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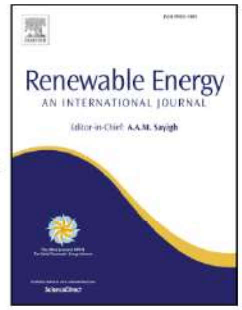

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Urban greenery management and energy planning: a GIS-based potential evaluation of pruning by-products for energy application for the city of Milan

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ABSTRACT

The present paper concerns the assessment of biomass by-products from the urban greenery maintenance with an energy perspective. Usually pruning is not organized by a consolidated planning practice, mainly because of lack of information. After estimating the quantity of wood pruning by-products by means of dendrometric equations and the availability of information on current greenery management, an innovative GIS-based method was implemented and tested on Milan, in northern Italy. The main outcome is the quantification of the energy potential in terms of available wood biomass, displayed on a geo-referred urban map. Moreover, the outcomes of the research could support the administrations in improving the management of these materials otherwise wasted and therefore in converting public expenses for maintenance into public profits available for further investments. On the energy supply side, the GIS database could support the local matching between available renewable sources and energy supply systems in operation (i.e. local district heating and cogenerative systems), providing a low-range and cost-effective renewable resource, also enhancing circular economy at the local scale.

KEYWORDS

Biomass to Energy; Urban Greenery Maintenance; Geographic Information System; Biomass Potential; Phytomass Estimation; Circular Economy.

ABBREVIATIONS

LHV: Low Heating Value
LiDAR: Laser Imaging Detection and Ranging
GIS: Geographic Information System
SDG: Sustainable Development Goal
TBB: Trunks and Big Branches
SB: Small Branches
TAP: Total aboveground Phytomass
PE: Primary Energy
BDHP: Biomass District Heating Plants
CHP: Combined Heat and Power
ORC: Organic Rankine Cycle
LCA: Life Cycle Assessment
MBT: Mechanical Biological Treatment

1. INTRODUCTION

The last update of the European Directive concerning the promotion of the use of energy from renewable sources [1] established the Union binding target of at least 32% share of renewable energy on the final energy consumption by 2030. To this end, the European Commission identifies in biofuels a large potential contribution and promotes their use.

As suggested by [2], the exploitation of biomass in energy conversion plants represents an interesting opportunity in mountainous regions, where the wide presence of woodlands fosters the development of local economic synergies. Additionally, as demonstrated by the authors of [3], the energy use of agricultural biomass residues can be a promising solution also in small and isolated rural communities of developing countries. In these contexts, such solution, compared to other available technologies, diesel generators in this case, reduces the environmental impact and improves the waste management practices.

Anyhow, an interesting untapped biomass potential can also be found in urban contexts by means of pruning by-products from the greenery maintenance [4]. This solution is especially relevant when considering that biomass adopted in urban plants refers, in most of cases, to a wide supply basin, that sometimes taps also into foreign markets.

Currently, municipalities do not use pruning by-products, but they rather pay significant disposal price to appropriate facilities [5]. This management approach can be traced to lack of information about the quantity and quality of this biomass [6] and because maintenance operations are often not programmable or not well documented [7, 8].

In Italy, the normative framework that regulates the energy use of urban pruning by-products is not completely exhaustive. In fact, at present, this biomass is considered as unhazardous waste, that needs to be properly treated and disposed in accordance with the regulation. The Law Decree 264/2016 [9] stated that pruning can be used in combustion plants, but that the plant operator is responsible for conducting such disposal. The latest updates concerning the subject are expressed by the Italian Law Decree n. 37/2019 in force since May 2019 [10], a national transposition of the European Law 2018, which comprehends the ultimate reformulation of the controversial art. 185 of the Italian Environment Regulation (Law Decree 152/2006 [11]). According to the art. 20 of [10], the urban pruning residues do not fall into a waste status and are instead treated as a by-product, with the potential to be used or sold to third parties as fuel for energy conversion processes.

Moving forward bureaucratic and regulatory issues, which fall beyond the purpose of research, the present work focuses on the estimation of the theoretical potential available and to the optimization of the management of urban pruning by-products considering the possible environmental, energy and economic benefits. Consequently, an alternative approach to the current practice concerning greenery maintenance is described.

There is extensive literature concerning the quantification of biomass potential from the urban trees pruning, which takes into account different urban and climate contexts. For example, [8], [12] and [13] combined on-site measurement of pruning residuals and dendrometric equations[1] (direct approach) for estimating the pruning by-product potential from urban greenery maintenance. The analysis regarded *Morus Alba, Platanus Hispanica* and *Sophora Japonica* trees, respectively, in the province of Valencia (Spain).

In a further development of the afore mentioned studies [14], the authors characterized the pruned biomass for energy applications in terms of moisture content and Low Heating Value

estimated the available biomass from pruning of 11 species of urban trees in Fort Collins (Colorado, US) by combining dendrometric equations and LiDAR[2] scanner system (indirect approach).
Lastly, through field measurements and dendrometric equations, [17] analysed the quantity and energy features of *Ficus Benjamina* trees pruning residues from the urban maintenance in the province of Guayas (Ecuador). The authors found that, despite a high content of ashes, the resource presented acceptable LHV and low content of Nitrogen, making them suitable for energy applications.
The results provided by these researches documented an interesting, yet unexploited availability of residual biomass, which has the advantage of being produced without demanding agricultural space, more suitable and sustainable for growing food [18]. Nevertheless, from the scientific literature review, it emerges that the development of a unified and replicable quantification method is hindered by its dependency on many factors that differ from context to context:

- Peculiar characteristics of each tree species and the growing climate context,
- Growing location of the trees within the urban context (e.g. streets, parks) [8],
- Management practices [19],
- Pruning techniques [12].

The studies reviewed have been mainly developed combining dendrometric equations, for the quantitative and qualitative estimation of the biomass residues, and Geographic Information Systems (GIS) tools. These latter are the most suitable and adopted for a proper estimation of the theoretical biomass potential, in absence of more precise, but more time consuming, on-field measurements [20]. There is a growing interest among municipalities in acquiring detailed topographical data to create a more accurate urban management, which promotes the development of a common framework for assessing urban greenery properties.
Even though biomass obtained from urban trees pruning often does not completely match the quality features for energy conversion [21], further treatments (selection, drying and chipping) can be adopted in order to achieve the requested characteristics for a more effective energy conversion. The present study aligns with this framework of operation and aims to provide a GIS-based method to explore pros and cons of the energy use of wood by-product against the current urban maintenance and waste disposal practices in the city of Milan.

1.1. State of art of Italian urban greenery maintenance plans and focus on Milan

It is widely recognized that green areas and trees in the urban context can significantly contribute to enhance the quality of urban life [5]. Beside the social and the aesthetic value, the presence of green spaces can also have a positive effect on air quality, heat island phenomena mitigation, urban water retention improvement and noise levels reduction. In order to achieve and maximize these benefits, municipalities should take care of the greenery management, which involves a variety of finance, policy, development and maintenance tasks [22].
According to the latest statistical information (2013) provided by the national office [23], less than 10% of the Italian main towns have adopted a proper, and compliant with regulations, plan of greenery management, and the issue is mainly tackled with emergency measures.
In spite of the current situation, in 2013 the Italian Parliament drafted a Law Decree ("Regulations for the development of Urban Green Areas" [24]) concerning Urban Public

a regulative and administrative structure for the management of the urban greenery. Specifically, the Law Decree of 2013 fosters the implementation, considering the peculiarities of each different urban context, of the following greenery management tools:

- The Greenery Inventory;
- The Greenery Regulation;
- The Greenery Plan;
- The Greenery Informatic System.

The Greenery Inventory is a sort of public census, compulsory for cities with more than 15,000 inhabitants. It contains the number and the species of trees lying on the municipal soil, and it is necessary for planning maintenance activities, designing new green areas and estimating economic investments to be made.

The Greenery Regulation contains the codes of conduct for users of public green areas and the relative penalties for misbehaviours. The Greenery Plan is aimed at implementing activities for the control and management of the municipal greenery, such as monitoring, cropping and safety measures. Finally, the Greenery Informatic System, provides the physical parameters for each tree lying on the municipal soil and its position on a map.

The tool presented in this paper is thought and designed to be compatible with the Greenery Informatic System. Data are elaborated by GIS environment according to its the structure of the Greenery Informatic System in order to be suitable in any Italian city provided in this system.

In addition, in 2017 the Italian Ministry of the Environment [25] released specific guidelines for a sustainable management of the urban greenery. Currently, the combination of the guidelines with the diffusion of GIS and topographic databases in the public administration enable new opportunities for improving the management of the urban greenery.

Furthermore, referring to the 2030 Agenda promoted by the United Nations [26], the goal of achieving sustainable cities and communities (SDG11) has to be linked to the goal of promoting responsible consumption and production (SDG12), encouraging cities to tackle circular economy policies, thus reducing material flows within their boundaries.

The current study addresses the aforementioned issues and it is based on the case study of the city of Milan. Since 2004, the municipality, in order to develop and manage the Greenery Informatic System, adopted the GIS tool R3-Trees[3] that allows to store and to manage geo-referenced information of the urban greenery. This initiative is part of a broader plan that promotes the valorisation of green areas and the enhancement of the city's maintenance management.

The results presented in the following sections regard the existing urban greenery, according to the new regulation for the use and protection of public and private green areas adopted in December 2017 [28]. However, it has to be noted that recently the municipality has released several projects and plans to enhance its greening attitude towards the 2030 vision. In particular, 20 new urban parks and specific rules for promoting nature-based solutions (e.g. green roofs and facades and de-paving soils) will be implemented [29] and an ambitious urban forestation program, aiming at planting three million trees by 2030 over the Metropolitan City of Milan, has been launched in 2018 [30].

[3] R3-TREES is a web platform, where all operators access a single, centralized application. The software allows

1.2. Description of the case study

Milan is the most densely populated city of northern Italy, with about 1.3 million of inhabitants over a surface of 181.76 km^2. As described in the previous section and according to [24], Italian municipalities should implement a complete inventory of the patrimony of trees, plants and green areas within the urban boundaries. In particular, the guidelines [25] mention the recovery of biomass from the urban greenery maintenance as part of the Regulation of Urban Green Spaces. Specifically, cities should indicate how they make use of this by-product, they should prioritize the recovery of the biomass resulting from pruning through composting or use on site as mulch and, in second instance, they should evaluate energy recovery.

The public administration of Milan provides a fully open database embedding several shape files accessible through GIS tools. From the inventory, it emerges that Milan counts 24 million m^2 of public green zones including historical parks, urban parks, gardens, street sides' green lines and squares. The data available for the present study cover about 75% of the total green areas, including about 270,000 trees, distributed into parks and gardens (60%), along roads (29%) and within the public building open spaces (11%) [31]. These areas, 17,860,651 m^2 overall, are managed by a consortium company in cooperation with the public administration offices, while other entities and associations manage the remaining ones.

The operation of the consortium company ensures ordinary and extraordinary maintenance of all green spaces, including flowerbeds and gardens. The different activities and interventions are based on an advanced computerized system, capable of recording several information. In this framework of public greenery management, the collection of by-products is not followed by energy use. Instead, final treatments such as composting (by 14 local plants, for a total potentiality of 23,438 tons per year [32]) and disposal, are conducted, and they result in a significant expense for the public administration. Therefore, the optimization of the current management can bring interesting benefits, also from an economic perspective.

2. MATERIALS AND METHODS

The estimation of the theoretical biomass potential available in an urban context can be carried out both directly and indirectly. The direct approach can produce more reliable results but involves time-consuming on-site sampling and measurements, and could not be applied in the case study of a complex metropolitan area like Milan. Therefore, the present study adopts an indirect approach by combining dendrometry equations [33] and literature information about maintenance activities with the aim of providing a replicable tool.

The development of a GIS tool able to estimate the biomass-to-energy potential from urban tree pruning is strictly linked to the data availability and the accuracy of the Greenery Informatic System, as previously mentioned [24].

In the present study, data available for the most part of the municipal green were considered and integrated with available information about maintenance operations.

2.1. Datasets and elaboration

In the framework of the development of the method of research, the scientific literature has been considered for defining the main features of the different tree species and therefore estimating the pruning potential. Furthermore, GIS has been adopted for quantifying and displaying biomass potential from pruning at different locations and environmental conditions. In fact, the capability of getting geographically distributed biomass data is detail. For each object of the dataset (i.e. for each tree), the following parameters are available:

- Age;
- Botanical division and species;
- Phyto-sanitary and stability conditions;
- Spatial coordinates, allowing the spatial indications of each tree;
- Total height, trunk diameter (measured at 1.3 m height) and canopy dimensions.

Due to the great variety of tree species present in the city of Milan and according to the ones available in [33], a sample of 11 species has been selected in order to include the most diffused in the municipality. To further enlarge the dataset and get a final sample size closer to the real case, tree species not available in [33] have been associated to the ones available, matching the botanical family first and, subsequentially, if still not matching, the botanical order (e.g., the trees under the category *Betula* were treated as *Carpinus*, because belonging to the same family of *Betulaceae*).

At the end of this process, 86% of the trees of the sample were covered (Tab. 1). Despite the risk of under or over estimation of the final biomass potential, this method was the only possible one based on the available data and, as confirmed by the technical literature [15], it is sufficiently reliable and robust.

Furthermore, the assumptions have been shared and discussed (by email, calls and written confirmation) with expert agronomists[4] of the Association of the Forestry Consortia of Lombardy Region. They have confirmed the robustness of the method and their final opinion is that, according to data availability, the prospect on trees and shrubs of Milan shows a substantial adherence to the inclusion of the individual species with the proposed combinations.

Botanical Genus	Num. of trees		Num. of trees (with matched species)		Average age	Average height	Average diameter
	[-]	[% tot.]	[-]	[% tot.]	[years]	[m]	[cm]
Acer	27,523	10%	35,839	13%	25.1	8.1	25.3
Tilia	17,812	6%	22,690	8%	22.3	7.8	22.8
Populus	11,047	4%	11,050	4%	25.0	10.6	32.5
Platanus	22,754	8%	22,870	8%	36.1	13.5	38.9
Ulmus	12,601	5%	59,285	21%	22.2	7.7	26.9
Robinia	7,333	3%	18,498	7%	22.3	7.3	20.9
Pinus	2,940	1%	15,817	6%	36.0	8.9	32.7
Salix	1,701	1%	1,707	1%	15.7	6.3	17.0
Quercus	12,786	5%	18,695	7%	22.6	8.3	22.1
Carpinus	9,173	3%	12,328	4%	21.8	6.0	15.9
Fraxinus	9,800	4%	17,799	6%	15.6	4.7	13.9
Tot./Av.	135,470	49%	236,578	86%	24.1	8.1	24.4

Table 1. Main properties of the sample divided by the species considered

As reported in Tab. 1, the final sample contains 11 botanical genera. At the end of the selection and association process described above, the most common species is the Ulmus. Except for Pinus, the other species, considering a woodlands context, could be treated as coppice. Of course, as mentioned, the management of trees in the city is slightly different to the one of woodlands. Considering the average age (24.1 years) and height (8.1 m) of the trees in the sample, most of the trees passed the physiological age to be cut and they are growing old, representing a danger for urban context. For this reason, in the urban maintenance, they are normally pruned in order to both maintain aesthetic features and prevent accidents. This issue is taken into consideration also in the biomass potential calculation method presented in Section 2.3.
The tool developed works as a plug-in of the GIS dataset and it consists of a GIS tool able to provide the spatial distribution and the overall urban wood biomass potential, from public trees' maintenance. Beside the estimation of biomass for each tree, the database was implemented also by census tract in order to get a spatial distribution of the resource (see section 3.2).

2.2. Dendrometric equations

The phytomass predictive models (dendrometric equations) of the National Forest Repository [33] have been adopted. To evaluate phytomass growth, starting from trees' diameter, height and species, it provides the dry weight of the total aboveground phytomass (w_{TP}) subdivided in weight of trunk and big branches (w_{TBB}) and weight of small branches (w_{SB}). Other subcategories available, such as weight of the tree's stump, have not been considered because not included in the elaborations. An example of a dendrometric function representing the total above ground phytomass for *Acer* trees is shown in Fig. 1.

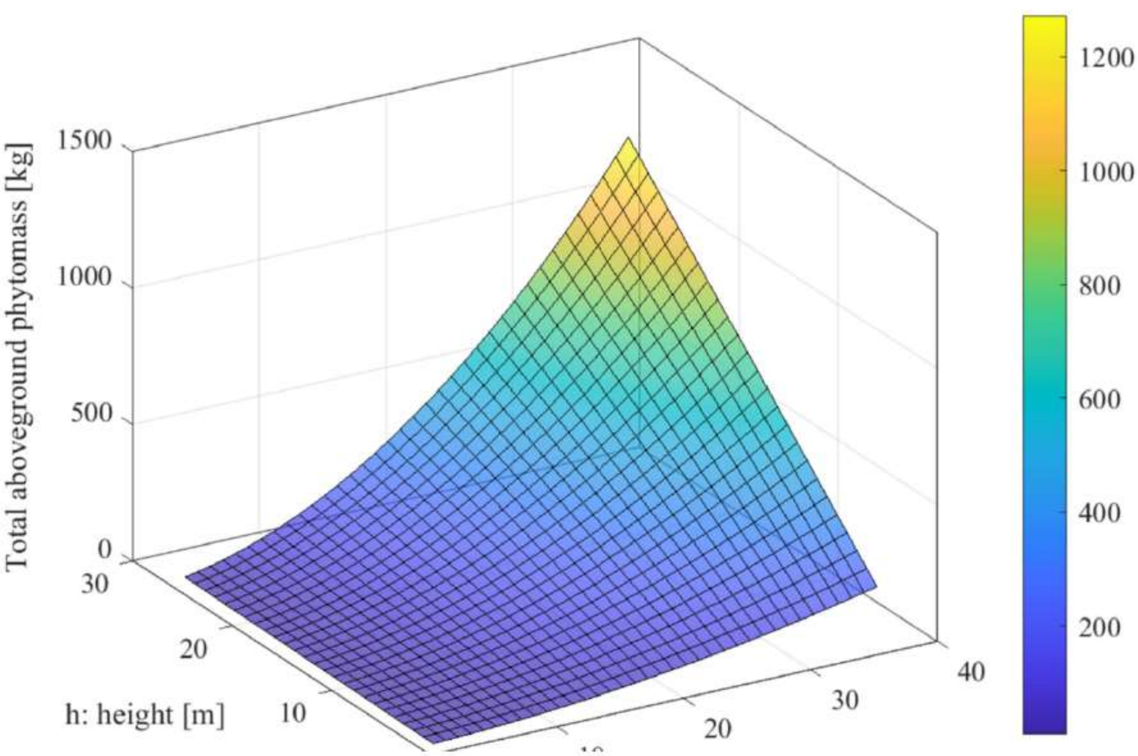

Figure 1. Example of graphical representation of a dendrometric function calculating the total aboveground phytomass from trunk diameter and total tree's height for an *Acer* tree.

These dendrometric equations allow the estimation of tree volume and aboveground phytomass over a large number of trees. Coefficients for the different species are calibrated through ordinary least-squares linear regression analysis by sampling and measuring a total of 1,283 trees for 25 different species [33]. A summary of the dendrometric equations used and the main coefficients for each species considered is provided in Tab. 2.

Botanical Genus	Eq.	Trunks and big branches, TBB (Dry weight, kg)			Small Branches, SB (Dry weight, kg)			Total aboveground phytomass, TAP (Dry weight, kg)		
		b_0	b_1	b_2	b_0	b_1	b_2	b_0	b_1	b_2
Acer	$w_d = b_0 + b_1 \cdot d^2 \cdot h + b_2 \cdot d$	0.87	0.020	-	5.33	0.006	-	6.460	0.026	-
Tilia		-9.11	0.007	2.37	-3.61	0.004	0.74	-12.825	0.012	3.155
Populus		-9.11	0.007	2.37	-3.61	0.004	0.74	-12.825	0.012	3.155
Platanus		-9.11	0.007	2.37	-3.61	0.004	0.74	-12.825	0.012	3.155
Ulmus		-9.11	0.007	2.37	-3.61	0.004	0.74	-12.825	0.012	3.155
Robinia		-3.11	0.022	0.24	-6.73	0.002	1.89	-10.114	0.024	2.207
Pinus		-5.94	0.013	0.78	5.95	0.004	-0.21	0.141	0.018	0.562
Salix		0.89	0.016	-	7.47	0.004	-	9.056	0.021	-
Quercus		-1.37	0.026	-	1.77	0.005	-	0.517	0.031	-
Carpinus		-1.05	0.024	-	3.88	0.006	-	3.249	0.030	-
Fraxinus		-0.66	0.025	-	2.79	0.007	-	2.189	0.033	-

Where: w_d: total dry weight [kg]; b_0, b_1 and b_2: coefficients of determination for the regression equations [-]; d: diameter of trees at the height of 1.3 m [cm]; h: height of trees [m]

Table 2. Dendrometric equations and relative coefficients adopted for the selected tree species

2.3. Assumptions and features for the definition of the maintenance practice

Unfortunately, few data related to the current pruning and maintenance practice were available, therefore an integration with further information from the technical literature was needed. The aim is to define, with the best approximation possible, the fraction of wood removed by pruning the trees as a function of their weight (i.e. the amount of wood residuals available from the current pruning practice and the periods in which the maintenance activities are carried out, see Tab. 3).

Besides the biomass potential calculation, these data allow to provide a temporal distribution of the resource availability across the year. Tab. 3 provides the synthesis of the information elaborated about the maintenance practice.

To that end, the following information and sources have been examined and elaborated:

- Information about the type and the time frame of maintenance operations have been acquired from a former contract for the assignment of Milan public greenery maintenance [34];
- The quantification of the different maintenance interventions has been elaborated from

- Statistics for estimating the amount of felled trees have been found in a report available on the Milan municipality website [37].

Considering the references adopted, the assumption described in the present section and the limited available information about maintenance activities, the set of equations presented in Table 3 have been designed as detailed as possible. The latter describes the biomass achievable from the main three typologies of maintenance intervention (A, B and C).
The group A includes the ordinary activities taking place between November and March, i.e. crown canopy lifting, dead branches cleaning and raising pruning for young trees. According to [34, 36] the pruning by products potential amount to the 10% of trunk and big branches (w_{TBB}) plus the 10% of the small branches for each tree younger than 5 years and the 30% of the same quantities for trees older than 5 years.
Dead branches cleaning (group B), taking place from May to September, amount to the 30% of the small branches (w_{SB}) for each tree. Lastly, the pruning by-products from felling activities consider the 2% of the total trees' weight (w_{TAP}), according to the statistics provided by Milan municipality [37] based on 2016 data.

	Description	Period	Ref.	Equation
A	Crown canopy lifting & dead branches cleaning (age > 5y); Raising pruning (age ≤ 5y)	Nov-Mar	[34, 36]	$w_{tot,A} = \begin{cases} \left[\sum_i^n (w_{TBB,i} \cdot 10\% + w_{SB,i} \cdot 10\%)\right], age \leq 5 \\ \left[\sum_i^n (w_{TBB,i} \cdot 30\% + w_{SB,i} \cdot 30\%)\right], age > 5 \end{cases}$
B	Dead branches cleaning	May-Sep	[34, 35, 36]	$w_{tot,B} = \sum_i^n (w_{SB,i} \cdot 30\%)$
C	Felling	Dec-Jan	[37]	$w_{tot,C} = \left(\sum_i^n w_{TAP,i}\right) \cdot 2\%$

$w_{tot,A}$, $w_{tot,B}$, $w_{tot,C}$: total pruning by-products dry weight in the pruning activities groups A, B and C [kg]; $w_{TBB,i}$: trunk and big branches dry weight of the i-th tree [kg]; $w_{SB,i}$: small branches dry weight of the i-th tree [kg]; $w_{TAP,i}$: total aboveground phytomass dry weight of the i-th tree [kg]

Table 3. Summary of the main assumptions for the identification of pruning activities

As mentioned, the time rate for this group of activities is unknown, and usually differs from tree to tree depending on the age, the location and the specific scheduling of the company responsible of the greenery maintenance. For this reason, in order to establish the yearly amount of pruning by-products available ($w_{tot,year}$), three different scenarios have been defined, considering that the above described pruning activities could take place every year, 2 years and 3 years:

- Scenario 3y (pruning every 3 years): $w_{tot,year} = (w_{tot,A}/3) + w_{tot,B} + w_{tot,C}$ [kg]
- Scenario 2y (pruning every 2 years): $w_{tot,year} = (w_{tot,A}/2) + w_{tot,B} + w_{tot,C}$ [kg]
- Scenario 1y (pruning every year): $w_{tot,year} = w_{tot,A} + w_{tot,B} + w_{tot,C}$ [kg]

The first scenario considers a pruning frequency of 3 years, according to common cropping practice. The second and the third scenarios are reduced to 2 and 1 years, taking into account

and dead branches cleaning (group of activities B and C) can be considered as a constant over the years because independent from the maintenance organization.
Based on the three different frequencies, different quantity of wood biomass can be estimated according to the scenarios defined and equations of Tab. 3.

2.4. Evaluation of biomass potential by GIS

The analysis and calculations described in the previous sections have been implemented in a *Phyton*[5] script and applied to the starting GIS dataset (see section 2.1). The main steps of the GIS computation are resumed in the following list:

- Filtering the GIS dataset as a function of the species for which data of pruning by-product quantification were available;
- Assessment of the total aboveground phytomass in terms of kg for each tree depending on the tree species and dimensions;
- Assessment of the pruning by-products in terms of kg/y for each tree as a function of the trees age, pruning practice and pruning scenario;
- Matching the pruning by-product potential of each tree with a reference LHV to estimate the achievable Primary Energy (PE).

In order to evaluate the PE related to the pruning by-products potential, the three pruning scenarios described in section 2.3 have been considered. Moreover, according to the common practice [2], a reference LHV of 9 MJ/kg and a variation of ± 20% have also been considered. The results are then compared to the biomass demand of a Biomass District Heating Plant (BDHP) located in the surroundings of the municipality, according to operative conditions and to real measurements carried out during recent years. These results are presented in section 4.

2.5. Evaluation of an alternative pruning management approach

The goal of the present study is to propose an optimised management of the pruning by-products, taking into account their theoretical potential for energy conversion. In particular, the authors of [2] evaluated the use of wood by-products for thermal energy generation by a small/medium size BDHP, eventually in cogeneration (Combined Heat and Power (CHP), i.e. with electricity and heat generation).
The technical literature concerning this kind of practise in relation to urban area is scarce. An interesting application was developed in Stockholm, where pruning by-products are collected and exploited for the production of syngas and biochar. Conversely, as described in [2], BDHP operation in mountainous areas adopt more often pruning by-products, but only in small percentage (<5%), since the wide availability of woodlands already represents a sustainable supply basin.
A virtuous use of pruning by-products happens in the Municipality of Tirano, located in a mountainous region of northern Italy and equipped by a cogenerative BDHP. The plant has a thermal power of 20 MW and an electric power of 1 MW provided by an Organic Rankine Cycle (ORC) turbine. It produces about 35 GWh of heat for 8,000 residential and commercial users, consuming approximately 25,000-30,000 tons of wood biomass per year.
The Municipality of Tirano oversees the management of public greenery. For this reason and in accordance with the European and national regulatory framework, in 2016 the Mayor of Tirano and the Head of the BDHP signed an agreement, in order to utilize the pruning

(e.g. absence of contaminants and pollutants) and the price of the by-products, and the approximate quantity to be delivered (i.e. 100 tons per year). Despite the small quantity of by-products supplied, the Tirano case is very significant, because it represents a striking example of overcoming the existing non-technical barrier in this field, and because the economic benefits derived benefit both parties involved.

As most of renewables, the exploitation of such resource is highly site-dependent and requires a proper resource assessment [38]. In the particular regards of the design and operations of a BDHP, biomass supply is one of the most delicate phases. In fact, the lack of clear and reliable information on supply represents the first cause of failure in the biomass energy conversion chain. In order to access the feasibility of a BDHP, it is paramount to access reliable information over time about the availability, cost and features of the biomass to be used for a given purpose. A detailed estimation of local biomass availability across the year is therefore necessary. This estimation should be further supported by a detailed territorial representation.

To estimate a biomass theoretical potential, it is important to refer to the actual availability and market conditions adopting reliable data and to take into account that the type of biomass determines the collection methods that, in turn, can be characterized by different levels of mechanization and treatments. In fact, the phases following supply are related to: treatments to be performed at the place of collection, transport, various treatments useful to provide appropriate characteristics to biomass (such as size and moisture content) and subsequent phases of storage and energy conversion.

The proposal of exploiting wood by-products from urban greenery maintenance as fuel in a BDHP is strictly related to the application selected for the present study, specifically due to the presence of an already existing BDHP nearby the city. However, in the absence of such boundary conditions, alternative solutions can be envisaged for the deployment of wood by-products.

The assessment of the most suitable solution is strictly related to the context of application and there could be the case in which energy conversion could be less convenient than the alternatives. For instance, the authors of [39], through a Life Cycle Assessment (LCA), compared the economic and environmental impact of thermal treatment with the more common Mechanical Biological Treatment (MBT), such as composting or anaerobic digestion, for the disposal of urban waste. In that specific case, the thermal treatment scenario was found to be more cost effective than MBT, but less convenient in terms of environmental impact.

In the present case, wood biomass combustion is taken as reference technology for the energy conversion process. However, other thermochemical methods are available on the market, such as gasification, pyrolysis and production of innovative cellulosic biofuels, even if they are still considered as niche options, at least in Italy.

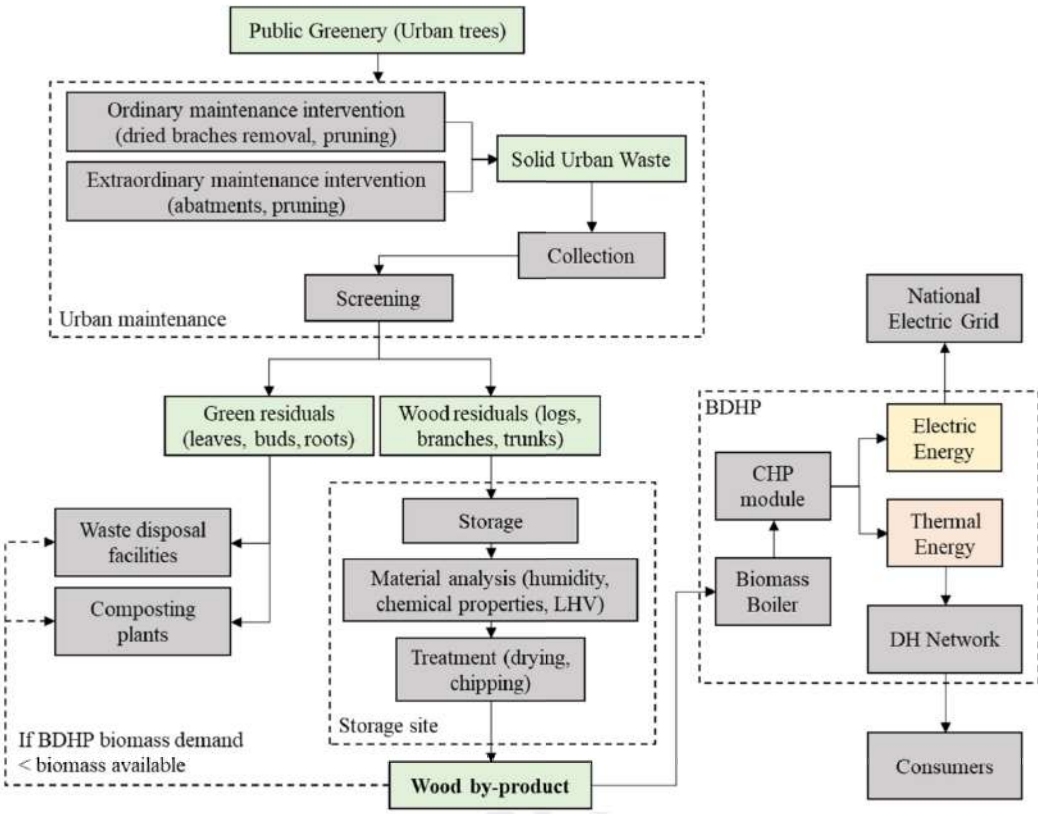

Figure 2. Flow chart of the proposed alternative approach for the management of the urban greenery maintenance aimed at the energy exploitation of pruning by-products

Given the previous considerations, the following method describes whether the collection of pruning by-products of public green areas in Milan, a source available over time and not affected by energy market variability, can support the primary energy supply of a BDHP, taking into account that similar plants already exist in urban surroundings [2]. A flow chart schematizing the main steps of the alternative approach to the urban maintenance proposed, is provided in Fig. 2.

2.6. Assumptions and limits of the estimation

The method is in its first stage of implementation and presents some limitations. Since the method involves the adoption of dendrometric equations developed for different contexts such as forests and woods, its application for tree species grown in an urban context can imply some errors in the evaluation. In fact, as the authors of [15] report, the dendrometry associated with trees in traditional forests does not accurately represent urban trees. Trees in urban settings, compared to those located in convention forests undergo a major level of stress, given by damages, diseases and pruning [8]. Nevertheless, it must be reported that the majority of studies involving the assessment of environmental and economic benefit related to urban greenery are currently carried out with dendrometric equations developed for trees in conventional forests due to the lack of information and measurement for urban environments. An attempt to overcome this barrier was presented by [40], who developed, through on-site measurements, dendrometric tables for several tree species located in an urban context in the United States. These have not been adopted in the present study because of the poor availability of the needed tree species and because of different climatic conditions, compared

Another limit in the method regards the definition of the current maintenance practice due to the difficulties encountered in gathering the needed information. The following steps of the research will be devoted to these improvements.

3. RESULTS AND DISCUSSION

The estimation of the pruning by-products within the municipality of Milan, considering the limit and the assumptions described previously, results in a relevant biomass potential. As shown in Fig 3, the resulting PE ranges between 26 and 76 GWh, depending on pruning frequency and on the chemical-physical properties of the obtained wood biomass. It has to be underlined that the hypothesis of energy use after collection implies specific phases of storage and transformation in order to make the source suitable for combustion or other technologies. At the current stage of the present study, energy consumption related to such treatments and processes are not taken into account.

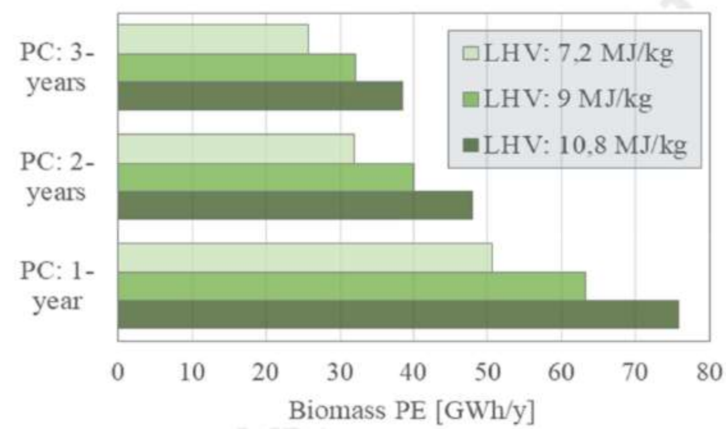

Figure 3. Yearly PE available in function of pruning frequency and properties (humidity, LHV) of the wood biomass source considering a range of LHV and pruning cycles. (PC: Pruning Cycle)

Considering that a medium plant in the Italian context has an average yearly biomass PE consumption of around 20 GWh [2], even in the scenario with 3 years pruning cycle, the urban pruning by-products could represent an important share on the total PE needed in a year.

A BDHP located close to the city of Milan, which has been active for many years, is regarded as an example of a possible destination for pruning by-products. It supplies heat to about 160,000 m^3 of residential buildings, with a total of 14 MW of heat power. Operative data of this plant has been compared to the biomass potential computed. The yearly biomass PE consumed by the plant is around 60 GWh per year. According to Fig. 3, even in the worst-case scenario, a meaningful share of the plant's PE demand could be satisfied by urban pruning by-products. Since the BDHP works in cogeneration (electric driven) and, hence, biomass supply is almost uniform along the year, the time discretization of the resource availability is therefore necessary at least to verify the matching at monthly level. Therefore, the availability of biomass (in tons) from urban pruning, divided into pruning typology (see Tab. 3), has been compared to the biomass consumption of the considered BDHP on a monthly basis (Fig. 4). The monthly discretization proposed in the graph takes into account the three different pruning scenarios considered. As explained in section 2.3, the variation in the biomass by-product availability among the three scenarios involves only the maintenance

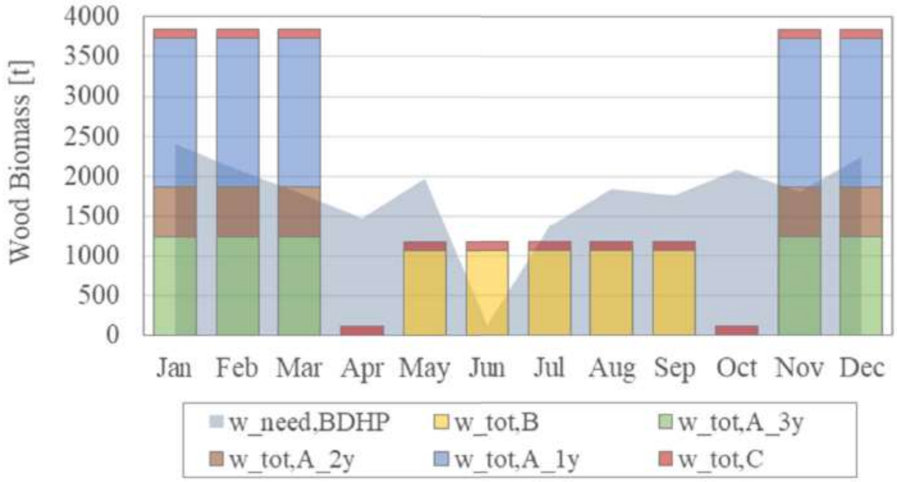

Figure 4. Monthly quantities of pruning by-products available for the different pruning cycles assumed in comparison to the biomass consumption of the BDHP ($w_{need,BDHP}$: total dry weight of biomass needs of the case study BDHP [t]; $w_{tot,B}$, $w_{tot,C}$: total dry weight of pruning by-products in the pruning activities groups B and C (see Tab. 3) [t]; w_{tot,A_1y}, w_{tot,A_2y}, w_{tot,A_3y}: total dry weight of pruning by-products in the pruning activities group A (see Tab. 3) for the three scenarios defined in section 3.3 [t])

In the graph the green bars represent the resource availability in the "Scenario 3y", while the brown and blue bars represent the surplus considering "Scenario 2y" and the "Scenario 1y", respectively. As shown, the availability of wood by-products from urban greenery maintenance, even considering the worst-case scenario, can cover a significant share of the wood consumption of the plant ($w_{need,BDHP}$).

It also results that, depending on the scenario considered, there could be months in which the availability of biomass from pruning exceeds the one needed by the BDHP. Hence, in this specific case, a share of pruning by-products can be either disposed through conventional practices or sold to other facilities or treated and stored. Considering a pruning cycle of 1 year and an average LHV of 9 MJ/kg, the PE need of the plant (grey area) can be fully satisfied by the pruning by-products (green area) for 6 months along the year evaluated (Fig. 5).

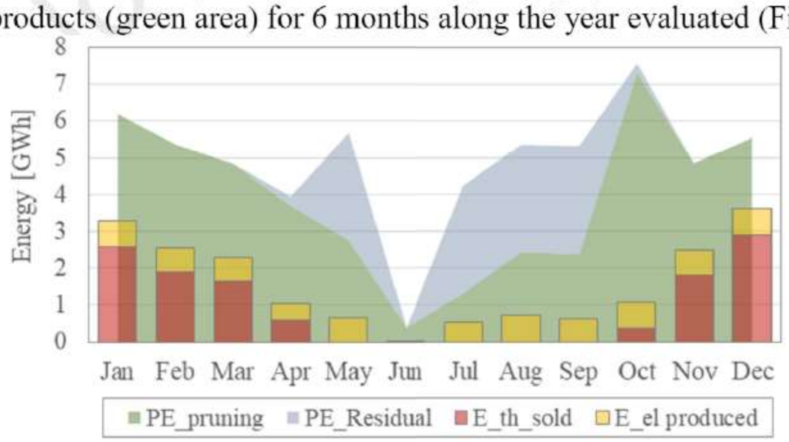

Figure 5. Energy balance of the BDHP highlighting the share of PE consumption covered by pruning by-products and the electric and thermal energy generation

(PE_pruning: Primary energy needs of the BDHP covered by pruning by-products [GWh];

In the same graph, measured values of electric and thermal energy production[6] are also highlighted to provide an outlook of the energy conversion taking place in the plant.
The method adopted and the results obtained cannot be properly validated because, as previously mentioned, not enough information about quantities collected from pruning are available. However, according to available public data related to the urban waste delivered to composting plants in the area of Milan [32], an amount of 23,438 tons of green waste has been registered in 2017. These data are consistent with the results obtained considering the 1-year pruning cycle scenario (25,297 tons), and thus can be considered as a sort of indirect first validation of the assumptions and elaborations carried out.

3.1. Considerations about the economic and environmental impact

Although the focus of the present study lays on different aspects, few remarks regarding environmental impact related to the use of urban pruning by-products in energy conversion plants must be addressed. Indeed, as mentioned in [41], direct combustion of wooden biomass is often associated with the production of a significant amount of combustion particles that, especially in urban areas, represent an issue that must be carefully considered, according also to the regulation in force. For this reason, it is important to mention that the size of the BDHP considered in the present study is large enough to require a mandatory continuous monitoring of pollutants emissions.
In order to control and limit the macro-pollutants emissions the plant is equipped with an effective flue gas abatement system including an advanced denitrification equipment and bag filters for reducing the emissions of NOx and Particulate Matter (PM), respectively. The system allows emissions concentrations far below the limits defined by law.
Regarding the economic benefits achievable from this alternative management of the urban greenery, so far no detailed analysis has been carried out and further developments of the present study will tackle this topic. Nevertheless, the alternative approach proposed allows transforming the cost of pruning residuals disposal into an economic gain by selling them as by-product, after a proper treatment, to energy conversion plants.
The quantification of the economic benefit is not immediate since it depends on many factors. Considering the current market of wood biomass products in the area of the case study, as a case in point, the price of wood chips is around 40-45 €/t [42]. Indeed, the economic value of pruning by-products would be lower than this range due to different properties. According to the few ongoing experiences in Italy, an economic value in the range 10 - 20 €/t can be considered as sustainable for this type of biomass.
Taking into account both the economic saving deriving from the avoided expense for pruning by-products treatment and disposal and the benefit deriving from their economic value, gains for the public administration seem economically sound and in accordance with circular economy practices.

3.2. Spatial representation

The development of a GIS tool allowing the spatial representation of urban pruning potential can provide significant benefits to the planning, management and maintenance of urban green areas. In fact, in the planning phase it is possible to properly identify the strategic areas where to organize the logistics of collection, storage, and waste disposal.
A spatial representation of the wood by-product potential is proposed in Fig. 6 at the scale of census tract. It helps revealing the identification of local basins for energy production within

the macro-areas of the city (the so-called 9 sub-municipalities) or even at the scale of the neighbourhoods (88 neighbourhoods are recognised in Milan).

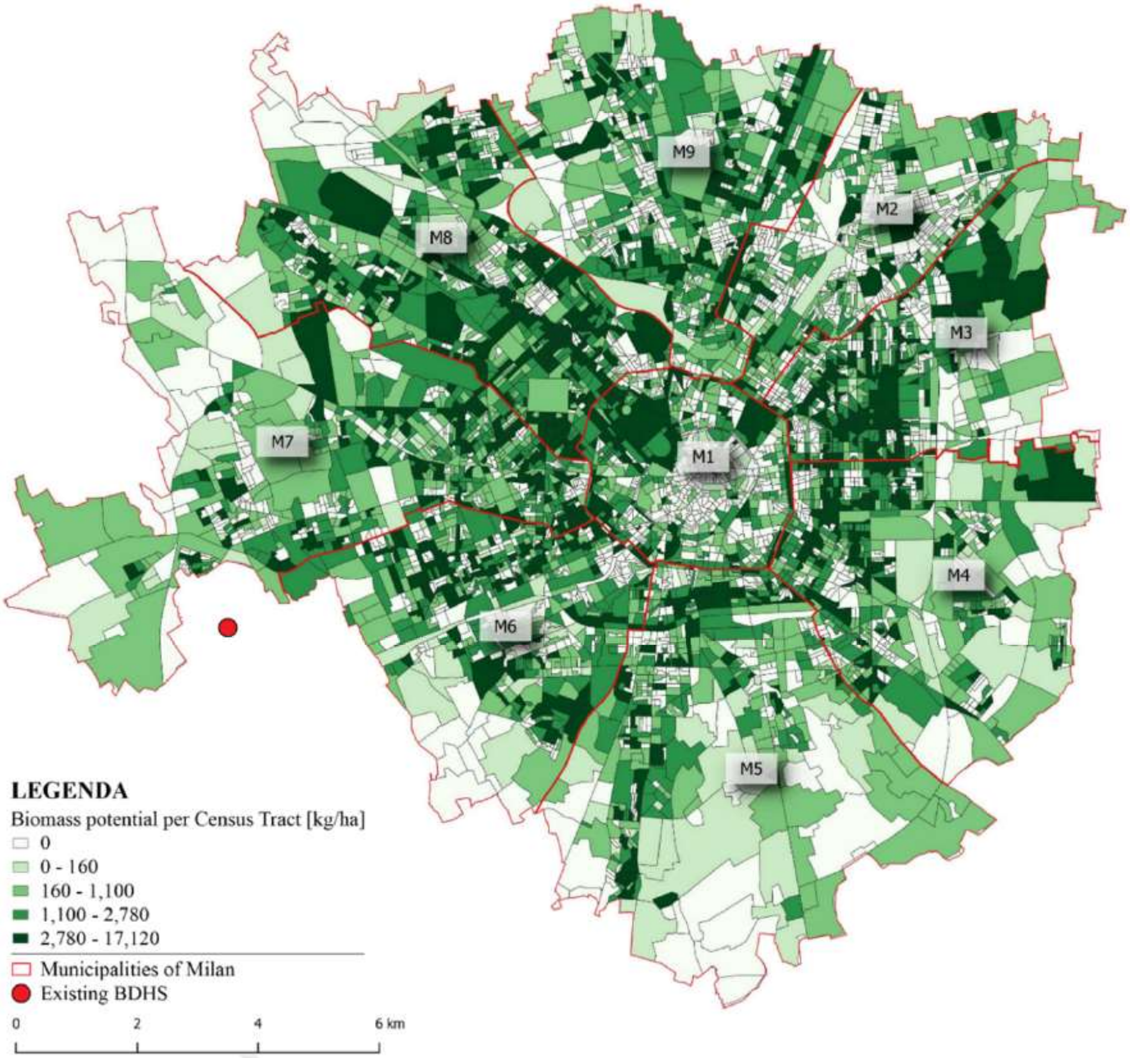

Figure 6. Yearly pruning by-product potential in kilograms, for the City of Milan for each census tract and for the nine municipalities (red boundaries and letter 'M' on the map).

This representation can also suggest the identification of proper basins of biomass production towards sizing and localizing future small size energy plants, according to circular economy principles and urban metabolism optimization. As highlighted in section 2.5 in order to support an alternative approach to pruning residuals disposal, a collection, storage and treatment facility should be properly identified, organized and designed (see Fig. 2). To this end, the spatial representation of the biomass potential could be useful for planning the urban biomass supply systems, including collection-treatment-storage platforms and energy conversion plants and optimising logistics and transportation.

4. CONCLUSIONS

Considering the overall framework related to the rational use of resources, urban districts and

The main outcome, that represents a novelty in relation to others similar studies, is the development of a GIS tool integrable with geographical datasets of urban trees. This tool was designed to be simple and replicable, not time consuming and applicable wherever information related to greenery maintenance are available in form of GIS dataset. To test the developed tool, the city of Milan was considered as case study.

The results allow an estimation of a theoretical biomass potential from pruning by-products, for the exploitation of such resource in an energy conversion plant. Anyhow, in order to get a more reliable result in relation to the urban context in which the tool is adopted, information about the greenery maintenance methods and scheduling and energy quality of the pruning by-products should be assessed and verified.

The possibility to exploit pruning by-products in an urban BDHP, besides the economic gain for the public administration derived by the selling of this resource, mainly results in energy and environmental benefits, such as the availability of a local renewable resource, fossil PE savings and CO_2 savings. Nevertheless, the implementation of such approach is still hindered by technical and non-technical barriers, such as a complicated regulation framework and the need of a proper resource collection structure able to separate wood residual by products from other ones.

The authors think that this method could be able to support local policies, taking into account the approaches of different stakeholders to develop low carbon models of settlements. In particular spatial representation could improve the development, in future energy scenarios, of small urban plants in terms of biomass supply basin identification. Moreover, the difference between biomass availability and biomass need should imply a proper supply and storage organization, which could be deepened in the next steps of the research.

As further development, biomass from large green private areas could be included as well as those managed by consortia devoted to forests and parks around the city boundaries.

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Highlights

1. A novel method for an effective urban greenery management is proposed and analysed;
2. Dendrometric equations and a GIS were combined for pruning by-products estimation;
3. The urban greenery of Milan was considered as case study;
4. A biomass PE potential between 26 and 76 GWh was assessed for the case study;
5. The use of pruning by-products in a biomass district heating plant is evaluated;