, in the south-eastern part of the region.

Figure 2.4 represents cereal biomass availability per cell, pointing out the great diffusion of cereal cultivations, such as barley, wheat, oat and rye in the central and southern part of the region, mainly belonging to the southern part of Po valley and to the province of Cremona, Lodi, Mantova and Pavia. Cereal cultivation also interests the central part of Lombardy region up to the pre-alpine areas, reaching the province of Bergamo, Brescia, Lecco, Milano and Varese.

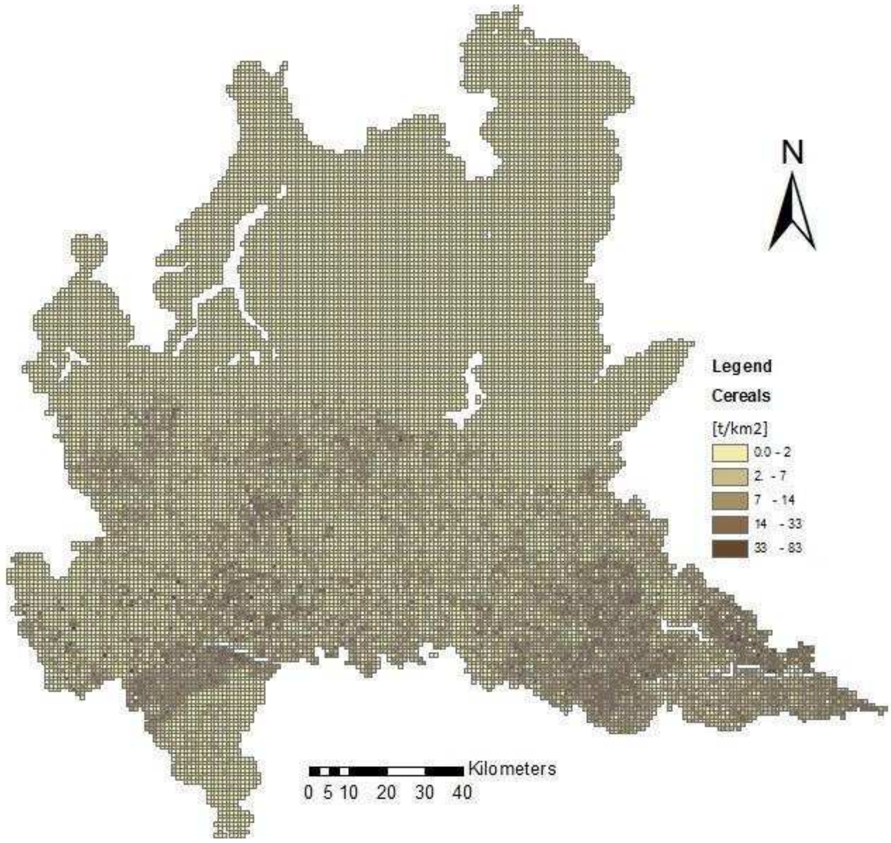

Figure 2.4. Cereal biomass availability per cell.

Figure 2.5 points out the great diffusion of maize cultivation especially in the central and southern part of the region, belonging to the Po valley and to the pre-alpine areas. Unlike the territorial concentration of all the other cereals, maize cultivation reaches its higher value in the province of Bergamo, Brescia, Cremona, Lodi and Mantova, even if provinces of Milano and Pavia also provide great quantity of maize residuals.

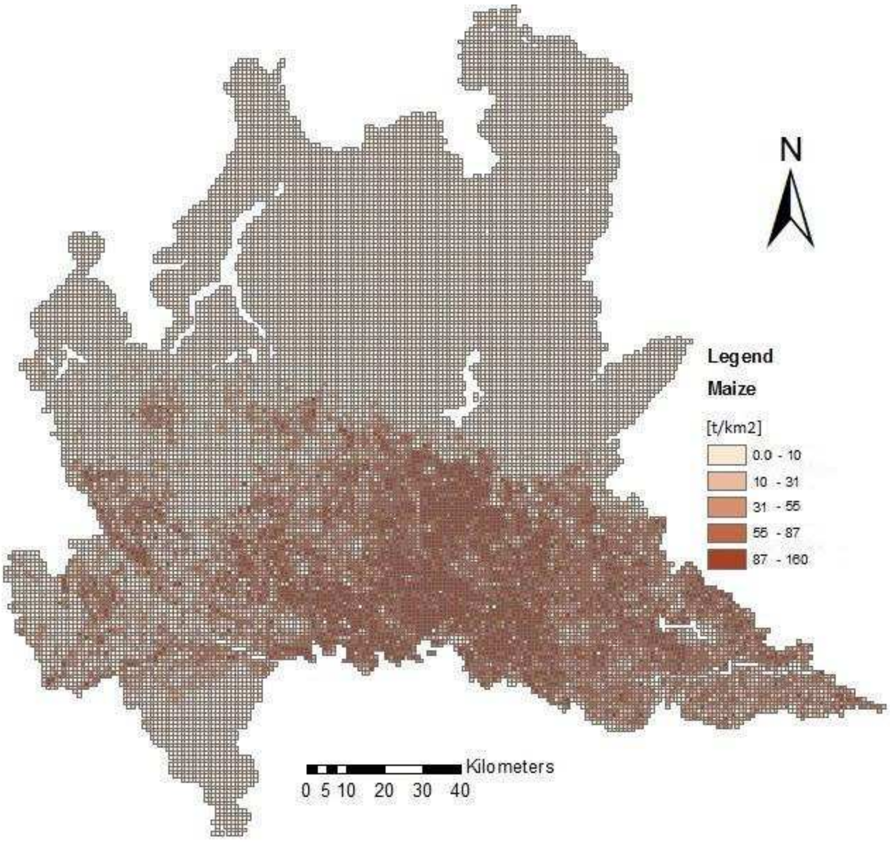

Figure 2.5. Maize biomass availability per cell.

With regard to the biomass quantities provided by the three different categories, expressed in tons of dry net material, maize quantity is much greater than all the other cereals one, one order of magnitude greater if we consider the total amount on the region (Table 2.2).

2.3 Zootechnics biomass

Zootechnics biomass is divided into 3 categories, identifying the kind of bred animal: bovine, chicken and suine. With regard to the typology of biomass provided, each category is composed by liquid (i.e. liquid manures) and solid materials (i.e. solid manures), for a total of 6 sub-categories. Since zootechnics biomass data production per farm are not known, we cannot assign them to point elements; however we could affirm that a farm could feed animals, besides by cattle feed, by hay and grass deriving from arable cultivated areas and permanent pasture areas. So we could hypothesize a direct proportionality between the extension of those areas within a municipality and the production of solid and liquid manures by the farm in the same territory. Once arable cultivated areas (code 21) and permanent pasture (code 231) had been identified by DUSAF cover land, we could apply the same method of biomass allotment described in the previous paragraph, obtaining a biomass quantity per cell. In Table 2.3 biomass sub-categories and their total regional quantities are listed, together with DUSAF codes used in the method application.

Table 2.3. Agricultural biomass categories, total quantity and SIARL 08 code.

Biomass sub-category	DUSAF code	Quantity [m^3/y]	Density [t/m^3]
Bovine liquid manures	21, 231	8657805	1.0
Bovine solid manures		9779860	1.0
Chicken liquid manures		70789	1.0
Chicken solid manures		1163318	1.0
Suine liquid manures		14628570	1.0
Suine solid manures		84467	1.0

Figure 2.6, 2.8 and 2.10 represent liquid manures from bovine, chicken and suine, Figure 2.7, 2.9 and 2.11 show solid manures ones.

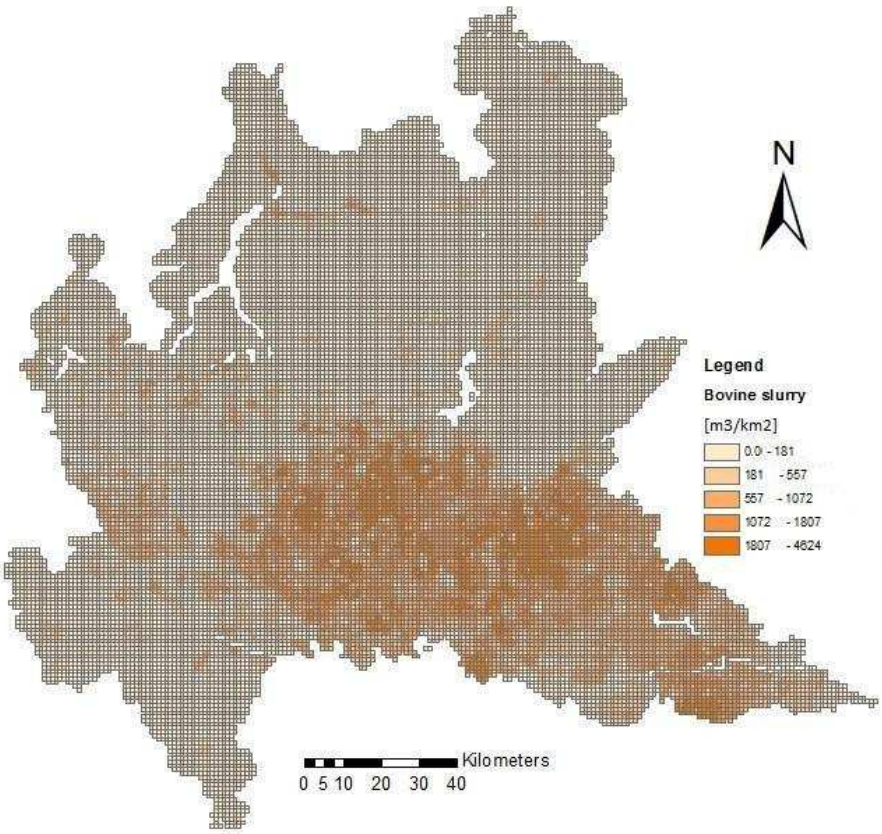

Figure 2.6. Bovine liquid manures availability per cell.

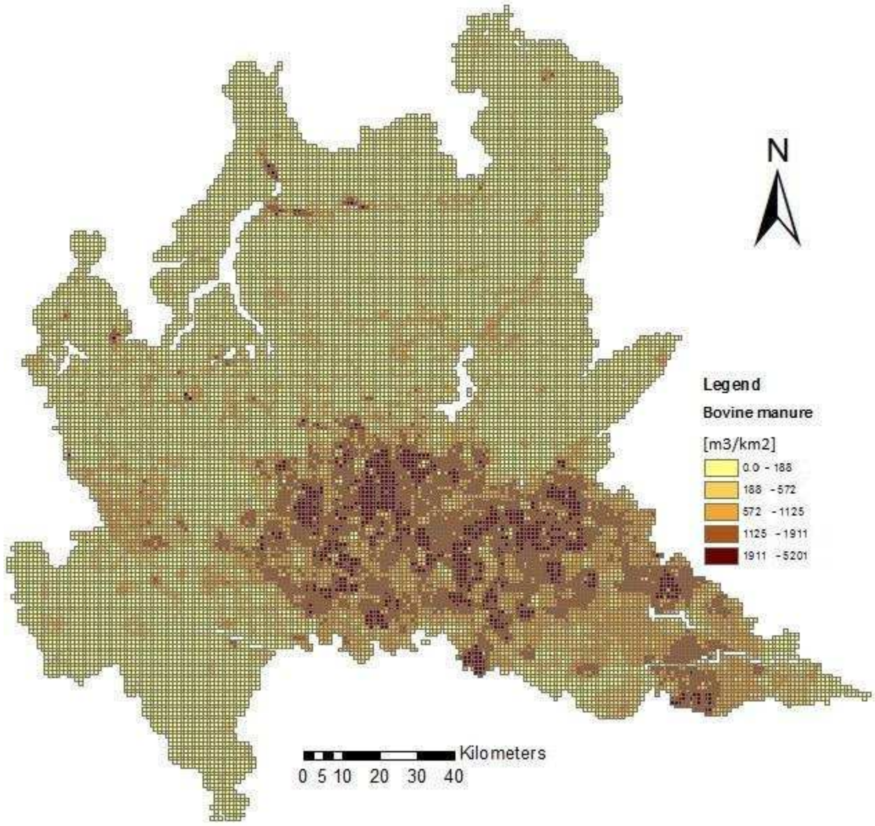

Figure 2.7. Bovine solid manures availability per cell.

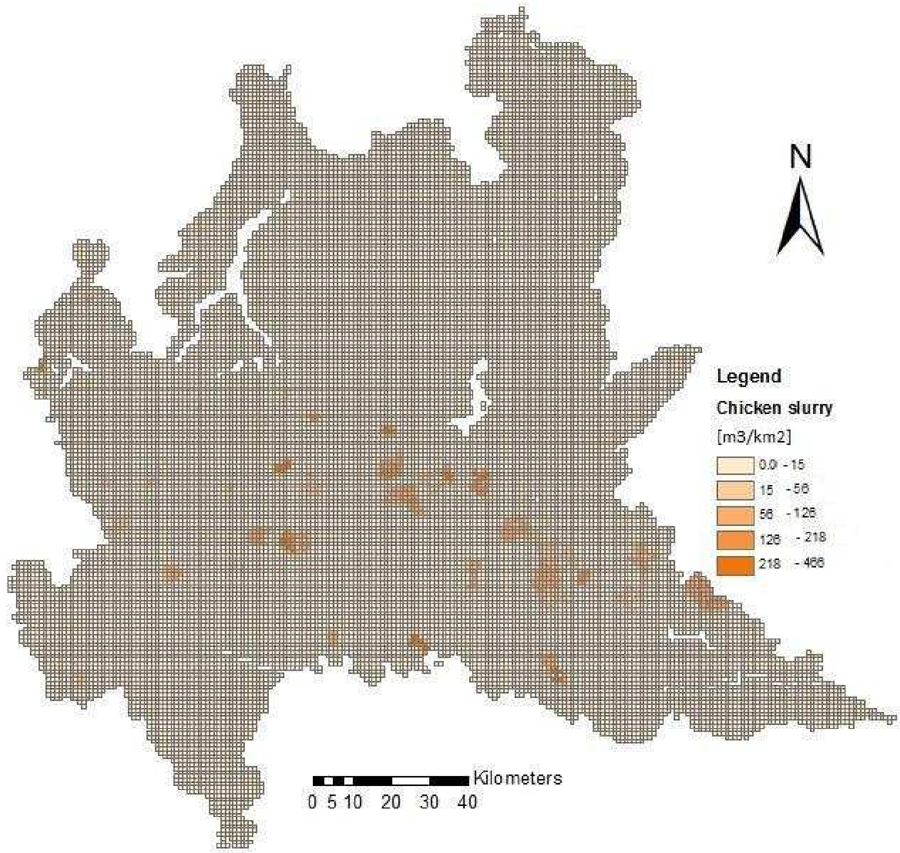

Figure 2.8. Chicken liquid manures availability per cell.

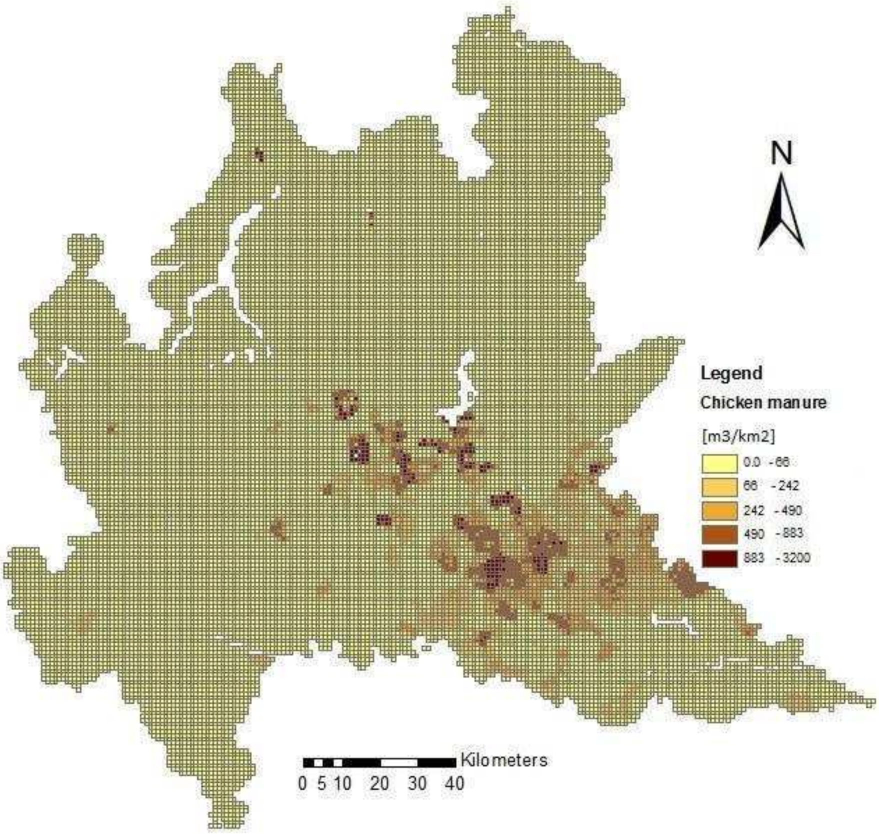

Figure 2.9. Chicken solid manures availability per cell.

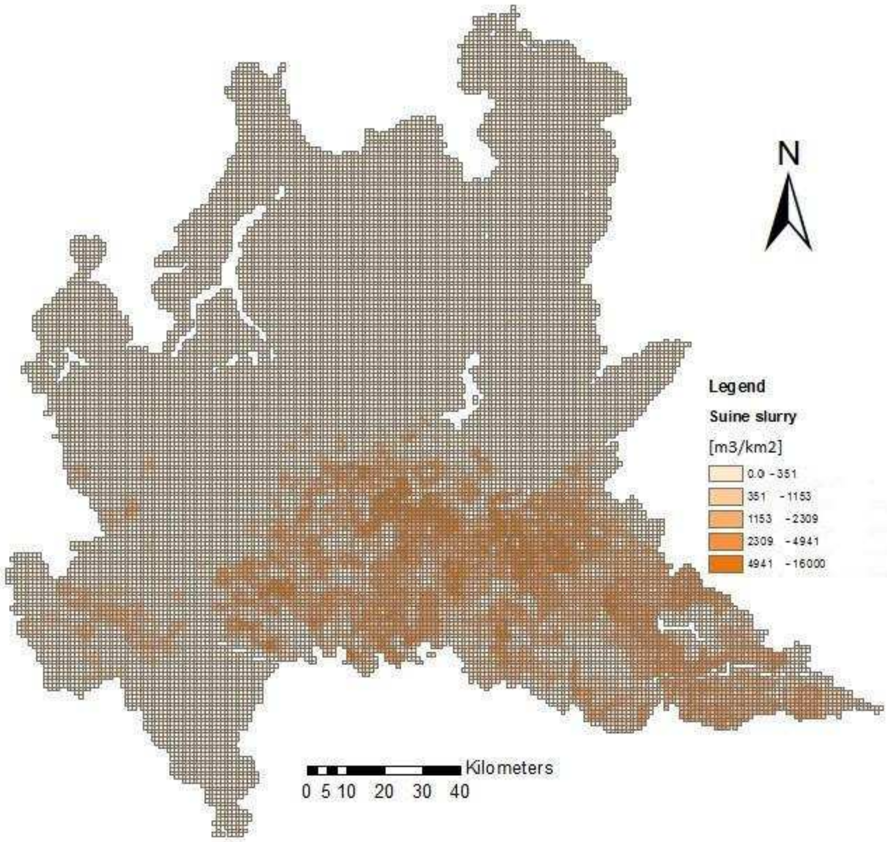

Figure 2.10. Suine liquid manures availability per cell.

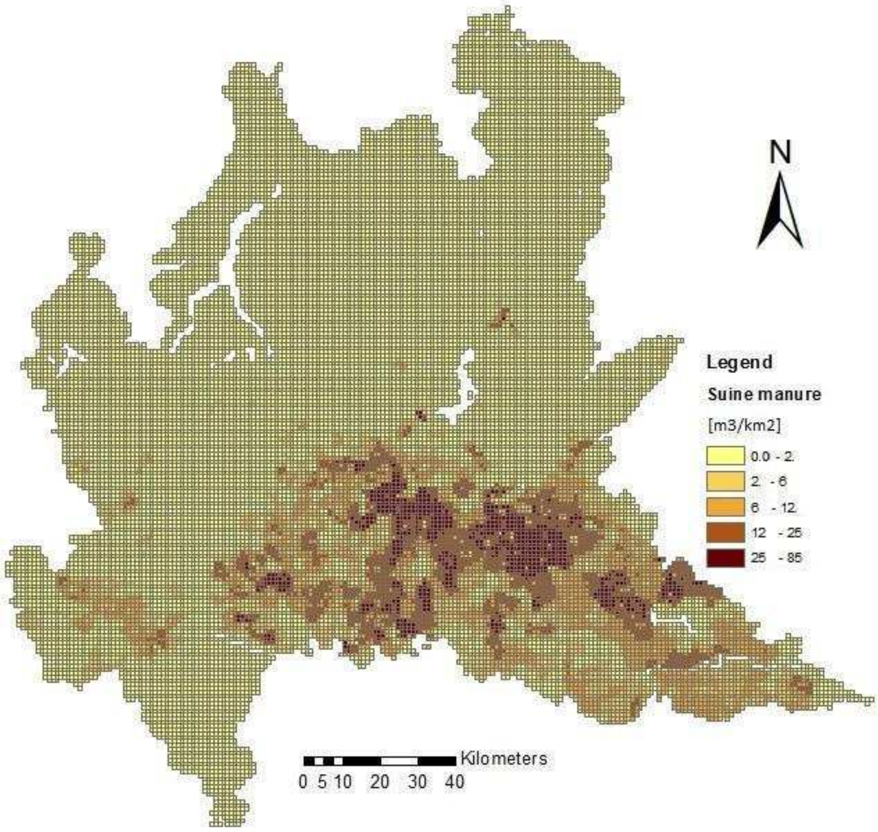

Figure 2.11. Suine solid manures availability per cell.

From Figure 2.6, 2.7 and Figure 2.10, 2.11 we can notice the greater liquid and solid manures availability from the breeding of bovines and suines rather than from chicken ones, primarily concentrated in Bergamo, Brescia, Cremona and Mantova provinces. With regard to the total regional quantities bovine and chicken categories produce more solid manures than liquid manures; on the contrary suine category provides a greater quantity of liquid manures.

2.4 Wastes biomass

The 3 categories included in wastes biomass are urban wastes, industrial wastes and by product wastes (Chapter 1), and the territorial unit they refer to is always the municipality. The method adopted in order to obtain a biomass quantity per cell is quite different from the previously dealt biomass macro-categories one, since in this case it would have no meaning to spread the biomass quantity on an area; in fact, urban wastes are usually collected within ecological waste centers (point elements), where residuals wait for being recycled or transported into traditional garbage dumps. With regard to industrial and by product wastes, however, biomass gathering within a specific place (i.e. ecological waste center) seems to be not best fitting, because it directly happens industry by industry. In order to point out a common method to represent urban, industrial and by product wastes gathering, we could hypothesize to assign the biomass quantity produced within each single municipalities to its barycenter (Figure 2.12); if this hypothesis could be very simplistic, on the other hand indicates a good compromise between logical meaning and computational complexity. In fact municipal ecological waste centers are usually external to urbanized area, in order to avoid problems to the population deriving from excessive nearness to wastes, but the approximation in localizing them in the municipal barycenters could be considered negligible for limited extended municipal areas (i.e. 10 km^2 order of magnitude). As well as for industrial and by product wastes, we could assign them to municipal barycenters without compromising their territorial affiliation, since DUSAF provides the industrial land cover of each municipality, but it would have no logical meaning to assign an average value of biomass residual production to undifferentiated industrial areas. So municipal barycenters of each single municipality has been found by ArcGis® toolbox, all the considered wastes biomass quantity have been assigned to them and, consequently, to the cells they belonged to with spatial joint function.

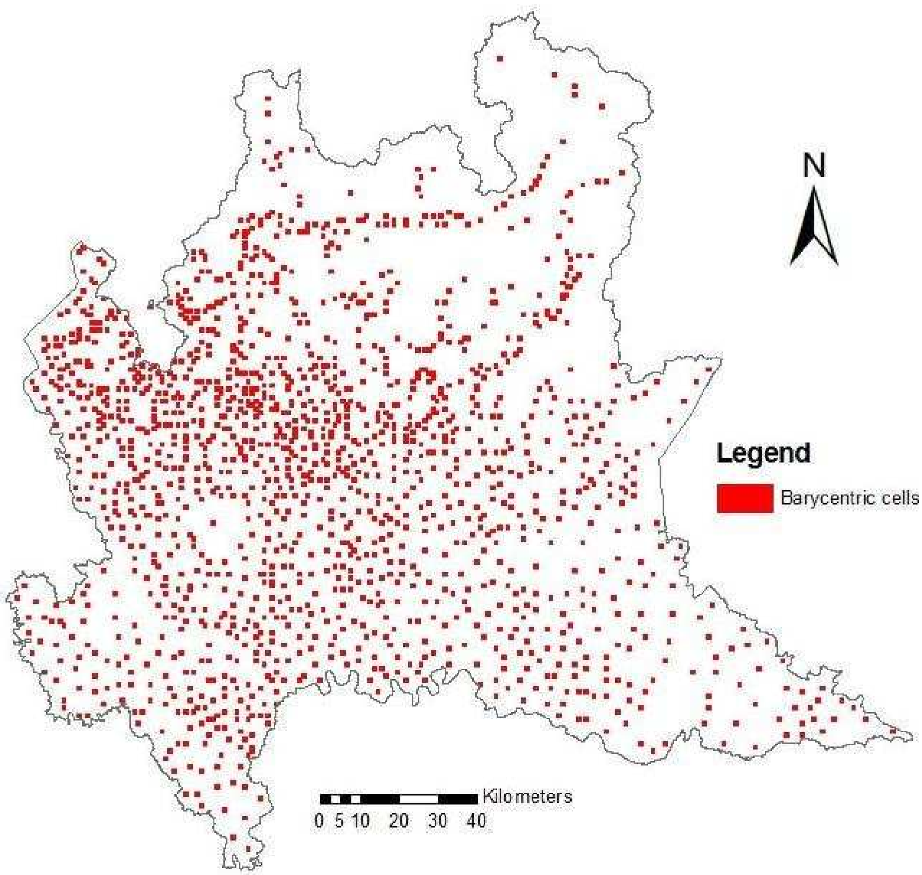

Figure 2.12. Municipal barycentric cells.

Table 2.4 summarizes wastes biomass categories and sub-categories, with their corresponding total quantity on the whole region.

Table 2.4. Wastes biomass categories, sub-categories and their total quantity.

Biomass category	Biomass sub-category	Quantity [t/y]
Urban wastes	Organic	334636.55
	Green	364294.66
	Wood	111530.58
Industrial wastes	Agricultural	20150.86
	Meat	67734.38
	Fruit and vegetable	129186.04
	Sugar processing	699.47
	Dairy	46188.33
	Baking	12287.40
	Alcoholic and non-alcoholic beverages	20506.99
	Wood processing and production of panels and forniture	755968.81
	Pulp, paper and cardboard production and processing	65272.10
By product wastes	Bovine slaughtering	16163.40
	Chicken slaughtering	84817.50
	Suine slaughtering	17187.00
	Whey	1629499.00
	Fruit and vegetable processing	41910.00
	Vegetable preserves	7878.60
	Fresh march from oil production	11252.00
	Olive residues from oil production	2526.90

2.5 Heat demand

The method adopted to discretize at cell level the municipal heat demand is the same adopted for forest, agricultural and zootechnics biomass. DUSAF land cover has been used to localize urbanized area (code 11), formed by urban continuous (code 111) and discontinuous (code 112) settlements. Industrial heat demand data have been assigned to the area deriving from the sum of previous urbanized one (code 11) and the area occupied by productive (i.e. industrial and handcraft) settlements (code 12111); tertiary and services heat demand data, instead, have been equally spread on urbanized one (code 11) and on all those areas occupied by hospitals (code 12121), public and private plants of services (i.e. school and university structures, tribunals, offices, prisons and religious buildings, code 12122) and public leisure centers (code 1421). The reason of this choice is that, using only productive area (code 12111) for the territorial assignment of the industrial heat demand, the method caused a loss of data, since several municipalities showed an industrial energy demand and not a relative area producing it. The same happened for tertiary and services heat demand per cell assignment, if only code 12121 and 12122 were used. So we had to regard less specific DUSAF land cover, in order to keep areas characterized by functional mix and point out an area within each municipality on which heat demand could be assigned. Through ArcGIS® toolbox each land cover have been intersected to municipal heat demand by sector data, obtaining an average area demand; then it has been assigned to the cells of the grid, pointing out the final heat demand per sector per cell. In Table 2.5 regional heat demand data per sector and the corresponding DUSAF code of the areas they belong to are summarized.

Table 2.5. Regional heat demand data per sector and corresponding DUSAF land cover codes.

Heat demand sector	Quantity [TOE/y]	DUSAF code
Residential	6043129.60	11
Industrial	1502593.30	11, 12111
Tertiary and services	2100346.00	11, 12121, 12122, 1421

The unit of measurement used for heat demand is TOE (TEP, chapter 1). From Table 2.5 we can notice that the residential heat demand is predominant in comparison to industrial and tertiary heat demand. Figure 2.13, Figure 2.14 and Figure 2.15 respectively represent residential heat demand per cell, industrial heat demand per cell and tertiary and services heat demand per cell. From Figure 2.13 we can notice that residential heat demand is concentrated in the metropolitan area of Milan and Monza, where the highest value is reached, and spread on the provinces of Lecco, Como, Varese and Bergamo.

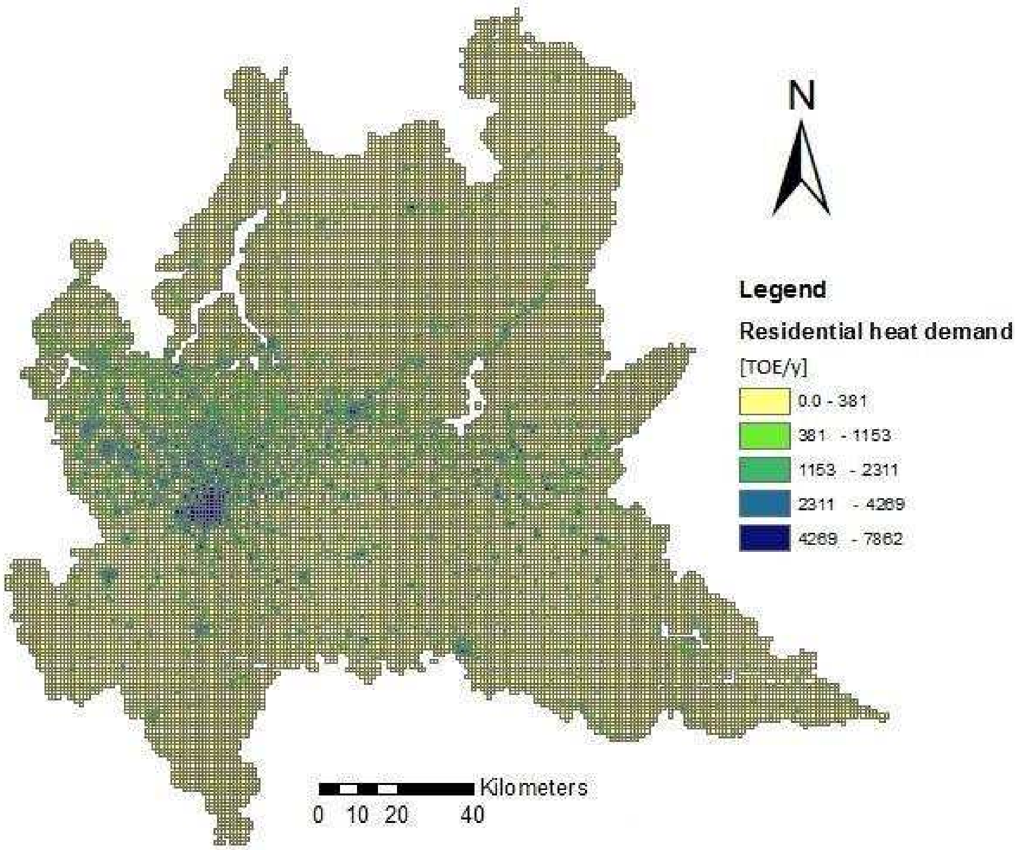

Figure 2.13. Residential heat demand per cell.

In the southern part of Lombardy Region it is possible to recognize the main cities, such as Vigevano, Voghera, Pavia, Lodi, Crema and Cremona, from their higher heat demand. Brescia could be equally recognized, even if the high heat demand of its province is spread on a extensive area. In the mountainous area the city of Sondrio could be easily recognized among a very low heat demand area.

As for industrial heat demand (Figure 2.14) it reaches significant concentration in the provinces of Varese, Como, Milano, Lecco, Bergamo and Brescia, constituting a uniform territorial area characterized by high industrial heat demand and localized in the whole pre-alpine area of Lombardy Region. As for residential heat demand all the main cities in the mountainous part of the region as in the southern part could be easily recognized from their higher heat demand.

With regard to tertiary heat demand its highest concentration is reached within bigger urban centers at regional level, as we can easily deduce from Figure 2.15, where all the greater Lombardy cities are easily intelligible from their higher heat demand. The highest tertiary heat demand is registered in the city of Milan, in the adjacent municipalities forming its metropolitan area, in the province of Monza, Varese, Bergamo, Como and Brescia.

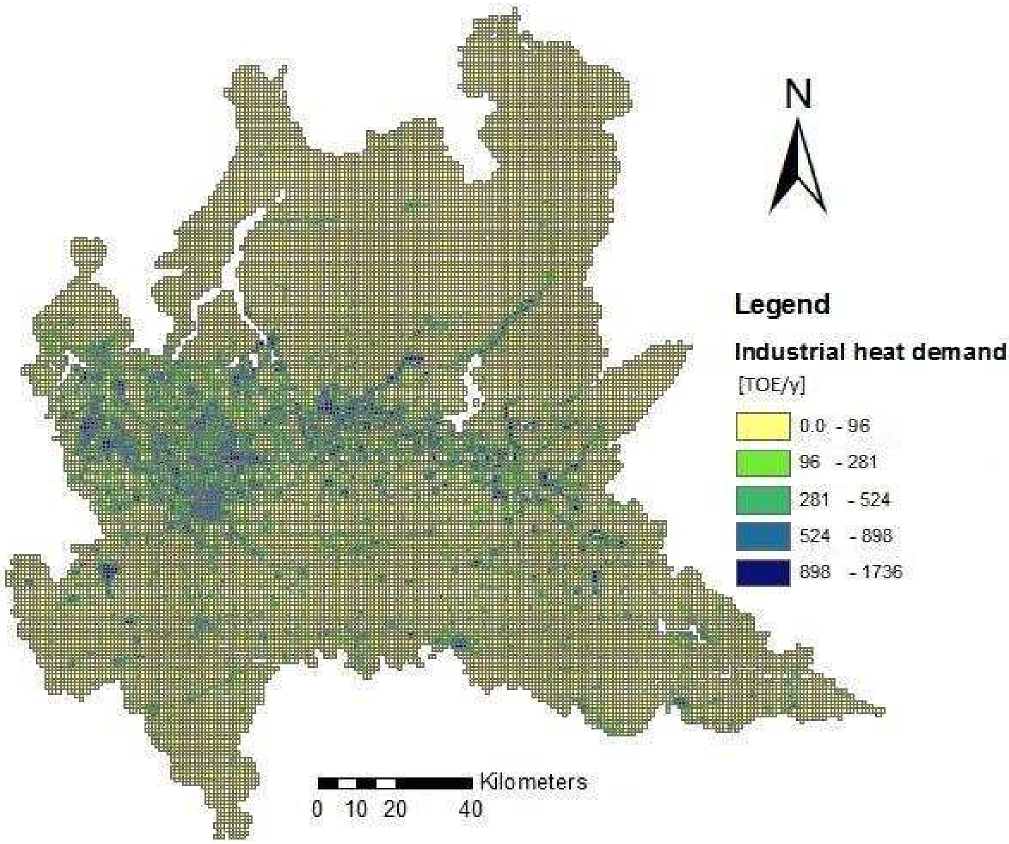

Figure 2.14. Industrial heat demand per cell.

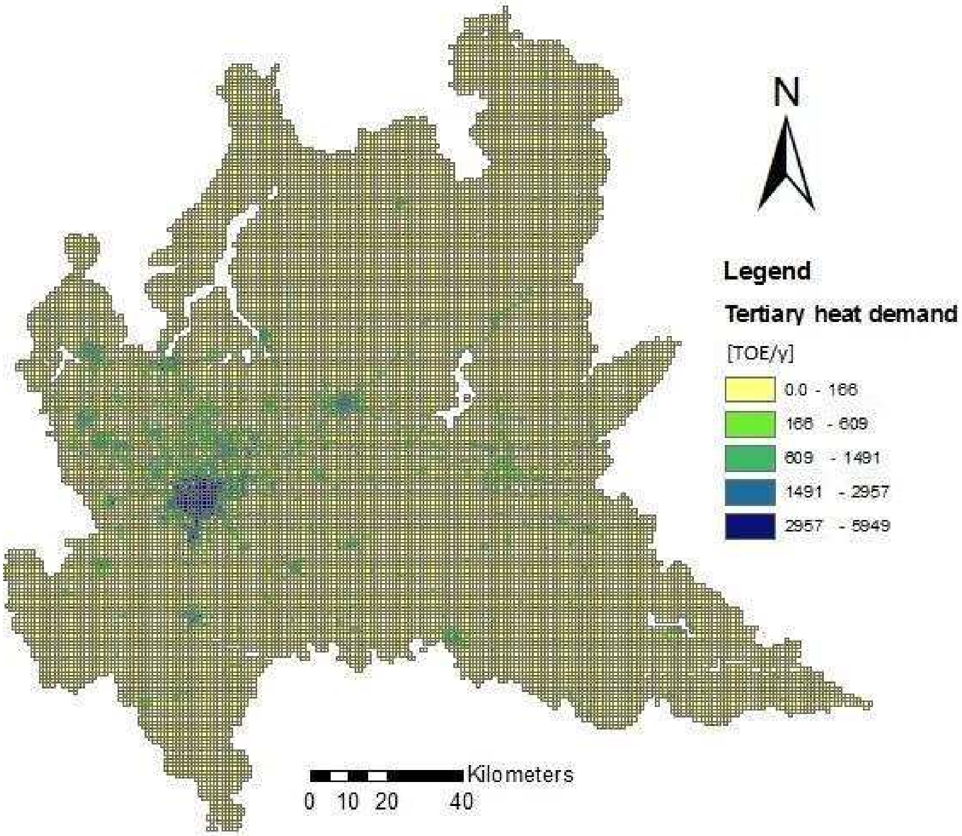

Figure 2.15. Tertiary and services heat demand per cell.

2.6 Admissible cells

The grid samples the whole territory of Lombardy Region into discrete units, but, as said in the previous paragraphs, it gives no information about the land cover within the cells and the physical feasibility of any kind of realization in them. So, the first action of the methodology consists of the determination of the territorial domain, excluding all those areas unsuitable for buildings realization; using DUSAF land cover, damp areas (code 4) and water bodies (code 5) have been identified and removed from the original grid. Damp areas include all those soils characterized by herbaceous vegetation and canes formation, proper to lake and river shores, and marsh grassland, while DUSAF category of water bodies is formed by the areas included within the external perimeter of lakes, reservoirs, compatibly with the minimum dimension reportable in cartography, rivers and canals. If a cell is characterized by a damp areas and water bodies land cover percentage greater than an arbitrary value (25%), it cannot be considered suitable for the realization of a biomass conversion facility. It has not been considered the exclusion of area belonging to SIC (*Siti Importanza Comunitaria*, sites of community importance), since within these areas physical feasibility could subsist and it could be only later denied by environmental law constraints. Furthermore no constraints have been imposed on the feasibility of a biomass conversion in mountainous areas, since it is automatically denied by the impossibility of a concurrent satisfaction of the constraints on biomass availability and heat demand into them. In fact we could hypothesize that many mountainous cells in Lombardy region might have an high biomass availability, but only a little part of them might have a sufficient heat demand to justify the realization of a conversion facility. These cell should be characterized by a urban land cover, and there the realization of a biomass plant could result perfectly feasible.

Figure 2.16 represents the domain of admissible cells and it can be easily recognized the exclusion of the main lakes of Lombardy region from them. The total number of the cells forming the grid on Lombardy region is 24727; the number of the cells excluded from the domain of potential solution is 2003, equal to the 8.1% of the total.

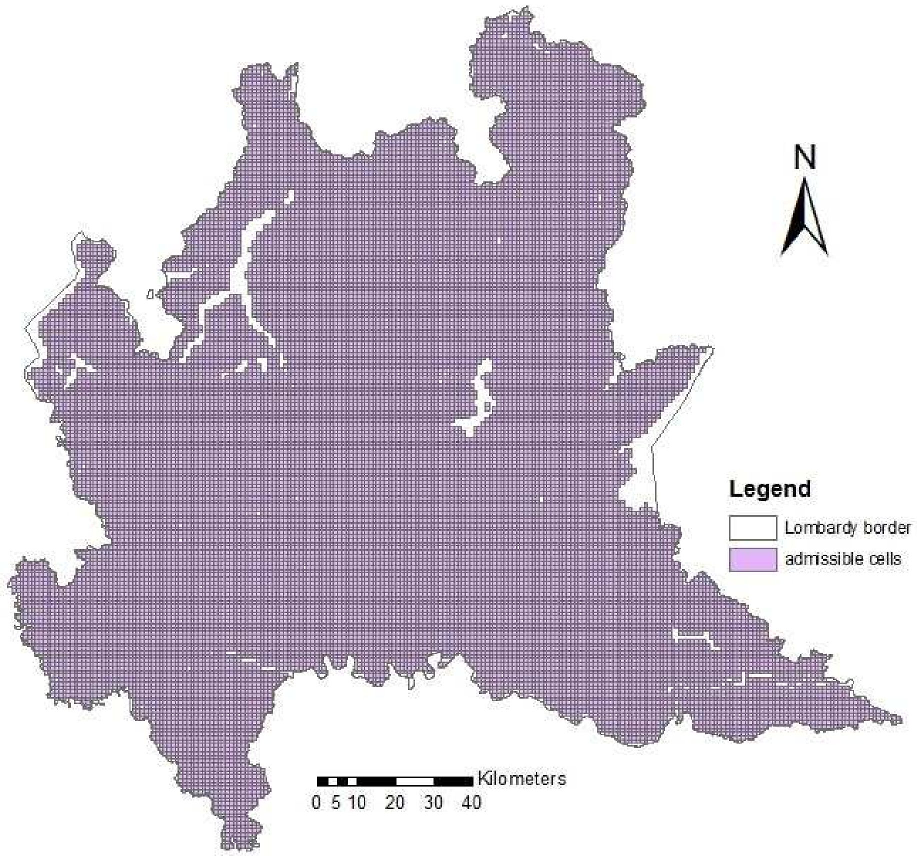

Figure 2.16. Admissibility domain of the cells of the adopted grid.

3. Biopole

This Chapter exposes the parameter for the localization of biomass DH that has been used in Biopole program, together with the solution of the operative problem of estimation of the distances between the cells of the grid. The constraints on heat demand and on biomass availability, necessary to the definition of suitable cells to the realization of a conversion facility, are here defined, as well as its electrical and thermal power characteristics. In a second part Biopole output is represented and commented, with the specification of three alternative criteria of choice and their relative solutions.

3.1 Parameters for the localization of biomass DH

The method used to determine the suitable cells to the realization of a biomass conversion facility and of a district heating network can be thought as divided into 3 logical successive steps (Figure 3.1):

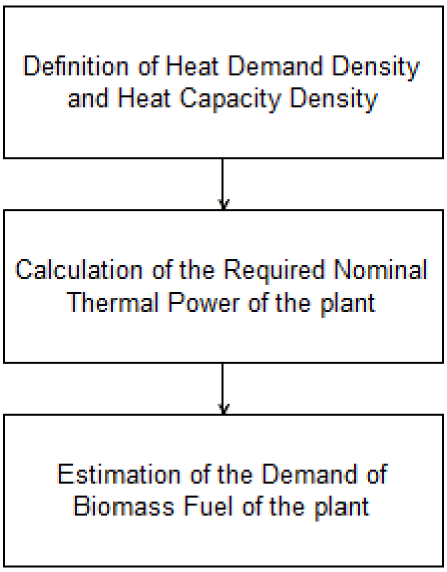

Figure 3.1. Logical steps to determine suitable cells to the realization of a biomass conversion facility.

1. Definition of *Heat Demand Density* and *Heat Capacity Density* on a discrete area
2. Calculation of the *Required Nominal Thermal Power* of the heat generation plant, in order to satisfy the heat demand on the considered area; at this step we can define the most suitable relation between the thermal power to be installed and the working annual full load hours for the plant
3. Find out if the *Demand of Biomass Fuel of the Plant* can be satisfied by the raw materials collected within the considered area

In the following these logical steps are briefly described, explaining the process that the algorithm has to complete in order to point out suitable cells for the realization of a biomass conversion facility, specifying the type of plant. This algorithm has been developed in Fortran® environment, and the program has been called Biopole. All the parameters and the equations showed within this chapter have been estimated and formulated with the partnership of BioEnergy2020+, an engineering consultancy firm specialized in technical energy services and, especially, in biomass plants and DH realizations.

3.1.1 Localization of urbanized cells

The distinction between urban and rural cells is fundamental in the settlement of the value of the constraint on heat demand density and heat capacity density, described in the following paragraphs. The method used to distinguish one class of cells from the other one consists of evaluating the percentage of urbanized area within each cell, and classifying it as urban if that percentage is greater than an arbitrary value, fixed in 33% of the total area of the considered cell. The urbanized percentage of each cell have been evaluated by ArcGis® field calculator on the shapefile obtained from the intersection of the grid 1 km ground resolution, described in Chapter 1 and 2, and DUSAF anthropized areas (code 1), primarily formed by urbanized area (code 11), productive installation and infrastructures (code 12). On the contrary a cell has been classified as rural if the urbanized area percentage has resulted to be smaller than 33%. On a basis of this value 3472 cells, constituting the 15.3% of all the admissible cell (Chapter 2), have been classified as urban cells, while the remaining 19252 admissible cells (84.7% of the total) as rural ones. In the specific, the urbanized area obtained has been used in the determination of both heat demand density and heat capacity density, while the classification of urban and rural cells has been used to identify different constraints on heat capacity density. In Figure 3.2 urban cells are represented.

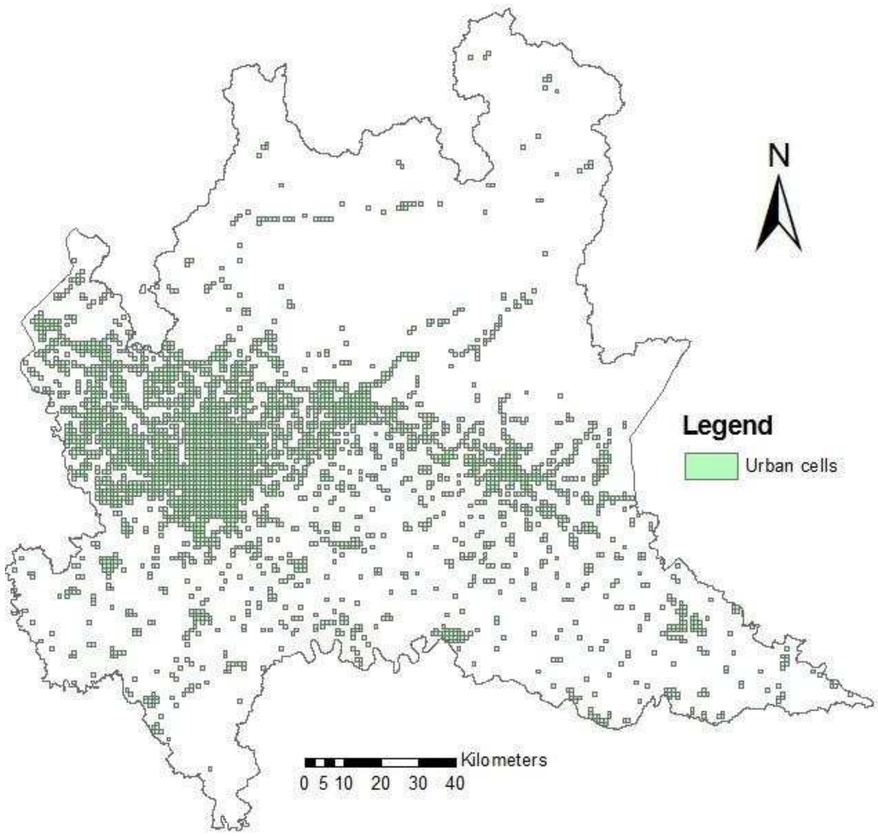

Figure 3.2. Urban cells in Lombardy region.

3.1.2 Identify heat demand density

As explained in Chapter 2, the different types of demand are kept separated, since they have different characteristics (i.e. different fluctuations during the day, peaks and average demand) realizing several full load hours per year. As first approximation we could think them as:

$$Q = \sum_s (Q_s \cdot L_s) \quad \text{Eq.3.1}$$

with $s \in S\{residential, productive, tertiary\}$

- $Q\left[{}^{TOE}/_{y}\right]$: total annual heat demand of buildings in a discrete area
- s: heat demand sector
- $Q_s\left[{}^{TOE}/_{y}\right]$: total annual heat demand of s sector buildings in a discrete area

- $L_s[\%]$: possibility of connecting buildings in the area to biomass DH network

The algorithm considers connection willing equal to 100% as default, since it aims to point out the maximum potential value of heat demand to be satisfied. The conversion of TOE into KWh (*Autorità per l'Energia Elettrica ed il Gas*, 2010) is

$$1\, TOE = 11630\, kWh \qquad \text{Eq.3.2}$$

The parameter we have to look on for a first distinction between suitable and unsuitable areas to the realization of a conversion facility is heat demand density$q$, defined as

$$q = \frac{Q}{A_u \cdot i} \qquad \text{Eq.3.3}$$

- $q\left[{}^{kWh}/_{y \cdot m^2}\right]$: heat demand density
- $A_u[m^2]$: expanse of the urbanized area within a cell
- $i[-]$: rate of territorial building

The average value of the rate of territorial building for Lombardy could be valued in 0.6. The adopted value for the constraint on this parameter has been iteratively varied within the range 20-70, in order to find out the right trade-off between a too strict and an excessive soft constraint. So, according to the value proposed by literature (QM HOLZHEIZWERK, 2008), one cell can be considered optimally suitable for a DH realization if

$$q > 70 \qquad \text{Eq.3.4}$$

3.1.3 Identify heat capacity density

In order to find out suitable cells to the realization of a biomass conversion facility another parameter, called thermal heat capacity density$p$, can be considered (SCHRAMEK, 2009 and UMSICHT, 2008). It can be calculated as the sum of the ratio of sector based heat demand of buildings to its annual full load hours, divided by the extension of the discrete area:

$$p = \frac{10^3}{A_u \cdot i} \cdot \sum_s \left(\frac{Q_s}{h_s}\right) \qquad \text{Eq.3.5}$$

with $s \in S\{residential, productive, tertiary\}$

- $p\left[{MW}/{km^2}\right]$: heat capacity density
- $A_u[m^2]$: expanse of the urbanized area within a cell
- $i[-]$: rate of territorial building
- s: heat demand sector
- $Q_s\left[{kWh}/{y}\right]$: total annual heat demand of s sector buildings in a discrete area
- $h_s\left[{h}/{y}\right]$: annual full load hours for residential space heating

Annual full load hours for residential space heating and for public buildings could be estimated in 2000 hours per annual building heating, 1500 hours in case of seasonal building heating. Annual full load hours for industrial space heating and low enthalpy processes should be defined case by case, or fixed in 4000 hours per annum (Chapter 1, Table 1.2).

In compliance with this second parameter, one cell can be considered suitable if

$$p > 40 \text{ for rural areas} \quad \text{Eq.3.6}$$

$$p > 20 \text{ for urban areas} \quad \text{Eq.3.7}$$

Heat demand density, in fact, gives no information about the power installed into the area, so we could have a cell satisfying the constraint in equation 3.4 and not satisfying constraint in equation 3.6 (or 3.7), because it is characterized by a small installed power working for a lot of hours. So, for an economic operation of the biomass DH plant, the compliance with a minimal heat demand density of 70 kWh/m^2 and a minimal heat capacity density of 20 MW/km^2 in urban areas (40 MW/km^2 in rural areas) is recommended (SCHRAMEK, 2009 and UMSICHT, 2008).

In Figure 3.3 urban and rural cells satisfying both the constraints on heat demand in equations 3.4 and 3.6 (or 3.7) are represented, for a total number of 2374 cells; among them, the number of the urban cells is 1008, equal to the 29.0% of urban total number of cells individuated at paragraph 3.1.1. The number of the rural cells is instead 1366, equal to the 7.1% of the total number of rural individuated cells. It is very interesting to notice that the great part of the urban cells satisfying both the constraints on heat demand belongs to the hill and flat parts of the region, corresponding to the pre-alpine and northern part of the Po valley, primarily concerning the cities of Milan, Varese, Como, Monza, Bergamo, Brescia and their provinces. On the other hand, almost all the rural suitable cells belong to the mountainous part of the region (i.e. Valtellina), the northern part of the province of Brescia (i.e. Val Camonica, Val Trompia and Valle Sabbia), and the province of Pavia.

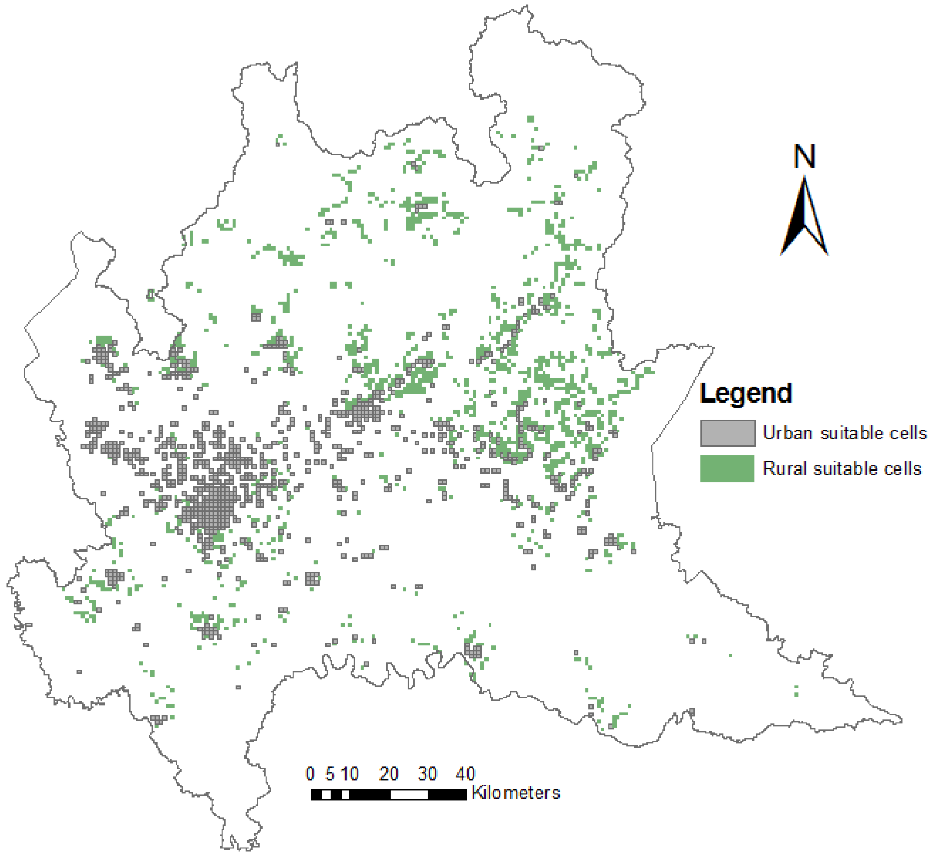

Figure 3.3. Urban and rural cells satisfying heat demand constraints.

3.1.4 Maximum length of a DH network

The motivation for the implementation of a DH network is that high boiler efficiency can be reached with large automatically feed biomass boilers, with low costs of heat generation as well as low pollutant emissions. The goal of planning a DH network should be a high heat demand and very short network extension, and the parameter thermal transport performance p_n can be considered a guideline to assure these advantages:

$$p_n = \frac{1}{l_n} \cdot \sum_S \left(\frac{Q_S}{h_S}\right) \qquad \text{Eq.3.8}$$

with $s \in S\{residential, productive, tertiary\}$

- $p_n \left[{}^{kW}/_{m}\right]$: thermal transport performance of pipe network
- $l_n[m]$: total length of pipe network
- s: heat demand sector
- $Q_s \left[{}^{kWh}/_{y}\right]$: total annual heat demand of s sector buildings in a discrete area
- $h_s \left[{}^{h}/_{y}\right]$: annual full load hours for residential space heating

Once we know annual heat demand per sector in a discrete area, hypothesizing a minimal transport performance for economic operation of 1 kW/m (AEE, 2008), it is possible to estimate the maximum length of the network. This empirical formula provides the upper limit to the total length of the pipe network, in order to assure an economical operation (BioEnergy 2020+).

3.1.5 Identify required thermal nominal power of the plant

In order to estimate the required thermal nominal power of the plant P_{th} we have to sum up all the different heat demand localized within the considered area, that is to say residential, productive and public spaces (i.e. schools, leisure centers, hospitals, etc.) ones. Moreover we have to estimate the annual full load hours required by each different heat demand type, in order to get the correct dimension of the thermal power of the plant to be installed. The estimation of this theoretic power is possible only if the efficiency of the distribution network and the thermal efficiency of the boiler are known; the value adopted for this parameter (BioEnergy 2020+, 2010) are summarized in Table 3.1.

Table 3.1. Boiler thermal and total efficiency as function of the biomass type.

k	Type of conversion facility	$\eta_{th}[\%]$	$\eta_{tot}[\%]$	$\sigma_{el}[-]$
1	Woody Biomass	80	80	-
2	Herbaceous Biomass	80	80	-
3	CHP Woody Biomass	70	85	0.21
4	CHP Herbaceous Biomass	70	85	0.21
5	CHP Biogas	42.5	80	0.89

The average thermal heat losses of heat distribution generally amount to 15-20% (LEUCHTWEIS, 2009), so the adopted value of efficiency of the distribution network η_d is 80%. The thermal efficiency of the boiler η_{th} depends on the type of the biomass used as fuel, and on the type of energy production realized by the boiler itself (i.e. thermal, or both thermal and electric).
The required thermal power of the biomass conversion facility can be consequently identified as

$$P_{th} = \frac{10 \cdot \varphi \cdot \beta}{\eta_d \cdot \eta_{th}} \cdot \sum_s \left(\frac{Q_s}{h_s}\right) \quad \text{Eq.3.9}$$

with $s \in S\{residential, productive, tertiary\}$

- $P_{th}[MW]$: thermal nominal power of the plant
- $\varphi[-]$: factor of simultaneity of the demand
- $\beta[-]$: safety factor
- η_d $[\%]$: efficiency of the distribution network
- η_{th} $[\%]$: thermal efficiency of the boiler
- $Q_s \left[{kWh}/{y}\right]$: total annual heat demand of s sector buildings in a discrete area
- $h_s \left[{h}/{y}\right]$: annual full load hours for residential space heating

The Factor of Simultaneity φ indirectly represents the end users composition; low values of this factor (about 0,5) show more differentiated users, characterized by different consume habits, while high values (0,8-0,9) indicate not differentiated users, that is to say very similar consume habits. Due to the diversified individual behavior of consumers there is a temporal spreading of the peaks of power demand, and the factor of simultaneity could potentially vary cell to cell. As first approximation, however, it has been consider the following simplification

$$\varphi \cdot \beta = 0{,}8 \cdot 1{,}2 \cong 1 \quad \text{Eq.3.10}$$

so that equation 3.9 can be rewrite as

$$P_{th} = \frac{10}{\eta_d \cdot \eta_{th}} \cdot \sum_s \left(\frac{Q_s}{h_s}\right) \quad \text{Eq.3.11}$$

In order to estimate the electrical power to be installed within a CHP biomass facility it should be used the electricity ratio σ_{el} expressed in Table 3.1. From this parameter, function of the type of conversion facility, the electrical power can be determined from the thermal one previously estimated as

$$P_{el} = \sigma_{el} \cdot P_{th} \qquad \text{Eq.3.12}$$

- $P_{el}[MW]$: electrical nominal power of the plant
- $\sigma_{el}[-]$: electricity ratio of the plant
- $P_{th}[MW]$: thermal nominal power of the plant

3.1.6 Identify Biomass Demand

Since a boiler could use different biomass types and each of them have a typical net calorific value NCV_b, satisfaction of net heat demand Q, considering network and boiler efficiency, could be thought as the subsequent summation:

$$\sum_{b \in B(k)} (m_b \cdot NCV_b) = \frac{10 \cdot Q}{\eta_d \cdot \eta_{th,k}} \qquad \text{Eq.3.13}$$

with $b \in B\{woody, herbaceous, anaerobic\ digestion\}$

- b identifies each considered type of biomass
- $B(k)$ identifies the set of biomass usable in k type plants
- $m_b \left[{}^{t}/_{y} \right]$: annual demand of b type raw material for combustion
- $NCV_b \left[{}^{kWh}/_{kg} \right]$: net calorific value of the dry b type fuel
- $\eta_{th,k}$ [%]: thermal efficiency of the k type of boiler
- η_d [%]: efficiency of the distribution network

NCV_b values are reported in Annex I. Each cell can gather biomass from neighboring cells if the distance between them is not greater of a specific parameter, function of the type of the considered biomass (Table 3.2).

Table 3.2. Catchment radius as function of biomass type.

b	Biomass Type	$r[km]$
1	Woody Biomass	30
2	Herbaceous	15
3	Slurry	10
4	Waste	30

This parameter is called biomass catchment radius r, and it mainly depends on the physical characteristics of the biomass and on its transport modality.
If we consider a j cell and all i cells potentially providing biomass to it, the total quantity of b type biomass that can be gathered within j cell could be estimated as

$$m_b{}^j = \sum_i m_b{}^i \cdot z_i \qquad \text{Eq.3.14}$$

with $b \in B\{woody, herbaceous, anaerobic\ digestion\}$

- $m_b{}^j \left[{}^t/_y\right]$: total quantity of b type raw material that could be gathered within j cell from all the neighboring i cells
- $m_b{}^i \left[{}^t/_y\right]$: territorial availability of b type raw material within i cell
- $z_i[-]$: binary variable

where

$$z_i \begin{cases} 1\ if\ d_{ij} \leq r(b) \\ 0\ else \end{cases} \qquad \text{Eq.3.15}$$

- $d_{ij}[km]$: distance between i cell and j cell
- $r[km]$: biomass catchment radius

If the total quantity of b type raw material that could be gathered within j cell from all the neighboring i cells is greater or equal to the annual demand of b type raw material for combustion, the j cell satisfies the constraint on the biomass availability in equation 3.16, rewritten in terms of energy content of the mix of similar biomass.

$$\sum_{b \in B(k)} \left(m_b{}^j \cdot NCV_b\right) \geq \sum_{b \in B(k)} (m_b \cdot NCV_b) \qquad \text{Eq.3.16}$$

with $b \in B\{woody, herbaceous, anaerobic\ digestion\}$

If a j cell at the same time satisfies the constraints expressed in equations 3.4, 3.6 (or 3.7) and 3.16, Biopole considers it suitable for the realization of a biomass conversion facility and a DH network.

3.1.7 Estimate problem of distances

Distance between the cell where biomass is collected (i cell) and the cell where the algorithm evaluates the realization of the plant (j cell) could be provided in at least two different ways:

a) *measured distance*: some regions, as Lombardy, provides a updated table of distances between municipalities, measured from one city hall to another one; known the distance between the municipalities respectively j cell and i cell belongs to, we could assign them the same distance, even if their city hall does not exactly belong to them

b) *Euclidean distance* between the corresponding centers of two cells; this hypothesis is easier from a computational point of view, but it is very simplistic, as we could not really move from a center to another in a straight line, but we should consider road network, since biomass transport is realized by lorries on the road. In this case distance d_{ij} could be represented as

$$d_{ij} = \sqrt{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2} \qquad \text{Eq.3.17}$$

- x, y: coordinates of the cells

However, from a computational point of view both these methods seem to be efficient solutions to estimate problem of distances, since the approximation can be considered negligible in the majority of cases. In Lombardy region the administrative subdivision biomass data refer to is the municipality, whose extension is usually limited to about 10 km^2; in these conditions, the error of approximation that we commit considering a table of distances between city halls is very small, even if we consider the farthest cell from the city hall ones in a municipality. On the other hand, except for municipal waste that is usually collected into defined gathering places, other biomass collection has to be made door to door, and raw materials are directly transported from agricultural and cattle farms, forests and fields to combustion plants. For this reason the distance covered to gather and transport biomass to the combustion plant could be appreciably bigger than the distance reported in a table of distances.

Nonetheless the presence of a table of distances is an important source of supplementary information, and we have to consider it every time it is possible; Euclidean distance would be used only if there is no measured information, since it

has no physical sense and it should undergo a process of weighing to consider the presence of physical obstacles (i.e. rivers, mountains, lakes, etc.).
The utilized table of distances provides both the type of previously described distances (i.e. measured and Euclidean), solving the problem of estimate formerly exposed. We have hypothesized that the transport of biomass could happen following the faster route, rather than the shorter one, since it could be thought as the most preferable. Each municipality is indicated by its Istat code.

3.2 Output analysis

Once Biopole has reached the end of the process described in Figure 3.1, it is possible to identify two different kinds of cells:

- *not suitable cells*, in which the constraint on heat demand or on biomass offer are not satisfied at the same time
- *suitable cells*, in which the feasibility of at least a combustion plant and of a DH network subsists

For each suitable cell Biopole has also defined:

- *type/s of energy biomass conversion* feasible in suitable cells; in fact a only thermal biomass conversion facility or a cogenerative one can be equally realized within a cell satisfying both the constraints on heat demand and biomass availability, provided that CHP option is characterized by a lower efficiency of the boiler (Table 3.1) and a higher demand of biomass to satisfy the same heat demand. However private operators on energy market could be mainly interested in cogenerative option, since sale of electrical energy guarantees higher and faster economical returns; so we have decided to show both the alternatives, because a public utility could be instead interested only in thermal production
- *thermal nominal power to be installed*, if only thermal energy conversion is allowed, or both thermal and electrical nominal power if CHP production is feasible

The output by Biopole is then described step by step, following the logical pattern exposed in the previous paragraphs: heat demand analysis, biomass availability analysis and a more detailed report of the number and of the type of the feasible plant, their thermal and electrical power and their territorial location are sequentially reported.

3.2.1 Heat demand and biomass availability analysis

On the basis of the constraints in equations 3.4 and 3.6 (or 3.7), a cell can be considered suitable from the demand point of view if it satisfies both them. Considering the whole territory of Lombardy region, a total number of 2374 cells manage to satisfy these constraints (Table 3.3); among them a total of 1008 cells belong to the urban category, while the remaining 1366 cells belong to the rural one (Figure 3.3).

Table 3.3. Total number of cells satisfying heat demand constraints.

Number of cells satisfying both the constraints on heat demand	2374
Number of urban cells satisfying both the constraints on heat demand	1008
Number of rural cells satisfying both the constraints on heat demand	1366

These cells are not equally spread on the territory among all the provinces of the region, as reported in Table 3.4.

Table 3.4. Number of cells satisfying heat demand constraint per province.

Province	Number of suitable cells	Number of suitable urban	Number of suitable rural
BERGAMO	364	147	217
BRESCIA	730	165	565
COMO	98	36	62
CREMONA	79	29	50
LECCO	104	34	70
LODI	37	19	18
MANTOVA	33	13	20
MILANO	389	307	82
MONZA	98	93	5
PAVIA	148	52	96
SONDRIO	170	11	159
VARESE	124	102	22
tot	2374	1008	1366

The provinces of Brescia and Milan counts higher numbers of suitable cells than all the other single provinces, followed by the province of Bergamo and then all the other provinces counting less than two hundred suitable cells on heat demand constraints. The province on Brescia is characterized by 77.4% (565 cells) of suitable

cells belonging to rural category, and this fact underlines the discontinuous urban settlements of its territory, not forming a unique metropolitan area as Milano (21.1%), Varese (17.7% of rural suitable cells) and Monza (5.1% of rural suitable cells) ones. Other provinces where suitable cells turn out to be mainly rural are Sondrio (93.5%), Lecco (67.3%), Pavia (64.9%) and Cremona (63.3%).
Once the cells satisfying heat demand constraints have been individuated, among them Biopole identifies the cells able to gather a sufficient biomass quantity to satisfy the constraint on biomass availability, expressed in equation 3.16. All the suitable cells for heat demand and biomass availability constraints could potentially host a biomass conversion facility that burns the specific type of biomass satisfying the constraint. All the 47 sub-categories of biomass have been traced back to only 3 typologies of conversion facility, on the basis of the kind of biomass used as fuel in the plant (i.e. woody, herbaceous or anaerobic digestion substrate). Since several types of biomass can satisfy the constraint in equation 3.16, the heat demand characterizing each suitable cell could be satisfied with the realization of alternative typologies of plant, and Biopole has to include this possibility of choice. Moreover woody and herbaceous biomass conversion facilities can be designed only for thermal production or even for CHP one; in this way in some suitable cells a total of 5 alternative typologies of realizations show to be feasible (Table 1.4). Opposite to 2374 suitable cells on the head demand constraints, the algorithm provides 5609 potential realizations of biomass conversion facilities belonging to the 3 considered typologies (Table 3.5).

Table 3.5. Number of potential realizations of biomass conversion facilities.

Number of potential realizations of biomass conversion facility	5609
Number of potential realizations of woody biomass conversion facility	2327
Number of potential realizations of herbaceous biomass conversion facility	999
Number of potential realizations of anaerobic digestion conversion facility	2283

Among all the potential realizations, 2327 (41.5% of the total) plants belong to the woody biomass typology, including both only thermal and CHP production, 999

(17.8%) to the herbaceous biomass typology, including both thermal and CHP production, and 2283 (40.7%) to the anaerobic digestion one. The territorial distribution of the potential realization is not uniform on Lombardy region (Table 3.6), and the province of Brescia and Milan show a higher number, followed by the provinces of Bergamo, Pavia, Sondrio and Varese. Less populated provinces, such as Lodi and Mantova ones, are characterized by a smaller and less concentrated heat demand, and the number of potential realizations is consequently minor.

Table 3.6. Number of potential realizations of biomass conversion facilities.

Province	Number of potential realizations
BERGAMO	851
BRESCIA	1652
COMO	219
CREMONA	234
LECCO	222
LODI	111
MANTOVA	95
MILANO	976
MONZA	223
PAVIA	441
SONDRIO	313
VARESE	272
tot	5609

The number of cells satisfying both constraints on heat demand but not biomass availability one is 31.

3.2.2 Woody biomass conversion facilities

A woody biomass conversion facility could potentially be realized in 2327 of the 2374 cells satisfying the heat demand constraints, since the energy content of the woody biomass that can be gathered within each of them satisfies the constraint on biomass availability in equation 3.16. In order to be really feasible, a woody biomass conversion facility has to satisfy a further constraint on the minimum thermal and electrical power to be installed, fixed in 0.1 MW. In fact biomass CHP in the power range below 100 kW_{el} is not commercially available yet (GADERER, 2008), and we have assumed to extend this constraint even on thermal nominal minimum power to be installed. In this way, on 2327 potential realizations 217 (9.3%) have been considered as not feasible at the present moment (Table 3.7). The total number of feasible realizations of thermal woody conversion facility is consequently 2110, equal to 90.7% of the total amount of potential realizations, while the number of feasible realizations of CHP woody conversion facility is 1739 (74.7%). The reason why the number of CHP feasible realizations is smaller than only thermal ones is simple: the thermal efficiency of the boiler is inferior in the first type of energy conversion (Table 3.1), so the woody biomass required by a CHP plant to satisfy the same heat demand is greater, and some potential cells have not a sufficient biomass availability.

Table 3.7. Number of feasible realizations of woody biomass conversion facility.

Number of potential realizations of woody biomass conversion facility	2327
Number of feasible realizations of thermal woody conversion facility	2110
Number of feasible realizations of CHP woody conversion facility	1739
Number of not feasible realizations of woody biomass conversion facility	217

Finally in 1739 cells, equal to 82.4% of all feasible cells, whether only thermal or CHP woody biomass conversion facilities turn out to be feasible.

The number of both potential and feasible realizations of woody biomass conversion facilities per province is reported in Table 3.8, with the installed power of only thermal annual operation typology and CHP ones expressed in MW.

Table 3.8. Number of feasible thermal and CHP woody plants per province.

Province	Number of potential plants	n y th1	P s th1 [MW]	n CHP1	P CHP1 [MW]
BERGAMO	361	321	3440	260	3646
BRESCIA	703	596	3506	451	3397
COMO	98	93	1204	77	1225
CREMONA	76	70	672	55	653
LECCO	102	85	692	61	785
LODI	37	37	498	36	569
MANTOVA	30	23	129	20	126
MILANO	388	383	14150	363	14240
MONZA	98	98	2822	98	3225
PAVIA	148	142	1652	121	1882
SONDRIO	162	138	213	78	228
VARESE	124	124	2717	119	3103
tot	2327	2110	31695	1739	33080

The provinces of Brescia and Milan hold higher numbers of feasible woody realizations, respectively equal to 28.2% and 18.2% of the total number of feasible thermal plants, and to 25.9% and 20.9% of feasible CHP ones. The province of

Bergamo is the third province as number of feasible thermal and CHP woody plants, holding respectively the 15.2% and 15.0% of the total number of feasible plants belonging to the two categories. Some provinces, such as Monza, Lodi and Varese, demonstrate the feasibility of whether only thermal or CHP production in all or almost suitable cells. This fact can be explained in the same ways: these provinces can gather a great quantity of woody biomass, even sufficient to the realization of a CHP plant requiring more biomass fuel. In Figure 3.4 the territorial distribution of woody feasible plants per class of thermal power is represented.

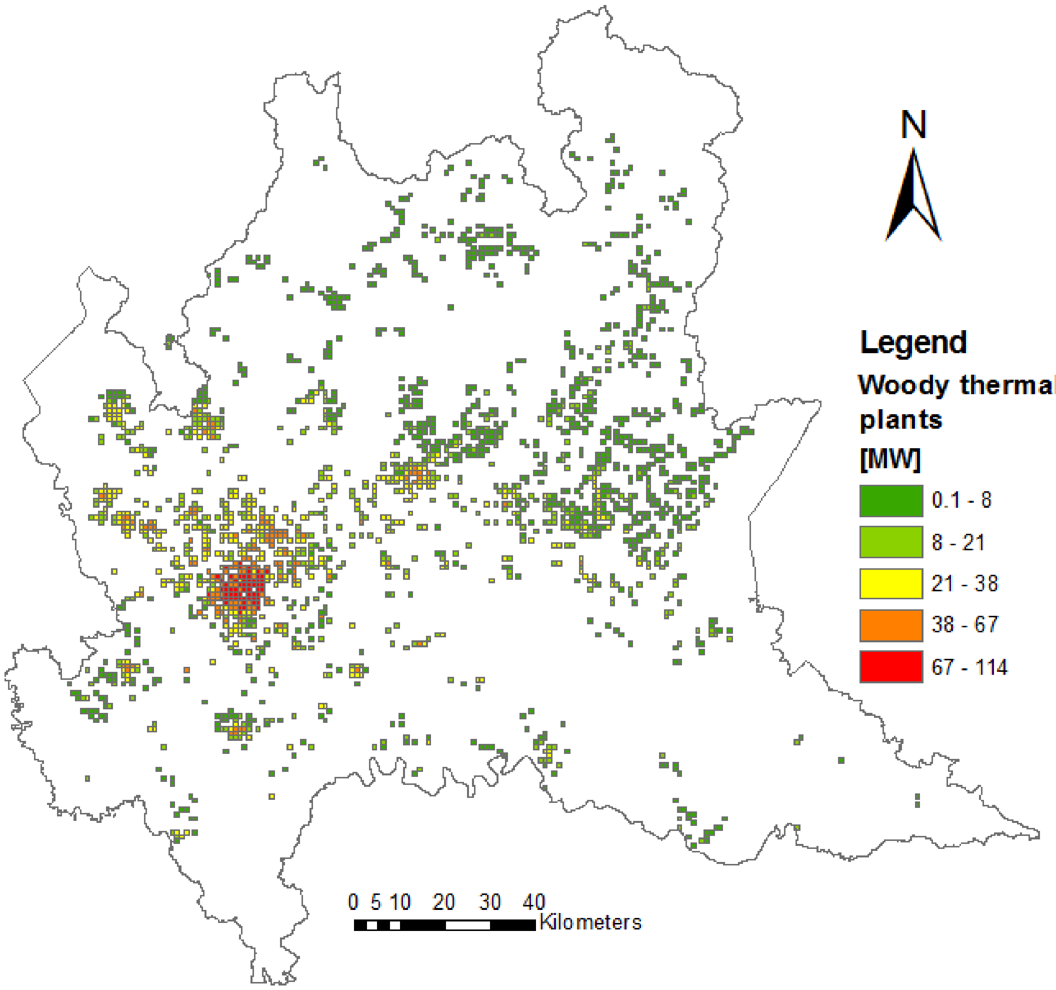

Figure 3.4. Territorial distribution of woody feasible plants per class of thermal power.

With regard to the nominal powers required in feasible plants, their maximum and minimum values have been summarized in Table 3.9, where the same distinction has been made between thermal and electrical power in CHP woody biomass conversion facilities. These nominal powers could be defined as theoretical ones, since most new constructed combustion plants belong to the capacity range between 0.5 MW_{th} and 20 MW_{th} (BioEnergy 2020+), and the economical feasibility of biomass plants characterized by such thermal nominal power has to be evaluated case by case. However we have decided not to fix a higher limit of thermal nominal power, in order to leave the algorithm free to calculate.

Table 3.9. Maximum, minimum and average values of nominal thermal power.

>=0.1 MW	y th1	CHP1
P max [MW]	114	114
P min [MW]	0.1	0.5
P average [MW]	15	19
P tot [MW]	31695	33080
number	2110	1739

Considering the simple frequency of the feasible realizations of woody biomass plant we can notice the more appealing classes of thermal nominal power for only thermal or CHP production (Figure 3.5).

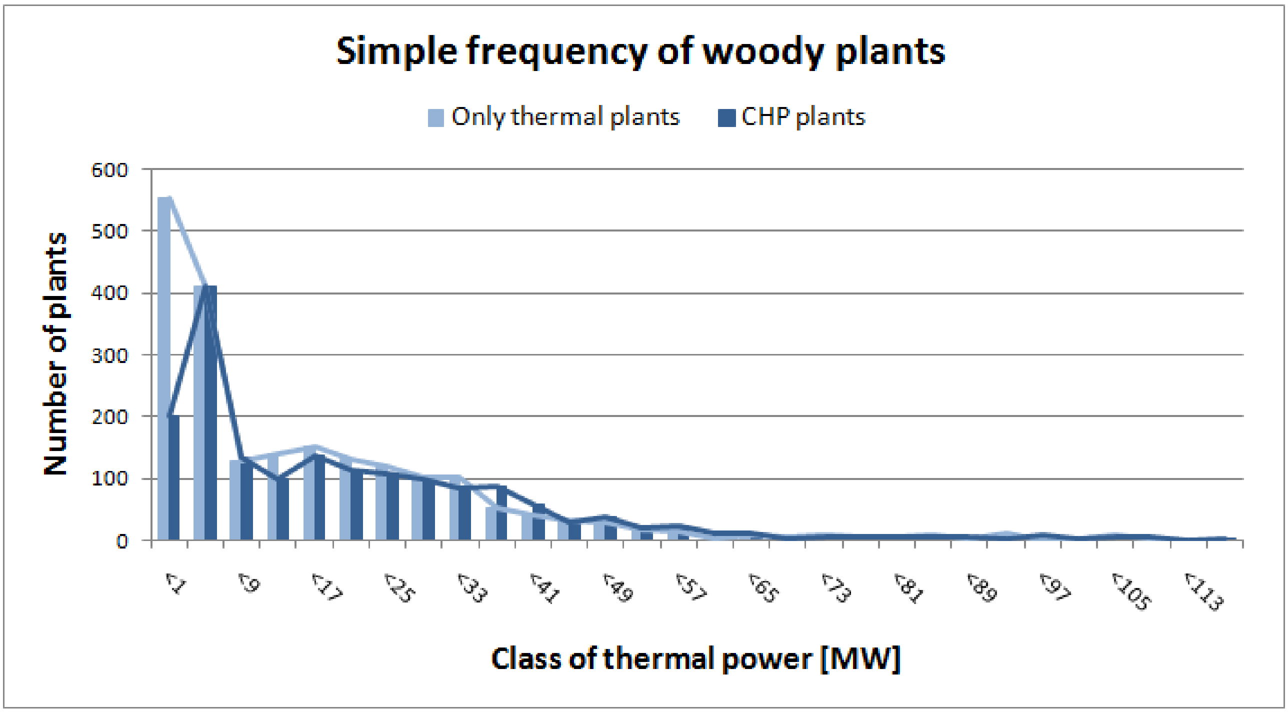

Figure 3.5. Simple frequency of woody plants per class of power.

The more appealing class for only thermal woody biomass conversion is in the range from 1 MW_{th} to 5 MW_{th} , with a significant number of plants belonging to the big-scale class from 9 MW_{th} to 37 MW_{th}.

About the distribution of thermal nominal power of CHP woody biomass plants it shows a smaller number of feasible plants belonging to the small-scale class. This fact can be explained as the effect of two concurrent events: the higher need of biomass as fuel, characterizing CHP plants, partially prevents some cells considered suitable for an only thermal realization from being suitable even for a CHP plant;

furthermore, the smaller efficiency of CHP boiler obliges the feasible realization to install a higher thermal power. As result the curve of distribution of thermal CHP nominal power is shifted towards higher classes of thermal power. Observing the cumulative frequency of woody plants (Figure 3.6), we have confirmation of the more appealing classes of thermal power, since we can notice an inflection point about at 5 MW_{th} and another about at 33 MW_{th}, underlining the range 1-5 MW_{th} as the more representative for only thermal woody biomass plants; the same characteristics can be noted even in the curve of cumulative frequency of CHP plants, where the first inflection point is about at 5 MW_{th} , while the second one is shifted towards higher values of thermal power, at about 37 MW_{th}.

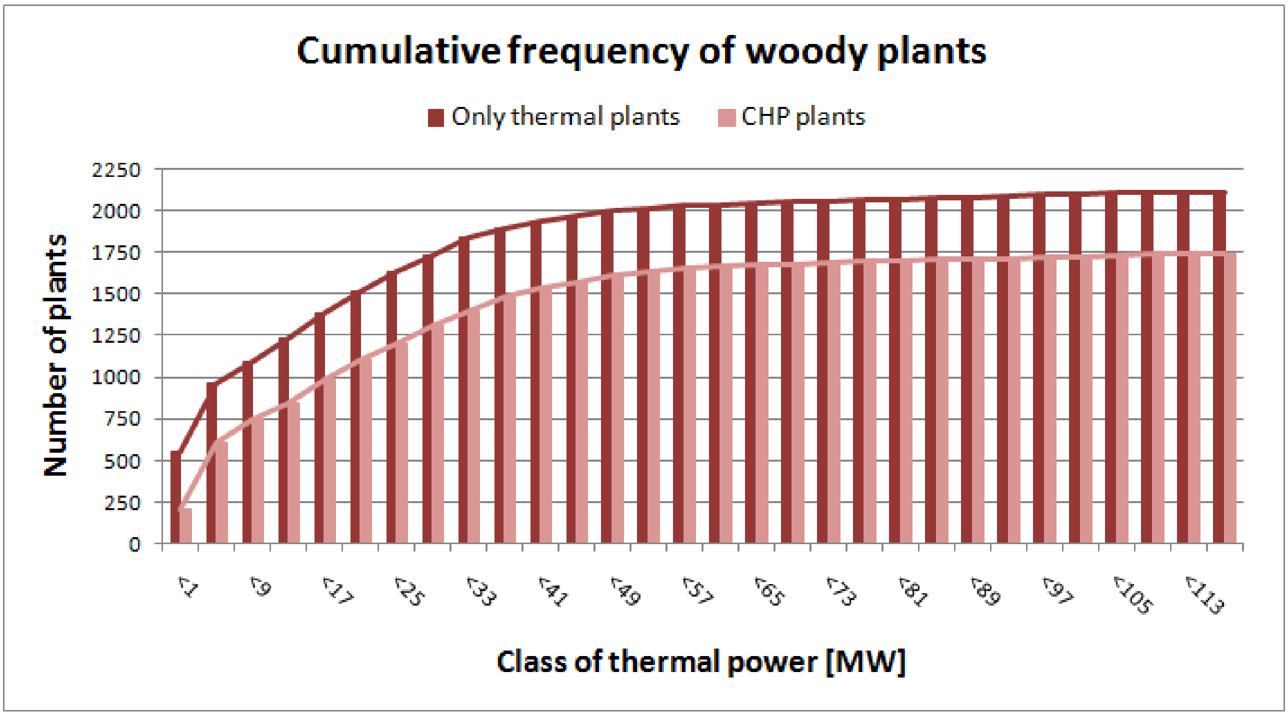

Figure 3.6. Cumulative frequency of woody plants per class of power.

3.2.3 Herbaceous biomass conversion facilities

An herbaceous biomass conversion facility could potentially be realized in 999 of the 2374 cells satisfying the heat demand constraints, since only in these cells the energy contents of the herbaceous available biomass satisfies the constraint on biomass availability in equation 3.16. As explained in the previous paragraph, a herbaceous biomass conversion facility has to satisfy a constraint on the minimum thermal and electrical power to be installed, fixed in 0.1 MW_{th} and 0.1 MW_{el} (GADERER, 2008) in case of CHP production, in order to be really feasible. In fact it is possible that a cell could satisfy both the constraints on heat demand and on biomass availability, but the thermal nominal power required to be installed would be smaller than the limit of commercial feasibility, so it has been rejected as not feasible. In this way, on 999 potential realizations 229 (22.9%) have been considered as not feasible at the present moment (Table 3.10).

Table 3.10. Number of potential realizations of herbaceous biomass conversion facility.

Number of potential realizations of herbaceous biomass conversion facility	999
Number of feasible realizations of thermal herbaceous conversion facility	770
Number of feasible realizations of CHP herbaceous conversion facility	628
Number of not feasible realizations of herbaceous biomass conversion facility	229

The total number of feasible realizations of thermal herbaceous conversion facility is consequently 770, equal to 77.1% of the total amount of potential realizations, while the number of feasible realizations of CHP woody conversion facility is 628 (62.9%). The number of CHP feasible realizations is smaller than only thermal ones because the thermal efficiency of CHP boiler is inferior (Table 3.1), so, as happened for woody biomass plants, the herbaceous biomass required by a CHP plant to satisfy the same heat demand is greater, and more potential cells have not enough biomass availability. Finally in 628 cells, equal to 81.6% of all feasible cells, whether only thermal or CHP herbaceous biomass conversion facilities turn out to be feasible. The number of potential realizations of herbaceous biomass conversion facility and feasible one per province is reported in Table 3.11, with the installed power of only thermal annual operation typology and CHP ones expressed in MW.

The provinces of Brescia and Milan hold higher numbers of feasible realizations of herbaceous plant, respectively equal to 27.1% and 18.3% of the total number of feasible thermal plants, and to 26.8% and 20.4% of feasible CHP ones. The province of Pavia is the third province as number of feasible thermal and CHP herbaceous plants, holding respectively the 17.5% and 18.2% of the total number of feasible plants belonging to the two categories; this placement is due to the very high availability of rice residuals that characterizes its territory, able to satisfy the heat demand of the greater part of its suitable cells.

Table 3.11. Number of feasible thermal and CHP herbaceous plants per province.

Province	Number of potential plants	n y th2	P s th2 [MW]	n CHP2	P CHP2 [MW]
BERGAMO	129	89	737	64	708
BRESCIA	276	209	1817	168	1853
COMO	24	13	50	6	31
CREMONA	79	74	880	62	1002
LECCO	23	15	67	4	54
LODI	37	37	498	36	569
MANTOVA	32	30	319	28	364
MILANO	200	141	1844	128	1775
MONZA	27	12	145	10	122
PAVIA	145	135	1525	114	1736
SONDRIO	3	0	0	0	0
VARESE	24	15	41	8	13
tot	999	770	7923	628	8229

In Figure 3.7 the territorial distribution of herbaceous feasible plants per class of thermal power is represented.

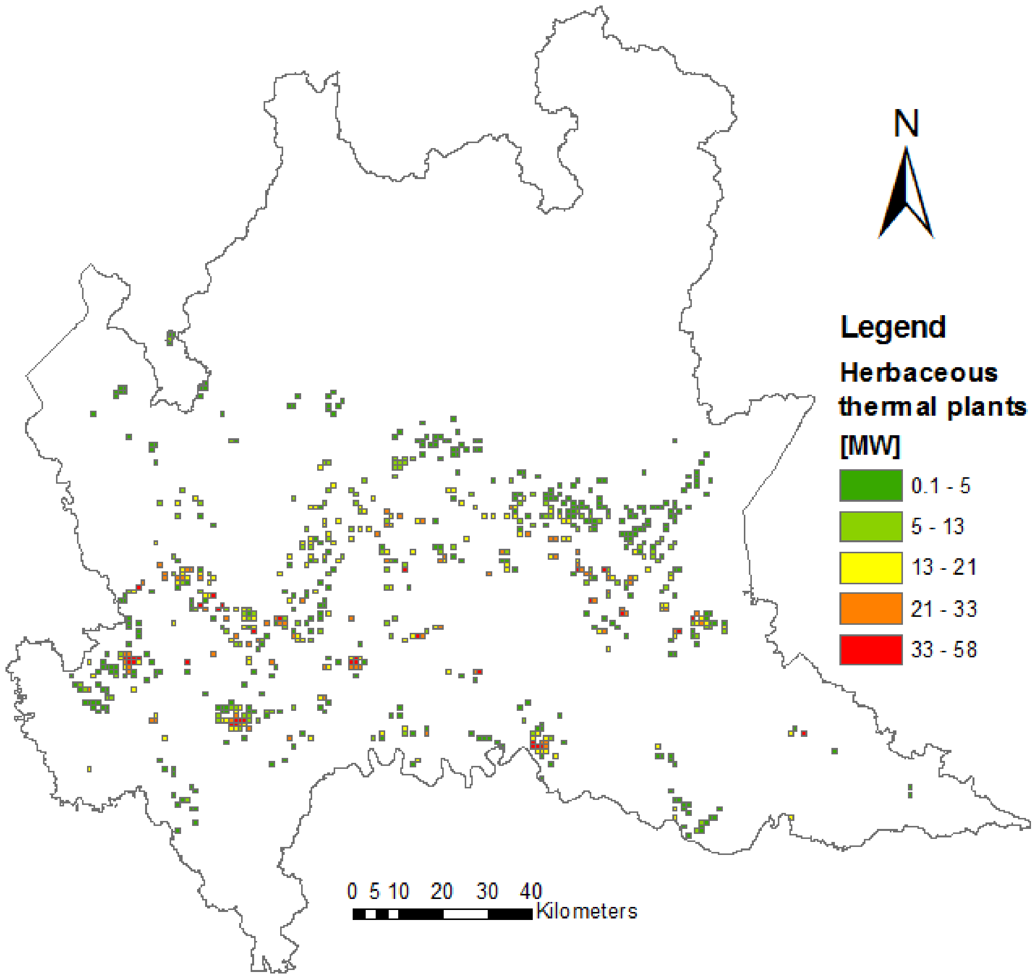

Figure 3.7. Territorial distribution of herbaceous feasible plants per class of thermal power.

Some provinces, such as Lodi and Mantova, demonstrate the feasibility of whether only thermal or CHP production in almost all the suitable cells. This fact happened because these provinces can gather a great quantity of herbaceous biomass, even sufficient to the realization of a CHP plant requiring more biomass fuel. The province of Sondrio has only 3 potential realizations, but it reaches the feasibility of nor thermal or CHP herbaceous plants; this result seem to be easily understandable, since this province is mainly characterized by a mountainous territory, not suitable for a massive production of those biomass categories (i.e. cereals, rice or maize) classified as herbaceous. In fact, comparing Figure 3.7 to Figure 3.4, we can notice the absence of herbaceous plants in the mountainous part of the region, due to the lack of herbaceous biomass availability, while the number of woody plants is higher. The highest thermal powers are required in southern area of Milan and in the provinces of Pavia and Mantova.

With regard to the nominal powers required to the feasible herbaceous plants their maximum and minimum values have been summarized in Table 3.12, where the same distinction has been made between thermal and electrical power in CHP herbaceous biomass conversion facilities.

Table 3.12. Maximum, minimum and average values of nominal thermal power.

>=0.1 MW	y th2	CHP2
P max [MW]	59	67
P min [MW]	0.1	0.5
P average [MW]	10	13
P tot [MW]	7923	8229
number	770	628

The maximum thermal power required is smaller than woody biomass plants both for only thermal and for CHP production plants; this fact can be explained with the shorter catchment radius adopted for herbaceous biomass (Table 3.2) and their smaller low calorific value, that allows the feasibility of herbaceous plants in a inferior number of potential cells, characterized by smaller heat demand. These nominal powers could be defined as theoretical ones, since, as said, most new constructed combustion plants belong to the capacity range between 0.5 MW_{th} and 20 MW_{th} (BioEnergy 2020+), but we have decided not to fix an higher limit of thermal nominal power, in order to point out the maximum value of power that could be reached saturating the heat demand.

Considering the simple frequency of the feasible realizations of herbaceous biomass plants we can notice the more appealing classes of thermal nominal power for only thermal or CHP production (Figure 3.8). The more appealing classes for only thermal woody biomass conversion are in the range between 1 MW_{th} and 5 MW_{th} , as we have even noticed for only thermal woody biomass plants, with a significant number of plants belonging to the big-scale class from 9 MW_{th} to 21 MW_{th}.

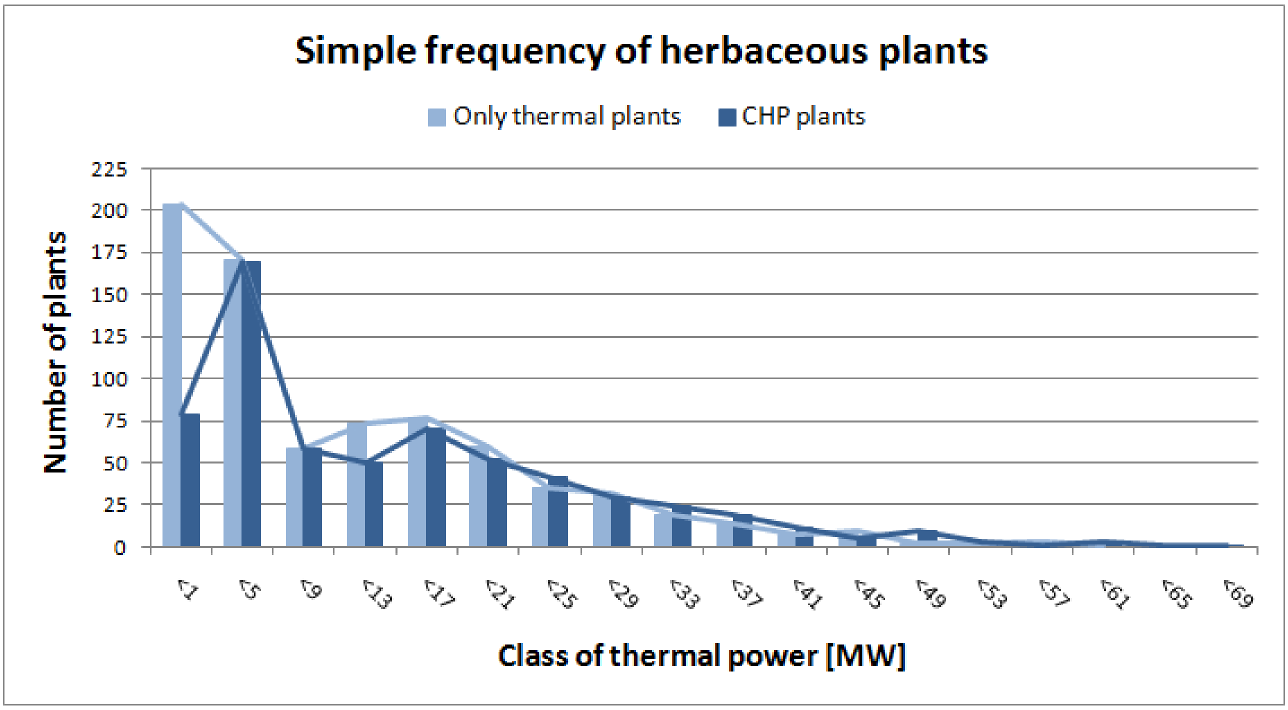

Figure 3.8. Simple frequency of herbaceous plants per class of power.

About the distribution of thermal nominal power of CHP herbaceous biomass plants it shows a smaller number of feasible plants belonging to the small-scale class in comparison to only thermal one. This fact can be explained as the effect of two concurrent events: the higher need of biomass as fuel, characterizing CHP plants, partially prevents some cells considered suitable for an only thermal realization from being suitable even for a CHP plant; furthermore, the smaller efficiency of CHP boiler obliges feasible realizations to install higher thermal powers. As result the curve of distribution of thermal CHP nominal power is shifted towards higher classes of thermal power.

Observing the cumulative frequency of herbaceous only thermal plants (Figure 3.9), we have confirmation of the more appealing classes of thermal power, since we can notice three inflection point about at 5 MW_{th} , 13 MW_{th} and 21 MW_{th}, underlining ranges 1-5 MW_{th} and 13-21 MW_{th} as the more representative for only thermal herbaceous biomass plants; the same characteristics can be noted even in the curve of cumulative frequency of CHP plants, where inflection points are at about 5 MW_{th} the first, 13 MW_{th} the second and about 17 MW_{th} the third, while for higher thermal power the curve of distribution seems to be very smoothed. This fact underlines that the distribution of thermal CHP power is more uniform for thermal power higher than 17 MW_{th}, where the number of feasible plants per class is diminishing but it is quite similar.

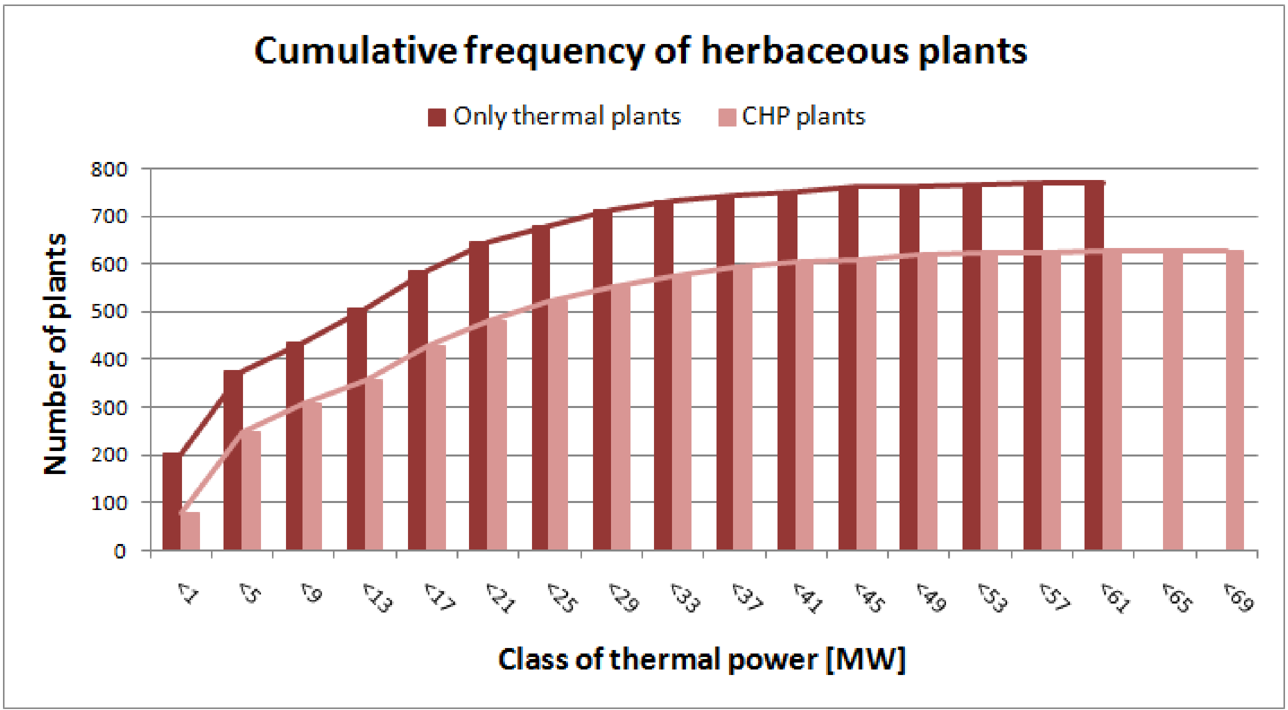

Figure 3.9. Cumulative frequency of herbaceous plants per class of power.

3.2.4 CHP biogas conversion facilities

A CHP biogas conversion facility could potentially be realized in 2282 of the 2374 cells satisfying the heat demand constraints (Table 3.13), since only in these cells the energy contents of the available substrates for anaerobic digestion and the production of the biogas satisfies the constraint on biomass availability in equation 3.16.

Table 3.13. Number of potential realizations of CHP biogas conversion facility.

Number of potential realizations of CHP biogas conversion facility	2282
Number of feasible realizations of CHP biogas conversion facility	2017
Number of not feasible realizations of CHP biogas conversion facility	265

As explained in the previous paragraphs, in order to be really feasible even a CHP biogas conversion facility has to satisfy the constraint on the minimum thermal and electrical power to be installed, fixed in 0.1 MW_{th} and 0.1 MW_{el} (GADERER, 2008). In fact it is possible that a cell could satisfy both the constraints on heat demand and on biomass availability, but the thermal nominal power required to be install would be smaller than the limit of commercial feasibility, so it has been rejected as not feasible. In this way, on 2282 potential realizations 265 (11.6%) have been considered as not feasible at the present moment. However, the potential realizations that have been rejected could be considered feasible if the hypothesis of micro-generation would be considered.

The total number of feasible realizations of CHP biogas conversion facility is consequently 2017, equal to 88.4% of the total amount of potential realizations.

The territorial distribution of the feasible plants is not uniform in Lombardy neither for CHP biogas typology. The number of potential and feasible realizations of CHP biogas conversion facility per province is reported in Table 3.14.

Table 3.14. Number of feasible thermal and CHP biogas plants per province.

Province	Number of potential plants	n CHP3	P CHP3 [MW]
BERGAMO	361	314	6039
BRESCIA	673	543	6346
COMO	97	89	2231
CREMONA	79	73	1346
LECCO	97	78	1240
LODI	37	37	938
MANTOVA	33	32	748
MILANO	388	371	24995
MONZA	98	98	5312
PAVIA	148	140	2929
SONDRIO	148	118	135
VARESE	124	124	5114
tot	2283	2017	57372

The provinces of Brescia and Milan hold higher numbers of feasible realizations of biogas plant, respectively equal to 26.9% and 18.4% of the total. The province of Bergamo is the third province as number of feasible realizations of this type of plant, holding about the 15.6% of the total number of feasible realization of CHP biogas plant in Lombardy region. Some provinces, such as Lodi, Mantova, Monza and Varese demonstrate the feasibility of all or almost all the potential realizations of biogas plant. This fact happened because these provinces can gather a great quantity of substrate for anaerobic digestion, primarily zootecnics residuals, industrial and urban wastes. The provinces showing a high number of feasible

realizations of CHP biogas plant are consequently characterized either by an high density of population producing wastes and high rate of their separate collection (i.e. Brescia, Milano and Monza), or a high territorial presence of food processing industry (i.e. Sondrio, Varese) or animal breeding (i.e. Cremona, Mantova and Lodi).
In Figure 3.10 the territorial distribution of CHP biogas feasible plants per class of thermal power is represented.

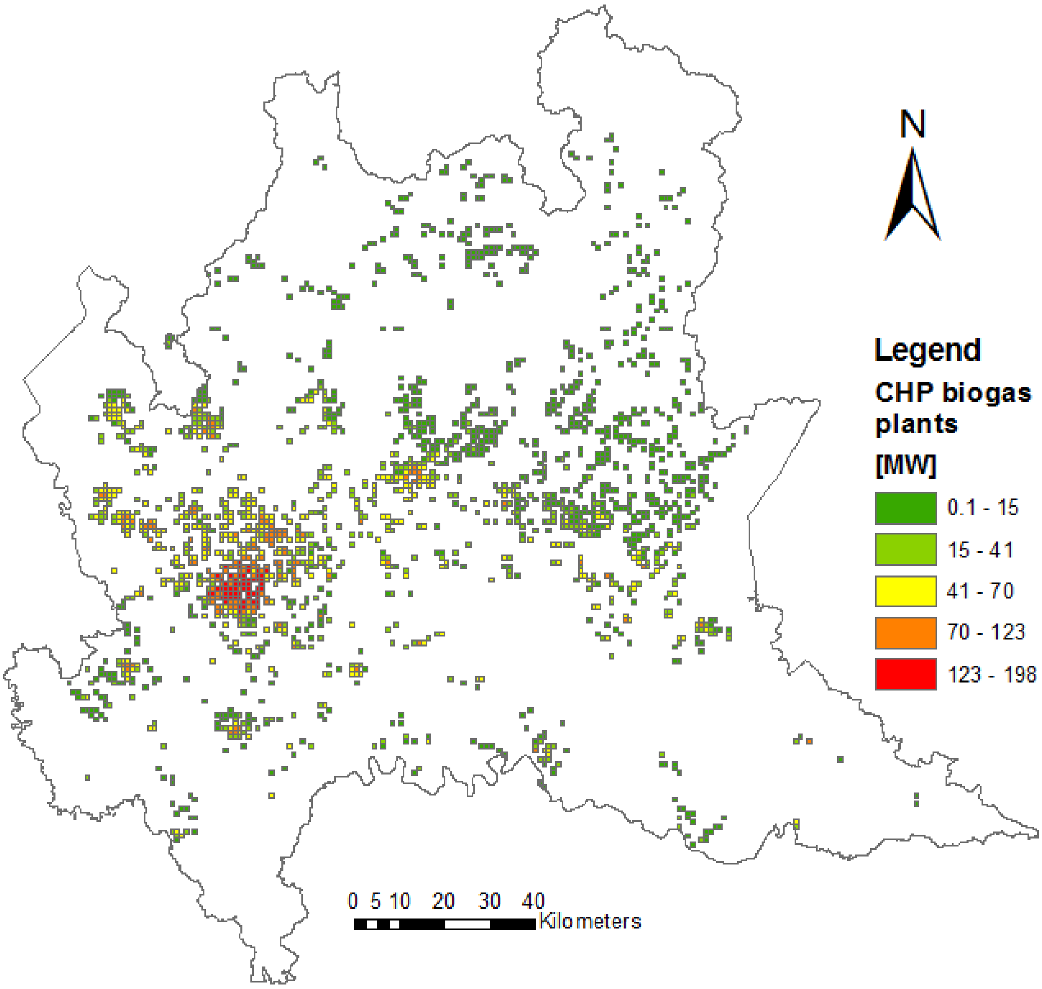

Figure 3.10. Territorial distribution of CHP biogas feasible plants per class of thermal power.

With regard to the thermal nominal powers of the feasible plants their maximum and minimum values have been summarized in Table 3.15.

Table 3.15. Maximum, minimum and average values of nominal thermal power.

> =0.1 MW	CHP3
P max [MW]	199
P min [MW]	0.1
P average [MW]	28
P tot [MW]	57372
number	2017

Both the maximum and the average thermal power required by CHP biogas plants are higher than all the other typologies ones, essentially due to the lower thermal efficiency of the biogas boiler (equation 3.11) and to the higher territorial availability of substrate for anaerobic digestion, that enable the satisfaction of greater heat demand. According to economies of scale and the laws regulating the feed in tariffs for electricity, biogas plants are rarely constructed under an installed power of 100 kW_{el} and most new constructed biogas plants in Europe operate at an installed power of 500 to 1000 kW_{el}, respectively 560 to 1125 kW_{th} (BioEnergy 2020+). So the maximum nominal power could be defined as theoretical ones, since we have decided not to fix a higher limit of thermal nominal power, as we made even for woody and herbaceous biomass plants, in order to leave the algorithm free to calculate. Plants characterized by a nominal thermal power greater than 10 MW_{th} have to be realized with a different technology, consisting of modular solutions of a series of boiler (BioEnergy 2020+). Considering the simple and the cumulative frequency of the feasible realizations of CHP biogas plant, we can notice the more appealing classes of thermal nominal power (Figure 3.11 and Figure 3.12).

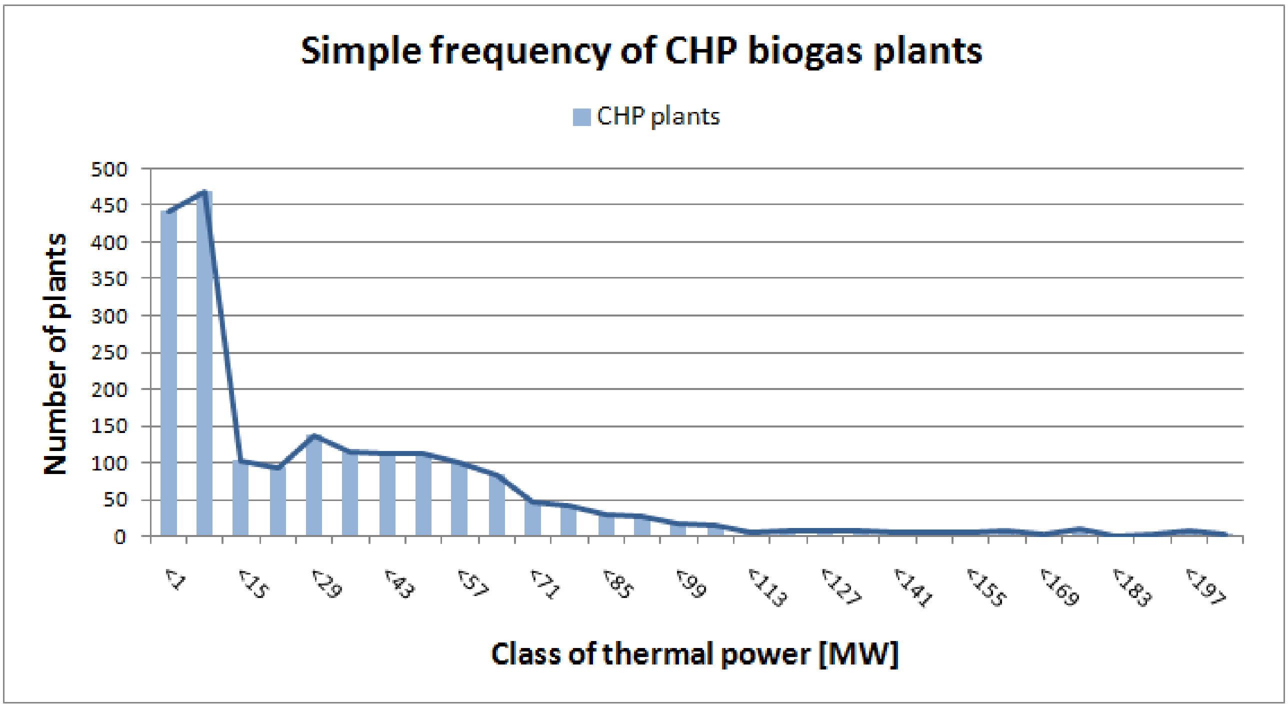

Figure 3.11. Simple frequency of CHP biogas plants per class of power.

The more appealing classes turn out to be in the range between 1 MW_{th} and 8 MW_{th}, with a significant number of plants belonging to the big-scale class from 22 MW_{th} to 64 MW_{th} (big-scale generation). The number of feasible realizations requiring a nominal thermal power included between 1 MW_{th} and 9 MW_{th} is significantly higher than herbaceous ones, and about the same of woody ones.

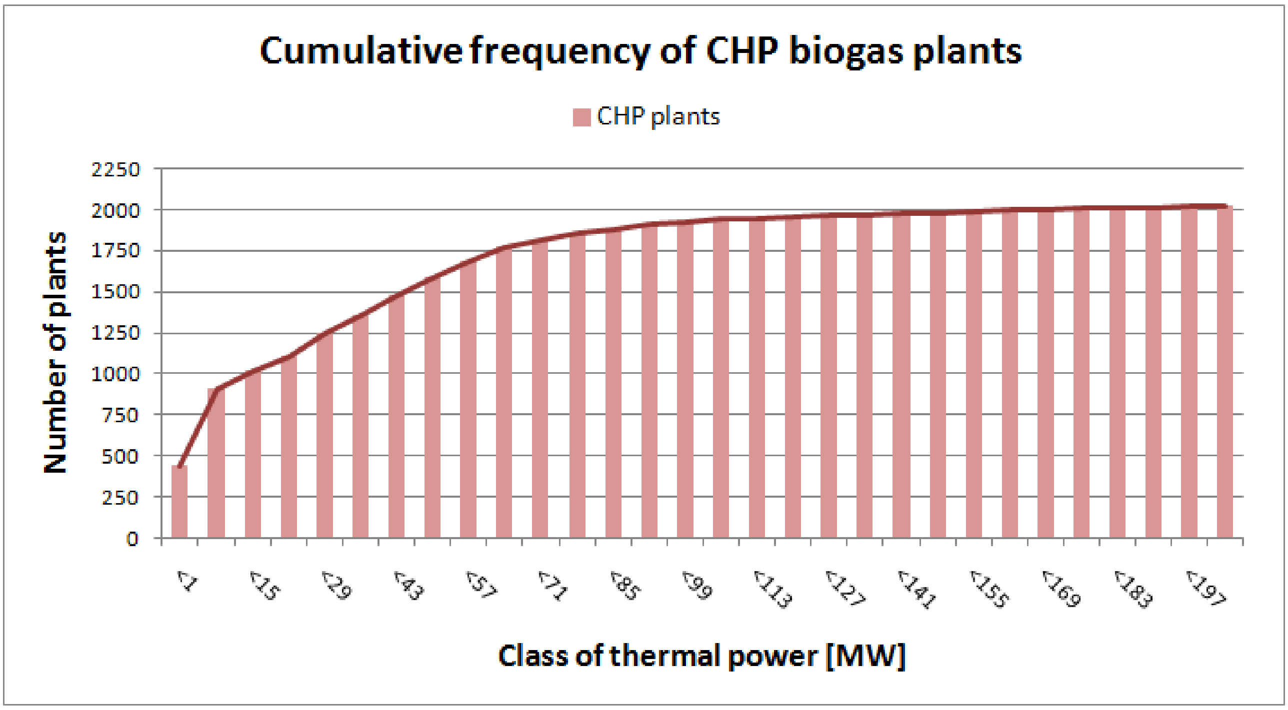

Figure 3.12. Cumulative frequency of CHP biogas plants per class of power.

Observing the cumulative frequency of CHP biogas plants (Figure 3.9) we can notice an inflection point about at 8 MW_{th}, another about at 22 MW_{th}, and a last one about at 64 MW_{th} , underlining as more interesting for CHP biogas plants two different ranges: 1-8 MW_{th} and 22-64 MW_{th}.

3.3 Ranking

At this point several plants could be realized in a single cell and we have to classify them, in order to point out the best realization constrained to certain preferences directly or indirectly expressed by the decision maker. There are two different ranking types that could be used:

1. the first ranking is made at *regional level*, so we have to consider the whole regional area pointing out the list of the best plants and the corresponding cells where they would be placed
2. the second ranking interests *each suitable cell*, in order to point out the best type of biomass conversion facility, its thermal (eventually electrical, too) power and the corresponding exploited raw material

In case of a plant, belonging to a cell ranking, will be realized, the same ranking could be removed, because, even if other biomass typologies are available, the heat demand would be already satisfied. The first ranking, instead, have to be updated whenever a biomass plant within the list is realized, because, erasing the biomass requested to its functioning, the hierarchy necessarily changes. In this work, for illustrative purpose, the first ranking type has been made before, in order to point out, in a second time, the dominated or semi-dominated type of biomass plants that could be alternatively realized within the same cell adopting other criteria. In order to make a ranking between different solutions we have to consider several criteria of choice; each of them stands for different approach of stakeholders to the problem and it is represented by an indicator. In fact, the application of a certain criterion rather than another could cause different position of the same type of plant within both the rankings; with several criteria a single ranking could be obtained, for example, with *weighting method*, that sums all the values assumed by indicators weighed with coefficients given by the end user. According to several interests that different stakeholders could express, we have identified three different criteria of choice:

- Supplying certainty criteria
- Pollutant emission criteria (global and local)

3.3.1 Supplying certainty criteria

The availability of enough quantity of a specific raw material is a constraint to the realization of a certain type of biomass plant. However we have to consider that territorial biomass supplying is aleatory, and it could vary during the life of the plant; so, in order to avoid the use of a model describing the supplying of raw material as a function of time, we could use a proxy indicator based on the quantity of available biomass per annum. In fact we could consider the most common biomass in a region as the safest, since we could hypothesize an easy availability of a certain biomass as a guarantee of supplying; furthermore a certain type of plant could use more than a single biomass, so the algorithm finally points out the best type of plant as function of the safest mix of biomass it can use. The corresponding indicator could be normalized in reference to the energy demand as:

$$I_{c,k}{}^{j} = \frac{E_{a,B(k)}{}^{j} \cdot \eta_{b,k} \cdot \eta_{d}}{E_{d}{}^{j}} = \frac{\sum_{b \in B(k)} \left(m_{b}{}^{j} \cdot NCV_{b} \right) \cdot \eta_{th,k} \cdot \eta_{d}}{Q^{j}} \qquad \text{Eq.3.18}$$

with $b \in B\{woody, herbaceous, anaerobic\ digestion\}$

- $I_{c,k}{}^{j}\,[-]$: indicator of supplying certainty to the k type plant in the j cell
- j identifies a suitable cell to DH installation
- k identifies the type of feasible considered plant
- $E_{a,B(k)}{}^{j}\,[MWh]$: energy availability deriving from the energy conversion of a B type biomass in the k type plant within the j cell
- $E_d{}^{j}\,[MWh]$: heat demand within the j cell
- $m_b{}^{j}\left[{}^{t}/_{y}\right]$: total quantity of b type raw material that could be gathered within j cell from all the neighboring cells
- $NCV_b\left[{}^{MWh}/_{t}\right]$: net calorific value of the dry b type fuel
- $\eta_{th,k}$ [%]: thermal efficiency of the k type of boiler
- η_d [%]: efficiency of the distribution network

The NCV_b parameter is necessary to convert a mass quantity into a most significant energy one, and the net calorific values used for each sub-categories of biomass are reported in Annex I. Since higher values of indicator $I_{c,k}$ identify safer biomass supplying, we want to maximize it and a plant fueled by a safer mix of raw material will be consequently placed higher into the cell ranking. The value of the indicator is at least equal to 1 for a cell satisfying both the constraints on heat demand and on the biomass availability.

3.3.2 Global pollutant emission criteria

The most significant emissions produced by a biomass plant are all those emissions characterizing combustion process: CO_2, NO_X, SO_X, VOC (Volatile Organic Compounds) and PM (Particular Materials). So the realization of a biomass conversion facility has significant consequences at two territorial levels: global and local. At global level, assuming as about null the total CO_2 emission balance for every type of biomass, we can affirm that the only emissions of GHGs deriving from the biomass energy conversion is due to the biomass road transport, realized with diesel lorries. In our method we formalize two different indicators, a first indicator for CO_2 emissions and a second one for all other emissions, expressed as an indicator of impact. Since we can assume as about null the total CO_2 emission balance for every type of biomass, we maximize avoided CO_2 emission in comparison to a natural gas plant (the less polluting among fossil fuels) producing the same energy. Later we have to subtract from CO_2 avoided emission the emissions due to biomass road transport, realized with diesel lorries. The CO_2 emission indicator, very important at global level, could be:

$$I_{g,k}{}^{j} = E_{gas} - E_{t,b\in B(k)}{}^{j} =$$

$$= 10^2 \cdot \frac{e_{gas}}{\eta_{gas}} \cdot E_{p,k}{}^{j} - 2 \cdot c_t \cdot \sum_{b\in B(k)} \sum_i \left(d_{ij} \cdot x_{ijb} \cdot a_{ib}\right) \qquad \text{Eq.3.19}$$

where

$$E_{p,k}{}^{j} = \frac{E_d{}^{j}}{\eta_{tot,k} \cdot \eta_d} = \frac{Q^j}{\eta_{tot,k} \cdot \eta_d} \qquad \text{Eq.3.20}$$

- $I_{g,k}{}^{j} \left[{}^{t_{CO2}}/_{y}\right]$: CO_2 emission indicator (global level)
- $E_{gas} \left[{}^{t_{CO2}}/_{y}\right]$: CO_2 emission from an equivalent gas plant
- $E_{t,b\in B(k)}{}^{j} \left[{}^{t_{CO2}}/_{y}\right]$: CO_2 emission due to the transport of the necessary quantity of b type biomass
- $e_{gas} \left[{}^{t_{CO2}}/_{MWh}\right]$: CO_2 emission factor for a gas plant generating the same output
- $\eta_{gas}[\%]$: efficiency of an equivalent gas plant
- $E_{p,k}{}^{j} \left[{}^{MWh}/_{y}\right]$: total energy production of the k-type plant
- $c_t \left[{}^{t_{CO2}}/_{km \cdot t}\right]$: CO_2 specific emission from biomass transport
- $d_{ij}[km]$: distance between i cell and j cell
- $x_{ijb}[\%]$: percentage of the total available b type biomass in i cell transported to j cell
- $a_{ib} \left[{}^{t}/_{y}\right]$: total b type biomass produced in i cell

Moreover, hypothesizing that the cost of the different b type ($b \in B(k)$) raw material usable in a k-type plant could be quite similar, the system catches the nearest biomass not discriminating the b type it belongs to.

3.3.3 Local pollutant emission criteria

At local level, instead, we have especially to consider the emissions of VOC and PM, but also the environmental impact of the realization and the potential troubles generated to the resident population during the operations of construction site and the operative life of the biomass plant. All these facts have to be considered in order to classify the real feasibility of a plant, which for all this reason should impact the less number of resident people. Even regarding all the other emissions from biomass combustion, we could hypothesize a circular area impact originating in the emission point; its radius is function of the height of the source, meteorological characteristics of the site and of the plant ones, but, as first approximation, it could be simply considered as a parameter depending on power installed into the plant (e.g. 3 km for plant's power 2-30 MW). The consequent indicator of impact represents resident population within the area impacted by the emissions. Emissions deriving from biomass road transport could be not considered in this evaluation, since they are negligible for short distances and for quantities of vehicles involved. So corresponding indicator could be

$$I_{l,k}{}^{j} = P \qquad \text{Eq.3.21}$$

- $P[citizens]$: resident population impacted by local pollutant emissions

3.3.4 Results

The presence of three different hostile criteria guarantees several approaches to the problem of localization of feasible biomass plants provided by Biopole. In order to reduce this many-objectives problem to a single-objective one we firstly should adopt a set of weights that could exactly reflect the expectations of the stakeholders involved in the decision; secondary we should normalize the values of the indicators, since their different units of measurement do not allow a simple summation. Considering that the purpose of this work is only to provide a decision support system and to prove the formal and logical accuracy of the formalized method, we have decided not to proceed with the adoption of weighting method, only providing the single-objective optimal solutions. This decision left the adoption of an arbitrary set of weights and of a method of normalization of the indicators to the end users, simplifying the treatment of the data.

The first objective maximizes the indicator in equation 3.18; this indicator has no dimension, and it is the ratio of the energy content provided by the available biomass that can be gathered in a cell to the heat demand of the cell. On this basis, cells characterized by a huge availability of biomass and by a limited heat demand, just enough to satisfy the constraint on the minimum thermal power to be installed, occupy the first positions of the consequent ranking. We have to underline that, for woody and herbaceous plants, the only thermal plants always placed better than CHP production ones, since their boiler efficiency is higher (equation 3.18).
In Table 3.16 the number of feasible plants per type of biomass conversion facility and ranking positions are listed.

Table 3.16. Number of feasible plants per type of plant and ranking position.

Type of plant	1st	2nd	3rd	tot
Woody	1312	570	228	2110
Herbaceous	91	253	426	770
Biogas	804	1127	86	2017
tot	2207	1950	740	4897

As we can notice from the Table 3.16, 2207 cells have at least a type of plant that can be realized on their territory, while only 740 have the complete choice on all the three types of biomass energy conversion facility, for a total number of 4897 feasible realizations on the whole Lombardy region (Table 3.7, 3.10 and 3.13). Only thermal or CHP production, where feasible, woody biomass plants have been classified as first alternative to be chosen in 1312 cells (59.4% of the total), demonstrating to be the best type of biomass conversion for the supplying certainty criteria, respectively followed by CHP biogas and herbaceous biomass plants.
Table 3.17 reports the value of the supplying certainty indicator in the first three positions of the regional ranking, indicating the specific cell of the grid where each plant has to be realized, with the municipality and the province the considered cells belong to.

Table 3.17. Regional ranking based on supplying criteria and localization of the first cells.

	1st	2nd	3rd
value ind 1	7712	6878	2523
id cell	3122	3016	21796
munipality	CAMPIONE D`ITALIA	CAMPIONE D`ITALIA	SABBIONETA
code Istat	013040	013040	020054
province	COMO	COMO	MANTOVA

As we thought, the three better realizations on this criterion are localized in cells characterized by a limited heat demand and by a great availability of biomass, approximately three orders of magnitude greater than the quantity required by the heat demand satisfaction of the cell.

In fact the best typology of plant to be realized within cell 3122 (Table 3.18) is CHP biogas production, since the province of Como shows one of the higher concentration of industrial wastes at regional level. Herbaceous and woody only thermal or CHP production are the dominated alternatives of cell 3122.

Table 3.18. Cell ranking based on supplying criteria.

	id cell	plant	ind_1	ind_2	ind_3	P th [MW]	P el [MW]
1st	3122	Biogas	7712	241	2117	1.017	0.905
2nd	3122	Herbaceous	3584	227	2117	0.540	
	3122	Herbaceous	3584	227	2117	0.617	0.130
3rd	3122	Woody	1439	227	2117	0.540	
	3122	Woody	1439	227	2117	0.617	0.130

The power to be installed within cell 3122 belongs to the small-scale range, in agreement with our hypothesis. Biogas CHP plant turns out to be the best realization for cell 3122 even considering the second criteria on global pollutant emission, while the third indicator on impacted population gives no further elements of decision.

The second objective maximize the indicator in equation 3.19; this indicator has dimension of saved tons of CO_2 per year, and it is calculated as the difference between the saved emissions of carbon dioxide deriving from the satisfaction of heat demand with biomass energy conversion rather than by gas combustion, and the emission due to the biomass transport. On this basis, cells characterized by great heat demand occupy the first positions of the consequent ranking, since the satisfaction of their demand with biomass rather than methane could definitely save a significant emission of GHGs.

In Table 3.19 the number and the positions of feasible plants in global emissions ranking are listed.

Table 3.19. Number of feasible plants per type of plant and ranking position.

Type of plant	1st	2nd	3rd	tot
Woody	1562	466	82	2110
Herbaceous	362	366	42	770
Biogas	283	1118	616	2017
tot	2207	1950	740	4897

The global emission criteria show a more marked preference towards a specific type of biomass plant, as we can see from the number of feasible realizations classified as the best ones (70.8% are woody biomass plants, 16.4% herbaceous and 12.8% biogas ones). This results underlines that the distance of biomass catchment is the determinant variable to be considered in the estimate of the global emission indicator, which is mainly function not of the typology of biomass plant, but of the territorial availability of biomass. So we could affirm that a plant will be placed higher in the global pollutant emission ranking if it is fueled by a very available biomass that could be gathered in great quantity at short distances. Table 3.20 reports the value of the global emission indicator in the first three positions of the regional ranking, indicating the specific cell of the grid where each plant has to be realized, with the municipality and the province the considered cells belong to.

Table 3.20. Regional ranking based on global emissions criteria and localization of the first cells.

	1st	2nd	3rd
value ind 2	47400	47312	47297
id cell	5436	4957	5603
munipality	MILANO	MILANO	MILANO
code Istat	015146	015146	015146
province	MILANO	MILANO	MILANO

According to the previous hypothesis, the first three feasible realizations of biomass plant belong to cells in the city of Milan, characterized by great heat demand and available biomass at short distances. As reported in Table 3.21, only thermal woody biomass conversion is the best typology of biomass conversion facility in cell 5436; this huge thermal power required to the satisfaction of the heat demand of such an urbanized area is theoretical, since Biopole, as repeatedly said, have no superior limit on the thermal power to be installed. There are no dominated alternatives in cell 5436, since woody biomass is the only type of considered biomass able to satisfy its great heat demand.

Table 3.21. Cell ranking based on global emissions criteria.

	id cell	id_plant	ind_1	ind_2	ind_3	P th [MW]	P el [MW]
1st	5436	Woody	1	47400	195093	113.537	
2nd	-	-	-	-	-	-	-
3rd	-	-	-	-	-	-	-

The third objective minimizes the indicator in equation 3.21; this indicator has dimension of impacted citizens by the operation of the biomass facility. Its value has been calculated through an ArcGis® processing: starting from the residential density data provided by Istat, they have been assigned to DUSAF urbanized land cover (code 11) and then gridded. On each feasible cell an operation of buffer has been made on a 3 km radius circular area , in order to estimate the residential population within the impacted area by local emissions. For this reason the realization of a plant within a low populated area is classified higher in the ranking, because potentially impacted population is smaller; in addition low populated area are basically characterized by smaller heat demand, so the required thermal power to satisfy it will be small scale (i.e. 0.5-1.5 MW_{th}). In Table 3.22 the number and the positions of the first three feasible plants in local emissions ranking are listed.

Table 3.22. Regional ranking based on local emission criteria and localization of the first cells.

	1st	2nd	3rd
value ind 3	33	144	263
id cell	10001	10136, 10139, 10274, 17602, 17960, 18136, 18662	11079, 11214, 11348,11349, 11350, 11351, 11486, 11622
munipality	PEDESINA	BEMA	TARTANO
code Istat	014047	014006	014064
province	SONDRIO	SONDRIO	SONDRIO

In agreement with what we expected, cells belonging to mountainous municipalities occupy the first three position of the regional ranking. These municipalities are characterized by quite large areas of jurisdiction (i.e. 6.2-47.4 km^2), and a very small urban settlement, where all the heat demand is concentrated. In cell 10001 only thermal or CHP woody biomass conversions are equally feasible, since there are no other dominated alternatives (Table 3.23).

Table 3.23. Cell ranking based on global emissions criteria.

	id cell	id_plant	ind_1	ind_2	ind_3	P th [MW]	P el [MW]
1st	10001	Woody	6	600	141	1.404	
	10001	Woody	6	600	141	1.605	0.337
2nd	-	-	-	-	-	-	-
3rd	-	-	-	-	-	-	-

A great quantity of available woody biomass, perfectly reasonable in the mountainous territory of the province of Sondrio, and the satisfaction of the greater quantity of heat demand are the reasons of these results.

Alternatively, if we consider the first criteria the realization of only thermal production rather than CHP production would be preferable, since it requires less biomass to guarantee its functioning, then if we consider the second criteria only thermal or CHP production should be regarded as the same, since to a greater quantity of avoided pollutant emissions due to energy production a CHP plant opposes a higher biomass demand, and higher emission due to its road transport. For this reason, as for the previous criteria the value of both the first and the second indicator have been calculated for woody and herbaceous only thermal plants, and extended to CHP ones.

The results provided by this separated analysis of the considered criteria constitute the extremes of the Pareto border of feasible solutions, since all the other possible realizations are semi-dominated by the best solutions singularly provided by each criteria. The adoption of a set of weigh in order to more properly represent the criteria of choice of the stakeholders would obviously furnish different trade-off solutions.

4. Short distribution optimizer

This Chapter explains the research of optimum solutions for each different type of conversion facilities considered within this study, constituting different scenarios of either only thermal or CHP production whole year operation of the biomass conversion facilities. Modifying the constraint on the inferior limit of nominal power to be installed, we have obtained several optimal solutions according with the hypothesis of short distribution chain of biomass, which sets the biomass energy conversion directly within the cell where it has been gathered. Through the use of Biopole program in Fortran® environment introduced in Chapter 3, we have been able to find out all the cells satisfying the constraints on heat demand, expressed by equations 3.4 and 3.6 (or 3.7), and evaluate a global optimal solution considering all the available biomass in each cells of the grid.

4.1 Domain and constraints

The domain is formed by all the cells characterized by heat demand satisfying the constraints on heat demand density (equation 3.4) and heat capacity density (equation 3.6 and 3.7), that respectively indicates the ratio of the total heat demand of residential, productive and tertiary buildings, and the relating installed power to the urbanized area of the cell. The number of the cells selected by Biopole to form the domain without any constraint on biomass availability is 2374, equal to the 10.4% of the total number of admissible cells forming the grid utilized on Lombardy Region. In the algorithm of optimal solution searching, each cell has been enabled to potentially satisfy its heat demand with whatever of the three types of biomass considered as fuel (i.e. woody, herbaceous biomass and substrate for anaerobic digestion), for a total of 7122 potential plants; then, if a woody or a herbaceous thermal plant had been considered feasible, the feasibility of a CHP plant, fueled by the same type of biomass, has been checked. According with the method adopted in

Biopole, the analysis has primarily considered the heat demand of cells belonging to the domain, in order to individuate those cells requiring a minimum thermal nominal power greater than the smallest commercial available one. Since biomass CHP based on combustion in the power range below 100 kW_{el} is not commercially available yet (GRIESMAYR, 2008), and, according to the economy of scale and the laws regulating the feed in tariffs for electricity in some European countries, biogas plants are rarely constructed under an installed power of 100 kW_{el} (GADERER, 2008), we have decided to adopt 100 kW_{th} as inferior limit of thermal power even in the optimal solution searching. This hypothesis is further more cautionary, since electricity ratio is always smaller than 1.
The procedure of optimization has been executed by *What'sBest®* optimizer by Lindo Systems. The optimizer used the same cell domain used in Biopole, and, as said, it considered those cells satisfying only the constraints on heat demand; the main difference between the algorithm at the basis of the optimizer and Biopole one is that to be considered a suitable cell to the realization of a biomass conversion facility a cell is not required to have an energy content of the available biomass equal or superior to its heat demand. In this way, the optimizer has two very important characteristics: it potentially enables the realization of smaller biomass plants satisfying only a part of the total heat demand of a cell, while in Biopole a plant could be considered feasible only if it was able to satisfy the whole heat demand of the cell; secondly the optimizer advantages the short distribution chain of the biomass, since if a cell has enough quantity of a certain type of biomass to satisfy the demand of fuel of at least 0.1 MW_{th} power plant, the cell has to be considered suitable for the realization of the plant. So the thermal nominal power to be installed could be estimated as

$$P_{th} = \frac{E^{j}_{a,B(k)}}{h_p} = \frac{\sum_{b \epsilon B(k)} \left(m^{j}_{b} \cdot NCV_b \right)}{h_p} \qquad \text{Eq.4.1}$$

with $b \epsilon B\{woody, herbaceous, anaerobic\ digestion\}$

- $P_{th}[MW]$: thermal nominal power of the plant
- $E^{j}_{a,B(k)}[MWh]$: energy availability deriving from the energy conversion of a B type biomass in the k type plant within the j cell
- $h_p[h]$: annual full load hours of operation of the plant

- $m_b^j \left[{}^{t}/_{y} \right]$: total quantity of b type raw material that could be gathered within j cell from all the neighboring cells
- $NCV_b \left[{}^{MWh}/_{t} \right]$: net calorific value of the dry b type fuel

This estimated nominal thermal power is a row approximation, since it does not take in account the factor of simultaneity of the demand and its peaks both during the day and the year, and it is not dimensioned on the whole installed power to be satisfied. However this is the simplest way in order to approximate a thermal power satisfying only a part of the heat demand of the cell; however we could hypothesize, for example, to provide these plants of an oil boiler able to satisfy peaks of demand, while the basic load could be provided by the biomass boiler. The best compromise solution should be assigned case by case. Concerning the values of full load hours of operation of a plant, they varies in function of the type of considered plant (Table 4.1): for these types of conversion facility based on biomass combustion three different values have been used, in order to estimate the potential nominal thermal power to be installed for either a whole year only thermal or CHP production, while for a biogas plant, since anaerobic digestion plants are suitable to inject constant base load of thermal energy into hot water and space heating networks, only CHP production is allowed.

Table 4.1. Full load hours of operation of a boiler per type of plant.

Type of plant	Annual h	CHP h
Woody biomass	2000	3500
Herbaceous	2000	3500
Biogas	-	7500

The target values for hours of full load operation of only thermal production plants can be fixed to 2000 for whole year operation (ÖKL-MERKBLATT, 2009). For an economic operation of a CHP biomass plant a high amount of full load hours (3500–5000 h/y) should be aimed, while for the success of a CHP biogas plant the full load hours per year should be above 7500 (FNR, 2006).

On the contrary, if the energy content of the available biomass within a cell is greater than its heat demand, that is

$$\sum_{b\epsilon B(k)}\left(m_b^j \cdot NCV_b\right) \cdot \eta_d \cdot \eta_{th} > Q^j \qquad \text{Eq.4.2}$$

- $\eta_d[\%]$: efficiency of the distribution network
- $\eta_{th}[\%]$: thermal efficiency of the k type boiler
- $Q^j\left[{MWh}/{y}\right]$: total annual heat demand of buildings within j cell

then the optimizer fixes the value of the thermal power to be installed on the basis of the heat demand to satisfy. This value could be estimated by the optimizer as

$$P_{th} = \frac{10}{\eta_d \cdot \eta_{th}} \cdot \sum_s \left(\frac{Q_s}{h_s}\right) \qquad \text{Eq.4.3}$$

with $s \in S\{residential, productive, tertiary\}$

- $Q_s\left[{kWh}/{y}\right]$: total annual heat demand of s sector buildings in a discrete area
- $h_s\left[{h}/{y}\right]$: annual full load hours for residential space heating

Equation 4.3 and equation 3.11 are the same; for this reason, cells characterized by a energy content, deriving from available biomass conversion, greater than their heat demand require the same nominal thermal power indicated by Biopole. There are no constraints on the alternative use of biomass in a cell rather than in a neighboring one, so the provided solutions are theoretical ones, since if a plant is actually realized, the quantity required by its functioning should be detracted from the available biomass of the neighboring cells. However, Italian laws (L. 99/2009) defined as biomass from short distribution system the biodegradable part of products, wastes and residuals produced by agricultural, forestry and industrial activities within a radius of 70 km from the plant of energy conversion. Adopting this higher catchment radius, a plant could virtually use almost all the available biomass in Lombardy region.

4.2 Global optimal solutions

This optimization primarily aims to show the potentialities of short distribution system of biomass, verifying if the partial or whole satisfaction of the heat demand characterizing suitable cells could take place with available biomass on the regional territory. Three different constraints (i.e. 0.1, 1 and 10 MW_{th}) on the minimum

thermal power characterizing the plants have been set, in order to obtain three different optimal solutions on the whole territory of Lombardy region.
The first constraint fixed the minimum thermal power to be installed at 0.1 MW_{th}, and the number and the nominal thermal power of woody plants per province are reported in Table 4.2; more precisely, white columns report the number of woody plants per province, while the grey columns report the total amount of thermal nominal power to be installed within the territory of each province.

Table 4.2. Number and nominal thermal power of woody plants per province (>= 0.1 MW_{th} scenario).

>=0.1 MW	n y th1	P y th1 [MW]	n CHP1	P CHP1 [MW]
BERGAMO	363	3248	363	2658
BRESCIA	730	4187	730	2990
COMO	98	981	98	813
CREMONA	79	651	79	487
LECCO	104	755	104	590
LODI	37	399	37	350
MANTOVA	33	254	33	167
MILANO	389	11382	389	8623
MONZA	98	2258	98	2174
PAVIA	148	1373	148	1276
SONDRIO	170	390	170	288
VARESE	124	2173	124	2077
tot	2373	28051	2373	22493

On 2374 cells forming the domain only one cell has not satisfied the constraint on the minimum thermal power to be installed, and so has been rejected. The number of only thermal whole year operation plants and the CHP one is the same, while the total thermal power to be installed in CHP plants is smaller, since a plant working for more full load hours per year would be characterized by a smaller installed power in order to energy convert the same quantity of biomass. The provinces of Brescia and Milan are characterized by higher number of realizations, followed by Bergamo, Sondrio and Pavia ones; this fact is not surprising, since Sondrio and Pavia provinces are respectively characterized by the highest availability of forest residuals and poplar biomass. Regarding the thermal power to be installed the province of Milan requires the greatest value (equal to 40.6% of the regional total).
Table 4.3 compares the optimal solution to the solution provided by Biopole. Grey columns identify Biopole solution, while white columns identify optimizer solution; yellow columns, instead, show the variation rate between the two different solutions.

Table 4.3. Differences between Biopole and SD optimizer result per woody typologies.

>=0.1 MW	Biopole y th 1	Optimizer y th 1	variation rate [%]	Biopole CHP 1	Optimizer CHP 1	variation rate [%]
number of plants	2110	2373	12.5%	1739	2373	36.5%
P min [MW]	0.1	0.1	-0.9%	0.5	0.1	-79.0%
P average [MW]	15.0	11.8	-21.3%	19.0	9.5	-50.2%
P max [MW]	114	75	-33.8%	114	39	-65.8%
P tot [MW]	31695	28051	-11.5%	33080	22493	-32.0%

As we can notice the optimizer solution provides a higher number of woody biomass plants, both only thermal production and CHP ones. The minimum, average and maximum thermal power to be installed are however smaller, as well as the total thermal power required. This fact underlines that the short distribution system of biomass involves a greater number of plants characterized by a smaller installed power.

The number and the nominal thermal power of herbaceous plants per province are reported in Table 4.4; more precisely, white columns report the number of herbaceous plants per province, while the grey columns report the total amount of thermal nominal power within the territory of each province.

Table 4.4. Number and nominal thermal power of herbaceous plants per province (>= 0.1 MW_{th} scenario).

>=0.1 MW	n y th2	P y th2 [MW]	n CHP2	P CHP2 [MW]
BERGAMO	217	1405	214	851
BRESCIA	325	2112	303	1488
COMO	71	217	69	117
CREMONA	79	738	79	644
LECCO	59	155	55	85
LODI	37	399	37	355
MANTOVA	33	305	33	241
MILANO	389	4786	389	2721
MONZA	98	769	98	396
PAVIA	148	1320	148	1244
SONDRIO	0	0	0	0
VARESE	124	545	124	276
tot	1580	12749	1549	8417

For herbaceous biomass plants both the number and the thermal power required for only thermal production are greater than CHP ones, since a plant working for less annual full load hours is characterized by a greater installed power to energy convert the same quantity of biomass. In this way an only thermal plant turns out to be feasible in more cells than a CHP plant, more easily satisfying the constraint on the minimum thermal power expressed in equation 4.3. The provinces of Milan, Brescia and Bergamo are characterized by higher number of realizations, followed by Pavia, Varese and Monza ones; this fact is not surprising, since Pavia is one of the more agricultural provinces in Lombardy, and the great availability of rice straws is able to satisfy medium size biomass plants (about 8.5-8.9 MW_{th}). Regarding the thermal power to be installed the province of Milan requires the greatest value on only thermal total (equal to 37.5%) and the greatest value on CHP production (32.3% on CHP total). As in Biopole solution, even the optimizer provided no feasible herbaceous plants in province of Sondrio. Table 4.5 compares the optimal solution to the solution provided by Biopole. Grey columns identify Biopole solution, while white columns identify optimizer solution; yellow columns, instead, show the variation rate between the two different solutions.

Table 4.5. Differences between Biopole and SD optimizer result per herbaceous typologies.

>=0.1 MW	Biopole y th 2	Optimizer y th 2	variation rate [%]	Biopole CHP 2	Optimizer CHP 2	variation rate [%]
number of plants	770	1580	105.2%	628	1549	146.7%
P min [MW]	0.1	0.1	-0.1%	0.5	0.1	-78.2%
P average [MW]	10.3	8.1	-21.6%	13.1	5.4	-58.5%
P max [MW]	59	47	-20.0%	67	32	-52.2%
P tot [MW]	7923	12749	60.9%	8229	8417	2.3%

Concerning herbaceous typologies, the optimizer solution provides a higher number both of only thermal plants and CHP production ones, but average and maximum thermal power to be installed are smaller. This fact underlines that the short distribution system of biomass involves a greater number of plants characterized by a slightly smaller average installed power. In fact herbaceous biomass are less available on the regional territory than both woody biomass and substrates for anaerobic digestion, and, since the optimizer allows the realization of biomass plants even where the energy content of the available biomass is not greater or equal to the heat demand, much more feasible realizations are counted. Unlike what we have noticed for woody biomass plants, in this case the total thermal power required by optimal solution is greater than Biopole one.

The number and the nominal thermal power of CHP biogas plants per province are reported in Table 4.6; more precisely, white column reports the number of CHP biogas plants per province, while the grey column report the total amount of thermal nominal power within the territory of each province. The provinces of Brescia and Milan are characterized by higher number of realizations, followed by

Bergamo, Sondrio and Pavia ones; regarding the thermal power to be installed the province of Milan requires the greatest value (equal to 34.3% on regional total), and the average thermal power (about 13.5 MW_{th}) installed in the plants on its territory, due to its very high heat demand density, is higher than all the other provinces.

Table 4.6. Number and nominal thermal power of biogas plants per province (>= 0.1 MW_{th} scenario).

>=0.1 MW	n CHP3	P CHP3 [MW]
BERGAMO	363	1677
BRESCIA	710	2102
COMO	98	707
CREMONA	79	499
LECCO	104	436
LODI	37	297
MANTOVA	33	290
MILANO	389	5225
MONZA	98	1865
PAVIA	148	947
SONDRIO	170	63
VARESE	124	1106
tot	2353	15216

Table 4.7 compares the optimal solution to the solution provided by Biopole. Grey columns identify Biopole solution, while white columns identify optimizer solution; yellow columns, instead, show the variation rate between the two different solutions.

Table 4.7. Differences between Biopole and SD optimizer result per biogas CHP typology.

>=0.1 MW	Biopole CHP 3	Optimizer CHP 3	variation rate [%]
number of plants	2017	2353	16.7%
P min [MW]	0.1	0.1	-11.9%
P average [MW]	28.4	6.5	-77.3%
P max [MW]	199	31	-84.2%
P tot [MW]	57372	15216	-73.5%

The same conclusion obtained for woody plants (Table 4.3) can be extended even to CHP biogas plants; in fact, according to the hypothesis of short distribution system of biomass, optimal solution provides a greater number of feasible plants and it concretize a lower installed power. This fact is always a logical consequence of the hypothesis of short distribution chain of biomass, since biomass transport towards neighboring cells is prevented if a cell expresses a own heat demand to be satisfied.

On the contrary, in Biopole the catchment radius used for anaerobic digestion (i.e. zootechnics residuals, urban and industrial wastes) was 15-30 km (Table 3.2).
Table 4.8 summarizes all the output from the algorithm of optimization, such as the number of feasible plants, the minimum, the average, the maximum and the total values of nominal thermal power to be installed on the constraint of minimum thermal power equal to 0.1 MW_{th}.

Table 4.8. Output from the algorithm of optimization per type of plant (>= 0.1 MW_{th} scenario).

>=0.1 MW	y th1	CHP1	y th2	CHP2	CHP3
number of plants	2373	2373	1580	1549	2353
P min [MW]	0.1	0.1	0.1	0.1	0.1
P average [MW]	11.8	9.5	8.1	5.4	6.5
P max [MW]	75	39	47	32	31
P tot [MW]	28051	22493	12749	8417	15216

The concurrent presence of great heat demand and biomass availability enable woody only thermal plants to reach the maximum value of thermal nominal power to be installed (75 MW_{th}). Woody biomass typologies even reach higher values of average and total thermal power, underlining that bigger quantities of woody biomass can be gathered at shorter distances than herbaceous biomass or substrates for anaerobic digestion. This fact allows the realization of plants characterized by greater thermal power. As previously noticed, the maximum value of nominal thermal power reached by a certain biomass CHP plants is always inferior than only thermal one, due to the higher number of annual full load hours characterizing CHP production. Regarding biogas CHP production we have to notice that the maximum thermal power required is smaller than other ones, since its full load hours per year is greater than all the other typologies.
The lower values of total thermal power performed by herbaceous biomass typologies is due to a inferior energy content provided by herbaceous biomass, because of their smaller total quantity. The energy content that can be obtained by the energy conversion of a certain biomass macro-category is in fact estimated as the product of the available quantity of biomass to its net calorific value (Annex I). The average net calorific value of woody and herbaceous biomass is quite higher than substrates for anaerobic digestion, but the total available quantity of this last category is much greater than the other one. The regional total energy content per biomass macro-category is reported in Table 4.9, so we can notice that the greater energy content is potentially provided by substrates for anaerobic digestion, followed by woody biomass and then herbaceous biomass.

Table 4.9. Total energy content of the macro-categories of biomass.

Biomass macro-category	Total energy content [MWh]
Woody	2.37E+08
Herbaceous	1.12E+08
Substrates for anaerobic digestion	5.72E+08

The second constraint fixed the minimum thermal power to be installed at 1 MW_{th}, and the number and the nominal thermal power of woody plants per province are reported in Table 4.10; more precisely, white columns report the number of woody plants per province, while the grey columns report the total amount of thermal nominal power to be installed within the territory of each province.

Table 4.10. Number and nominal thermal power of woody plants per province (>= 1 MW_{th} scenario).

>=1 MW	n y th1	P y th1 [MW]	n CHP1	P CHP1 [MW]
BERGAMO	267	3207	267	2617
BRESCIA	500	4089	498	2891
COMO	72	971	72	803
CREMONA	56	641	56	477
LECCO	69	744	69	578
LODI	29	394	29	345
MANTOVA	27	252	27	164
MILANO	367	11368	367	8609
MONZA	98	2258	98	2174
PAVIA	105	1354	105	1257
SONDRIO	90	364	76	250
VARESE	114	2169	114	2073
tot	1794	27809	1778	22238

Both the number and the thermal power required for only thermal energy production are greater than CHP ones, due to their different annual hour of full load. The provinces of Brescia and Milan are characterized by higher number of realizations, followed by Bergamo, Varese and Pavia; regarding the thermal power to be installed the province of Milan requires the greatest value (equal to 40.9% of the thermal power to be installed for only thermal operation, and to 38.7% for CHP production). If we compare this optimal solution to the solution provided by the previous scenario, we can notice that both the number and the thermal nominal power to be installed are smaller both in only thermal and in CHP production (Table 4.2 and Table 4.10). Moreover the loss of total thermal power is smaller in comparison to the loss of the number of feasible plants: this fact underline that the number of feasible plants belonging to the small-medium scale (i.e. < 1 MW_{th}) is very high for woody biomass typologies.

The number and the nominal thermal power of herbaceous plants per province resulting in the second scenario are reported in Table 4.11; more precisely, white columns report the number of herbaceous plants per province, while the grey columns report the total amount of thermal nominal power within the territory of each province.

Table 4.11. Number and nominal thermal power of herbaceous plants per province (>= 1 MW_{th} scenario).

> =1 MW	n y th2	P y th2 [MW]	n CHP2	P CHP2 [MW]
BERGAMO	147	1372	132	817
BRESCIA	230	2074	215	1448
COMO	56	213	25	83
CREMONA	56	728	56	634
LECCO	17	136	14	73
LODI	29	394	29	350
MANTOVA	27	302	27	238
MILANO	367	4772	367	2707
MONZA	98	769	98	396
PAVIA	105	1301	105	1225
SONDRIO	0	0	0	0
VARESE	110	539	76	253
tot	1242	12599	1144	8224

Even for herbaceous biomass, the number and the thermal power of herbaceous CHP plants is smaller than annual only thermal operation, since woody CHP plants are characterized by a greater annual full load hours and higher thermal boiler efficiency.

If we compare this optimal solution to the solution provided by the previous scenario, we can notice that both the number and the thermal nominal power to be installed are smaller both in only thermal and in CHP production (Table 4.4 and Table 4.11). The provinces of Milan and Brescia are always characterized by higher number of realizations, followed by Pavia, Cremona and Bergamo ones; regarding the thermal power to be installed the province of Milan requires the greatest value for only thermal production, equal to 37.9% of the total, while for CHP production its value is equal to 32.9% of the total. This fact follows the great herbaceous biomass availability of the province of Milan (e.g. Parco Agricolo Sud Milano and the intensive agricultural area of the Po valley), able to satisfy the request of fuel of higher thermal power plants. The province of Sondrio, as registered in Biopole

solution and in the previous scenario, have no feasible herbaceous plants characterized by minimum thermal power installed of 1 MW_{th}.
The number and the nominal thermal power of CHP biogas plants per province are instead reported in Table 4.12. The number and the total thermal power installed for the biogas CHP typology follow the trend of woody and herbaceous ones in this scenario, registering a reduction of both the number of plants and the power installed. The highest number of plants and thermal nominal power to be installed belong to the province of Milan (24.4% of the total number of feasible plants and 35.0% on total thermal power installed).

Table 4.12. Number and nominal thermal power of biogas plants per province (>= 1 MW_{th} scenario).

> =1 MW	n CHP3	P CHP3 [MW]
BERGAMO	256	1631
BRESCIA	327	1947
COMO	62	697
CREMONA	56	489
LECCO	57	425
LODI	29	292
MANTOVA	27	287
MILANO	367	5211
MONZA	98	1865
PAVIA	105	928
SONDRIO	9	9
VARESE	114	1102
tot	1507	14886

Table 4.13 summarizes all the output from the algorithm of optimization, such as the number of feasible plants, the minimum, the average, the maximum and the total values of nominal thermal power to be installed on the constraint of minimum thermal power equal to 1 MW_{th}.

Table 4.13. Output from the algorithm of optimization per type of plant (>= 1 MW_{th} scenario).

> =1 MW	y th1	CHP1	y th2	CHP2	CHP3
number of plants	1794	1778	1242	1144	1507
P min [MW]	1	1	1	1	1
P average [MW]	15.5	12.5	10.1	7.2	9.9
P max [MW]	75	39	47	32	31
P tot [MW]	27809	22238	12599	8224	14886

The maximum values of nominal thermal power to be installed are the same of the previous scenario; the total thermal power to be installed slightly decrease in all the considered typologies, underlining the modest importance, in relative terms, of the small-medium scale (< 1 MW_{th}) plants on the total.

The third constraint fixed the minimum thermal power to be installed at 10 MW_{th}, and the number and the nominal thermal power of woody plants per province are reported in Table 4.14.

Table 4.14. Number and nominal thermal power of woody plants per province (>= 10 MW_{th} scenario).

>=10 MW	n y th1	P y th1 [MW]	n CHP1	P CHP1 [MW]
BERGAMO	133	2545	112	1841
BRESCIA	165	2611	89	1141
COMO	41	803	40	635
CREMONA	28	500	28	336
LECCO	31	543	31	412
LODI	17	346	17	297
MANTOVA	12	188	4	49
MILANO	314	11105	314	8346
MONZA	91	2211	91	2128
PAVIA	50	1089	50	992
SONDRIO	4	47	0	0
VARESE	100	2105	100	2009
tot	986	24093	876	18187

Both the number and the thermal power required for only thermal production are greater than CHP ones, such as in the previous scenarios, since woody CHP plants are characterized by a greater annual full load hours. In this scenario the greatest part of feasible plants belong to the province of Milan, both for only thermal production (31.8% of the total number) and CHP one (35.8% of the total), such as the total thermal power (respectively 46.1% and 45.9% of the total), underlining the presence of the higher heat demand and the sufficient biomass availability to satisfy it on its territory.

The number and the nominal thermal power of herbaceous plants per province resulting from the second scenario are reported in Table 4.15. Unlike what happened in the previous scenarios, some provinces, such as Como, Lecco, Monza and Varese have no feasible CHP herbaceous plants, while the province of Sondrio do not manage to realize neither only thermal or CHP herbaceous plants characterized by a nominal thermal power equal or greater than 10 MW_{th}. This fact can be explained with a lack of enough herbaceous biomass to satisfy the fuel need of such a great thermal nominal power. On the contrary, the province of Milan, Brescia, Pavia, Bergamo and Cremona demonstrate a higher availability of herbaceous biomass; the province of Pavia, Cremona and Lodi report high thermal power installations in comparison to all the other provinces, especially on CHP production (26.0%, 13.5% and 8.3% of the total thermal power required).

Table 4.15. Number and nominal thermal power of herbaceous plants per province (>= 10 MW_{th} scenario).

>=10 MW	n y th2	P y th2 [MW]	n CHP2	P CHP2 [MW]
BERGAMO	52	739	22	269
BRESCIA	87	1422	51	754
COMO	4	43	0	0
CREMONA	28	587	28	493
LECCO	9	106	0	0
LODI	17	346	17	303
MANTOVA	12	239	10	160
MILANO	271	4163	53	730
MONZA	18	227	0	0
PAVIA	46	1012	45	951
SONDRIO	0	0	0	0
VARESE	11	123	0	0
tot	555	9005	226	3659

The number and the thermal power realizations of CHP plant can be definitely considered as indexes of certain biomass availability, since the realization of a big-scale biomass plant (> 10 MW_{th}) requires a greater biomass quantity than only thermal production, because of CHP boiler lower thermal efficiency and higher full load hours per year. All the provinces diminished the number of feasible plants and the installed power, preceding the logical trend already registered in the second scenario.

The number and the nominal thermal power of CHP biogas plants per province are instead reported in Table 4.16.

Table 4.16. Number and nominal thermal power of biogas plants per province (>= 10 MW_{th} scenario).

>=10 MW	n CHP3	P CHP3 [MW]
BERGAMO	67	796
BRESCIA	61	913
COMO	39	549
CREMONA	14	218
LECCO	11	165
LODI	15	230
MANTOVA	12	224
MILANO	279	4721
MONZA	91	1819
PAVIA	25	454
SONDRIO	0	0
VARESE	45	640
tot	659	10728

Even in this case, the province of Milan hosts the greater part of feasible plants and of thermal nominal power, respectively equal to 42.3% and 44.0% of the regional total. All the other provinces do not exceed one hundred feasible plants, while the province of Sondrio counts no feasible CHP biogas plants. The province of Monza reports 91 feasible realizations (13.8%, equal to 17.0% of the total thermal power to be installed), while in the province of Brescia there are 61 feasible realizations (equal to 9.3% of the total number) and the nominal thermal power to be installed is equal to 8.5% of the total.

Table 4.17 summarizes all the output from the algorithm of optimization, such as the number of feasible plants, the minimum, the average, the maximum and the total values of nominal thermal power to be installed on the constraint of minimum thermal power equal to 10 MW_{th}.

Table 4.17. Output from the algorithm of optimization per type of plant (>= 10 MW_{th} scenario).

>=10 MW	y th1	CHP1	y th2	CHP2	CHP3
number of plants	986	876	555	226	659
P min [MW]	10	10	10	10	10
P average [MW]	24.4	20.8	16.2	16.2	16.3
P max [MW]	75	39	47	32	31
P tot [MW]	24093	18187	9005	3659	10728

Comparing Table 4.8 and 4.13 to 4.17 we can notice that the minimal thermal power installed reflects the specific constraint characterizing each scenario, while the maximum installed power is always fixed at the same values for each typology of plants. This fact happens because the same cells result suitable to the realization of plants characterized by the same thermal power and which consume all the cell available biomass in each scenarios.

Figure 4.1 and 4.2 represent the data of Table 4.8, 4.13 and 4.17. The greatest part of nominal thermal power to be installed turns out to belong to the big-scale plants (> 10 MW_{th}) for all the considered plants and type of energy production; regarding the number of feasible plants the most significant category is from 1 MW_{th} to 10 MW_{th}, where all the typologies of plants count the greater number of feasible realizations, except for woody only thermal production, which count the greater part of its feasible plants in big-scale class. As we can notice from Figure 4.1 the loss of thermal power installed passing from the first to the second scenario is quite small, while shifting to the third scenario the quantity lost is more significant, especially for the typologies of CHP production (estimated losses between 18.2% and 38.4% of the total).

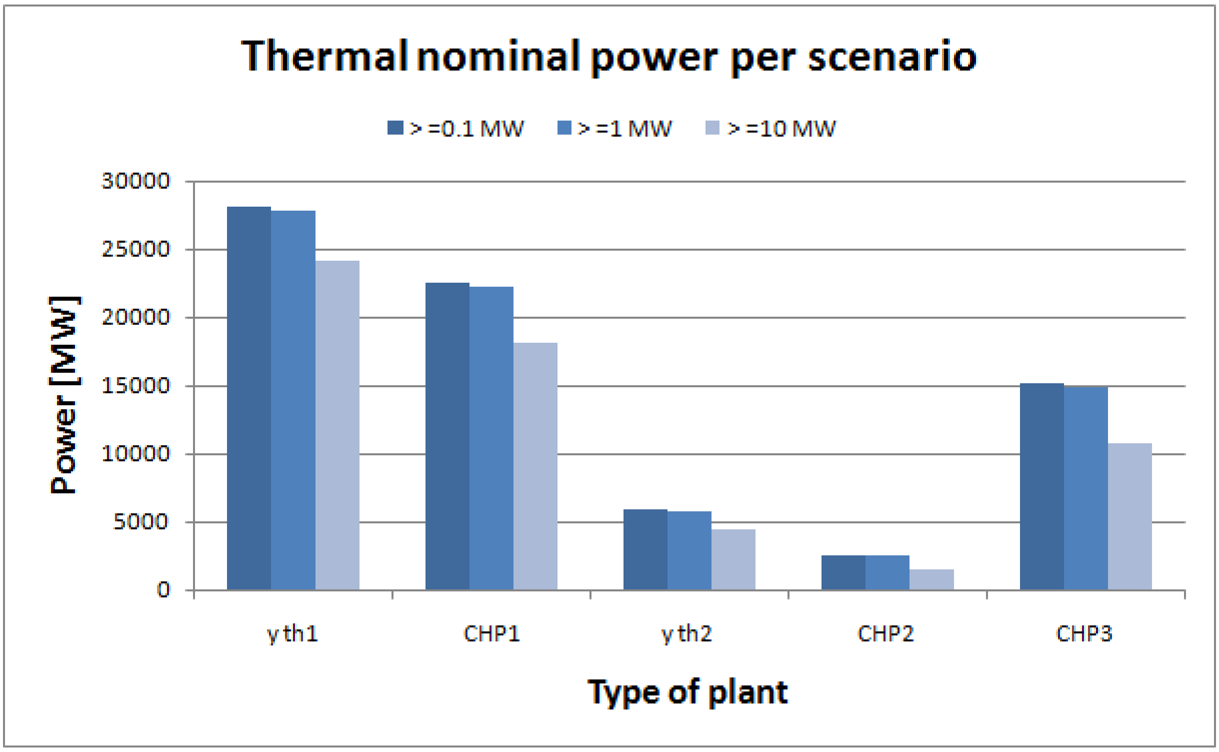

Figure 4.1. Total thermal nominal power per type of plant and per scenario.

In Figure 4.2 the same trend can be even more easily comprehended, especially passing from the second to the third scenario, where the losses can be estimated between 45.0% and 55.3% of the total number of feasible only thermal plants and between 27.9% and 80.2% on the total number of feasible CHP plants.

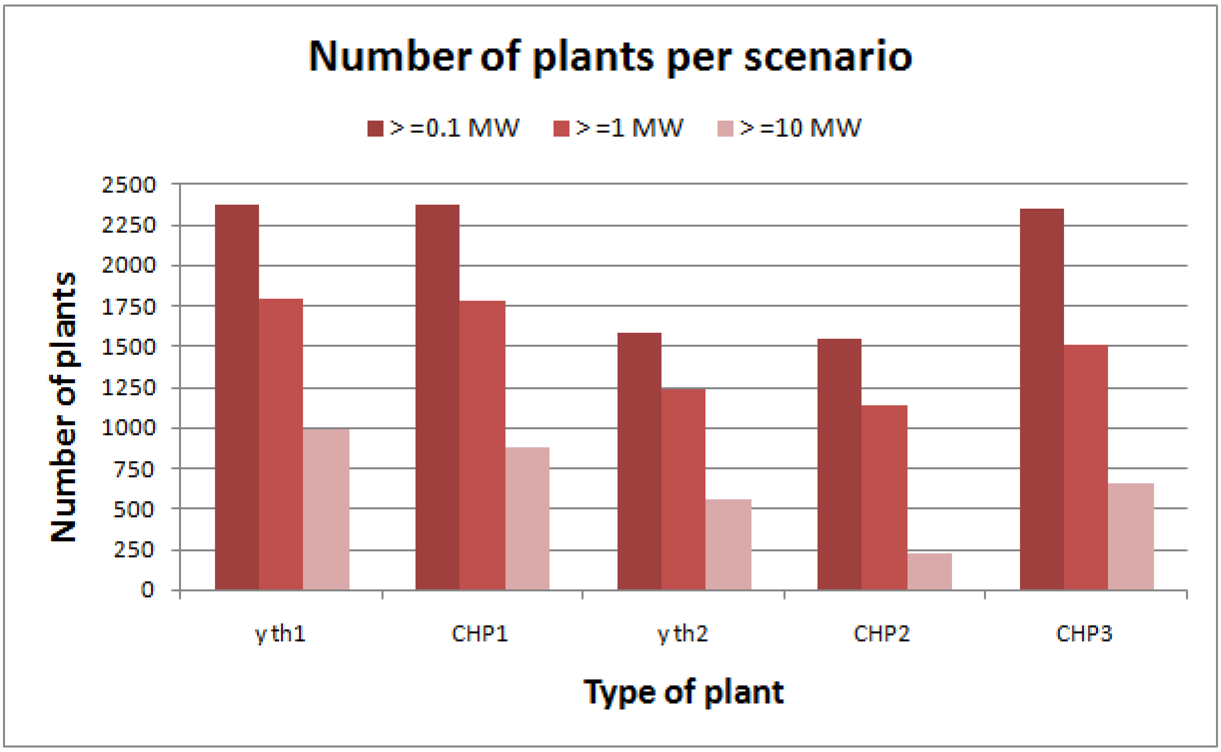

Figure 4.2. Number of potential realizations per type of plant and per scenario.

These results provide two important conclusions: the first is that the greater part of the optimal realizations of biomass plant for whole year operation of the boiler is comprehended in the range of nominal thermal power greater than 10 MW_{th}, and secondly that the greater part of feasible medium and large-scale (> 5 MW_{th}) biomass plants should be realized in the provinces of Brescia, Milan, Monza and Bergamo, characterized by the higher heat demand on the whole Lombardy region. So we can finally conclude that short distribution system optimizer tends to provide a higher number of feasible plants than Biopole; these plants are marked by a smaller average thermal power and they sometimes satisfy only a part of the whole heat demand of a suitable cell to economical operation. Smaller power plants, characterized by the same full load hours of operation per year, require smaller biomass quantities, potentially reducing the need of biomass transport on the road. This fact could prevent all the environmental and social externalities deriving from a massive and additional use of road transport, such as global and local pollutant emission and traffic congestion on the road network.

The optimizer results per scenario (i.e. >= 0.1 MW_{th}, >= 1 MW_{th} and >= 10 MW_{th}) and per thermal power of each considered typology of conversion are represented in Figure 4.3, 4.4 and 4.5.

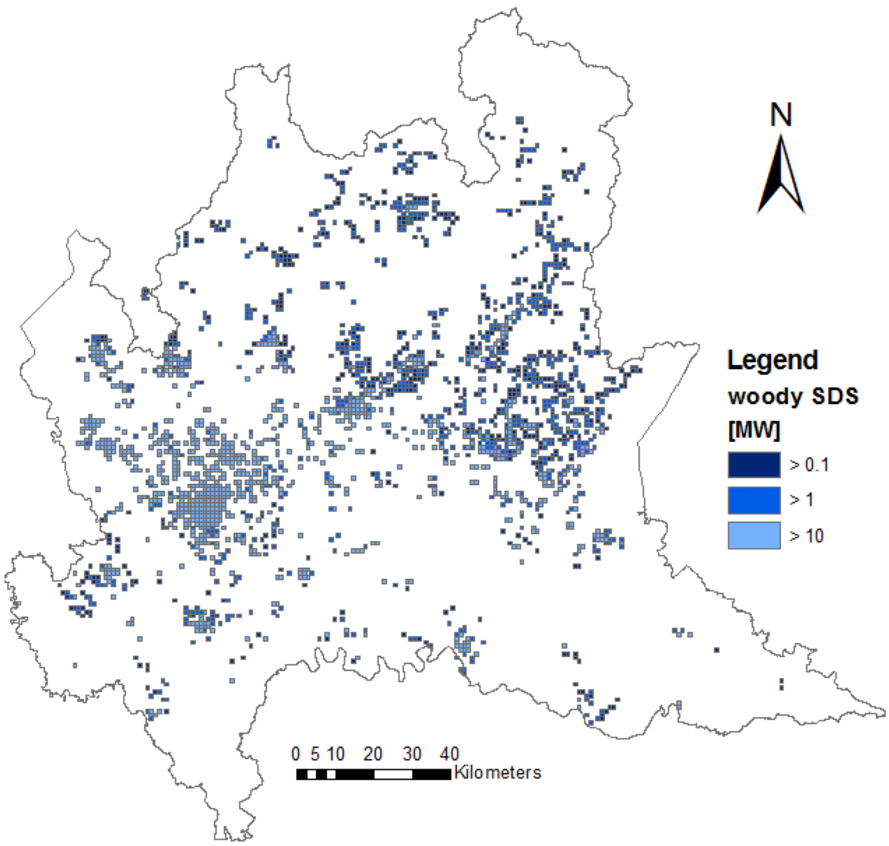

Figure 4.3. Woody SDS biomass plants per scenario.

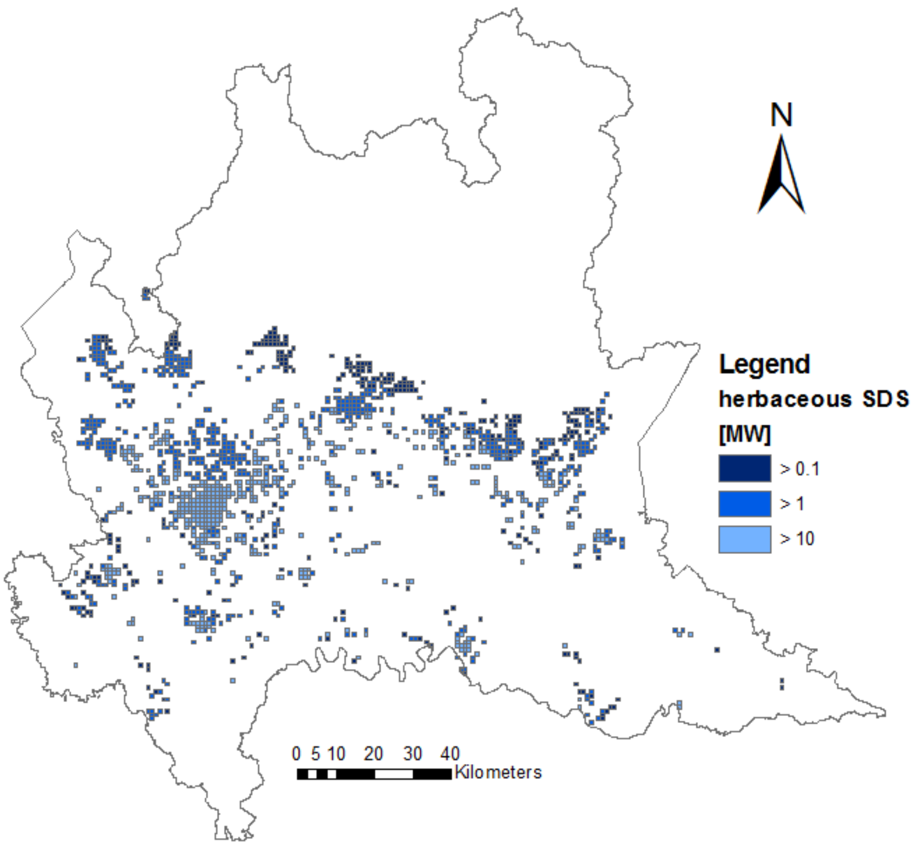

Figure 4.4. Herbaceous SDS biomass plants per scenario.

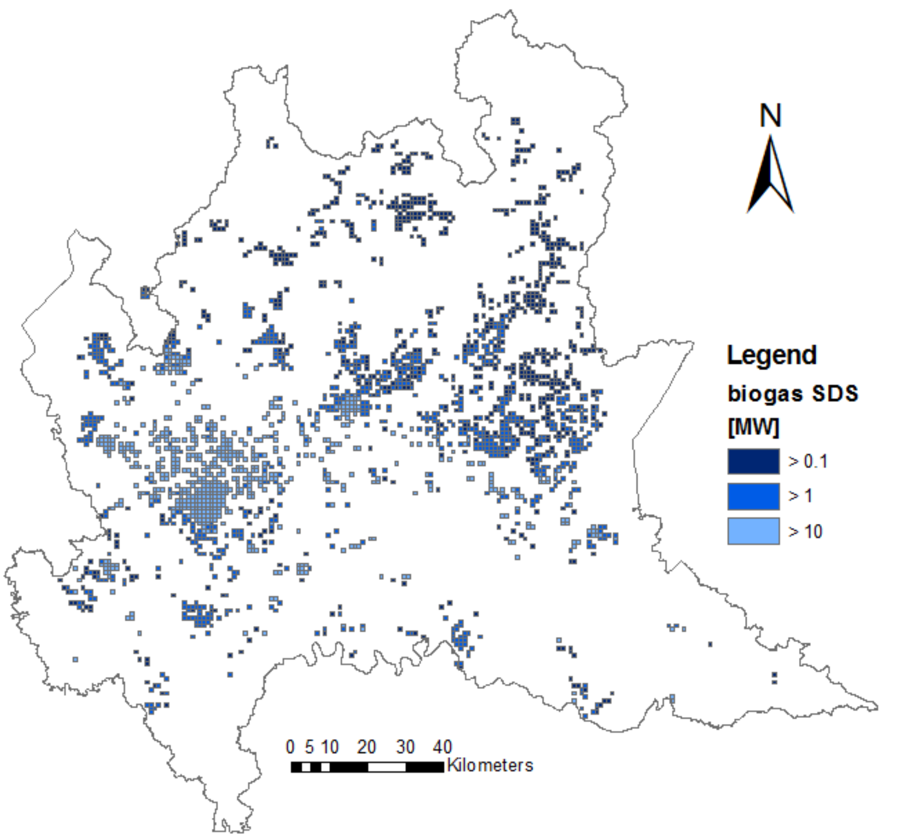

Figure 4.5. Biogas SDS biomass plants per scenario.

5. Conclusion

BioEnerGIS project intends to provide an instrument helping decision makers to plan, on a regional scale, a sustainable exploitation of biomass. A GIS-based decision support system (DSS) will be developed within 2011 on the basis of the methodology exposed in this work; this DSS will be ask to locate the most suitable sites for biomass plants installation, in terms of energetic, environmental and economic sustainability.

The general outline of this work have embraced four sequential steps, starting with the collection of available biomass data, heat demand data and commercial available typologies of biomass energy conversion. Then a GIS-based analysis, aimed at mapping the biomass potentially exploitable for energetic purposes, has been made; at the same time even the spatial distribution of thermal energy demand has been mapped, in order to provide the second element concurring to justify the feasibility of a plant within a certain area. The territorial discretization of biomass availability and heat demand data have been completed using DUSAF and SIARL land cover in ArcGis® environment. Once biomass and heat demand data have been assigned to the cells of the grid 1 km ground resolution arbitrarily adopted within this work, we had to create a methodology able to localize suitable cells to the realization of biomass conversion facilities, estimating the correct thermal nominal power to be installed in order to satisfy their heat demand. This methodologies have been later implemented in a Fortran® executable called Biopole, and iteratively improved until we reached a prototypal version, able to take as input the gridded data of biomass availability and heat demand, and to provide as output the localization of the suitable cells with the characteristics of thermal power, typology of energy production and type of biomass used as fuel in each feasible plant. Biopole output data have been statistically analyzed and the results have been summarized and commented. According to several possible approaches to the problem of localization and dimensioning of the biomass plants, three different criteria of choice have been separately adopted, pointing out different best solutions at regional and cell level. Using *What's Best!* ® optimizer by Lindo System three different scenarios have been created on the basis of the minimum thermal nominal power to be installed (i.e. 0.1, 1 and 10 MW_{th}), in the hypothesis of short biomass distribution system; these results have been compared to the solution provided by Biopole, and commented.

All these methodological and operative steps constitutes only a part of the whole BioEnerGis project, that finally aimed at the development of a web-GIS DSS able to identifying directly on the web the most suitable sites for the installation of appropriate biomass energy conversion plants.

During this work several problems have submitted, and we had to formulate hypothesis or constraints in order to keep a formal and logical accuracy. Some biomass data, such as forestry residues, poplars and zootechnics slurry and manure, have been provided as measurements of volume, but, in order to calculate their energy content, we had to convert them into mass measurements. The density of forest residuals and poplars has been assumed equal to 0.5 t/m^3, while zootechnics residuals one equal to 1 t/m^3 (i.e. water density). This assumption seems to be reasonable both for woody biomass and zootechnics residuals, but the density could be different according to several type of wood, while the parameter adopted in this work is only an average value. As agricultural biomass their available quantities has been provided with CRASL method, calculating the available biomass on a certain area as the product of a specific coefficient of biomass production to the use of land of the same agricultural production; alternatively the ANPA method could be used, in order to assign to a certain area the really available biomass, calculated as the total available biomass diminished of the already allotted quantity.

Regarding Biopole we had to consider the constraint on the minimum thermal power to be installed, equal to 0.1 MW_{th}. Even if the accuracy of this constraint is confirmed by actual commercial power and by energy sector operators (BioEnergy 2020+), it constitutes a limit to the co domain of feasible solutions to the problem of localization. On the contrary, the lack of a superior limit to the thermal nominal power to be installed, except for the heat demand to satisfy, sometimes provides very high values of required power (e.g. 199 MW_{th}, CHP biogas plant in cell 5272 in Milan). This consideration however reflects two different approaches to the problem of dimensioning of the plants: if on one hand small and medium-scale plants (i.e. 0.5-5 MW_{th}) provide several advantages, such as reduced environmental and landscape impacts, smaller quantity of used biomass and a consequently lower biomass transport by diesel lorries, on the other hand they cannot take advantage from the economies of scale characterizing bigger plants (i.e. >10 MW_{th}). In this way two different and alternative solutions appear: big scale biomass energy conversion plants, furnished with more advanced system of reduction of pollutant emissions and costs lowering, or small and medium scale plants, providing thermal energy to a few blocks of houses, or even to a single block of flats, and refueled by a short chain distribution of biomass. The second alternative is very appealing, since heat and power micro-generation (i.e. 20-100 kW_{th}, equal or slightly higher than the power of a domestic boiler) could be economical and more sustainable from the environmental point of view, and it would make consumers to grow their awareness and attention to energy consumptions, since they would be themselves the producer of the energy they consume. This solution should rely on an efficient system of biomass distribution, and Lombardy region seems to move in this direction. This work has identified no financial support schemes and business plans, and no economical evaluations related to the realization of the plants have been made. A possible development could be the integration of a further indicator, regarding the life cycle economical costs to be afford for the realization of a biomass plant and its maintenance during the operation; in fact the next step of BioEnerGIS project would be to take in account the economical side of the realization of feasible biomass plants.

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ANNEX I: Net Calorific Value (NCV)

	biomass	LCV [MJ/t, dm]	LCV [kWh/t]
1	forest residues	16918.4	4703.3
2	poplars	19400.0	5393.2
3	cereals	17974.3	4996.8
4	rice	14286.1	3971.5
5	maize	16848.6	4683.9
6	arboreous(p&s)	17211.0	4784.7
7	bovine solid	882.9	245.4
8	suine solid	1177.2	327.3
9	chicken solid	1569.6	436.3
10	bovine liquid	490.5	136.4
11	suine liquid	637.7	177.3
12	chicken liquid	1275.3	354.5
13	organic	1994.7	554.5
14	green	3433.5	954.5
15	wood	16000.0	4448.0
16	020103	1419.2	394.5
17	020201	1726.6	480.0
18	020203	1062.8	295.4
19	020204	1062.8	295.4
20	020301	359.7	100.0
21	020304	1079.1	300.0
22	020305	359.7	100.0
23	020403	114.5	31.8
24	020501	5313.8	1477.2
25	020502	21.3	5.9
26	020601	6065.9	1686.3
27	020603	19.6	5.5
28	020701	19.6	5.5
29	020704	1618.7	450.0
30	020705	19.6	5.5
31	030101	15500.0	4309.0
32	030105	16000.0	4448.0
33	030301	17727.7	4928.3
34	BOV_BLOOD	915.6	254.5
35	BOV_RUM	784.8	218.2
36	BOV_CAT3	1062.8	295.4
37	SU_BLOOD	915.6	254.5
38	SU_GUTS	1913.0	531.8
39	SU_CAT3	1062.8	295.4
40	CHI_BLOOD	915.6	254.5
41	CHI_GUTS	1913.0	531.8
42	whey	1030.1	286.4
43	FR_VEG	1419.2	394.5
44	VEG_PRES	1798.5	500.0
45	DIST_MARCH	5696.3	1583.6
46	WINE_MARCH	5696.3	1583.6
47	OLIVE_RES	7848.0	2181.7

Source BioEnergy 2020+