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Impact of Biomass Ratio as a Synthetic Parameter in Soft Computing Approaches for a Decision-Making Tool for Biogas Plants in Urban Areas

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Abstract: The EU's energy transition strategy highlights the significance of developing innovative energy models to encourage the utilization of renewable energy sources in urban areas. Utilizing local urban biomasses, including food waste, sewage, and green waste, can contribute to the establishment of energy systems that harness bio-waste for energy generation, thereby promoting circular economy principles and urban metabolisms. This paper proposes using a pre-design tool (based on soft computing approaches) that incorporates an initial analysis of the multidisciplinary feasibility of such systems as an effective strategy and valuable support for preliminary studies. It focuses on validating three "biomass ratio" parameters, integrating urban morphology and district characteristics with the amount of bio-waste in a peri-urban district comprising multifamily buildings. These parameters can be incorporated into a pre-design tool that facilitates multi-criteria decision analyses, aiding the design of innovative models that promote renewable energy sources in urban areas. The findings suggest that synthetic parameters can guide initial considerations, but they may overestimate the energy potential and should be further investigated. Hence, future research should explore complementary strategies for estimating biomass energy potential and extend the application of this methodology to other types of districts.

Keywords: renewable energy source; energy efficiency; resilient cities; sustainability; adaptation; optimized design; bio-waste; urban district typology; decision support tool; multi-criteria decision analysis

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1. Introduction

The European Union (EU) is committed to transitioning towards a decarbonized and sustainable energy system, as demonstrated by the European Green Deal [1]. In line with this, the EU has set ambitious targets to reduce greenhouse gas emissions, increase renewable energy production, and improve energy efficiency to limit global warming to 1.5 °C above pre-industrial levels [2]. One potential solution to meet these targets is utilizing biogas. This renewable energy source can be produced from organic waste, and it can also offer waste management benefits and contribute to circular economy goals [3]. Furthermore, the potential of biogas and its applicability is increasingly being recognized in urban areas [4]. Therefore, its possible role in decarbonizing the EU's energy system is gaining attention, as highlighted in recent publications [5–7].

1.1. Objectives and Limits of the Study

This study aims to contribute to the debate on biogas utilization in urban areas for community energy by examining the drivers and barriers to its adoption and highlighting successful case studies. In this scenario, it draws upon the latest research [8–10] to provide an up-to-date analysis of the potential of biogas for community energy in the context of the EU's energy transition. Since the White Paper was published in 1997 [11], the challenge has been to reduce Greenhouse Gas emissions (GHG) and support alternative solutions for diversifying the energy supply. These are central issues in the European Union's strategies [12–17]. In particular, energy efficiency practices and renewable energy sources (RESs) represent crucial topics in this framework. Although European and national targets issued by the community have produced good results after 25 years of policies, a step over the common RES application is fundamental for post-2020 strategies. Technological know-how should be used for upgrading holistic energy system solutions, as, in addition to supporting current energy efficiency practices at the population level, they can enhance them, involving social and economic actors. With this purpose, RESs represent opportunities to optimize existing energy models and existing urban areas. However, the district scale is a challenging perspective. Cities are crucial for multiple reasons, including the growing worldwide population [18], the slow renovation of the existing building stock, and the current low energy standards [13]. Urban areas need constant energy growth for residential activities and services, and energy production from local sources can be a valuable contribution. Several ongoing research works on RESs' application in urban areas [19–21] are facing the topic of energy production inside the city. On the one hand, energy production can be maximized through technical analyses and studies—orientation and roof inclination for PV and solar heating systems, amount of people for biomass production, etc. However, on the other hand, the optimization of the whole energy chain relies on aspects that include the commitment of all the potentially involved actors, including energy producers, energy suppliers, energy users, institutions, associations, business activities, etc.; all these players should be included in the decision-making processes. The design of RESs in urban areas is even more complex when considering using a potential energy source such as urban bio-waste, commonly considered only as waste. Despite this, the energy potential of bio-waste and sewage produced by human activities requests a change of perception on bio-waste, which could be disruptive for introducing and promoting virtuous practices of circular economy and urban metabolism management. These processes are complex and not easy to manage. Their involved actors are not all part of the energy production chain, and their specific—technical and non-technical—aspects must be managed by qualified personnel. This integration asks for predesigned tools that work in the early stages to investigate different possible scenarios preliminarily.

1.2. The Importance of Decision Support Tools in Planning Biogas District Plants for Resilient Cities

The transition towards sustainable and decentralized energy systems requires the engagement of local communities in planning and managing energy resources. In this context, decision support tools (DSTs) based on multi-criteria decision analyses (MCDA) [22–24] are valuable instruments providing technical and economic information to support stakeholders in making conscious decisions. DSTs can enable the identification of feasible and cost-effective solutions for implementing community energy projects and facilitate the integration of renewable energy sources into urban areas. Furthermore, DSTs can play a pivotal role in driving the European Union's (EU) energy transition, as ambitious targets have been set to reduce greenhouse gas emissions and increase the share of renewable energy sources. The adoption of DSTs allows designing tools based on soft computing approaches [25], alternatively to usual hard computing methodologies, which typically rely on precise mathematical models and algorithms. These methodologies aim to provide solutions through deterministic models and optimization techniques, to achieve exact solutions for the optimization of system efficiency, energy production, and cost-effectiveness, including all relevant factors to be determined, such as feedstock availability, anaerobic digestion process parameters, gas composition, energy conversion efficiency, optimal size and configuration of biogas plants, suitable feedstock mix, and operational parameter optimization. In deploying DTSs, this simulation approach can be replaced with soft computing, which deals with approximate models and provides solutions to complex real-life problems more flexibly and tolerantly. Soft computing methodologies are suitable for situations where imprecision, uncertainty, and partial truth exist, often encountered in evaluating biogas systems in urban areas. In soft computing, several techniques can be employed for biogas system evaluation. Expert systems are considered the most relevant, as they can integrate knowledge from domain experts into a computer-based system [3] to provide intelligent recommendations, diagnose problems, and support decision-making in a biogas system evaluation. For this purpose, these soft computing methodologies enable a more flexible and adaptable approach to a biogas system evaluation, considering the inherent complexity and uncertainty present in urban environments. By leveraging approximate models and intelligent algorithms, soft computing techniques can provide valuable insights and support decision-making in the planning, design, and operation of biogas systems in urban areas. Indeed, despite the potential benefits of DSTs with soft computing, the design and implementation of these tools face several challenges, such as the availability and quality of data, the involvement of stakeholders, and the consideration of multidisciplinary aspects. This study aims to investigate a soft computing approach based on the data available from the analysis of the district typology. Indeed, the district is the city's elementary cell. Its morphology drives opportunities and limitations to create urban biomass systems, relating aspects ranging from the technological applicability of biomass production to the number of inhabitants and the presence of public areas. District characteristics are crucial and they can be pondered in predesign tools through synthetic parameters. Integrating soft computing as a decision support tool for multi-criteria analysis in evaluating and redesigning urban biogas systems can significantly enhance the early-stage assessment and micro-generation solution planning in neighborhoods. Soft computing techniques can use existing data from various sources, such as urban designer planning for urban morphology, GIS data, and 3D scanner data collected through UAVs (Unmanned Aerial Vehicles). Soft computing can effectively analyze and process the information by comparing these data sets with national, regional, and local household dimensions and urban waste generated. Using urban design planning, GIS, and 3D scanner data allows for comprehensive urban context analysis, including spatial distribution, infrastructure availability, and demographic factors. This data-driven approach empowers decision-makers, urban planners, and designers to make informed choices regarding the opportunity for a biogas system in specific neighborhoods. By integrating these insights into the decision support tool, stakeholders can evaluate various scenarios, assess trade-offs, and identify the most suitable micro-generation solutions for urban areas.

Within the energy and urban forms explored over the past decades, this paper presents one possible parameter to define the district typology, the so-called "biomass ratio". This parameter relates urban district typology, population, and energy potential with the aim to focus on biomass-population-urban forms relations to recognize the most energy-performing district to locate biogas systems. This parameter is defined within a set of parameters that consider district typology and its multidisciplinary features: environmental, normative, technological, social, and economic.

2. Materials and Methods

The methodology adopted identifies the biomass ratio as part of a broader multi-criterial systemic vision that considers the role of district typology in urban biogas system realization within a multi- and inter-disciplinary analysis focused on presenting aspects related to the only energy field.

Considering the district typologies from the literature [26], Table 1 reports terms used in district classification, with their initials and definitions. Using data from a literature review (Table 2 [27–30], Table 3 reports the characteristics of the presented district [26,31,32] and energy estimation methodology (phase 1 of the method). The lower part of Table 3 shows the synthetic parameters studied as indexes for the energy urban biomass calculation. Working on energy potential, we focused on the main components for characterizing urban forms: the built-up area and the total surface.

Three consequential phases have been identified/set and developed to define and validate the biomass ratio.

Table 1. All terms used in the following tables are reported in this table, with their initials and definitions.

Term	Initial	Definition
Built-up Area	BA	Built-up surface results from the maximum area covered by a horizontal projection of all aboveground stories
Built Area Ratio	BAR	Built Area Ratio is the Gross Built Area on the Cluster Area (%)
Cluster Area	CA	Cluster Area is the gross surface of the District considered a reference
District	Ds	District is the urban area considered as a reference or case study; District is the section with the related data
District Dry Matter of Organic Fraction of Municipal Solid Waste	Ds DM of OFMSW	District Dry Matter of Organic Fraction of Municipal Solid Waste is the dry part of the gross Organic Fraction of Municipal Solid Waste, calculated at the district scale
District Dry Matter of Sewage	Ds DM Sew	District Dry Matter of sewage is the dry part of the gross sewage, calculated at the district scale
District Municipal Solid Waste	Ds MSW	District Municipal Solid Waste is the gross amount of Municipal Solid Waste, calculated at the district scale
District Organic Fraction of Municipal Solid Waste	Ds OFMSW	District Organic Fraction of Municipal Solid Waste is the gross amount of Organic Fraction of Municipal Solid Waste, calculated at the district scale
District Sewage	DsSew	District Sewage is the gross amount of sewage, calculated at the district scale
Dry Matter	DM	Dry Matter is the dry portion of biomass, calculated as the difference between the total weight and the moisture content
Energy Built Area Ratio	EBR	Energy Built Area Ratio is the synthetic parameter based on the model of reference, calculated as the gross energy estimated from district waste (Sewage and OFMSW) on Built Area
Energy from EBR	E_{EBR}	Energy from EBR is the gross energy estimated using EBR as synthetic parameter
Energy from EGBR	E_{EGBR}	Energy from EGBR is the gross energy estimated using EGBR as synthetic parameter
Energy from EGBMSNR	$E_{EGBMSNR}$	Energy from EGBMSNR is the gross energy estimated using EGBMSNR as synthetic parameter
Energy Gross Built Area Ratio	EGBR	Energy Gross Built Area Ratio is the synthetic parameter based on model of reference, calculated as the gross energy estimated from district waste (Sewage and OFMSW) on the Gross Built Area
Energy Gross Built and Mean Story Number Ratio	EGBMSNR	Energy Gross Built and Mean Story Number Ratio is the synthetic parameter based on the reference model, calculated as the gross energy estimated from district waste (Sewage and OFMSW) on Gross Built Area and Mean Story Number
Energy Produced	Energy Production	Energy Produced is the amount of Energy by OFMSW or Sewage
Gross Built Area	GBA	Gross Built Area is the sum of whole area of all aboveground stories
Gross Calorific Value of Dry Matter	HHV	Gross Calorific Value of Dry Matter is the energy released as heat when a Dry Matter of biomass undergoes complete combustion
Household Sewage	HSew	Household Sewage is the biomass derived from household sewage activities
Household Size	Hsz	Household Size is the number of people part of the same household
Household Waste	HW	Household Waste is the biomass derived from household biowaste
Housings for Buildings	HsgBld	Housings for Buildings are the average of housings for each building of case study reference
Housings for Floor	HsgFl	Housings for Floor are the average of housings for each floor of case study reference

Table 1. *Cont.*

Term	Initial	Definition
Land Use	Land Use	Land Use is the section with data related to the amount of surfaces divided for their destination use
Mean Story Number	MSN	Mean Story Number is the mean number of stories, calculated by dividing the Gross Built Area by the Built-up Area
Organic Fraction	OF	Organic Fraction is the percentage of organic part of MSW
Population	PP	Population is the number of people resident in the District
Population Density	Pden	Population Density is the section with data related to the amount connected to population, housing, and building
Built Area Share	BASh	Built area Share is the Built-up Area on Cluster Area
Synthetic Parameters	SyP	Synthetic Parameters are indexes based on model of reference
Total Buildings	Tot Blds	Total Buildings are the number of buildings hosted in the District
Total Energy	Tot Energy	Total Energy is the amount of energy calculated at district scale, as the sum of energy derived from Household Waste and Household Sewage
Total Housings	Tot Hsgs	Total Housings are the number of housings in the District

Table 2. Data from literature reviews used for energy biomass estimation.

Urban Organic Fraction		**Unit**	**Household Waste**		**Household Sewage**	
			(a)		**(b)**	
(20)	Total amount	kg/pp/yr	literature review [30]	475	literature review [28]	19.71
(21)	OF	%	literature review [27]	0.46		1
(22)	DM	%	literature review [29]	0.46	literature review [29]	0.901
(23)	HHV-DM	MJ/kg	literature review [29]	17.3	literature review [29]	15.1

Table 3. Synthetic parameters identification. District model-based analysis addresses the studying indexes for biomass estimation using energy compared with the built-up area dimensions.

District Category		**Unit**	**Id**	**Calculation Methodology**	**Peri-Urban District with Multifamily Buildings**
Ds	CA	m^2	(1)	model/district survey	14,400
Land use	BA	m^2	(2)	model/district survey	3600
	BASh	%	(3)	(2)/(1)	25.00%
Pden	GBA	m^2	(4)	model/district survey	18,000
	HsgFl	nr	(5)	model/district survey	4
	Tot Blds	nr	(6)	model/district survey	9
	MS	#	(7)	(4)/(2)	5.00
	HsgBld	nr	(8)	(7) × (5)	20
	Tot Hsgs	nr	(9)	(8) × (6)	180
	BAR	%	(10)	(4)/(1)	125.00%
	Hsz	pp/hsg	(11)	literature review [33]	2.30
	PP	#	(12)	(9) × (11)	414

Table 3. *Cont.*

District Category		Unit	Id	Calculation Methodology	Peri-Urban District with Multifamily Buildings
HW	Ds. MSW	t/ds/yr	(13)	(12) × (20a)/1000	196.65
	Ds. OFMSW	t/ds/yr	(14)	(13) × (21a)	90.46
	Ds. DM of OFMSW	t/ds/yr	(15)	(14) × (22a)	41.61
	Energy produced	MWh/ds/yr	(16)	(15) × (23a) × 0.2777	199.91
HSew	DsSew	t/ds/yr	(17)	(12) × (20b)/1000	8.16
	Ds DM Sew	t/ds/yr	(18)	(17) × (22b)	7.35
	Energy produced	MWh/ds/yr	(19)	(18) × (23b) × 0.2777	30.83
Total Energy		MWh/ds/yr	(24)	(16)+(19)	230.74
SyP	EBR	kWh/m^2/yr	(25)	(24)/(2) × 1000	64.09
	EGBR	kWh/m^2/yr	(26)	(24)/(4) × 1000	12.82
	EGBMSNR	kWh/m^2/yr	(27)	(26)/(7)	2.56

2.1. 1st Phase—Parameters Identification

In this first step, a district model-based analysis has been considered to identify three biomass ratios for district typologies. District typologies, spatial dimensions, land destination uses, and housing density embed the potential for population density and biomass production perspective. The biomass ratio is associated with the district-based biomass potential, with specific-district measurable characteristics. This phase allows for identifying biomass ratios as synthetic parameters, which is helpful for preliminary studies on the relationship between urban forms and energy biomass potential. This district model-based analysis is basilar to the first critical reflections on district typologies and urban biomass energy systems permeability.

2.2. 2nd Phase—Parameters Verification

This phase validates the quality and the error of biomass ratio parameters calculated for district typologies, using real districts as control systems. The previous phase is a unique approach that aims to connect district features with biomass potential dependent on the population settled; for this reason, validation is fundamental, and the calculation of biomass ratios in real case studies helps to validate the synthetic parameters. This stage aims to check if the district model-based parameters identified and calculated in phase one are representative of the energy potential status in real existing districts. Each biomass ratio calculated for the district model is compared with the biomass ratio from existing district case studies to verify the proximity and reliability of theoretical values with actual results. As a consequence of this step, a rate of error is calculated to assess the quality and validity of the three different biomass ratios. Parameters with no significance for this benchmark are discarded.

2.3. 3rd Phase—Parameters Threshold Value

The over-calculated rate of errors identifies a threshold used as a benchmark value to create a reference matrix for the multi-criteria decision analysis within the predesign tool.

2.4. Study Limitations

Some research limitations are considered in the methodology: the district typology model is residential-only, and only the biomass generated by the population is contemplated, therefore, excluding the contribution of urban biomass from green areas' maintenance. Indeed, population guarantees a base load of biomass independent of other activities, such as services, industries, other urban destinations, or district green areas, which are specific situations to be considered case by case. Indeed, other activities, besides residential ones, represent a high added value for urban biomass evaluation, but their specificities ask for in-depth analysis dependently mostly on real case studies. For this reason, the biomass ratio is calculated based on population density connected with the built-up residential area in the presented work.

In the next paragraph, the adopted methodology is presented and applied to identify biomass ratios for one of the district typologies studied: the peri-urban district with multifamily buildings (Figure 1). The peri-urban district with multifamily buildings tests the methodology presented, verifies its replicability for other district typologies, and identifies the biomass ratio to be used in the further predesign tool for urban biogas systems.

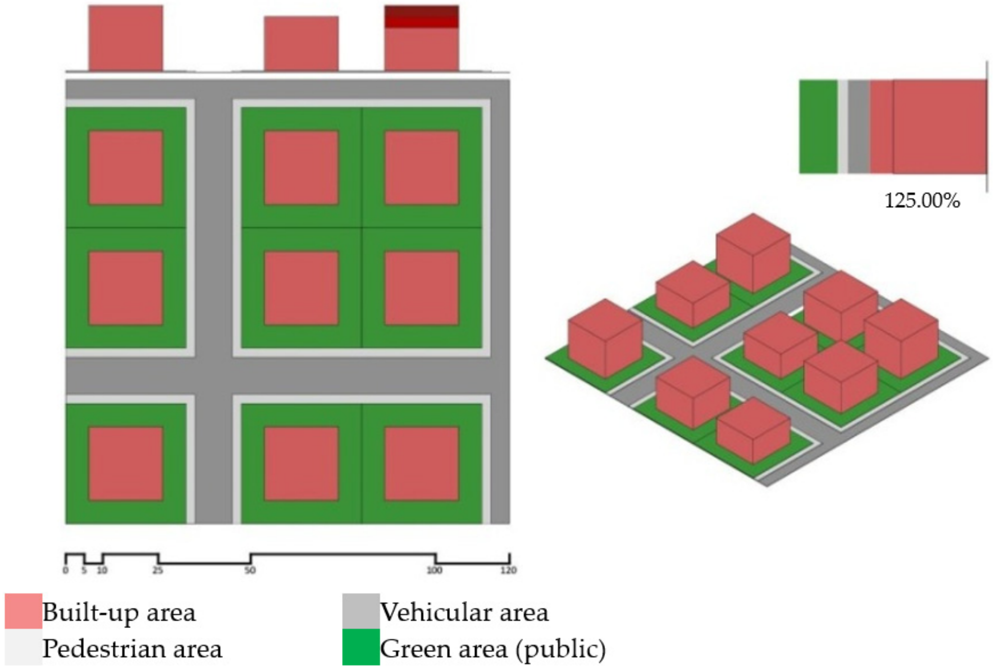

Figure 1. Peri-urban district with multifamily buildings. The percentage reports the gross built-up area, and the black is the district dimension (equal to 100% as reference).

3. Results: Biomass Ratios for the Peri-Urban District with Multifamily Buildings

The peri-urban district with multifamily buildings presented here is an archetypical urban form inside an urban area [26]. A peri-urban district with multifamily buildings is an urban cluster characterized by a mean density built-up area with high inhabitant concentrations; housings are part of multifamily high-rise buildings, four-to-six-story, with usually four housings each.

Three different indexes are identified:

- *Energy Built-up area Ratio* (*EBR*): this ratio is calculated considering the energy produced by the population in the *Built-up Area* of the district;
- *Energy Gross Built-up Area Ratio* (*EGBR*): this ratio is calculated considering energy produced by the population, divided by the *Gross Built-up Area* of the district;
- *Energy Gross Built Area and Mean Story Number Ratio* (*EGBMSNR*): this ratio is calculated considering the energy produced by the population in the *Gross Built Area* of the district, pondered with the Mean Story Number of the buildings in the neighborhoods.

Tables 4–6 report the process validation of identified parameters (phase two of the methodology). Using case studies from the literature [34,35], biomass ratios identified in phase one are calculated for real districts, moving from the district models of reference to scientific validation through case studies.

The selected case studies have the same typological characteristics as the reference model. Due to the unavailability of data on household size for each district and looking for general indexes, it was chosen to consider the average household size from Eurostat

Statistic [33], except for non-EU case studies 12 and 13, for which national household size data is considered [31]. This choice allows for going beyond residential population trends typical of different periods, focusing the attention on urban forms and their biomass potential, based on specifics of urban forms.

The result reports many differences between biomass ratio applications in real districts and their values for district models, with significant varieties in parameter application. Indeed, comparing energy estimated through extended calculation (24) and energy calculated through synthetic parameters (28), (29), (30), it is possible to identify differences in energy approximation, which are analyzed with a study of errors conducted as reported in Tables 4–6. Firstly, each biomass ratio estimated through the district-based model is compared with the biomass ratio from the extended calculation to obtain its relative error (31), (33), (35). Secondly, the mean relative errors for the case studies are considered (32), (34), (36), showing differentiations in the indexes' application, and consequently addressing their uses.

Table 4. Case studies and extensive energy calculation, phase two. The table reports case studies (CS), from CS1 to CS3, considered in the scientific validation processes. The ID codes refer to extended references presented in Table 2.

District Category		**ID**	**CS1**	**CS2**	**CS3**
			Tamariskengasse District 1, Wien, Austria	**Tamariskengasse District 2, Wien, Austria**	**Kabelwerk District, Wien, Austria**
Ds	CA	(1)	38.700	41.000	3.700
Land Use	BA	(2)	15.294	12.517	1.670
	BASh	(3)	39.52%	30.53%	45.14%
Pden	GBA	(4)	26.000	36.300	3.674
	HsgFl	(5)	/	/	/
	Tot Blds	(6)	/	/	/
	MS	(7)	1.70	2.90	2.20
	HsgBld	(8)	/	/	/
	Tot Hsgs	(9)	231	169	26
	BAR	(10)	67.18%	88.54%	99.30%
	Hsz	(11)	2.30	2.30	2.30
	PP	(12)	531	389	60
HW	Ds. MSW	(13)	252.37	184.63	28.41
	Ds. OFMSW	(14)	116.09	84.93	13.07
	Ds. DM of OFMSW	(15)	53.40	39.07	6.01
	Energy Produced	(16)	256.55	187.69	28.88
HSew	DsSew	(17)	10.47	7.66	1.18
	Ds DM Sew	(18)	9.44	6.90	1.06
	Energy Produced	(19)	39.56	28.95	4.45
Total Energy		(24)	296.11	216.64	33.33
SyP	E_{EBR}	(28)	980.25	802.26	107.04
	Relative Error	(31)	−2.31	−2.70	−2.21
	E_{EGBR}	(29)	333.29	465.32	47.10
	Relative Error	(33)	−0.13	−1.15	−0.41
	$E_{EGBMSNR}$	(30)	113.32	269.89	20.72
	Relative Error	(35)	0.62	−0.25	0.38

Table 5. Case studies and extensive energy calculation, phase two. The table reports case studies (CS), from CS4 to CS8, considered in the scientific validation processes. The ID codes refer to extended references presented in Table 2.

ID	CS4	CS5	CS6	CS7	CS8
	Borneo Island 1, Amsterdam, The Netherlands	**Borneo Island 2, Amsterdam, The Netherlands**	**Drotárska District, Bratislava, Czech Republic**	**De Bongerd District, Amsterdam, The Netherlands**	**Ruggächern District, Zürich, Swisserland**
(1)	5.600	9.700	18.700	25.200	37.800
(2)	2.542	4.963	3.958	7.097	8.017
(3)	45.39%	51.16%	21.17%	28.16%	21.21%
(4)	6.100	13.400	19.790	22.000	47.300
(5)	/	/	/	/	/
(6)	/	/	/	/	/
(7)	2.40	2.70	5.00	3.10	5.90
(8)	/	/	/	/	/
(9)	67	126	135	151	278
(10)	108.93%	138.14%	105.83%	87.30%	125.13%
(11)	2.30	2.30	2.30	2.30	2.30
(12)	154	290	311	347	639
(13)	73.20	137.66	147.49	164.97	303.72
(14)	33.67	63.32	67.84	75.89	139.71
(15)	15.49	29.13	31.21	34.91	64.27
(16)	74.41	139.94	149.93	167.70	308.75
(17)	3.04	5.71	6.12	6.85	12.60
(18)	2.74	5.15	5.51	6.17	11.35
(19)	11.48	21.58	23.12	25.86	47.61
(24)	85.89	161.52	173.05	193.56	356.36
(28)	162.93	318.10	253.68	454.86	513.84
(31)	−0.90	−0.97	−0.47	−1.35	−0.44
(29)	78.19	171.77	253.68	282.01	606.33
(33)	0.09	−0.06	−0.47	−0.46	−0.70
(30)	37.53	92.76	253.68	174.85	715.47
(35)	0.56	0.43	−0.47	0.10	−1.01

Table 6. Case studies and extensive energy calculation, phase two. The table reports case studies (CS), from CS9 to CS13, considered in the scientific validation processes. The ID codes refer to extended references presented in Table 2.

ID	CS9	CS10	CS11	CS12	CS13
	Mühlweg District, Wien, Austria	**Karree St. Marx District, Wien, Austria**	**Werdwies District, Zürich, Swisserland**	**Linked Hybrid District, Beijing, China**	**Sunrise 100 District, Jinan, China**
(1)	25.700	29.400	20.400	48.600	64.800
(2)	7.500	7.639	4.891	8.825	7.944
(3)	29.18%	25.98%	23.97%	18.16%	12.26%
(4)	30.000	55.000	31.300	139.675	152.607

Table 6. *Cont.*

ID	CS9	CS10	CS11	CS12	CS13
	Mühlweg District, Wien, Austria	**Karree St. Marx District, Wien, Austria**	**Werdwies District, Zürich, Swisserland**	**Linked Hybrid District, Beijing, China**	**Sunrise 100 District, Jinan, China**
(5)	/	/	/	/	/
(6)	/	/	/	/	/
(7)	4.00	7.20	6.40	15.83	19.21
(8)	/	/	/	/	/
(9)	252	406	152	1.079	1.441
(10)	116.73%	187.07%	153.43%	287.40%	235.50%
(11)	2.30	2.30	2.30	2.97	2.97
(12)	580	934	350	3.205	4.280
(13)	275.31	443.56	166.06	1522.20	2032.89
(14)	126.64	204.04	76.39	700.21	935.13
(15)	58.26	93.86	35.14	322.10	430.16
(16)	279.87	450.91	168.81	1547.42	2066.58
(17)	11.42	18.41	6.89	63.16	84.35
(18)	10.29	16.58	6.21	56.91	76.00
(19)	43.16	69.54	26.03	238.64	318.70
(24)	323.03	520.44	194.85	1786.06	2385.28
(28)	480.70	489.61	313.46	565.63	509.16
(31)	−0.49	0.06	−0.61	0.68	0.79
(29)	384.56	705.03	401.23	1790.46	1956.24
(33)	−0.19	−0.35	−1.06	0.00	0.18
(30)	307.65	1015.25	513.57	5667.60	7515.99
(35)	0.05	−0.95	−1.64	−2.17	−2.15

The application of phase three of the methodology leads to some considerations on these biomass ratios and their applicability as synthetic parameters in predesigned tools. Among the three identified ratios (Tables 7 and 8), the EGBR calculated for the district model is the closest to real cases, thanks to the lower mean relative error (−36.24%). For this reason, this biomass ratio is preferred and used as the threshold value. Some additional comments on these biomass ratios can be made. First, EBR considers only the built-up area. This simplification excludes urban form the parameters, such as the number of floors and housings. The error demonstrates a need for working on other measurable, specific parameters. The ratio between energy biomass produced by the population settled in the district and gross built area relates energy to the total residential floor area. Consequently, EGBR adopting gross built area demonstrates a better approximation with a meaningful error decrease concerning EBR. The last parameter identified, EGBMSNR, weights the previous energy district ratio with the mean story number; despite being better than EBR, its performance is worse than the EGBR and, therefore, excluded.

Table 7. ID (31) is the relative error for each CS referring to EBR, and (32) is their mean relative error. ID (33) is the relative error referring to EGBR, and (34) is their mean relative error. ID (35) is the relative error referring to EGBMSNR, and (36) is their mean relative error.

District Category	Calculation Methodology	ID	CS1	CS2	CS3	CS4	CS5	CS6
Tot Energy	(16) + (19)	(24)	296.11	216.64	33.33	85.89	161.52	173.05
E_{EBR}	(25) × (2)/1000	(28)	980.25	802.26	107.04	162.93	318.10	253.68
Relative Error	((24) − (28))/(24)	(31)	−2.31	−2.70	−2.21	−0.90	−0.97	−0.47
Mean relative error		(32)	−83.98%					
E_{EGBR}	(26) × (4)/1000	(29)	333.29	465.32	47.10	78.19	171.77	253.68
Relative Error	((24) − (29))/(24)	(33)	−0.13	−1.15	−0.41	0.09	−0.06	−0.47
Mean relative error		(34)	−36.24%					
$E_{EGBMSNR}$	(27) × (4) × (7)/1000	(30)	113.32	269.89	20.72	37.53	92.76	253.68
Relative Error	((24) − (30))/(24)	(35)	0.62	−0.25	0.38	0.56	0.43	−0.47
Mean relative error		(36)	−50.01%					

Table 8. ID (31) is the relative error for each CS referring to EBR, and (32) is their mean relative error. ID (33) is the relative error referring to EGBR, and (34) is their mean relative error. ID (35) is the relative error referring to EGBMSNR, and (36) is their mean relative error.

Calculation Methodology	ID	CS7	CS8	CS9	CS10	CS11	CS12	CS13
(16) + (19)	(24)	193.56	356.36	323.03	520.44	194.85	1786.06	2385.28
(25) × (2)/1000	(28)	454.86	513.84	480.70	489.61	313.46	565.63	509.16
((24) − (28))/(24)	(31)	−1.35	−0.44	−0.49	0.06	−0.61	0.68	0.79
Mean Relative Error	(32)	−83.98%						
(26) × (4)/1000	(29)	282.01	606.33	384.56	705.03	401.23	1,790.46	1956.24
((24) − (29))/(24)	(33)	−0.46	−0.70	−0.19	−0.35	−1.06	0.00	0.18
Mean Relative Error	(34)	−36.24%						
(27) × (4) × (7)/1000	(30)	174.85	715.47	307.65	1015.25	513.57	5667.60	7515.99
((24) − (30))/(24)	(35)	0.10	−1.01	0.05	−0.95	−1.64	−2.17	−2.15
Mean Relative Error	(36)	−50.01%						

4. Discussion

Peri-urban districts with multifamily buildings only represent a small share of available urban forms. Consequently, the presented methodology should be applied to other district typologies to identify specific EGBRs for each urban form more than this. EGBRs should then be compared to find possible relations. It cannot be excluded that EGBR could be a cross-functional parameter to be used independently of district typologies. Consequently, it offers a potential for simplifying the energy evaluation process, intersecting urban forms' typological characteristics.

The fact that synthetic parameters overestimate energy addresses further steps of research. Although synthetic parameters can be good tools, their utilization should be evaluated in two ways. The first one is estimating biomass energy potential, accepting a certain approximation, and overestimating district biomass potential. The second is that EGBR, and eventually other synthetic parameters, could be calculated district by district and be referred to as threshold values derived by the model of reference in the evaluation process. Further studies should investigate these complementary strategies, but the methodology of a biomass ratio so defined within a soft computing approach to decision-making for urban biogas systems. Additionally, the district-scale analysis appears to be able to play a pivotal role in meeting the challenges of urban growth and resilience by 2050. As cities expand and face increasing pressures, such as energy demand and waste management, it becomes essential to develop solutions that adapt to changing conditions. By leveraging a synthetic parameter, such as biomass ratio, decision-makers can use simplified data sets, including urban morphology, demographic information, and energy demand patterns, to optimize the design and placement of biogas systems at a district level. This holistic analysis enables the integration of multiple factors, such as energy generation, waste management, and environmental impact, to create resilient and sustainable urban biogas networks and support changing scenario analysis in cities expected to grow in the next decades quickly but with the ambition to be resilient, also taking decision fast and with confidence about the risks to be faced.

Implementing a biomass ratio in soft computing approaches for urban biogas systems has challenges, particularly regarding data collection. The utilization of a biomass ratio as a critical parameter for decision support relies heavily on the availability of specific data and local data: the higher the precision and georeferenced of this data, the higher the adherence of biomass ratio to real district analyzed and the lower the error with traditional methodologies will be. However, obtaining accurate and reliable data on biomass composition, waste generation rates, and energy demands at a district scale can be complex and time-consuming, and the variability in data collection methods and discrepancies in data quality across different sources pose additional challenges. Furthermore, the integration of urban morphology data, GIS data, and 3D scanner data requires coordination and collaboration among various stakeholders, including urban planners, waste management agencies, and energy providers, to ensure data availability and consistency becomes crucial for the successful implementation of soft computing techniques in urban biogas system analysis. Efforts should be made to establish robust data collection protocols, improve data sharing mechanisms, and enhance data interoperability to overcome these challenges and enable accurate and comprehensive analysis for decision-making purposes. Additionally, ongoing monitoring and data validation processes are necessary to ensure the continuous improvement and reliability of the soft computing approach for urban biogas system evaluation.

5. Conclusions

The presented results lead to different conclusions and address further possible steps in this research direction.

Synthetic parameters that connect biomass production and urban districts can be helpful to direct initial considerations for biomass and urban biogas plants. Indeed, without a deep knowledge of the population settled in the community, the biomass ratio can drive the estimation of potential biomass. Moreover, EGBR demonstrates that it is possible to identify indexes for urban biomass estimation. However, it is essential to underline that the only utilization of the biomass ratio for energy calculation is misleading, and its utilization should be restricted to predesign phase of complex urban energy models that consider the "energy" issue as one of the multiple aspects; in-depth studies to quantify the real quantity and quality of biomass is mandatory in the subsequent designing phase to appropriately address affordable strategies and policies and use effectiely settled populations to estimate the potential of bio-waste production precisely.

The approximation of a biomass ratio needs to be evaluated in a more comprehensive predesign tool based on a soft computing approach defining one of the components of a multi-criteria decision matrix, a base for the further multi-criteria decision analysis of a biomass/biogas energy system in urban areas. The final scope of this research is to generate a matrix to test biomass energy system feasibility as part of an all-inclusive estimation process, which includes other components related to social, cultural, technological, and economic aspects, which are complementary parts of the system. In this scenario, a biomass ratio that connects energy potential with the district typology is one of the parameters to be preliminarily considered as part of a multi-disciplinary matrix that evaluates the district under different aspects. The next step should be the evaluation of the biomass ratio in the matrix in relation to other district characteristics.

For this purpose, within a holistic approach deployed by a DST, the utilization of the biomass ratio can be considered a preliminary estimation replicable in different urban morphologies and with different data available. By utilizing more specific and local data surrounding household size, building typology, number of households, and bio-waste generation, the biomass ratio can be more precise to support decision-making. While this paper investigates a peri-urban district, the biomass ratio could be adopted for other urban patterns within the EU's existing and new urban patterns, as well as in extra EU. In particular, considering how biogas and micro/home digester projects are well established in areas such as Asia or Africa [36–38], the utilization of synthetic parameters could support the creation of a more mature urban biogas system, a community of interest enabling better control of energy and environmental results and risks, going beyond the current conventional home digesters.

All these aspects presented in the conclusion pave the way to contribute to several targets outlined in "Sustainable Development Goal 11: Sustainable Cities and Communities" [39]. Here are some targets that urban biogas systems can help fulfill and the reasons behind their contribution:

1. Target 11.2: By 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport. Urban biogas systems can contribute to this target by producing biogas that can be used as a renewable and sustainable fuel for public transportation systems. Biogas can be used as a clean alternative to fossil fuels, reducing greenhouse gas emissions, improving air quality, and promoting sustainable transportation options in urban areas.
2. Target 11.3: By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning and management in all countries. Urban biogas systems can promote sustainable urbanization by effectively managing organic waste within cities. These systems enable the conversion of organic waste, such as food scraps and sewage, into biogas through anaerobic digestion. By diverting organic waste from landfills and utilizing it for energy production, biogas systems contribute to a more sustainable waste management approach and support integrated urban planning for a healthier and cleaner environment.
3. Target 11.6: By 2030, reduce cities' adverse per capita environmental impact by paying particular attention to air quality and municipal and other waste management. Urban biogas systems can play a crucial role in reducing the environmental impact of cities, particularly in terms of waste management and air quality. By diverting organic waste from landfills, biogas systems help reduce methane emissions, a potent greenhouse gas. Additionally, using biogas as a clean fuel source contributes to reducing air pollution, as it produces fewer harmful emissions than traditional fossil fuels. This contributes to improved air quality and reduces the adverse environmental impact of urban areas.
4. Target 11.a: Support positive economic, social, and environmental links between urban, peri-urban, and rural areas by strengthening national and regional development planning. Urban biogas systems can foster positive links between urban and rural areas by creating opportunities for the sustainable utilization of agricultural and organic waste generated in rural regions. Biogas production from agricultural residues and animal manure can provide an additional source of income for rural communities. Furthermore, transporting biogas or the by-products, such as biofertilizers, from rural to urban areas can promote regional development and strengthen economic, social, and environmental connections.

Overall, urban biogas systems align with Sustainable Development Goal 11 by addressing waste management, promoting sustainable transportation, improving air quality, and fostering linkages between urban and rural areas. By embracing these systems, cities can move closer to achieving a more sustainable and inclusive future.

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