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MULTICRITERIA MODEL OF OPTIMAL EXPLOITATION OF THE BIOMASSES BASED ON DIFFERENT DEVELOPMENT SCENARIOS

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MODELLO MULTICRITERIA PER L'OTTIMO SFRUTTAMENTO DELLE BIOMASSE IN BASE A DIVERSI SCENARI DI SFRUTTAMENTO

Coordinatore: Ch.mo Prof. Marco Borga
Supervisore: Ch.mo Prof. Andrea Pezzuolo
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Try and leave this world a little better than you found it and when your turn comes to die, you can die happy in feeling that at any rate you have not wasted your time but have done your best.

(Last message, Baden-Powell)

Acknowledgements

At the end of this intense study period, I became convinced that I would not have been able to accomplish this path on my strength alone.

First and foremost, I would like to thank my supervisors, Andrea Pezzuolo and Francesco Marinello, who allowed me to embark on this path and have accompanied me during these three years. Thanks to their advice, guidance, and criticism, I had the opportunity to learn and mature a lot, acquiring new skills and confidence in my possibilities. A warm thank you goes to all the colleagues and friends who helped me over these years, sharing their experiences. In particular, I would like to thank Marco and Eugenio, who have never failed to listen to and support me.

Finally, I would like to thank all my family, who never let me lack moral support and sincere encouragement. Thank you, mom, and thank you, Gioia.

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Abstract

Bioenergy represents one of the critical sectors for building a sustainable energy system. In particular, one of the most critical aspects of energy production of any kind is the location of plants and their inclusion within the industrial and social fabric. Local and national governments are faced with making decisions that are often difficult, affected by many factors and with significant consequences for many people and environments. To determine the optimal location of plants, it is essential to apply effective decision-making processes in which technical decisions are used with a scientific method, considering the wishes of the stakeholders and environmental needs. In the bioenergy field, the traditional system of the farm plant, fueled by the biomass produced internally by the firm, must be complemented, and in some cases replaced, by district plants, appropriately located with the agreement of local administrations and citizens. In this thesis, a study is presented for the optimal location of biogas and biomethane plants, aiming to maximize the use of biomass and reduce the impact on the territory. The main objective of this thesis is to provide an adequate and comprehensive and, at least in theory, replicable methodology for choosing a site where to install a plant. This goal was achieved in three steps. First, the bioenergy potential of the area was calculated, analyzing the geographical and production context and the chemical and physical characteristics of biomass. Next, economic, environmental and social factors related to biomass exploitation and their impact on the benefits and problems associated with bio-resource exploitation were studied. Finally, the optimal location of facilities to maximize environmental, social and economic benefits was determined. The different reviewed scenarios prove the importance of careful spatial analysis and close dialogue with local stakeholders to establish the investigation and identify priorities to be pursued. Future studies could apply the findings of this thesis to other forms of renewable energy, serving private citizens, entrepreneurs and public institutions in building a sustainable energy system.

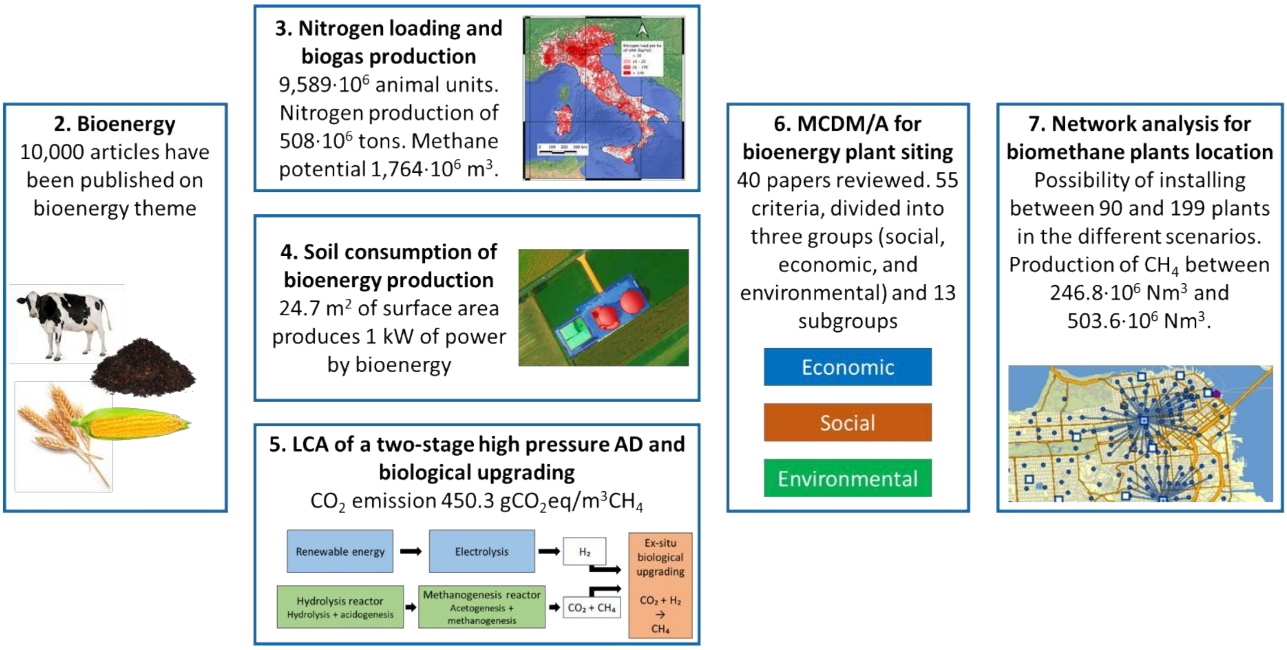
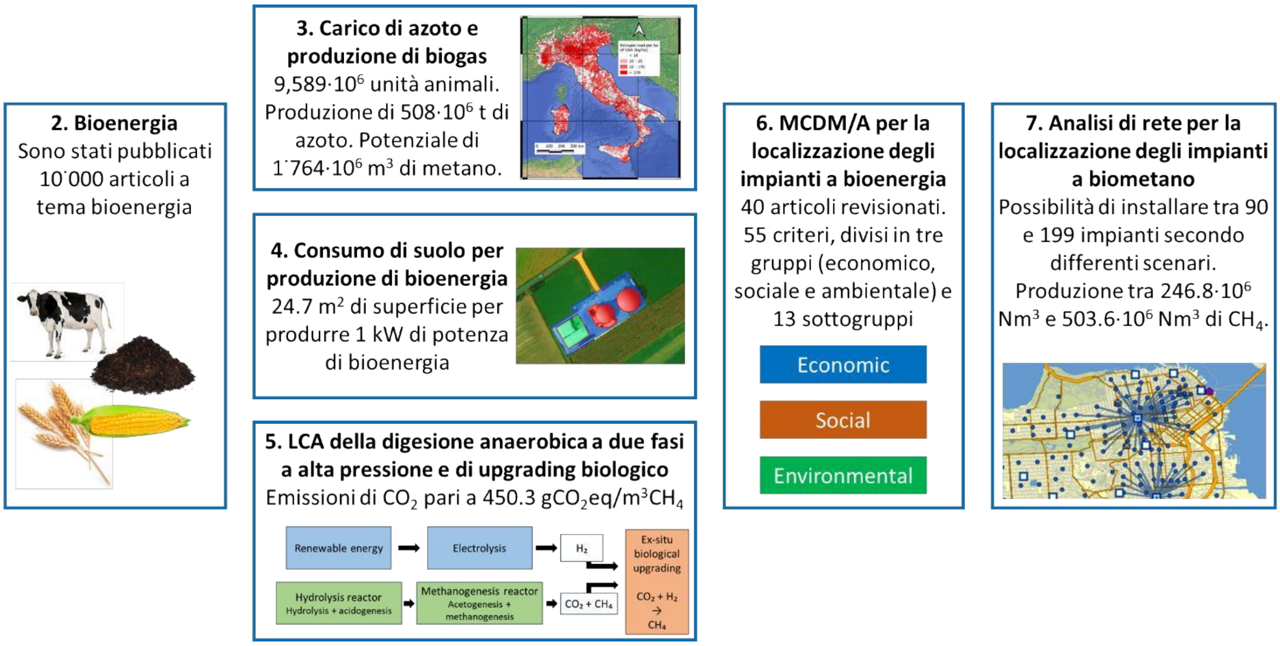


Figure 0-1 Graphical abstract of the thesis. Each box represents an article published and included in the thesis. The boxes are numbered following the numbering of the chapters to which the articles correspond.

Riassunto

La bioenergia rappresenta uno dei settori chiave per la costruzione di un sistema energetico sostenibile. In particolare, uno degli aspetti più critici della produzione di energia, di qualunque tipo, è la localizzazione degli impianti e il loro inserimento all'interno del tessuto produttivo e sociale. Le amministrazioni locali e nazionali si trovano a dover prendere decisioni spesso difficili, condizionate da molti fattori e con notevoli conseguenze su molte persone e ambienti. Per determinare l'ottima localizzazione degli impianti è fondamentale applicare processi decisionali efficaci, in cui le decisioni tecniche siano applicate con metodo scientifico, tenendo conto delle volontà degli attori coinvolti e delle esigenze ambientali. In campo bioenergetico, il tradizionale sistema dell'impianto aziendale, alimentato dalle biomasse prodotte internamente all'azienda, deve essere affiancato, e in alcuni casi sostituito, da impianti consortili, opportunamente localizzati con l'accordo delle amministrazioni locali e dei cittadini. In questa tesi viene presentato uno studio per l'ottima localizzazione degli impianti a biogas e biometano, in modo da sfruttare al massimo le biomasse e ridurre l'impatto sul territorio. L'obiettivo principale di questa tesi è fornire una metodologia adeguata e completa e, almeno in teoria, replicabile per la scelta del sito dove installare un impianto. Questo scopo è stato raggiunto in tre fasi. In un primo momento è stato calcolato il potenziale bioenergetico del territorio, analizzando il contesto geografico e produttivo e le caratteristiche chimico-fisiche delle biomasse. Successivamente sono stati studiati i fattori economici, ambientali e sociali correlati allo sfruttamento delle biomasse e il loro impatto sui benefici e i problemi correlati allo sfruttamento delle bio-risorse. Infine è stato determinata l'ottima localizzazione delle biomasse per massimizzare i benefici ambientali, sociali e economici. I diversi scenari studiati provano l'importanza di un'attenta analisi territoriale e uno stretto dialogo con gli stakeholder locali per impostare l'analisi e identificare le priorità da perseguire. Studi futuri potrebbero applicare le conclusioni di questa tesi a altre forme di energia rinnovabile, ponendosi al servizio di privati e istituzioni pubbliche nella costruzione di un sistema energetico sostenibile.



2. Bioenergia
Sono stati pubblicati 10˙000 articoli a tema bioenergia

3. Carico di azoto e produzione di biogas
9,589·10^6 unità animali. Produzione di 508·10^6 t di azoto. Potenziale di 1˙764·10^6 m^3 di metano.

4. Consumo di suolo per produzione di bioenergia
24.7 m^2 di superficie per produrre 1 kW di potenza di bioenergia

5. LCA della digestione anaerobica a due fasi a alta pressione e di upgrading biologico
Emissioni di CO_2 pari a 450.3 gCO_2eq/m^3CH_4

6. MCDM/A per la localizzazione degli impianti a bioenergia
40 articoli revisionati. 55 criteri, divisi in tre gruppi (economico, sociale e ambientale) e 13 sottogruppi

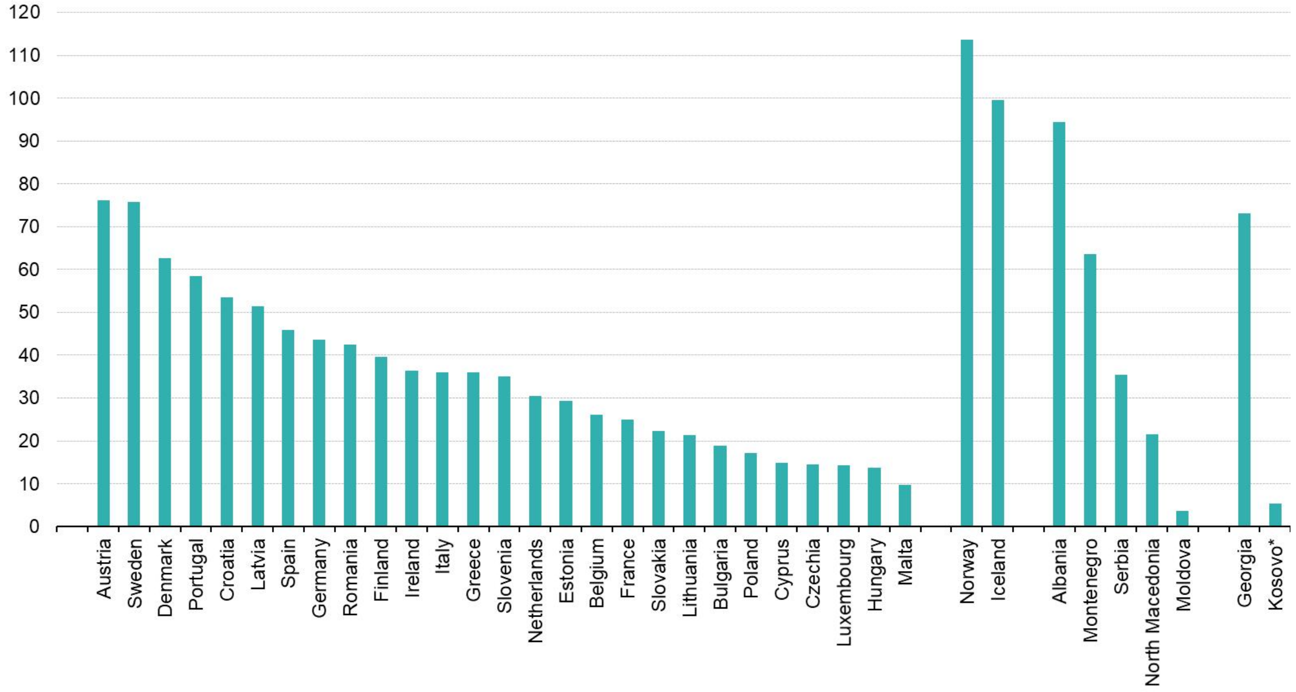
7. Analisi di rete per la localizzazione degli impianti a biometano
Possibilità di installare tra 90 e 199 impianti secondo differenti scenari. Produzione tra 246.8·10^6 Nm^3 e 503.6·10^6 Nm^3 di CH_4.

Figure 0-1. Riassunto grafico della tesi. Ogni riquadro rappresenta un articolo pubblicato e inserito nella tesi. I riquadri sono numerati seguendo la numerazione dei capitoli a cui corrispondono gli articoli.

1 Introduction

1.1 Background

Protecting the environment and finding a balance between human activities and the availability of natural resources has become increasingly important in people's awareness. An increasing number of people perceive climate change as an issue that directly affects them. This awareness leads to the greater direct involvement of citizens, who are increasingly inclined to adopt environmentally sustainable behaviors aimed at reducing greenhouse gas emissions and limiting the consumption of natural resources. However, such virtuous behaviors are not limited to the private sphere; the call for greater attention to sustainability and environmental protection are now part of the political agenda of all national and international institutions.



** This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence.*

Source: Eurostat (online data code: nrg_ind_ren)

Figure 1-1. Share of energy from renewable sources in gross electricity consumption, 2021

In recent years, many national and international institutions have set very ambitious goals regarding environmental preservation and sustainable development (United Nations, 2015). Therefore, many public and private administrations have invested considerable resources in developing renewable energy (Moriarty and Honnery, 2016). The Renewable Energy Directive set targets for EU member states to achieve 32% energy production from renewable sources by 2030 (European Parliament, 2018). This value was further raised to 40% (European Parliament, 2021), and a goal of reaching complete climate neutrality by 2050 was added (European Commission, 2021). A specific renewable energy share of 14% has been set for the transport sector, and in particular, a 2.2% share of the total is reserved for biofuels. As a result, 11.9 GWe of electricity from biogas was installed in the EU in 2020, with a total production of 55.8 TWhe of energy. The countries with the largest biogas electricity production are: Germany, 33.495 GWh; Italy, 8166 GWh; France, 2734 GWh; Czechia, 2596 GWh; Poland, 1233 GWh (Eurostat, 2022).

Renewable energy production requires questioning classical power generation and distribution systems based on large generating plants and high- and extra-high-voltage electric transmission lines. A renewable energy-based system must consider power plants with random production (photovoltaic panels and wind farms) and a medium- and low-voltage distribution network, which needs an intelligent grid that can handle peaks and troughs in production. To meet this need, many governments are focusing on smart grids, i.e., the combination of an information network and an electric distribution network, such that "smart" grid management can be achieved, realizing more efficient management and more rational use of energy. The system involves large distributed generation, including small-scale generation, located at the peripheral nodes of the grid, which is designed with a mesh pattern, unlike traditional grids that generally have a tree pattern.

Therefore, a smart grid is equipped with an intelligent management and communication system to manage energy flow reversals between peripheral nodes distributed throughout the territory. In addition, since renewable sources are not programmable, distributed generation requires greater intelligence in managing surplus energy, redistributing it to contiguous areas where deficits may occur, operating appropriate storage systems, or constantly adjusting generation.

The smart grid is not a single grid but a collection of grids that connect different energy producers. Italy was the first nation in the world to have a nationwide smart grid in 2006: the first working smart grid network was implemented through simulations in limited areas by Enel, such as, for example, the European Grid4eu project.

Italy has adopted and increased European targets in the National Energy Strategy (MISE and MATTM, 2017):

- Electricity from renewable sources to 55% by 2030, compared to 33.5% in 2015,
- Thermal energy from renewable sources to 30% by 2030, compared to 19.2% in 2015,
- Renewable energy in the transportation sector at 21%, compared to 6.4% in 2015

To achieve these goals, Italy has identified biomethane as one of the key sectors. Italy is currently one of the European countries that has placed the most emphasis on developing biomethane production. Since 2008, biogas production has been directed mainly to electricity production; by 2021, 2010 biogas plants were working in Italy (GSE, 2021). This situation led to a lack of attention to biomethane, so that by 2017, only one plant was operating in the country. The situation has radically changed with the entry into force of the Biomethane Decree: from 2017 to 2021, 26 new plants came into operation, with a total theoretical production capacity of $220 \cdot 10^6$ Nm^3 of biomethane (AssogasMetano, 2021). One of the most important innovations introduced by the decree concerns the diet of the plants; only livestock by-products, second-crop crops, agricultural by-products, and organic fraction of municipal solid waste can be used. The goal is to discourage the use of energy crops to protect food production. Recent studies have shown the effectiveness of the incentives introduced with the Biomethane Decree to make investments in upgrading technologies profitable for existing plants (Barbera et al., 2019).

In agriculture, livestock and agricultural by-products enable the development of a profitable and sustainable bioenergy system. These biomasses make it possible to reduce costs and produce additional earnings, with significantly less environmental impact than energy crops. In this way, it is possible to target advanced biofuels, particularly biomethane. As a result, CO_2 emissions into the atmosphere can be limited, by using biofuels instead of traditional fuels derived from fossil sources, with significant social and environmental benefits. However, these biomasses have a very dispersed and uneven distribution over the territory, resulting in high transportation costs. For this reason, careful spatial analysis is needed to optimize the entire supply chain.

Spatial analysis involving biomass distribution and land features is necessary to optimize biomass utilization. However, focusing the attention of the study only on biomass is not enough; it is essential to consider the conditions and ease of harvesting, the situation in which it is found (dispersed, such as grass, or concentrated, such as livestock manure), and the seasonality of production. In addition, analysis of the road network reduces transport distances; this is particularly significant when dealing with highly dispersed biomass, such as agricultural by-products, or with plants supplied by different operators (Schnorf et al., 2021). All these factors are decisive in choosing the location of a biomass plant.

The location of bioenergy plants impacts local communities in various ways; therefore, less densely populated areas are preferred to minimize the influence on local communities and avoid adverse NYMBI effects (Batel et al., 2013). At the same time, the involvement of local people allows citizens to be included in the decision-making process, explaining the positive effects of these facilities and identifying shared choices (Walker and Devine-Wright, 2008). This dialogue is critical in developing renewable energy, as the paradigm of significant fossil fuel thermoelectric plants is changed to diffuse generation, in which local communities constitute energy communities. From this perspective, integrating bioenergy with other forms of renewable energy is valuable and indispensable.

Bioenergy production can be adjusted according to market demands by balancing the deficit or excess of other renewables (Rossi and Hinrichs, 2011); thus, it reduces the influence of meteorological factors that determine solar and wind energy production (Szarka et al., 2013). In addition, some research institutes and private companies are trying to achieve integration among the various forms of renewable energy by using bioenergy as a storage system. It is possible to use the excess electricity produced by photovoltaic and wind power plants to produce hydrogen (Lecker et al., 2017). This hydrogen can be used in biogas upgrading plants to produce methane. With the technique of biological upgrading, it is possible to combine hydrogen with carbon dioxide present in biogas, according to Sabatier's reaction (Lecker et al., 2017). In this way, it is possible to obtain a gas similar to methane that can be fed into the grid or stored in liquid or gaseous form and used as needed (Ferrari et al., 2022b).

Interest in biomethane is based on numerous studies that have shown its importance in achieving emissions neutrality of the energy system as of 2050 (Brémond et al., 2021). Currently, most biogas production is used for combustion to produce electricity, often in combination with the utilization of the related heat generated (Balussou et al., 2018). This process works with relatively low efficiency, about 35%, thus nullifying much of the potential of this resource (Nock et al., 2014). Biomethane production makes it possible to overcome this limitation, which is why many national and international institutions are encouraging its production (Brémond et al., 2021): as a result, biomethane plants in the EU have increased from 305 in 2015 (Scarlat et al., 2018) to 994 in 2022 (AssogasMetano, 2021). This gas is fully comparable with fossil methane and, therefore, suitable for use as a vehicle fuel or to be injected into the natural gas distribution network. However, biomethane production is a complex process, requiring resource analysis and careful design of production centers (Baccioli et al., 2018). The study of the facilities' location and size must consider different financial and environmental costs. Installed power must ensure efficient and sustainable use of resources with environmentally compatible land consumption. The decision-making process must start with identifying and describing these needs and all the factors that determine them.

Based on all these factors, the decision must select one or more options from various alternatives. Multicriteria Decision Models/Analysis (MCDM/A) is expected to solve these decision-making processes. These models allow solving multi-objective problems by aggregating different ratings for different parameters and then ranking the alternatives in order of preference. Among these systems, the AHP is one of the most widely used in agronomic and environmental fields (Ferrari et al., 2022a) and is also the most commonly used for locating biomass plants. This thesis presents a study for plant location; criteria for site selection were developed by surveying experts in the field and then identified with a multicriteria analysis model. The biomass distribution model was created using network analysis tools in a GIS environment.

1.2 Research questions and objectives

Sustainable development and renewable energy production are gaining increasing importance in the policies of many institutions and administrations. In this context, the active cooperation of citizens is an indispensable factor in the success of these policies.

Citizen participation and integrating energy policies with environmental protection and economic development facilitates the implementation of projects and increases community benefits.

For this reason, many studies have examined the consequences of energy policies and come up with many development scenarios to identify the key factors and criteria that lead to the success of such decision-making processes.

The central questions of the study, identified as fundamental to the research project, are:

- What methods can be adopted to evaluate and quantify bio-resources, with a focus on agro-livestock by-products?
- What are the benefits and costs related to the exploitation of agricultural and livestock by-products?
- How can energy production facilities be integrated to maximize benefits while reducing social and environmental impacts?

The overall objective of this study is **to study each step in the chain leading from the production of by-products to their valorization as energy, bio-fuels and biomaterials, and to optimize the process with the use of mathematical software tools**.

The following specific objectives have been identified to achieve the aim of the study:

- To map available resources and define specific evaluation indices to be implemented for drawing possible agro energy districts scenarios
- To study economic and environmental factors related to the exploitation of biomasses and their impact on benefits and problems associated with the exploitation of bio-resources
- To determine the optimal location of biomass plants to maximize environmental, social, and economic benefits.

A comprehensive analysis of the topic allows for a replicable methodology that can be easily applied to different contexts: other study areas and other renewable energy plants. In addition, this study provides important conclusions for engineers and policymakers involved in the technical-decisional process of defining the energy system.

1.3 Explanation of the thesis format

The objectives and the themes presented in the introduction result from research work and analysis of the scientific literature that has demonstrated the growing interest in bioenergy in recent years. Based on the results of this review work, it was decided to develop the doctoral work on three key concepts:

Energy: Study of energy systems and renewable energy production.

Land: Land modeling, including natural and anthropogenic features.

Resources: Calculating biomass potential, distribution over the territory, and consequences of their use.

The first theme includes studying energy systems from both technical and management perspectives. Although this Ph.D. is focused on biomass energy, it has already been extensively explained that integration among various forms of renewable energy is imperative. Therefore, how bioenergy can also be harnessed in relation to other forms of renewable energy has been explored. Furthermore, bioenergy production also involves the consumption of natural resources; one specific aspect in this doctoral program has been studied: land consumption due to the construction of the plants and associated facilities.

The second theme deals with the effects on the territory of biomass exploitation. The land is intended in both geographical-spatial and economic-environmental senses. Land consumption due to plant construction results in the loss of arable land. In addition, among the adverse effects, soil sealing, due to the construction of structures and yards, should not be forgotten; this phenomenon, on a large scale, leads to a decrease in the water absorption capacity of the soil and an increase in hydrogeological risk, due to sudden and extreme rain events (Cogato et al., 2019). Bioenergy production also has significant economic and environmental protection consequences. Anaerobic digestion allows obtaining a product, digestate, useful as a fertilizer and with a more stable nitrogen component than that contained in the starting biomass. Significant benefits are realized in nitrate-vulnerable areas, where control of nitrogen application to the field is substantial.

The last important issue is available resources, that is, usable biomass. First, the study of biomass concerns the calculation of available quantities and their distribution over the territory. Numerous researchers have studied the potential of agricultural biomass to obtain solid and reliable values of the energy potential of livestock manure and agricultural by-products. The data available from public registries make it possible to define biomass distribution over the territory. Once the available biomasses have been determined, it is necessary to decide on the best process and method for their use. This doctoral course has considered anaerobic digestion, but even this process can be accomplished with different technologies. It is necessary to determine the environmental impacts of these technologies and compare the results.

Based on the three key concepts, the studies were developed to respond to the final objectives of the project. First, the criteria that determine the suitability of a site to host a biomass plant were studied and defined. Then the criteria reviewed were applied to a real case, and through a specific methodology, a plan was proposed for the optimal location of biogas and biomethane plants in the Veneto Region.

The structure of the research is represented graphically in Figure 1-1.

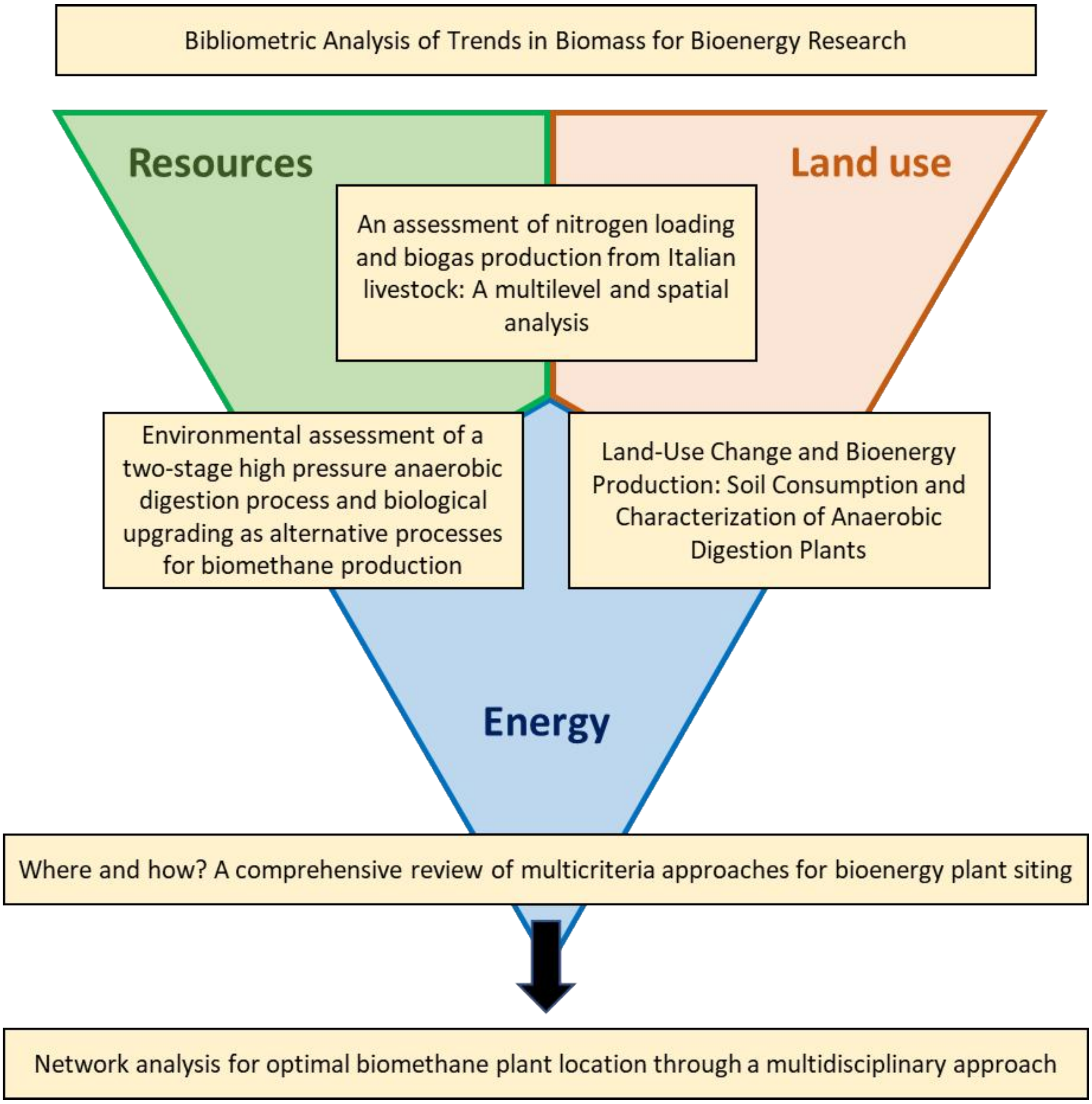


Figure 1-2. Structure of the thesis with the three key-concepts. The titles of the articles are reported in the boxes

The thesis is organized into seven chapters. Six of these chapters are the main articles published during the doctoral period.

Chapter 2 is the starting point of the research project. The work began with a review of the scientific literature on bioenergy to define the areas of interest. The goal was to identify the main topics on which research had been directed to determine possible future developments. The contents of approximately 10,000 articles published on the Scopus database were analyzed through a meta-analysis. The review, published in the journal Energies, showed that interest in bioenergy had grown recently. Moreover, within this theme, some topics emerged where research had directed less interest, notably "Environment" and "Field," the latter understood as biomass production sites. The review generated and directed subsequent research work.

Chapters 3, 4, and 5 include the papers with research in the three key areas identified. All three papers cut across the three themes, demonstrating the importance of an organic approach to the subject to seek connections between different fields.

Chapter 3 concludes a work cycle aimed at quantifying and spatial identification of biomass. The first two papers, not reported in this thesis, were:

"Valorization of agricultural by-products in different agro-energy districts: a case study in northeast Italy," presented at the EUBCE 2020 conference, scheduled in Marseille (F) but then held online due to the Covid-19 pandemic.

"A comparison of performance indices of biogas plant feedstock," presented at the Venice 2020 conference; the conference was conducted online due to the health emergency.

In the first conference, biomass available for energy use was estimated. Agricultural by-products and livestock manure were considered. In the second one, the diets of biogas plants in the Veneto Region were analyzed based on data provided by the regional agency in charge. Performance indices of feedstock supply systems based on source diversification were proposed.

The analysis of resource distribution was extended to the national level in the article reported in Chapter 3, considering cattle, pig, and poultry manure. A description of the Italian livestock system is provided; in addition, the distributions of livestock manure were compared with the map of nitrogen-vulnerable zones. The article was published in the Journal of Cleaner Production. The analysis considered 9,589 million animal units (AU) and indicated an overall nitrogen production of 508 $\times 10^6$tons, while the methane potential can reach 1,764 $\times 10^6 m^3$, equal to 6.1% of the national electric energy consumption. To organize the effective collection and treatment of effluents, their spatial distribution was investigated using spatial statistical tools: Moran's index and local indicator of spatial association (LISA). The results demonstrated the robustness of these instruments in evaluating the presence of nitrogen/biogas production clusters and the possibility of combining the treatment of nitrogen and the production of biogas from animal effluents.

The article that constitutes Chapter 4 is a study regarding the land consumption of biogas plants currently working in Italy. Through satellite observation, the areas occupied by the plants were measured, discriminating among the various components: digester, storage, roads, and other structures. The biogas plants analysis proved that 24.7 m^2 of surface area produces 1 kW of power by bioenergy. The obtained model estimated a total soil consumption by biogas plants in Italy of 31,761,235 m^2. This research can support stakeholders in cost-benefit analyses to design energy systems based on renewable energy sources. Land consumption was the first environmental impact due to bioenergy studied in detail in the PhD course. The work was published in the Open Access journal Energies.

Chapter 5 addresses a second and equally important environmental impact of anaerobic digestion: carbon dioxide and methane emissions due to biogas production and subsequent upgrading to biomethane. The LCA of three alternative processes for biomethane production was carried out to address this topic. This work was carried out in Germany, at the University of Hohenheim, as part of the ProBioLNG project. The two primary agricultural bioenergy resources in Germany were analyzed: cattle manure and sugar beet. The study demonstrated the importance of both biomethane in increasing system efficiency and using waste materials over energy crops to limit CO_2 emissions. This work was published in the journal Bioresource Technology.

Once the key topics were defined and the necessary data were collected, it was possible to develop the methodology and arrive at the desired results.

Chapters 6 and 7 describe the final phase of the project. Chapter 6 includes the review conducted to establish the essential criteria for plant locations. Based on a literature review, it was possible to associate the characteristics of the area and production system with the fundamental criteria chosen for plant location. In total, 40 papers were reviewed, studying i) the adopted criteria and multicriteria decision model/analysis and ii) the environmental and social conditions that influence this type of analysis. In the final and concluding work, this relationship was reported in our specific case, the Veneto Region.

Chapter 7 reports the conclusion of the project. A multicriteria analysis is introduced for the optimal location of biomass plants in a region of Northern Italy. First, to establish the optimal location of the plants, the Multi Criteria Analysis Model AHP, Analytic Hierarchic Process, was applied. Then, the Network Analysis tool, available on ArcGIS, was used to define biomass distribution. The results showed the possibility of installing between 90 and 199 plants in the different scenarios, resulting in a biomethane production between $246.8 \cdot 10^6$ Nm^3 and $503.6 \cdot 10^6$ Nm^3. Both of these two papers were published in the Journal of Cleaner Production.

2 Bibliometric Analysis of Trends in Biomass for Bioenergy Research

2.1 Abstract

This paper aims to provide a bibliometric analysis of publication trends on the themes of biomass and bioenergy worldwide. A wide range of studies have been performed in the field of the usage of biomass for energy production, in order to contribute to the green transition from fossil fuels to renewable energies. Over the past 20 years (from 2000 to 2019), approximately 10,000 articles have been published in the “Agricultural and Biological Sciences” field on this theme, covering all stages of production—from the harvesting of crops to the particular type of energy produced. Articles were obtained from the SCOPUS database and examined with a text mining tool in order to analyze publication trends over the last two decades. Publications per year in the bioenergy theme have grown from 91 in 2000 to 773 in 2019. In particular the analyses showed how environmental aspects have increased their importance (from 7.3% to 11.8%), along with studies related to crop conditions (from 10.4% to 18.6%). Regarding the use of energy produced, growing trends were recognized for the impact of biofuels (mentions moved from 0.14 times per article in 2000 to 0.38 in 2019) and biogases (from 0.14 to 0.42 mentions). Environmental objectives have guided the interest of researchers, encouraging studies on biomass sources and the optimal use of the energy produced. This analysis aims to describe the research evolution, providing an analysis that can be helpful to predict future scenarios and participation among stakeholders in the sector.

Keywords: renewable energy; bioenergy scenario; biomasses; systematic review

2.2 Introduction

Bioenergy is renewable energy derived from the treatment of several types of organic sources, which are generically named biomass (Appels et al., 2011; Nizami and Ismail, 2013). Biomass is biological material derived, either directly or indirectly, from the transformation of solar energy into chemical energy (Amon et al., 2007). It may be constituted of wood, forestry waste, crop residues, manure, urban waste, food industry residues, and the many by-products of agricultural processes (Chiumenti et al., 2018; Dinuccio et al., 2010; Mattioli et al., 2017; Nizami et al., 2012). International organizations and national governments are increasingly committed to pursuing environmental sustainability policies, setting even more ambitious targets for reducing pollution and the impact of human activities (Theuerl et al., 2019; Visser et al., 2020). The production of bioenergy obtained from natural and agro-industrial sources represents one of the most critical points of this path (Chiumenti et al., 2019).

The European Union (EU) has included, in their Sustainable Development Goals (SDGs), “… 7. Affordable and clean energy…”; specifying as indicator “… 7.2.1 Renewable energy share in the total final energy consumption…” and “… 7.a.1 International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems…" (United Nations, 2015). The EU, in the "Renewable Energy Regulation", has established the goal of 32% of energy production from renewable sources by 2030 and reducing greenhouse gas emissions by 40% compared to 1990 (European Parliament, 2018).

In 2016, bioenergy is the most significant renewable energy source globally, covering 70% of the energy production by renewable sources. In every continent, biomass is the most important renewable energy source; it accounted for 40% of the energy in Oceania and almost 96% in Africa (World Bioenergy Association, 2018). Biopower (or electricity from biomass) is the third largest renewable electricity generation source, with a share of 571 TWh of electricity produced. Asia is the leader in the sector, with a share of almost 40% of electricity from biomass produced (World Bioenergy Association, 2018). In the transport sector, the primary renewable sources are liquid biofuels. From 2000 to 2017, biofuel production registered a significant growth: From 16 to 143 billion L. The 86% of the production of biofuel and bioethanol is concentrated in the U.S. and Brazil, with a production share of 87% (World Bioenergy Association, 2018). Biofuels could help reduce greenhouse gases and many countries have set targets for the production and use of these resources. Ahorsu et al. (Ahorsu et al., 2018) discussed the relevance of biomass for different generations of biofuels, also showing the main bioethanol producers: USA, Brazil, Europe, China, and Canada.

The widespread use of biomass determines numerous research areas for each phase of the energy supply chain: Biomass production, transport (Delivand et al., 2015; Shu et al., 2017), treatments and digestion (Valenti et al., 2018), energy production (Solarte-Toro et al., 2018) and distribution (Weinand et al., 2019), and plant planning and management (Resch et al., 2014; Valenti et al., 2018), as well as the social, economic (Patrizio et al., 2015), and environmental (Mirkouei et al., 2017) impacts that the use of biomass implies. Many review articles have been written from 2016 to 2019 to gather the periodical progress in the topic and identify possible future goals in the research. Long et al. (Long et al., 2013) reviewed the results of previous studies that had investigated biomass resources and the estimation of their bioenergy potential, finding values of energy potential for 2050 between 96 and 161 EJ. Ferrarini et al. (Ferrarini et al., 2017) assessed the potential impact of bioenergy buffers, linear areas placed around cultivated fields and watercourses with perennial herbaceous crops or wood biomass, and the biomass supply chain on ecosystem services. Pulighe et al. (Pulighe et al., 2019) studied the exploitation of marginal lands in the Mediterranean area as lands to cultivate energy crops. Authors examined the environmental impact of crops in order to assess the ecological costs of cultivations: Mekonnen et al. (Mekonnen and Hoekstra, 2011) quantified the consumption of green, blue, and gray water of global crop production for the period 1996–2005.

The research has revealed that the long-term exploitation of bioenergy buffers on previous croplands is more advisable than on grasslands, in order to sustains the long-term provision of multiple ecosystem services: climate, water quality, biodiversity regulation, and soil health. Qadir et al. (Qadir et al., 2014) presented a series of case studies to show the potential economic and environmental benefits of restoration of salt-affected lands. These areas can be dedicated to food production with particular crops, or to bioenergy crops. Kluts et al. (Kluts et al., 2017) reviewed European land studies on bioenergetic potentials and suggested that a more comprehensive approach, combining energy crop production with land demand for food/feed, is necessary for the identification of sustainable courses for European bioenergy production requires a more integrative approach, combining land demand for food, feed, and energy crop production. Kuhmaier et al. (Kühmaier and Erber, 2018) reviewed the research trends regarding the comminution and transport of forest biomass in Europe. According to their review, future research should be focused on customizing the product quality, taking into consideration the user's requirements and on developing simulation and automatization tool for the co-ordination of chippers and trucks by simulation and automatization tools. Ba et al. (Ba et al., 2016) focused the attention on the Operations Research perspective studying recent research on models for biomass supply chains models and underlined the importance of multi-disciplinary research teams with the contribution of industrial engineering departments. Pari et al. (Pari et al., 2017) studied the harvesting technologies available in Europe to manage and take advantage of pruning. These residues could power approximately 200–500 kW electric power plants, with an annual output of 0.8 TWh. Garcia et al. (Garcia et al., 2019) evaluated the biomethane potential and the chemical characteristics of a large number of organic biomasses obtained in the agro-industrial sector. Balussou et al. (Balussou et al., 2018) analyzed possible future developments of the German biogas plant capacity up to 2030, taking into consideration technical, economic, and normative conditions, underlining how this sector is strictly connected to political choices. The model results show rapid growth of small-scale manure plants and large-scale bio-waste plants in the German biogas market. Scarlat et al. (Scarlat et al., 2018a) studied the biogas market in Europe (in particular, biofuels), analyzing production and consumption trends. Subsequently, they examined a model on a European scale to quantify the biomass potential deriving from livestock activities and the relative optimal location of the exploitation plants (Scarlat et al., 2018). The theoretical biogas potential of manure was estimated, according to the analysis, at 26 billion m^3 biomethane, while the realistic biogas potential, counting on collectable manure, was assessed at 18 billion m^3 biomethane in Europe. These values are compatible with the construction of 13,866–19,482 new biogas plants could be built in Europe, with a total installed capacity between 6144 and 7145 MWe, and with an average capacity between 315 and 515 kWe. Seay et al. (Seay and Badurdeen, 2014) reviewed the latest research in the supply-chain, process simulation, discrete event simulation and risk assessment into a sustainable point of view for integrated biorefining. Manfren et al. (Manfren et al., 2011) presented a selection of currently available systems for the planning and design of distributed generation, and analyzed them together their opportunities in an optimization framework; they determined the optimal solutions for providing energy services through distributed generation by adopting a multicriteria perspective. Particular attention should be given to fuel consumption due to biomass transport: Ruiz et al. (Ruiz et al., 2013) quantified that the maximum cost of logistics is 11.05 € per ton. An analysis of the Italian situation of biogas plants was presented by Benato and Macor (Benato and Macor, 2019); they investigated the construction and operation management costs of six plants and measured the composition of the emissions produced.

Preliminary models which are able to perform the described procedure have been implemented and are currently being tested. McCormick et al. (Mccormick and Kautto, 2013) presented an overview of the bioeconomy and bioenergy, examining it from a political point of view. They focused on two important topics: the involvement of communities and stakeholders in the decisional process and huge attention by the government and industry to innovation, in order to achieve sustainable development of the bioeconomy. Bioenergy research is inter-disciplinary, with connections in many different areas. Indeed, the published articles affect specific sectors in many journals. The various and numerous publications in the sector require a systematic and updated bibliographic review, which is the focus of this study.

Due to the vastness and the importance of the topic, the analysis was carried out using a quantitative method based on text mining techniques, following the guidelines presented by Cogato et al. (Cogato et al., 2019): (i) Inter-disciplinary, studying the topic from a general point of view; (ii) clearly communicating the state-of-the-art and the research gaps; and (iii) supporting the study and work of the researchers and stakeholders. The use of bibliometric analysis to describe publications trends is widespread also in the bioenergy sector: Weindand (Weinand, 2020) described the evolution of the research in local planning of energy system between 1991 and 2019 by analyzing 1235 articles; De La Cruz-Lovera (De La Cruz-Lovera et al., 2019) focused attention on the contribution of international institutions in the area of energy saving, analyzing 20,095 articles on the Scopus database from 1939 to 2018. The aim of the present analysis is to provide a comprehensive review of the state-of-the-art of the literature concerning bioenergy in Agriculture and Biological Sciences field. The specific objectives of this work are: (i) Describe the temporal trend of publications over the years; (ii) identify in which field the research has been mainly directed; and (iii) analyze the most important links between topics. A quantitative analysis represents the most effective methodology to perform the above-mentioned objectives.

2.3 Materials and Methods

A bibliometric analysis was carried out by selecting documents indexed by the SCOPUS database, using the advanced search to define the field of interest. This allows for showing how the research has developed and changed, following changes in society and, in some cases, determining them. Given the large number of publications, it is possible to hypothesize the influences, economic trends, and/or political decisions on the subject (Chen and Ho, 2015; Yu and Meng, 2018).

A text mining process was used to perform the analysis. The words appearing in the title, keywords, and abstract were analyzed using the textual modification instruments in Block Note, the frequency functions in Microsoft Excel, and the graphic representation in Gephi (Gephi® Consortium, Compiegne, France), an open-source software for network analysis. Text mining is a process which derives significant numeric indices from text by analyzing unstructured (textual) information. The statistical analysis of these indices provides the key to text interpretation, obtaining considerable and high-quality information (Cogato et al., 2019; De La Cruz-Lovera et al., 2019; Weinand, 2020).

2.3.1 Article Selection

The analysis was based on the term "bioenergy". To include also its derived forms, the script "bioenergy *" was used for the research on SCOPUS. With the initial examination, the program selected the articles that contain the string "bioenerg" or its derived terms (here and in the following the asterisk "*" indicate lemma declination as, in this case (e.g., bioenergy, bioenergies, bioenergetic, and so on) in the title, in the keywords, or in the abstract. Some filters were applied for a more pertinent selection of the articles. The review articles were excluded, and the field was limited at "Agricultural and Biological Sciences". As we were expecting, many articles (more than ten thousand) resulted from the search. This reflects the great interest in the topic and the interdisciplinarity of the matter (Table 2-1).

Table 2-1. Scripts for extraction of research papers.

Step	Script	Number of Papers
Initial research	*TITLE-ABS-KEY (bioenerg *)*	40,364
Filter application	*TITLE-ABS-KEY (bioenerg *) AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (SUBJAREA,"AGRI"))*	10,274

To better understand the evolution of the research, data was selected year by year, adding a time filter at the query. The script used was *"TITLE-ABS-KEY (bioenerg*) AND (LIMIT-TO (PUBYEAR ,2019)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SUBJ AREA,"AGRI"))"*, substituting the value for the year of research. The analysis was performed from 2000 to 2019 and included a total of 9504 papers. To perform the download, data relating to the title, keywords, and the full abstract were selected and the .csv extension was chosen.

2.3.2 Article Elaboration

The text extracted was saved as a .txt file. The first step was tokenization, the procedure in which the sentences are broken into pieces, removing punctuation marks, hyphens, and brackets, reducing the text only to its single words. The result of tokenization was a list of single words. Further elaboration was required to convert all letters to lowercase and to identify and convert all terms that can be written in two ways (e.g., bioenergy/bio-energy or bioenergetic/bio-energetic).

The final list of terms was exported to Microsoft Excel. The software allowed us to order the terms and count how many times each one appeared. This kind of elaboration allowed us to identify the more frequent terms in each year. Using Excel, the 100 most relevant words (occurring in at least 4% of the analyzed papers) were identified and used for the subsequent analysis. Finally, the results were processed with the software Gephi (Gephi® Consortium, Compiegne, France), which is a free tool that allows for the creation of a graphic representation of an association of terms. The representation is a graph in which the nodes are the connected terms (eventually with a specific weight) and the vectors -directed or undirected- are the connections between the terms. The conceptual flux of the analysis is represented in Figure 2-1.

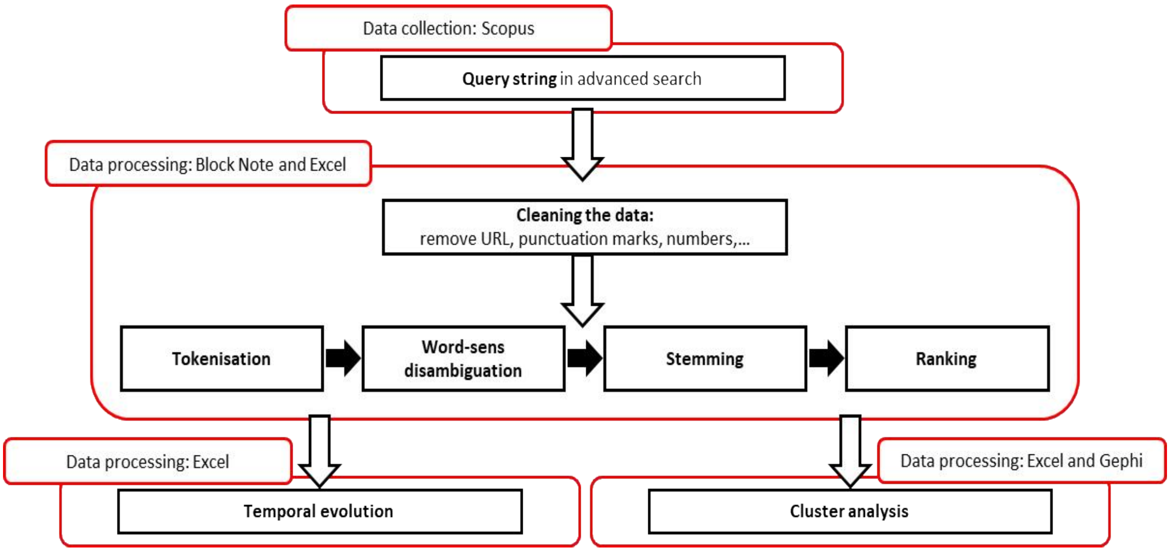


Figure 2-1. The conceptual flux of the analysis: model and used software

2.3.2.1 Combination Matrix

With the 100 most used terms, a word–word connection matrix was built. The matrix had 100^2 cells and, so, 10,000 couples. Starting from this matrix, we built a connection matrix in which, for each couple of words $\{w_1 w_2\}$, the number of articles that contained both the terms was indicated. The connections are not directional, as the value of $\{w_n\, w_m\}$ was the same as that of $\{w_m\, w_n\}$. Moreover, the number $\{w_n\, w_n\}$ was exactly the number of articles the word w_n appeared in. As a result of the matrix, 4950 couples of terms were obtained; the value that corresponds to the *k*-combinations from a given set of *n* elements, with *k*-value of 2 and *n*-value of 100.

2.3.2.2 Clusters Definition

Cluster analysis, or clustering, is defined as the task of grouping a set of elements in such a way that the objects in the same group (cluster) share one or more features that make them more similar to each other than to those in other groups. When the object of the analysis is a multidisciplinary topic, cluster analysis makes it possible to investigate the relationship between two or more fields in which the topic is used. By clustering, the most relevant settings and connections are identified. Moreover, it is possible to describe how these rankings and relationships develop and modify over the years. The bioenergy production phases were chosen as criteria to shape the clusters. Five clusters were identified: Environment, Field, Biomass, Process, and Energy. The number and topic of the Clusters were chosen to adequately cover all aspects of the theme, avoiding an over-fragmentation of the sets. Multiplying the number of clusters could increase time fluctuations and make it challenging to identify trends. The 100 most relevant words previously found were inserted into one of these groups, whichever was more suitable. For more specific analysis, some sub-clusters were created (e.g., crops), as type of produced energy. These groups covered very particular fields, and the included words had a very similar field of application. Some of the included lemmas were not in the top 100 by relevance but, due to their particular significance and pertinence to the sub-cluster, they were included in the analysis: This is the case of some secondary crops (e.g., rice, wheat or barley) or some energy terms (such as heat or methane). It is worth noting that alternative energy sources (e.g., wind or solar power) have not been considered in the analysis. Indeed, the occurrence of related lemmas is almost zero (<1%). Table 2-2 shows the cluster composition.

Table 2-2. Cluster composition.

Cluster	Lemmas
Environment	Biodiversity, carbon, ecological, ecosystem, emission, environment, environmental, greenhouse, habitat, impact, land, natural, sustainability, sustainable
Field	Breeding, climate, crop, cultivation, field, harvest, harvesting, population, productivity, rotation, season, soil, species, water, yield
Biomass	Agricultural, animal, biomass, cellulose, corn, feedstock, fish, food, foraging, forest, forestry, grass, lignin, lipid, maize, miscanthus, nitrogen, oil, organic, panicum virgatum, perennial, protein, residue, resource, sorghum, sugar, switchgrass, tree, wood
Process	Acid, availability, biological, chemical, composition, cost, cycle, diet, dry, economic, efficiency, feeding, management, metabolic, metabolism, model, nutrient, physiological, physiology, plant, policy, process, respiration, supply, temperature, transport, treatment
Energy	Bioenergy, bioenergetic, biofuel, energ, energetic, ethanol, fossil, fuel, gas, potential, power, production, renewable

2.4 Results

2.4.1 Analysis of the Trends

The first consideration concerns the number of articles published per year in the Bioenergy topic and its ratio with the total number of publications in the Agricultural and Biological Science field. As can be seen in Figure 2-2, the number of publications in the field of Bioenergy registered a slight increase between 2000 and 2006, and then accelerated rapidly until 2017. In the following year, a 12% drop in publications was shown, a stable value in the last year.

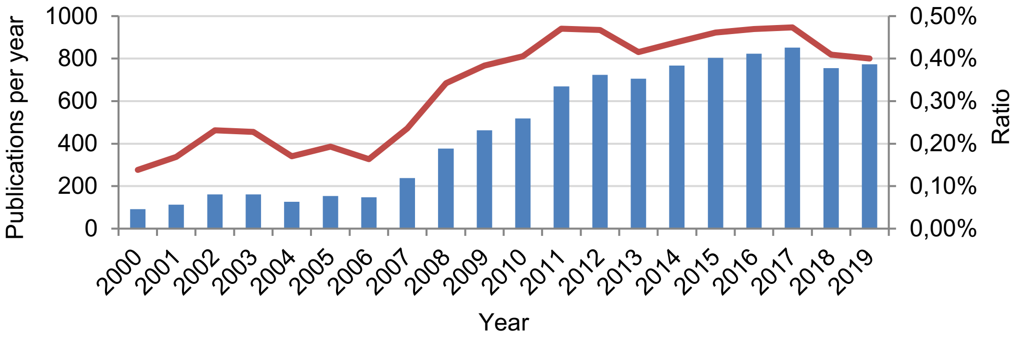


Figure 2-2. Publications per year (blue histogram) and ratio between publications in the Bioenergy topic in the sector "Agri" and total publications in Agricultural and Biological Science field (red line).

The variations in the number of articles depend both on the increase in the interest of the researchers on the subject and on the overall growth in publications. To clarify this aspect, in Figure 2, the ratio between the Bioenergy articles and total publications in the Agricultural and Biological Science field is represented. It is interesting to note that, from 2006 to 2011, the ratio between the two values tripled; indicating that, in that period, the interest in the topic Bioenergy increased. Since 2011, the ratio has been almost constant, which means that the variations in the articles on the Bioenergy topic are mainly linked to the total number of publications.

To clarify this aspect, a broader analysis was developed. On SCOPUS, articles with the string "bioenerg *" in the Title-Abstract-Keywords and the limitation of "AR" (without the restriction of the sector "Agri") were identified. This series of articles was compared to the total number of publications in the Agricultural and Biological Science field. Results are shown in Figure 2-3.

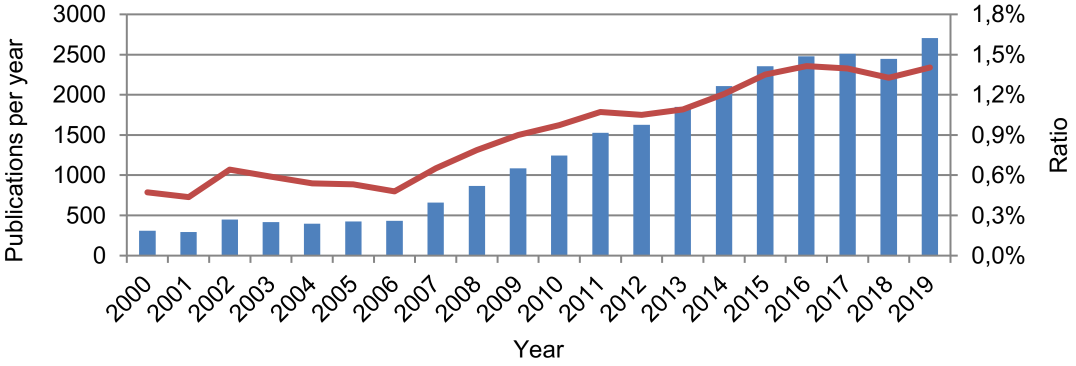


Figure 2-3. Publications per year (blue histogram) and ratio between publications in the Bioenergy topic and total publications in Agricultural and Biological Science field (red line).

Figure 2-3 shows a more regular growth of both indicators. The values of articles with the term "Bioenerg*", not limited to the "Agri" sector, have steadily increased from 2006 to 2019, except for a weak decrease in 2018. A comparable trend was shown by the ratio between the value of the same set of articles and the total articles in the "Agricultural and Biological Science" field. The diagrams obtained indicate that, between 2005 and 2006, interest in the bioenergy theme began to increase, occupying even more importance in the efforts of researchers. Interestingly, the Kyoto Protocol entered into force on 16 February 2005, so it is conceivable that it influenced the interests of researchers, encouraging them to find solutions to reduce CO_2 emissions, in order to comply with the agreement.

A further incentive may have been given by the 2009 United Nations Climate Change Conference (commonly known as the Copenhagen Summit) for climate change mitigation. Following this pattern, a slowdown starting from 2016 can be noted. The Paris Agreement in 2015 seems not have made a substantial contribution to research in the renewable energy sector. A confirmation of this trend came by comparing the publications with the term Bioenergy with the total publications on SCOPUS in the same period. Figure 2-4 shows that the total number of publications has a steady but slower growth than publications with the bioenergy theme.

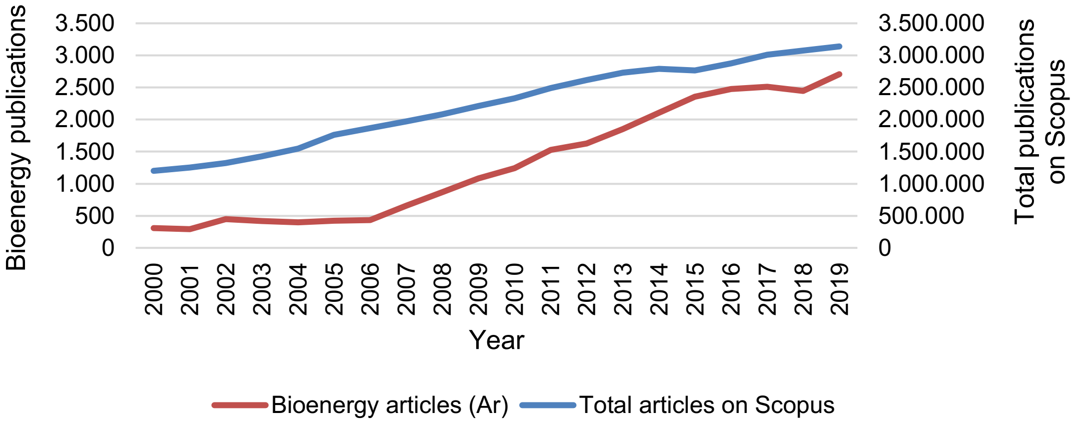


Figure 2-4. Trends of Bioenergy publications and total publications on SCOPUS

Another quantitative research performed was the analysis of the affiliations and the international collaborations. Countries of all the continents contributed to the publications on the theme. The United States is the most important contributor, with 39% of the total publications. The top five contributors provide about 49% of the publications (Figure 2-5). Countries with the highest growth in the last 20 years were Brazil (eight publications from 2000 to 2004 and 301 from 2015 to 2019) and China (12 publications from 2000 to 2004 and 370 from 2015 to 2019).

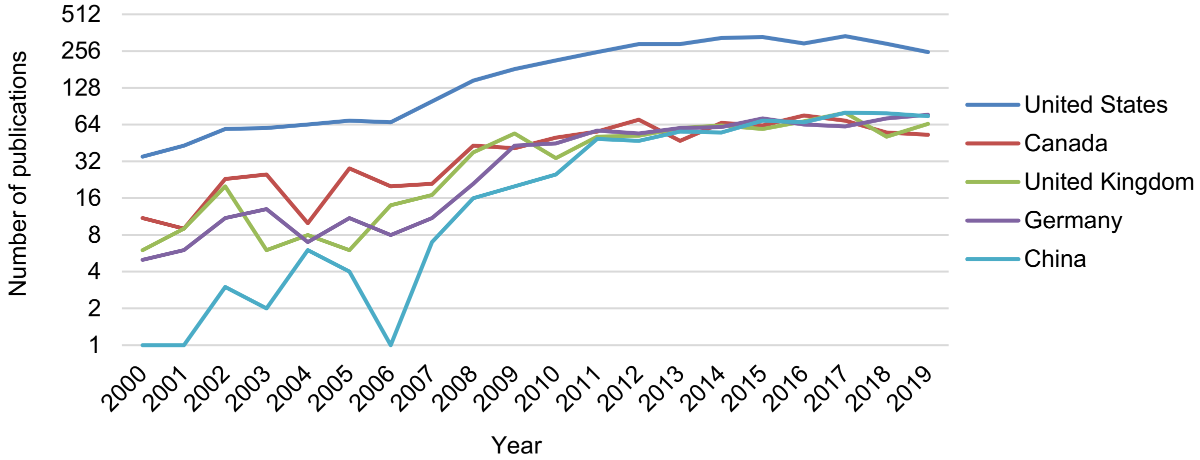


Figure 2-5. Top five contributors in the last 20 years. The y-axis is represented in log2 scale

The international research collaboration was analyzed. The most relevant collaborations are between the USA and five countries: Canada (201 articles), China (150 articles), the U.K. (106 articles), Germany (101 articles) and Australia (96 articles). Sixth and seventh positions are between the U.K. and Germany (88 articles) and Canada (71 articles) (Table 2-3).

Table 2-3. Top 20 international research cooperation

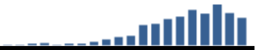
Countries	Collaborations	Countries	Collaborations
Canada-USA	201	France-U.K.	56
China-USA	150	Germany-Netherlands	54
U.K.-USA	106	Mexico-USA	54
Germany-USA	101	Japan-USA	50
Australia-USA	96	Australia-U.K.	47
Germany-U.K.	88	South Korea-USA	46
Canada-U.K.	71	Canada-France	43
France-USA	70	Italy-U.K.	43
India-USA	64	Netherlands-U.K.	43
Brazil-USA	56	Netherlands-USA	43

2.4.2 Research on Most Recurrent Terms

Using .txt files and .xlsx files, a ranking of the top words used year-by-year was created. For each term, the number of occurrences in which it was cited in the title, abstract, and keywords was calculated. The ranking is different in different years. The results regarding the words belonging to Cluster "Field" are shown in Table 2-4.

Table 2-4. Variation of top used words of Cluster "Field".

YEAR	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Temporal evolution
breeding	4	16	48	30	28	20	15	27	62	112	117	85	105	115	140	122	142	171	149	161	
climate	10	10	5	6	9	20	35	20	70	111	179	201	203	257	337	329	323	357	209	232	
crop	16	17	19	24	17	35	44	44	87	133	177	463	322	358	464	550	566	587	488	427	

cultivation	1	2	0	0	5	8	7	6	3	19	44	120	90	96	100	125	112	124	133	132	
field	30	16	20	40	34	28	27	34	82	94	98	109	109	127	145	246	174	200	188	169	
harvest	4	15	17	24	17	23	25	27	47	24	55	180	138	212	210	242	254	238	154	137	
harvesting	22	10	18	12	19	23	32	45	37	54	146	234	172	271	244	234	308	207	213	123	
population	21	25	45	47	33	49	61	101	205	171	178	184	218	203	183	178	201	227	213	159	
productivity	8	4	11	20	4	25	15	22	42	63	104	111	115	209	157	198	194	183	171	172	
rotation	2	11	5	20	7	6	3	12	17	28	57	123	101	113	140	150	141	152	107	117	
season	4	10	40	34	32	9	19	22	55	71	89	80	109	129	123	116	126	154	91	92	
soil	26	21	23	9	7	37	34	56	128	157	230	447	436	561	537	779	963	989	862	799	
species	35	78	98	109	73	128	112	185	340	382	353	483	553	542	552	573	643	642	515	601	
water	38	70	102	106	70	101	61	81	149	218	257	198	363	309	386	521	415	622	365	528	
yield	5	7	24	35	5	22	26	47	81	113	125	272	289	353	387	470	423	546	432	370	

To classify the terms in the two considered decades, the weighted average of the values over several years was made. For each year, the ratio between the occurrences of a term and the total number of articles in the Bioenergy field was created. The overall score of a term (Equation (1)) was obtained by the weighted mean of the values over the years, giving higher weight to the most recent years to better focus the attention on the current situation:

$$S_T = \frac{\sum_{i=1}^{20} w_i \cdot \frac{o_i}{B_i}}{\sum_{i=1}^{20} w_i} \qquad (1)$$

where w_i is the weight of the *i*th year, *oi* is the number of occurrences of the given term in the *i*th year, and *Bi* is the number of articles in the Bioenergy topic in the *i*th year.

2.4.3 Cluster Analysis

The first 100 terms among the pre-processed ones were grouped into five conceptual clusters. The weight of a cluster was determined by the sum of the weights of the terms that belong to it. This weight was calculated using the ratio between the occurrences of the terms in a given year and the total articles in the Bioenergy topic in the same year.

The broader cluster was that with the theme “Biomass”, which included all words regarding the possible sources of biomass and their characteristics (e.g., “protein”, “nitrogen”, “organic”, “feedstock”, and so on). The most important sources of biomass in the cluster were, in descending order: food (8.2%), fish (7.7%), forest (6.0%), wood (4.6%), animal (3.3%), switchgrass (3.1%), agricultural (3.0%), and miscanthus (2.9%). Other significant clusters were Energy (24.6%) and Process (23%), as shown in Table 2-5. The cluster “Energy” included the terms and the concepts linked to the step of energy production, while the cluster “Process” considered the phase of treatment of the biomass resources, including the economic and management aspects. Features regarding production and resource conditions were included in the cluster “Field”, while environmental and sustainability concepts were listed in the “Environment” cluster.

Table 2-5. Main clusters: Clusters reported by highest frequency terms

Cluster	Lemmas and Relative Occurrence [%]	Cluster [%]
Biomass	Biomass 21.4%, food 8.2%, fish 7.7%, forest 6.0%, wood 4.6%, protein 4.4%, nitrogen 3.5%, foraging 3.4%, animal 3.3%, switchgrass 3.1%, agricultural 3.0%, miscanthus 2.9%, forestry 2.5%, resource 2.3%, lipid 2.3%, organic 2.1%, feedstock 1.8%, grass 1.8%, tree 1.7%, sorghum 1.7%, oil 1.5%, corn 1.5%, residue 1.4%, perennial 1.4%, lignin 1.3%, panicum virgatum 1.1%, source 1.1%, sugar 1.1%, maize 1.0%, cellulose 0.9%	26.6%
Energy	Energy 30.8%, bioenergy 16.7%, production 13.7%, bioenergetic 9.4%, potential 7.5%, fuel 3.7%, energetic 3.3%, gas 2.9%, power 2.9%, biofuel 2.6%, ethanol 2.3%, renewable 2.3%, fossil 1.9%	24.6%
Process	Model 10.3%, temperature 8.0%, metabolism 7.2%, plant 6.5%, metabolic 5.0%, management 4.7%, feeding 4.5%, diet 4.2%, efficiency 4.1%, cost 3.8%, composition 3.6%, supply 3.2%, availability 3.2%, acid 3.2%, physiological 2.7%, cycle 2.6%, dry 2.6%, economic 2.4%, nutrient 2.4%, respiration 2.4%, physiology 2.2%, biological 2.2%, transport 2.0%, treatment 1.9%, chemical 1.7%, process 1.7%, policy 1.7%	23%
Field	Species 16.7%, soil 12.6%, water 12.1%, crop 9.1%, yield 7.4%, population 7.0%, climate 5.5%, harvesting 5.1%, field 4.8%, harvest 4.2%, breeding 4.0%, productivity 3.6%, season 3.4%, rotation 2.5%, cultivation 2.0%,	15.2%
Environment	Carbon 17.9%, environmental 12.5%, land 10.3%, emission 6.8%, habitat 6.3%, impact 5.8%, ecosystem 5.8%, greenhouse 5.6%, CO_2 4.9%, environment 4.7%, ecological 4.6%, sustainable 4.5%, natural 4.4%, biodiversity 3.0%, sustainability 2.9%	10.5%

By the results of the analysis, production and treatment were the sectors in which researchers have mainly focused during the last 20 years. Considering the selected words, the sources of biomass (i.e., food, fish, wood, switchgrass, miscanthus, grass, sorghum, oil, corn, residue, panicum virgatum and maize) occupied about 37.7% of the occurrences. The terms “emission” and “greenhouse” (mainly related to the greenhouse gases) influenced the cluster for about 12.3%. In the cluster “Energy”, specific terms such as “fuel” and “biofuel” presented an impact of 6.3%; meanwhile, other topics such as “electricity” and “biogas” were not even among the most frequent words.

In the “Process” cluster, an important contribution was given by terms relating to chemical and biological aspects: temperature (8.0%), metabolism (7.2%), metabolic (5.0%), feeding (4.5%), diet (4.2%), composition (3.6%), physiological (2.7%), nutrient (2.4%), respiration (2.4%), physiology (2.2%), biological (2.2%), treatment (1.9%), and chemical (1.7%). It is worth noting that some of these terms are important parameters in the production process of biofuels and biogas: the same process is also deeply influenced by the specific implemented crops, which; however, were included in the generic “biomass” cluster for the diverse meaning and use they might have in research papers. The residual contribution consisted of technical and economic terms. The “Field” cluster was made up of terms with fewer occurrences than the others, but it indicated that there was interest in the biomass production aspects. The environmental issue seems to have had minor importance (10.5% of the total), which is likely to tend to increase in the coming years.

The percentage of occurrences of the clusters per number of articles in the bioenergy field were compared. Observing the trends over the last 20 years (Table 2-6), it is noteworthy to observe that the percentage weight of the "Process" cluster has steadily decreased, from 26.5% to 21.0%. The "Energy" cluster has suffered a comparable, but less accentuated, reduction—from 25.8% to 21.5%. Both the "Field" and "Environment" clusters have been continuously growing; the cluster "Field" from 10.4% to 18.6% (therefore, an increase of about 79%), and "Environment" from 7.3% (the 2001 value was taken, as that in 2000 seemed to be out of scale) to 11.8% (therefore, increasing by 62.3%). It appears that environmental and sustainability issues have been of increasing interest in research, a consequence of the ecological policies promoted by national governments and international institutions.

Table 2-6. Percentage of occurrences in the clusters aggregated by groups of five years

YEAR	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Temporal evolution
Energy	25.8%	28.3%	24.7%	25.1%	22.9%	25.5%	24.4%	23.8%	25.0%	24.0%	23.7%	24.8%	23.7%	22.4%	22.2%	21.5%	20.9%	19.9%	20.9%	21.5%	
Environment	12.3%	7.3%	7.2%	9.1%	8.2%	9.2%	10.4%	9.6%	9.0%	9.2%	10.6%	10.2%	11.6%	10.7%	10.6%	12.1%	12.6%	11.5%	11.0%	11.8%	
Field	10.4%	12.1%	14.5%	13.2%	13.2%	14.9%	13.8%	12.1%	15.0%	14.2%	15.0%	15.1%	15.2%	16.7%	16.8%	18.8%	18.3%	19.1%	18.2%	18.6%	
Process	26.5%	26.8%	29.4%	25.1%	31.1%	25.1%	24.9%	26.9%	27.0%	24.4%	23.7%	20.9%	21.5%	21.1%	21.3%	20.3%	20.3%	20.5%	21.5%	21.0%	
Biomass	25.1%	25.4%	24.1%	27.6%	24.6%	25.3%	26.5%	27.6%	24.0%	28.2%	26.9%	29.0%	28.0%	29.1%	29.1%	27.4%	27.8%	28.9%	28.4%	27.1%	

2.4.4 Interrelationships Between Terms

The objective was to provide specific information on how main topics belonging to the same or different clusters were addressed together, so interrelations of the terms were studied. Therefore, each of the already mentioned 100 most frequent words in the title, keywords, and abstract section was coupled with each of the remaining 99 words, generating 4950 possible combinations. Such combinations were studied in terms of occurrences on analyzed 20 years bibliography and graphically represented, generating a very complicated net of relationships (Figure 2-6). The same combinations occurrences were also represented in a table format (Table 2-7).

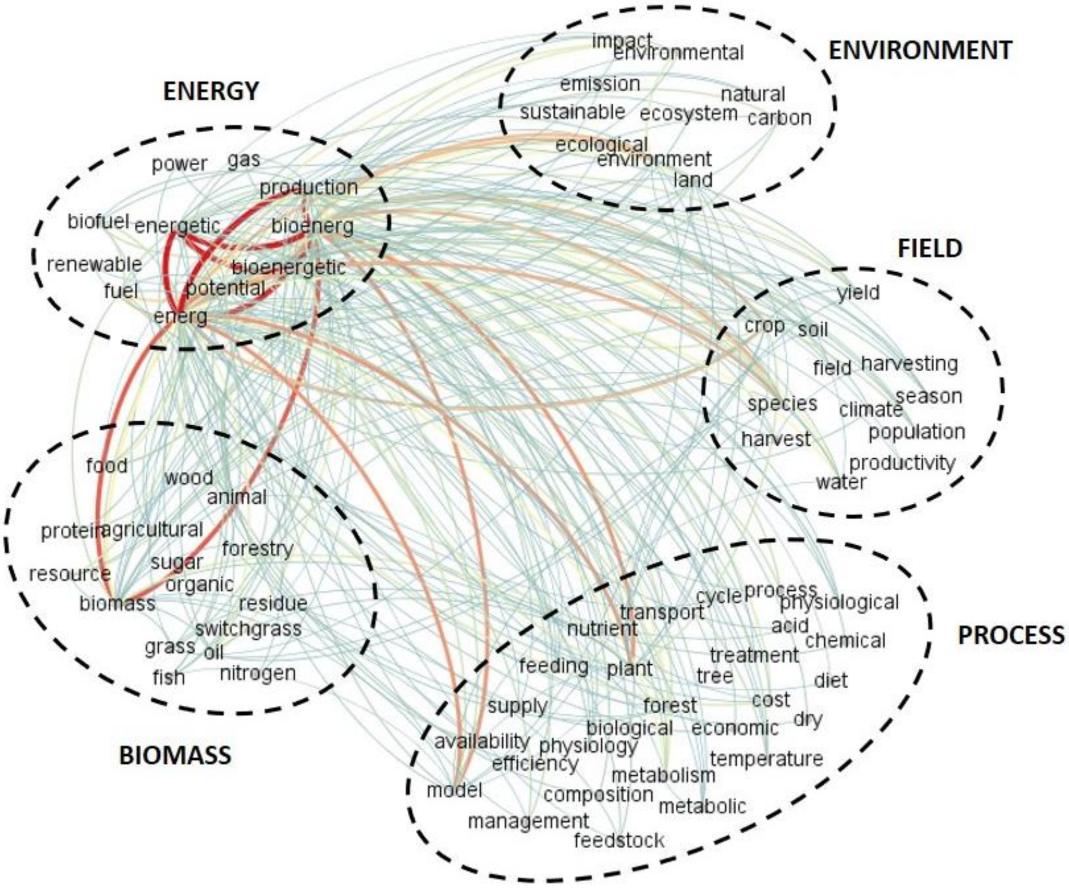


Figure 2-6. Interrelations between terms in the title, keywords, and abstract sections. Thicker and darker colored lines indicate a more significant number of connections. The circles indicate different clusters. For better visualization, only terms with at least

Given the research theme, the "Energy" topic was expected to include the terms with the highest number of co-occurrences. It presented the maximum value of co-occurrences both between terms inside the cluster and terms belonging to different clusters. Excluding these groups, the cluster with the maximum number of co-occurrences was "Biomass". This result was also due to the large number of terms belonging to this cluster, including all sources of biomass and energy. The group of words with fewer relationships with other terms was the cluster "Environment", which also presented the minimum value of connections between words inside the same cluster (Table 2-7).

Table 2-7. Relationships between the terms of the clusters

	Energy	Environment	Field	Process	Biomass
Energy	86.613	84.875	99.820	161.622	149.200
Environment	***	24.656	49.549	68.229	70.549
Field	***	***	29.900	79.833	90.528
Process	***	***	***	65.335	118.926
Biomass	***	***	***	***	65.325

To better understand the connections between the terms, Figure 2-6 was exploded, focusing the view on pairs of groups of words. In the first one (Figure 2-7a), the statistical analysis highlighted that the scientific community has studied every type of energy achieved by biomass.

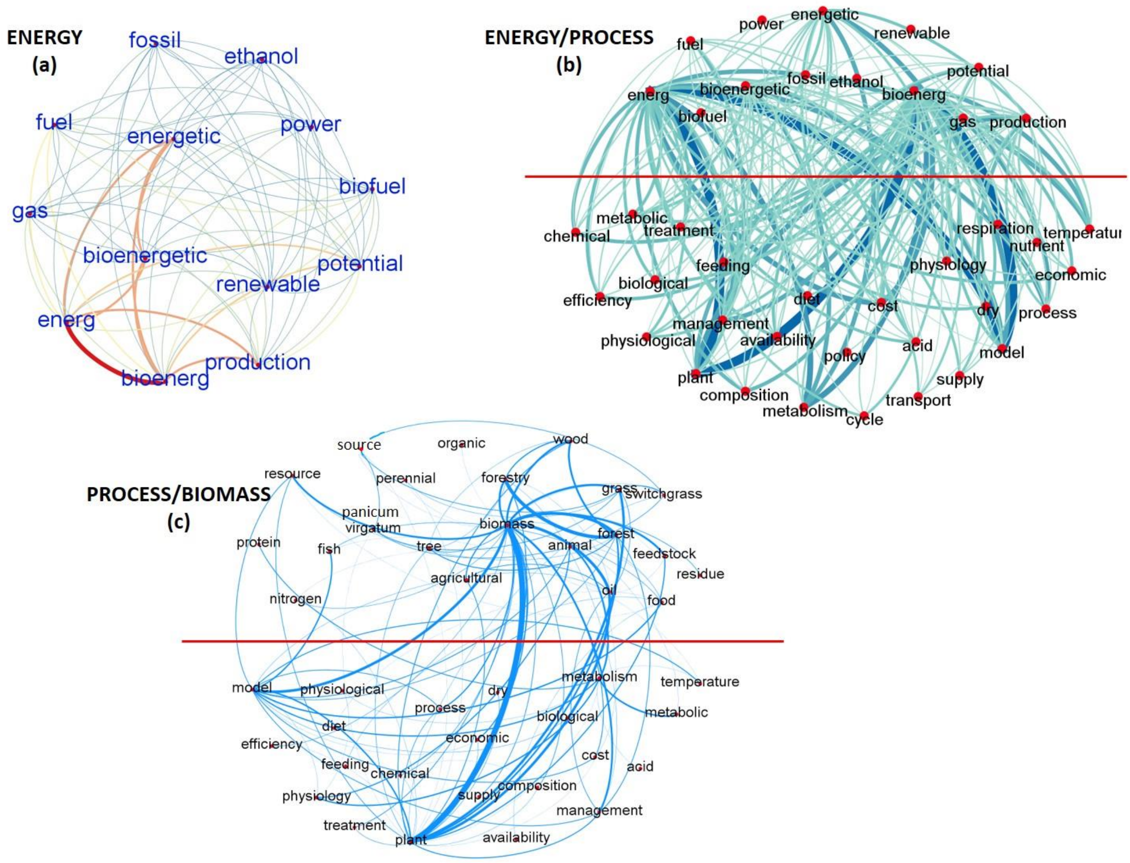


Figure 2-7. Co-occurrence of topics within the “Energy” cluster (a); between the “Energy” and the “Process” clusters (b); and between the “Process” and “Biomass” clusters (c)

The analysis of single couples of terms, without considering the cluster they belong to, allowed to show which topics were the most related. The following schemes were elaborated by taking the first 30 couples of terms by relationships. Trivial or non-relevant couples were excluded; for example, “environment–environmental”, “fuel–biofuel”, and all those that contained the terms “energy” or “bioenergy”. The results are summarized in Table 2-8.

Table 2-8. Couples of terms with the highest number of relationships during the period 2000–2019, values of the occurrences.

Source	Target	Weight	Source	Target	Weight
biomass	production	2261	crop	potential	1367
biomass	plant	1858	animal	bioenergetic	1358
potential	production	1840	environment	production	1334
plant	production	1794	bioenergetic	food	1296
crop	production	1774	bioenergetic	environment	1271
crop	plant	1700	production	yield	1256
biomass	potential	1686	model	production	1252
biomass	crop	1683	biomass	yield	1250
bioenergetic	species	1682	crop	fuel	1244

bioenergetic	model	1609	bioenergetic	fish	1237
fuel	production	1581	fuel	plant	1220
biomass	fuel	1532	fuel	potential	1219
bioenergetic	metabolism	1479	biofuel	production	1152
plant	potential	1416	bioenergetic	production	1149
land	production	1384	crop	yield	1142

2.4.5 Temporal Comparison of Related Terms

To describe the evolution of research publications in the bioenergy sector, groups of words with very particular bonds were taken. These groups were constituted by terms that expressed alternative solutions in the study and, by analyzing the variations with which these solutions are cited in the articles, it is possible to understand in which direction the research was addressed.

The first specific cluster considered was related to “Crops” (Figure 2-8), which included potential biomass sources from agricultural activities. Considering the trend over the last 20 years, a temporal analysis allowed us to identify if there were crops that have gained interest as sources of biomass for energy purposes and if there were others that, on the contrary, are considered less valid at present than in the past.

The first general consideration was that citations of crops per article in the bioenergy theme have generally grown over the considered period. In other words, a growing attention has been paid to the selection of specific or alternative crops as potential source for bioenergy production. Above all, Miscanthus has showing the largest evolution, moving from 0 to 0.584 occurrences per article (occ/art), which signifies that there were about 0.58 citations of the term per each article considered to fall under the bioenergy theme. One other significant result is the trend exhibited by the term “sugarcane”, the ratio of which increased from 0 to 0.306 occ/art; a result that is particularly important, considering that the production of this product is mainly concentrated in developing countries. The term switchgrass was the most cited for several years (from 0.187 to 0.282 occ/art), although it registered some deep falls. Some types of crops have shown growth over time, albeit with fluctuating trends such as grass (from 0.044 to 0.221 occ/art), corn (from 0.033 to 0.202 occ/art), sorghum (from 0 to 0.195 occ/art), or algae (from 0.099 to 0.256 occ/art); trends and applications of algae were studied by Deviram et al. (Deviram et al., 2020) and by Yang et al. (Yang et al., 2015), showing growing interest in recent years, particularly in the USA and China. Some other crops have given evidence of an initial interest, but with a loss of relevance in the last years, as in the case of wheat or thale cress (Arabidopsis). Other crops (including Arundo, Beets) have been taken into consideration; however, they still play a weak role in research publications.

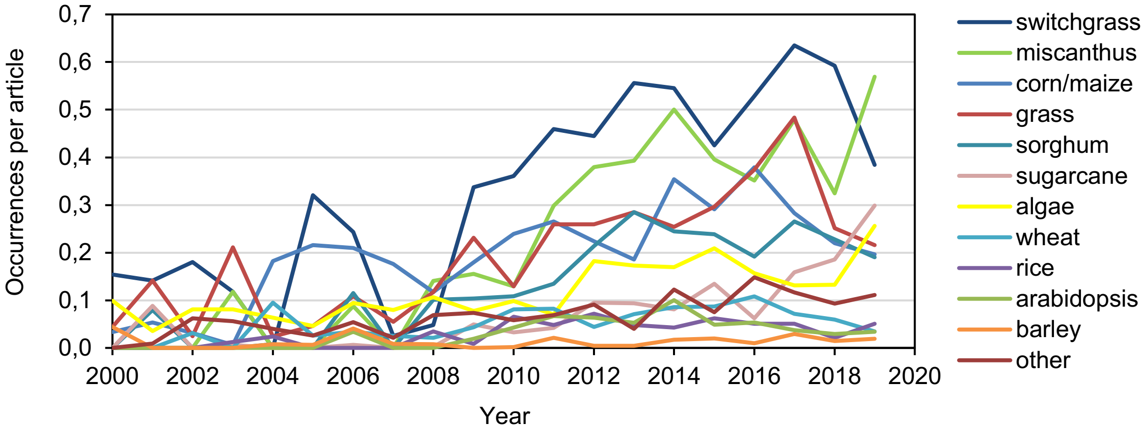


Figure 2-8. Trend chart of related terms in the “Crops” cluster

The second specific considered cluster was related to “Energy produced” (Figure 2-9), which included the energy forms that can be obtained using biomass. The relevance of the argument and the benefits and costs associated with each type of utilizations was studied by Guo et al., expecting a growing of the sector in the next future, in particular bioethanol and biogas (Guo et al., 2015). This type of analysis makes it possible to understand which kind of produced energy the publications focused on, assessing whether politics or international agreements have had an influence on the research. The occurrences of the terms “heat” and “electricity” were almost constant over the two considered decades. Excluding the first three years, which exhibited an anomalous peak, occurrences of the term “heat” moved from 0.155 to 0.145 occ/art, while the citations of the term “electricity” moved from 0.130 to 0.102 occ/art.

The slow but steady growth of the other terms related to biogases and biofuels is significant. Indeed, in the first case citations increased from 0.143 to 0.414 occ/art (i.e., with an average increase of 9.5% per year), while in the second case the number of occurrences per article moved from 0.143 to 0.378. For biofuels, a more evident growth can be recognized between 2007 and 2011 (+0.404) occ/art: Such increment might be associated to the increasing impact on economy of crude oil prices (which reached a maximum in July 2008), along with international and in particular European strategies for biofuels, published in 2006 (European Commission, 2006).

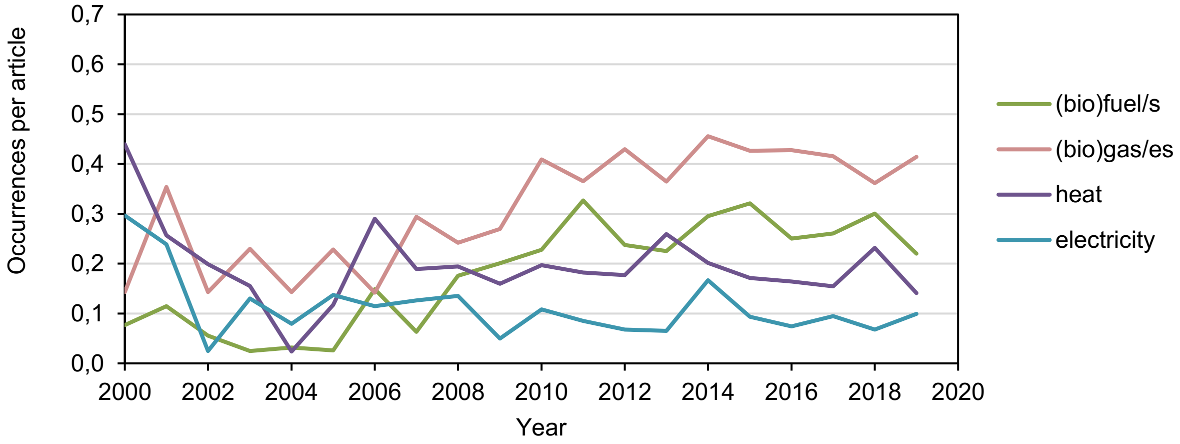


Figure 2-9. Trend chart of terms related to produced energy

Biofuels and biogases are detailed also in Figure 2-10. The most recurrent term in two decades of published research is ethanol, with an average of 0.200 occ/art. On the other hand, a clearly growing interest is being devoted to methane, with a number of occurrences which has moved in the last decade from 0.019 to 0.175 occ/art. Other types of fuels (such as methanol or ethylene) and other types of gases (such as propane, ethane or butane) still exhibit a minor interest for the scientific community, with a total number of citations lower than 0.025 occ/art. Development of the types of renewable sources of energy in recent years has led to specialization in their use. Biomass-derived energy is particularly suitable to be stored and used in case of requirements; more so than the electricity produced by wind farms and solar plants. Furthermore, the objectives of reducing greenhouse gas emissions due to the transport sector can be validly achieved not only by optimizing harvesting process (Boscaro et al., 2018) but also by using fuels derived from biomass. These considerations could explain the growing interest in research in the biofuel and methane sector, which are adequate products for storing produced energy and fueling vehicles, and in the comparison of different ways of use of the energy produced (Pöschl et al., 2010).

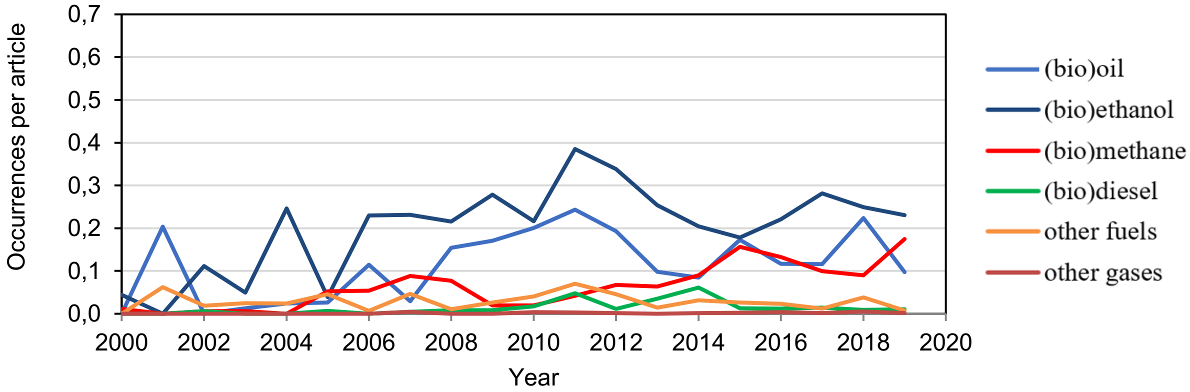


Figure 2-10. Trend chart of terms related to produced biogases and biofuels

2.5 Discussion

The presented research was performed by a text-mining analysis, taking into consideration the title, abstract and keywords of every article. The most critical and frequent terms were identified and analyzed. The most significant relationships were recognized, both between specific terms and aggregated clusters.

The temporal analysis allowed us to describe the evolution of publications; in particular, which topics have gained or lost importance and which relationships have been strengthened.

2.5.1 Temporal Analysis of Publication Trends

Themes related to bioenergy and its production, management, and use are not recent topics in research. However, interest has risen sharply in recent years, with a growth of about 726% in publications and around 183% by weight of total articles in the Agricultural and Biological Sciences field. Research in the branch has affected every aspect related to the theme in a different way, as was shown in the cluster analysis.

Although the interest of research has been influenced by the economic and environmental policies of countries and international institutions, given the extensive range of topics, it is difficult to establish a link between single events and temporal trends. However, it is legitimate to hypothesize a relationship between the growing number of publications in the bioenergy theme and the even more ambitious targets in renewable energies matters.

2.5.2 Cluster Analysis and Trends

By the described analysis, it can be seen that the most studied topics were those relating to the phase of the production process. The chemical and biological processes on which the energy production of biomass are based have been the subject of numerous studies. Management and economic aspects seem to have had less quantitative impacts on research works.

The simultaneous growth of the topic “Environment” and reduction of the topic “Process” can be explained by the achievement of a high standard of efficiency in the digestion and transformation processes of biomass into various types of energy. In the meantime, the efforts of researchers have shifted to investigate how these energy sources can be integrated into the overall transformation process of the energy system, from fossil fuel-based to renewable energies-based.

The growth of the “Field” cluster (the highest in the identified clusters) reveals a greater interest in the production phase of the biomass sources. Indeed, the latest goals of international institutions, including the EU directives, have underlined the importance that the collection of biomass does not affect food production. For this reason, crops cultivated for energetic purpose should be avoided, and by-products or wastes of agricultural and livestock activities should be used. Research into the types of plants allows researchers to identify the best way to exploit them for energy purposes.

The most cited crops in the selected articles are miscanthus, switchgrass, and corn, which can all be included in the crop category. It should be investigated whether the use of miscanthus and switchgrass derives from an interest in crops dedicated to energy production or, at least in part, plants that grow spontaneously. Corn is one of the most common crops used for energy purposes. The reduction of the related occurrences in the examined publications can be a positive signal, suggesting that this crop is somehow experiencing a decreasing interest as energy dedicated source, hopefully returning to its food production vocation, at least at a scientific level.

The analysis of the most significant relationships confirmed the decreasing trend of the “Energy” cluster and the growth of the “Biomass”, “Field”, and “Environment” clusters. This is another sign of the changing interest of research, towards the environmental aspects of bioenergy concerning the technical and processing phases.

2.6 Conclusions

The last twenty years have seen a growing attention on bioresources for energy applications. In particular, renewed interests have been devoted to specific and different topics in the wide research field of bioenergy science. The present research is aimed at characterizing such evolving trends, highlighting most relevant terms or relations in terms of occurrences in scientific papers.

The most important contributions are concentrated in three macro areas: North America, Western Europe, and China, while the developing countries are actually less represented. Such distribution suggests that political decisions and favorable economic conditions deeply influenced the interest in the topic. As for the contributions of the top five countries, the United States is the most significant contributor for every type of biomass, but it is interesting to note that publications are mainly focused on switchgrass. Considering also data related to rice in China, wheat in Canada, and maize in Germany, it seems that the attention of the research is mainly focused on those crops that are particularly common in the country. Articles with UK affiliation are particularly targeted at miscanthus; the interest in this energy crop indicates the objective of seeking solutions not in competition with food production. Additionally, the results of the review suggest that efforts in the future might be focused both on the biomass production phase and in the analysis of the environmental impacts and benefits, which up to now (compared to process, biomass and energy clusters) have exhibited the lowest percentage of occurrences but on the other hand the highest growth rate.

A systemic approach would be in particular recommendable, where the different elements of the bioenergy process chain from the field to the consumer are studied in a concurrent way, integrating source and process optimization, environmental sustainability, and final users’ needs. The use of crops not of interest for food production, as well as the use of wastes from the agricultural and food industries, must be examined in depth. From environmental and economic points of view, studies regarding the integration of bioenergy and other types of renewable energy sources (as e.g., wind, hydro, or solar power) are still lacking and represent another possible goal of research. Combined analyses of integrated energy sources with a systemic approach can potentially further increase environmental benefits, allowing optimization of important factors such as soil or water consumption, use of raw materials, and interaction with anthropogenic activities. To this end, specific and innovative mathematical models would be needed in order to help designing of decision-making tools that allow for more accurate simulation and planning of future scenarios. Political actors and stakeholders will then be able to evaluate the proposed solutions, based on community needs as well as environmental impacts.

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3 An assessment of nitrogen loading and biogas production from Italian livestock: A multilevel and spatial analysis

3.1 Abstract

The management of livestock effluents to reduce their environmental impact requires knowledge of not only the quantity produced but also the availability of agricultural areas, the condition of contiguous areas and the opportunity to exploit the energetic value of effluents. In this paper, a description of the Italian livestock system is provided, with a focus on its consequences in terms of the nitrogen load and biogas potential produced by the management of effluents. The analysis considered 9,589 million animal units (AU) and indicated an overall nitrogen production of 508 $\times 10^6$ tons, while the methane potential can reach 1,764 $\times 10^6 m^3$, equal to 6.1% of the national electric energy consumption. To organize effective collection and treatment of effluents, their spatial distribution was investigated using spatial statistical tools: Moran's index and local indicator of spatial association (LISA). Moran's index analysis showed that animal units (Moran's I = 0.63), nitrogen load per hectare of UAA (Moran's I = 0.35) and methane potential per square kilometre (Moran's I = 0.58) were significantly clustered. Using LISA, a series of maps and scatter plots were elaborated to identify clusters of high nitrogen loads and high methane production. The analysis showed that 764 municipalities are included in clusters of a high density of livestock, and 635 municipalities resulted in clusters of high methane potential. The results demonstrated the robustness of these instruments to evaluate the presence of nitrogen/biogas production clusters and the possibility of combining the treatment of nitrogen and the production of biogas from animal effluents. Analysing the distribution of livestock and the 2,723 biogas plants operating in Italy, the study found that 75.0% of the bioresources are available 5 km from the nearest biogas plant, 89.9% at 10 km, 94.7% at 15 km and 97.4% at 20 km.

Keywords: anaerobic digestion, livestock effluents, biogas plant, biomethane, spatial analysis

3.2 Introduction

Livestock farming is an important sector of the Italian economic system, and its development also has significant consequences on the social and environmental system. The farm distribution in Italy is very heterogeneous and is characterized by regional concentrations that can potentially compromise environmental targets, such as those fixed by the Nitrates Directives (European Commission, 2000). The activities in livestock farms, housing, storage, and field application of manure and slurry can constitute a considerable load on the ecosystem, a theme that is even more important for researchers. In fact, those activities are sources of nutrients/pollutants, such as greenhouse gases (GHGs), e.g., carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ammonia (NH_3) (Erisman et al., 2008). European agriculture is responsible for 94% of ammonia

(NH_3), 8% of nitrogen oxide (NO_x), and 5% of methane (CH_4) emissions in Europe (European Environment Agency, 2020), and Webb et al., 2005, calculated that 75% of NH_3 emissions are due to livestock activities. The overuse of effluents contributes to the contamination of surface water and groundwater because of their uncontrolled input of nutrients, particularly phosphorus (P) and nitrogen (N), in soil (Oenema et al., 2007). Their management must respect not only agricultural policies but also environmental legislation, such as the Nitrates Directive, part of the Water Framework Directive and a key instrument in the protection of waters against agricultural pressures (European Commission, 2000). The sustainability of human activities is becoming a crucial point for public policies and the activities of researchers (Ferrari et al., 2020). Several researchers in different contexts have explored the impact of different livestock categories on the environment and a possible solution to the problem, and the pressure of nitrogen is considered one of the most critical issues (Rockström et al., 2009). However, with regard to this phenomenon, the consequences of the spatial distribution of livestock farms with respect to Nitrogen Vulnerable Zones (NVZs) have not been sufficiently studied. For example, Oenema et al., 2007, considered effluent management systems in the European Union and the nutrient effects of these systems; the total nitrogen (N) excretion in 2,000 by livestock in EU-27 was estimated to be 10,400 kton, but only 52% of the N excreted was recycled as a plant nutrient. Steinfeld et al., 2007, discussed attempts to combine the environment and livestock farming, evaluating the potential effects of alternative mitigation policies. Halberg et al., 2005, considered several assessment tools at the European level that were elaborated to predict the environmental impacts of various livestock types.

To avoid these environmental consequences, different management solutions are available. The feasibility of any effluent treatment depends on the specific characteristics of the livestock farms, geographic conditions, environmental requirements, type and amount of nutrients to be removed (García-González et al., 2016) and the opportunity and the economic convenience to produce bioenergy (Finzi et al., 2020). For this reason, it became essential to define the areas or the particular location where a N surplus occurs; if the crisis situation appears in very restricted areas, a possible solution can be to transfer the effluent or, depending on economic considerations, its solid fraction (Hjorth et al., 2010). This solution requires that the amount of effluent, dry fraction, or nitrogen surplus, depending on the chosen treatment, is large enough to justify transport from an economic point of view. Chadwick et al., 2011, reviewed the solutions for the treatment of effluents and their influences, both direct and indirect, on N_2O emissions and CH_4 emissions. The contribution that effluent management makes to the total national agricultural emissions of N_2O and CH_4 can exceed 50%. Nardin and Mazzetto, 2014, discussed the management of livestock effluents (particularly N) in the process of the biogas supply chain. They analysed biogas plants as a unique system, from the production of biomass to anaerobic digestion. To achieve a reduction of 10% for the total effluent amount and 24% for excreted N, a hypo-protein diet was proposed.

Anaerobic digestion (AD), even if it does not alter the nitrogen content or the other nutrient composition (Flotats et al., 2009), produces an effluent that is more suitable for subsequent treatments, for either recovering nutrients (Provolo et al., 2017) or removing nutrients (Bernet et al., 2000). Guštin and Marinšek-Logar (2011) demonstrated that using ammonia stripping bench plants made it possible to remove up to 92% of ammonium and 88% of total nitrogen from the AD effluent. Provolo et al., 2017, simulating the operating conditions of a biogas plant in the laboratory, obtained a reduction of NH3 of up to 87%, depending on the starting condition of the pH in the digester. Bernet et al. (2000) observed a removal of total Kjeldahl nitrogen (TKN): 85 to 91% in denitrification followed by AD of organic carbon. In addition to the benefits of nitrogen removal, the exploitation of livestock effluents as a source of bioenergy is considered to be a promising solution for a sustainable energy system in collaboration with other substrates (Mattioli et al., 2017), and it is a crucial goal of development policies in many countries (Delzeit and Kellner, 2013). The use of bioresources must consider the temporal evolution of agricultural activities (Chang et al., 2014) to prevent bias due to a single year of exceptionally high or low production (Jia et al., 2018).

Despite the importance of combining the management of animal effluent impacts, in particular nitrogen, and exploiting the bioenergy available, spatial analysis tools that allow the simultaneous analysis of pollution and resources have not yet been sufficiently investigated in Italy. Furthermore, it is necessary to study the phenomenon of the spatial distribution of livestock effluents and their consequences while maintaining both a wide space for analysis and an adequate level of detail. This allows to appreciate the differences between different regions but at the same time, allows to work with a level of detail that is congruent with the transport distances used in these applications and in the literature.

Livestock effluent management is strongly influenced by several factors, as highlighted above. Furthermore, the transport of livestock effluents, as for other types of biomass (Mattioli et al., 2017), is economically sustainable only if the road network is adequately developed (Zheng and Qiu, 2020) and the distances do not exceed a certain value which depends on the type of biomass and the way in which it is stored: 20-50 km for chips in trucks (Boukis et al., 2009), 10 km for feedstock with low dry matter content, such as slurry (< 10%) and 50 km collection radius for feedstock having high dry matter content (~70%) (Scarlat et al., 2018). For these reasons, detailed data collection is necessary to build an adequate mapping of livestock effluent production to implement an efficient system for the management of nitrogen and enhance bioenergy production (through biogas/biomethane plants). Specific analysis, tools and spatial statistics models have been used by several authors both to describe the distribution of livestock activities (or livestock effluents) (Fu et al., 2012) and to plan systems of management (Zheng and Qiu, 2020). A typical question is whether features (areas) with a similar distribution of livestock activities are clustered, randomly distributed or dispersed. In most cases, the distribution of attribute values does not show evidence of complete spatial randomness

(CSR) but tends to be clustered into specific areas. Although these studies are performed by authors (Allen, 2011), their application in Europe and Italy has not been adequately developed.
This research aimed to provide a spatial analysis of the effect of the livestock system, considering both nitrogen pollution and methane production for energy purposes, and to identify areas that are more suitable for the location of plants dedicated both to nitrogen treatment plants and biogas production, combining the benefits and costs of livestock effluent management. The study was not based on a sample of farms but on data surveyed throughout the national territory by control institutes, obtaining a municipal and non-regional detail as in other works reported by literature. Implemented data made it possible to analyze efficient solutions for the management of livestock effluents. In the analysis, the existing biogas plants were considered in their actual positions; this in order to study the effects of the modification of the plant diets, currently mainly fed with dedicated energy crops.

3.3 Materials and Methods

The methodology adopted for a concurrent analysis of nitrogen and methane produced by livestock effluents can be summarized by the flowchart reported in Figure 3-1. The first part of the diagram is related to data collection, which took advantage of the competent national authority database. The second part mainly refers to conversions related both to nitrogen load and to methane potential, and provides needed inputs for the geographical spatialization. In the third part, the spatial analysis allows the development of scenarios at different distance, to eventually converge to a best clusterization. It is worth noting that the road network was not considered in the distance calculation: for sake of simplicity the Euclidean distance was implemented in the exploitation of scenarios and the Manhattan distance in the spatial analysis. Moreover, the study does not consider the possible transfer of effluents between different municipalities: for such reason the nitrogen load was calculated not considering the contribution from neighbor municipalities.

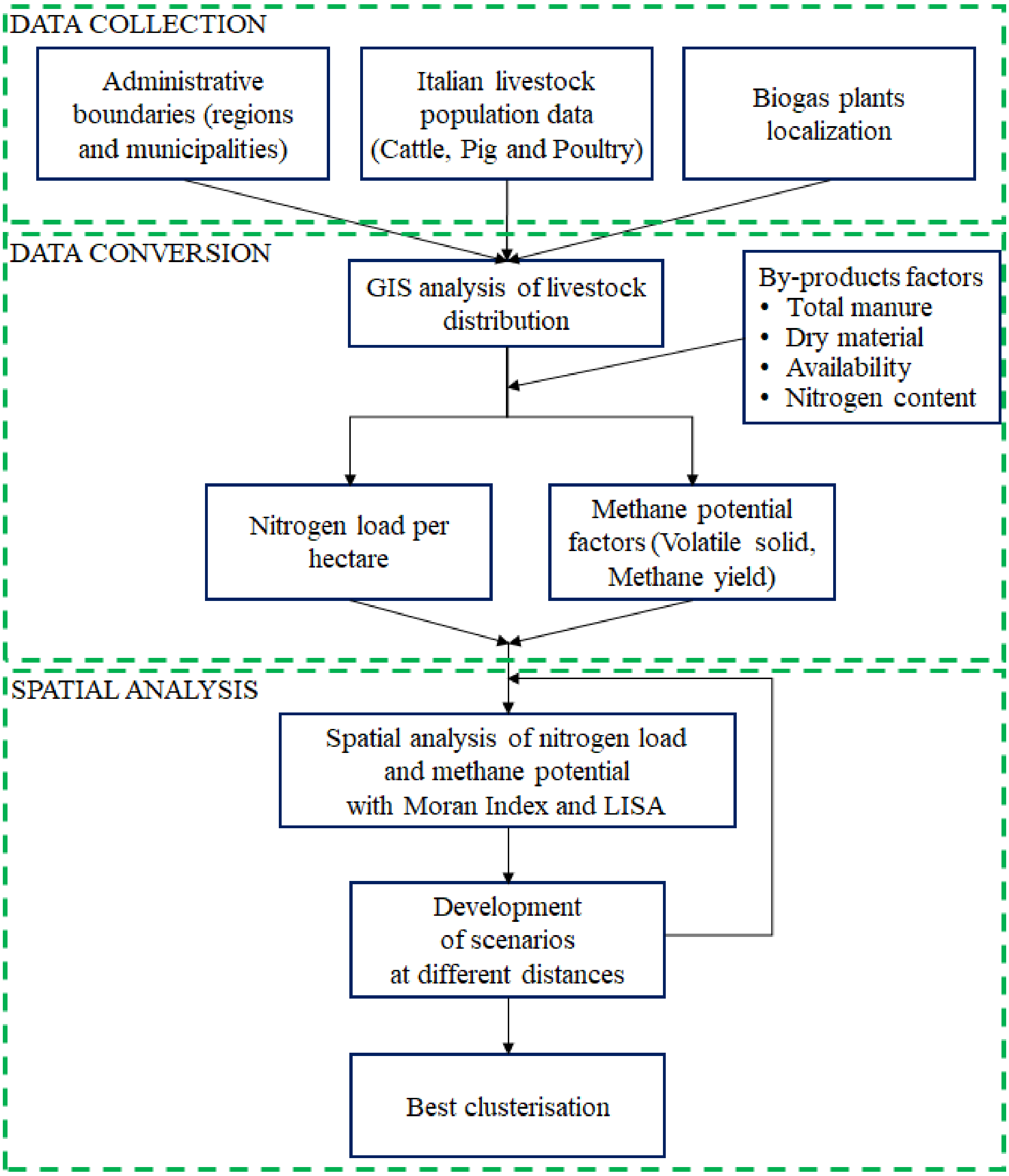


Figure 3-1. Flow chart describing the operating steps of the methodology

3.3.1 Data collection and processing

3.3.1.1 Italian livestock population

Data related to the livestock distribution were provided by the National Livestock Population Database (NLP), managed by the Italian Ministry of Health. NLP collects data/information regarding the animal population of livestock interest and characterizes the livestock system: productive orientations (e.g., meat, milk, eggs), size and characteristics of farms and distribution in the territory. Data and categories of livestock animals, especially dairy cows, beef cattle, pigs (sows and swine) and poultry, were used to estimate the total nitrogen excreted and the amount of effluent available for energy production. To avoid the bias of underestimating the value of emissions, the value used for the analysis was the average value of the last five years (2016-2020) multiplied by three times the standard deviation. Collected data allow to hypothesize both scenarios with a mix of bioresources for biogas plants (Scarlat et al., 2018), and scenarios with digesters powered by a single biomass source: cattle (White et al., 2011), pig (Thien Thu et al., 2012) and poultry (Jurgutis et al., 2020). In recent years, this opportunity has also been considered for plants fed with chicken manure, for which both national estimation studies (Tańczuk et al., 2019) and specific laboratory analyses aimed at determining the methane potential have been conducted (Molinuevo-Salces et al., 2010).

The most important categories of livestock were selected for this study (Table 3-1). The data collected represent 95.9% of the animal unit (AU) of the total Italian livestock sector, which also includes extensive livestock and familiar farms with a nonsignificant number of animals. To obtain a comprehensive view of livestock present in the Italian territory, the total AU was calculated considering the impact of livestock on the consumption of natural resources. The following coefficients of the conversion into AU were found in the literature (Scarlat et al., 2018) and used in the present analysis: 1 AU per 1 cattle; 0.800 AU per 1 beef; 0.300 AU per 1 pig bred for reproduction; 0.200 AU per 1 pig bred for meat; 0.013 AU per 1 unit of poultry.

Table 3-1. Categories of livestock/animals included in the research

Livestock	Category of livestock farming	Production
Cattle	Extensive, Intensively housed livestock	Meat, milk, mixed
Pig	Semi-intensive, intensive	Reproduction, meat
Poultry	Intensive, extensive, biological	Meat, eggs, reproduction

3.3.1.2 Nitrogen limits and vulnerable zones

The Council Directive 91/676/EEC (European Commission, 2000), regarding the protection of waters against nitrogen pollution from agricultural sources (Nitrates Directive), establishes that the amount of livestock effluents (expressed in kg of N per hectare per year) per used agricultural area (UAA) is equal to i) 170 kg of N per hectare per year in nitrate vulnerable zones (NVZs) and ii) 340 kg N per hectare per year for all remaining areas per year (Huygens et al., 2020).

As a result of a national survey (Frizza et al., 2018), 16,076 vulnerable zones have been identified, covering a total area of 25,364.8 km^2 (Figure 3-2). In these areas, the limit of 170 kg N per hectare must be respected (in the remaining territory, the limit is 340 kg N per hectare per year). Areas with a higher risk are concentrated in the Po Valley, in the northern Italy, in the north of Campania region and in Sicily (south of Italy). In these areas a careful control of nitrogen emission must be organised. In this study, the nitrogen load per hectare was assessed. The used surface was equal to 100% of the UAA and was considered to have a fixed value that could be used to perform more specific analyses in specific study areas. The map of NVZs was combined with the municipality map to identify the nitrogen amount that could be absorbed by each municipality.

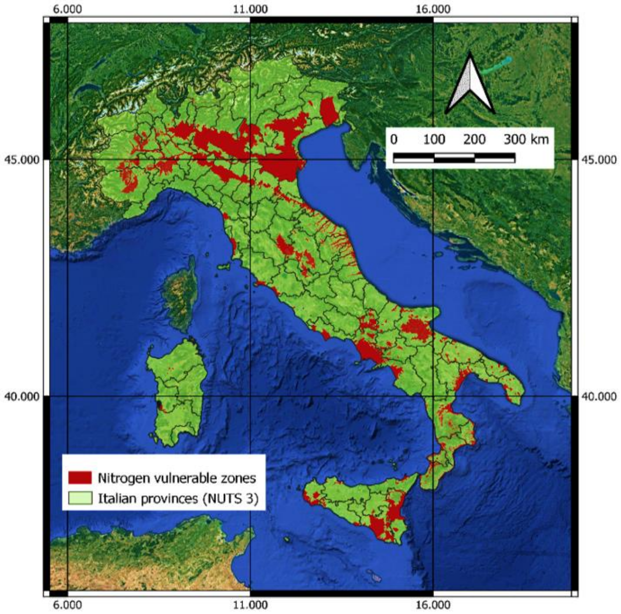


Figure 3-2. Map of vulnerable zones in Italy referring to the Nitrates Directive

3.3.2 Livestock effluents and biogas potential

To calculate the amount of nitrogen and methane produced by livestock effluents, the values of manure and slurry excreted for each category of animal were assigned. Livestock effluents were characterised by their chemical/physical composition, which allowed to associate a robust value of nitrogen and biogas production to each head per year. The chosen values are expressed in tons per head per year of fresh material (FM) and were provided by the Italian discipline of livestock waste management (Regione Veneto, 2019) (Table 11). To characterize the waste composition, the values of dry matter (DM) as a percentage of FM, volatile solids (VS) as a percentage of DM and the amount of methane (CH4) per ton of VS were collected and applied to the starting amount of manure and slurry (Table 3-2). To assess these potentials, percentages of availability of 50% for cattle effluents, 80% for pigs and 80% for poultry effluents were considered (Meyer et al., 2018).

Nitrogen production in livestock effluents net of losses per category of livestock animal was defined based on the procedural guidelines of the Italian discipline of livestock waste (Regione Veneto, 2019). In the present analysis, the following values were used: pigs - sows 26.4 kg/(heads·year) (Nardin and Mazzetto, 2014), pigs - swine 20.0 kg/(heads·year) (Xiccato et al., 2005), dairy cows 83.0 kg/(heads·year), beef cattle 33.6 kg/(heads·year) (Bernal et al., 2009), and poultry 0.25 kg/(heads·year) (Garcia et al., 2019). The resulting values of effluents and nitrogen production were compared with those reported in the literature to obtain a set of more reliable indicators.

Table 3-2. Livestock waste characterization for each category of animal

	Slurry*				Manure**				Reference
	FM t/head/y	DM %FM	VS %DM	CH_4 m^3/tVS	FM t/head/y	DM %FM	VS %DM	CH_4 m^3/tVS	

Dairy Cow (a)	9.8	8	80	200	10.8	20	80	100	(Al Seadi et al., 2013; Allen et al., 2016; Batzias et al., 2005; Browne et al., 2013; Caliskan et al., 2020; Garcia et al., 2019; Kouas et al., 2017; Tańczuk et al., 2019)
Beef Cattle (b)	5	8	80	200	5.40	20	80	100	
Pig Sow (c)	6	5	80	300	1.89	20	80	300	
Pig Swine (d)	5	5	80	300	1.89	20	80	300	
Poultry (e)	-	-	-	-	0.015	20	80	300	

* Feces and urine.

** Feces, urine and bedding material.

(a) cows for milk production, (b) cattle for meat production, (c) pig breeding production, (d) pig fattening production and (e) poultry production; according to National Livestock Population Database (NLP)

A comprehensive analysis of Italian biogas plants was conducted to determine the areas that make the highest contribution of bioenergy. A data survey of 2,723 biogas plants operating in Italy was performed based on reports provided by the National Energy Services Administration (GSE, 2020). For each biogas plant, the power, location and type of feedstock were associated, and a complete map of the biodigesters was generated (Figure 3-3). Agricultural biogas plants are powered by different types of biomass. Dedicated energy crops still play an important role for bioenergy plants in Italy, around 30% (Kampman et al., 2020). Many of these plants were installed following the introduction of an incentive system of 280 Euro/MWh with no restrictions on the matrices used, nor any obligation for heat recovery. The only constraint was the possibility of application only on plants with an average annual nominal power not exceeding 1 MWe. This determined that most of the plants had a maximum power of less than 1 MWe and that their operation involved extensive use of dedicated energy crops, mostly corn silage. The updating of the legislation required the search for solutions that would take into consideration only by-products for feeding the plants (Statuto et al., 2019).

The distribution of biogas plants is very heterogeneous in Italy. In the regions of northern Italy, there are 2,035 plants (74.7%) that produce 1,294 MW of biopower (75.2% of total). Observing the power of the facilities, 2,555 (93.8%) biogas plants have an installed power of less than 1 MW and produce 1,351 MW (78.5% of total). Nine hundred-one (33.1%) plants have very low installed power, less than 250 kW, and produce 114.6 MW (6.7% of the total).

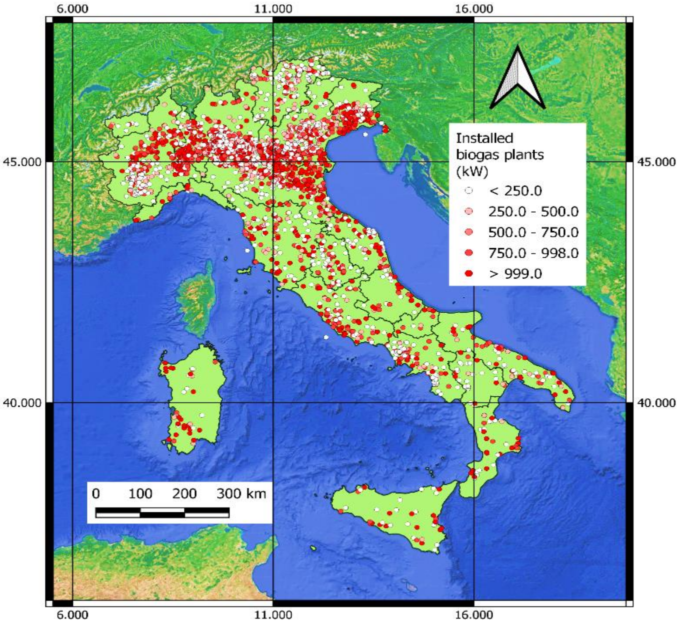


Figure 3-3. Map of biogas plants in Italy

3.3.3 Spatial analysis

3.3.3.1 Range of exploitation distance

The distance between livestock effluent production areas and biogas plants is a key element because the cost and consumption of energy due to transport can prevent convenient exploitation of effluents (Ruiz et al., 2013).

The biomass collection areas for biogas plants are not limited to the municipality in which they are located; to assess an index of the theoretical power installed in a municipality, the total power of the plants located at distances of 5, 10, 15, and 20 km from the centroid of the municipality was calculated and assigned to the municipality. By this analysis, it was possible to assign the index of currently installed power in an area to municipalities where there are no plants. This index, calculated for the four supply distance scenarios (5, 10, 15, and 20 km), was compared with the potential methane production in the territory.

In the second analysis of transport, the effects of the full exploitation of livestock resources based on existing plants and different supply distances were studied. Starting from the location of biogas plants, buffers of 5, 10, 15, and 20 km were drafted for each plant. The hypothesis was that all the animal wastes inside the buffer could be used to feed the biogas plant and could be removed from the availability map. By this process, the total amount of collected methane inside the buffer in each scenario of distance and the not exploited production that are outside the buffer zones were evaluated.

3.3.3.2 Distribution of the livestock effluents

Italian livestock farms showed a heterogeneous distribution; therefore, a spatial analysis was carried out to determine whether there were areas (clusters) subjected to high nitrogen pollution or that were particularly profitable at producing biogas and where they are located. To determine if there were clusters of effluent production, spatial statistics tools were used to calculate the spatial autocorrelation among the parameters of the elements: animal units per square kilometre, nitrogen load per hectare and methane potential.

In spatial statistics, spatial autocorrelation is a measure of correlation between the same attribute observed in two nearby observations. The most widely adopted indicator to assess spatial autocorrelation (i.e., to reject the null hypothesis of complete spatial randomness, CSR) is global Moran's index (Moran, 1950), a correlation coefficient for the relationship between a given variable and its surrounding values (Eq. (1))

$$I = \frac{n \cdot \sum_{i=1}^{n} \sum_{j=1}^{n} v_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} v_{ij} \sum_{i=1}^{n} (x_i - \bar{x})^2} \qquad \text{[Eq. 1]}$$

where:

I: Moran's index;

n: number of geographical elements of the considered set;

v_{ij}: denotes the elements of a spatial weight contiguity matrix;

x_i: the variable of interest;

$\bar{x}$: the mean of attribute x;

In this study, the assessment of Moran's index was applied to the following parameters: (*i*) AU density in each municipality (expressed as animals per square kilometre), (*ii*) nitrogen load per hectare of used agricultural area (UAA) expressed as kilograms per hectare, and (*iii*) methane potential density in each municipality expressed as cubic metres per square kilometer.

The process was conducted using ArcGIS 10.5 (ESRI, Redlands, CA) software and defined the neighbors of the municipalities; the inverse distance method was applied using the Manhattan method to calculate the distances. A typically representative range for the efficient management of livestock effluents is generally between 5 and 20 km. In this study, a distance of 15 km was applied based on the results obtained that confirmed average values reported in the literature. These are the transport distances that can be used as a reference for a conversion of the diets of the plants towards a scenario completely based on by-products and livestock effluents.

However, Moran's index provides a unique statistical value for the entire set of elements. The absence of clustering at the global level does not imply the absence of clusters at the local level and, eventually, where they are localized. To answer this question, the general local indicators of spatial association (LISA) elaborated by Anselin, 1995, was used to determine the contribution of Moran's index for each observation. The required parameters must be coherent with those used in Moran's index calculation. By this analysis, cluster maps and Moran's scatter plots were developed, in which the features analysed and represented were municipalities. The maps of the municipalities were coloured according to whether they belonged to a cluster; thus, it was possible to directly identify clusters of "high" or "low" production on the map. Moran's scatter plot allowed to identify potential outliers and the influence of single observations and establish whether a municipality is included in a cluster.

3.4 Results and discussion

3.4.1 Livestock, nitrogen load and methane production

In Italy, there are a total of 6,022 thousand heads of cattle, 8,796 thousand heads of pigs and 151,273 thousand heads of poultry (Table 3-3). Animals were divided based on the production orientation: 3,297 thousand cows for milk production (54.8% of the total) and 2,725 thousand for beef (45.2% of the total). The number of pigs for reproduction was 2,968 thousand (33.7% of the total), while those for meat were 5,828 thousand (66.3% of the total).

Table 3-3. Italian livestock distribution (values expressed in thousands)

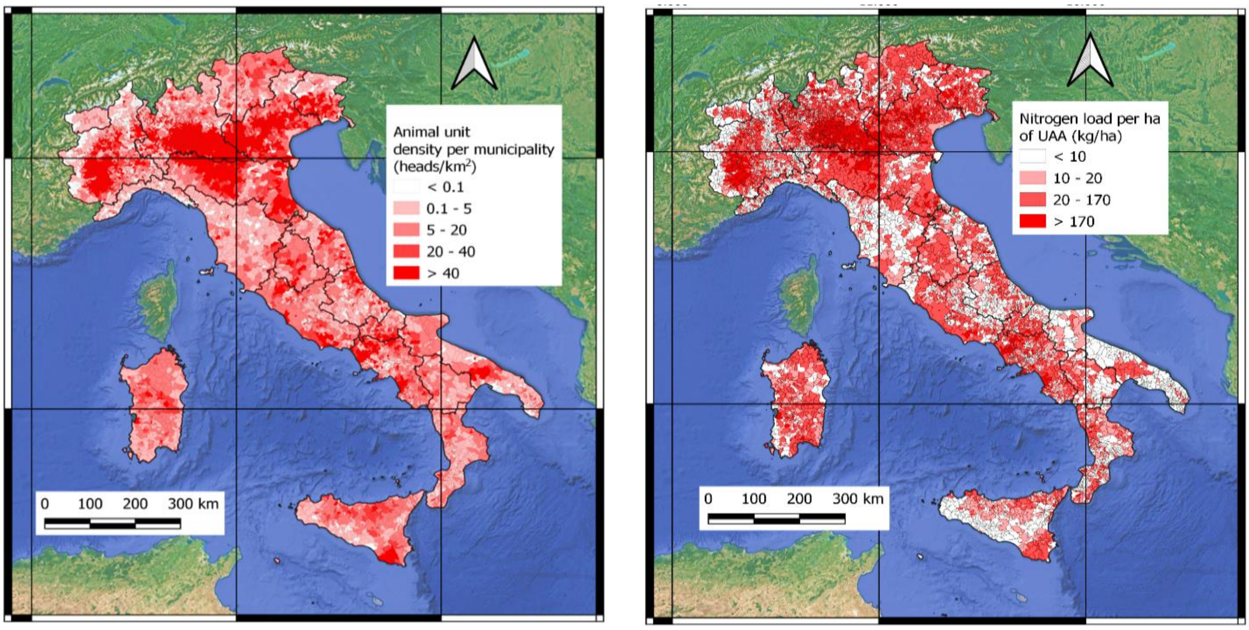
	Cattle	Pig	Poultry	Animal Unit
Piedmont	818	1,289	9,349	1,180
Aosta Valley	32	0	6	29
Lombardy	1,505	4,390	26,642	2,799
Liguria	13	1	64	12
North-west	2,368	5,680	36,061	4,020
Trentino-Alto Adige	170	9	723	164
Veneto	756	682	50,445	1,507
Friuli Venezia Giulia	75	244	6,838	218
North-east	1,001	935	58,006	1,889
Emilia-Romagna	572	1,130	23,061	1,097
Tuscany	89	117	1,174	125
Umbria	56	203	3,004	140
Marche	48	113	4,905	135
Middle-north	765	1,563	32,145	1,498
Lazio	278	41	2,802	297
Abruzzo	63	70	3,837	124
Molise	39	20	4,521	99
Middle-south	380	131	11,161	520
Campania	459	85	3,316	477
Apulia	188	38	4,049	232
Basilicata	105	62	125	112
Calabria	119	47	581	126
South	870	231	8,070	947
Sicily	361	77	5,027	409
Sardinia	278	180	804	306
Isles	638	257	5,831	715
TOTAL	6,022	8,796	151,273	9,589

The regions with the highest number of animals are Lombardy and Veneto. In this area, there are 3,941 thousand cattle heads (65.4% of the total), 7,749 thousand pig heads (88.0% of the total) and 117,128 thousand poultry heads (77.4% of the total) (Figure 3-4a). Municipalities with high values are mainly located in northern Italy, the area where the livestock sector is most relevant. The areas with the highest value of nitrogen per hectare of UAA (Figure 3-4b) are the south of Lombardy and the coast of Campania, which are characterized by a high concentration of livestock farms. The distribution of the nitrogen load is more widespread than the distribution of the farms since municipalities with elevated concentrations of livestock farms also have vast areas of UAA available for the distribution of nitrogen.

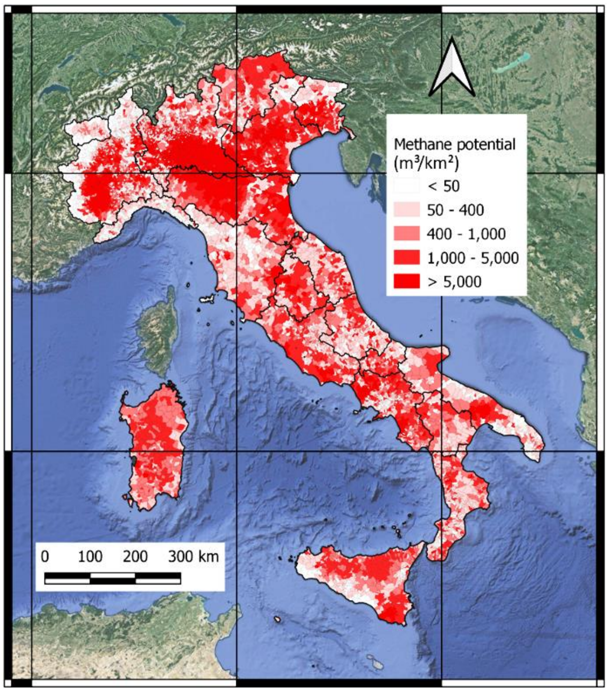
Table 3-4. Nitrogen production in Italian municipality

Amount of nitrogen	Number of municipalities	Percentage
< 10 kg/ha	2,971	37.6
10 - 20 kg/ha	1,110	14.0
20 - 170 kg/ha	2,981	36.6
> 170 kg/ha	929	11.7

The distribution of the areas with high value of nitrogen load per hectare corresponded to the nitrogen vulnerable zones (Figure 3-2), underlining the importance of a proper management of livestock effluents in these areas.



(a) (b)



(c)

Figure 3-4. Thematic maps of the livestock system in Italy and its consequences: (a) AU per square kilometre in the Italian municipalities, (b) nitrogen load per hectare of UAA (kg/ha), (c) methane potential in the Italian municipalities (m^3/km^2)

The distribution map of the methane potential follows the distribution of livestock farms. The regions with the highest potential are Lombardy, Emilia Romagna, Piedmont, Veneto and Campania. Other regions contribute $397 \cdot 10^6$ m^3 (20.1% of the total) (Figure 3-4c). The overall potential is $1{,}764 \cdot 10^6$ m^3, which is able to provide 6,879.2 GWh of electric energy per year, and this amount is equivalent to 2.3% of Italy's total electric energy consumption, equal to 301,804 GWh (Terna Rete Italia, 2019), highlighting the importance of this source of energy for the national energy system (Chiumenti et al., 2019).

The regions with the highest percentage of bioenergy production compared to their electric energy consumption are Lombardy, Piedmont and Emilia Romagna (Terna Rete Italia, 2019). According to the municipality level, the analysis demonstrated that in 2,393 municipalities (30.3) there are enough livestock effluents to autonomously supply almost one biodigester with 999 kW of power: 551 are located in Lombardy (36.6% of the municipalities of the region), 345 are located in Veneto (61.3% of the region), 238 are located in Piedmont (20.2% of the region), and 239 are located in Emilia-Romagna (72.9% of the region) (Table 3-5).

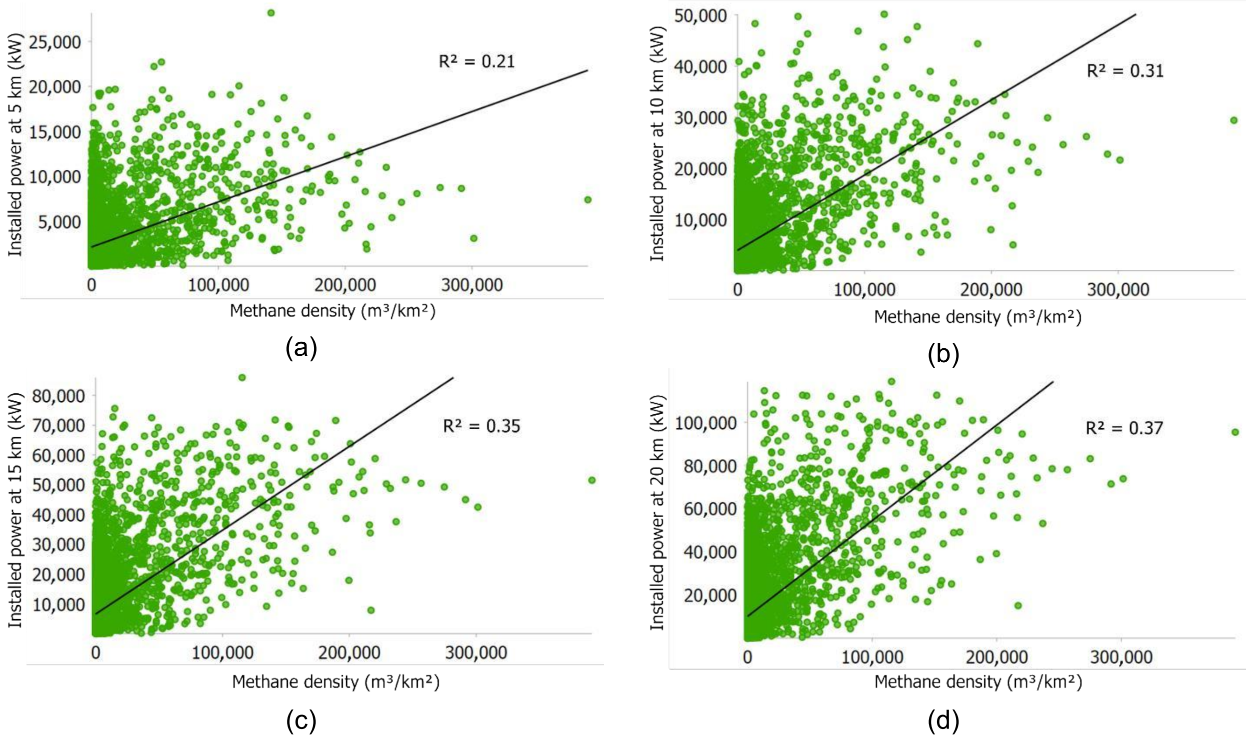
Table 3-5. Methane produced in the regions and contribution to the regional energy demand

	Methane ($\times 10^6$ m^3)	**Percentage on national production (%)**	**Energy potential (GWh)**	**Energy demand (GWh)**	**Percentage of bioenergy potential (%)**	**Municipalities with energy potential for a plants of 1 MW**	**Percentage on municipalities in the region (%)**
Piemonte	202	11.5	1,013	23,827	4.3	387	32.8
Valle d'Aosta	1	0.1	5	966	0.5	5	6.8
Lombardia	642	36.4	3,219	66,505	4.8	743	49.3
Liguria	2	0.1	8	6,102	0.1	12	5.1
North-west	847	48.0	4,246	97,400	4.4	1,147	38.3
Trentino-Alto Adige	35	2.0	175	6,780	2.6	164	58.2
Veneto	198	11.2	993	30,864	3.2	437	77.6
Friuli Venezia Giulia	43	2.5	217	10,066	2.2	119	55.3
North-east	276	15.7	1,385	47,711	2.9	720	67.9
Emilia-Romagna	221	12.5	1,108	28,294	3.9	276	84.1
Toscana	22	1.3	111	19,481	0.6	97	35.5
Umbria	25	1.4	124	5,307	2.3	62	67.4
Marche	16	0.9	82	6,868	1.2	109	47.8
Middle-north	284	16.1	1,424	59,951	2.4	544	59.1
Lazio	52	2.9	259	21,610	1.2	158	41.8
Abruzzo	16	0.9	80	6,275	1.3	98	32.1
Molise	11	0.6	54	1,361	3.9	64	47.1
Middle-south	78	4.4	393	29,245	1.3	320	39.1
Campania	103	5.9	518	16,934	3.1	224	40.7
Puglia	38	2.1	189	16,826	1.1	85	33.1
Basilicata	15	0.9	76	2,806	2.7	84	64.1
Calabria	18	1.0	92	5,178	1.8	129	31.9
South	175	9.9	876	41,743	2.1	522	38.9
Sicilia	54	3.1	272	17,283	1.6	179	45.9
Sardegna	50	2.8	249	8,472	2.9	264	70.0
Isles	104	5.9	521	25,755	2.0	443	57.8
Italy	1,764	100	8,845	301,804	2.9	3,696	46.8

3.4.2 Scenarios of exploitation

3.4.2.1 Relation between biogas production and installed power

The total value of installed power of the biogas plants at 5, 10, 15, and 20 km was assessed and assigned to each municipality; then, this value was compared to the energy potential density of the territory. This relation indicated which regions experienced higher exploitation of resources and which experienced lower exploitation. The diagrams in Figure 3-5 show the relationship between the methane potential density in each municipality and the power installed at the considered distances: 5 km (Figure 3-5a), 10 km (Figure 3-5b), 15 km (Figure 3-5c), and 20 km (Figure 3-5d). The relation between the two parameters is low for short distances due to the high number of outliers, municipalities with no plants or farms, but were included in areas where such facilities are present or livestock activities are practiced. However, the higher the analysis distance, the higher the proportionality between the methane potential density in each municipality and power installed at the considered distances; the proportionality between the parameters ceases to increase when the transport distances are over 15 km, a value considered suitable for profitable enhancement.



(a) (b)

(c) (d)

Figure 3-5. Methane potential and spatially lagged installed power: (a) 5 km, (b) 10 km, (c) 15 km, (d) 20 km

3.4.2.2 Exploitation scenarios at different distances

Hypothesizing the average distribution of methane production in each municipality, the amount of methane produced in the area overlapping with the buffer and the amount of methane still available were assessed (Figure 3-6). The analysis determined that 75.0% of resources (1,322·10^6 m^3) are located at a distance of less than or equal to 5 km. At a distance of 10 km, the methane included increases to 1,585·10^6 m^3 (89.9% of the total). At a distance of 15 km, 1,671·10^6 m^3 (94.7% of the original amount) can be collected. Finally, with a supply distance of 20 km, almost all the methane is included in the buffer: 1,717·10^6 m^3 (97.4% of the original value). These results confirmed and validated previous research on the topic.

Regions hosting the largest number of plants are also those with the highest value of methane potential. In these regions, most of the areas are located within a short distance from the biogas plants, often less than 5 km from the nearest plant (Table 3-6).

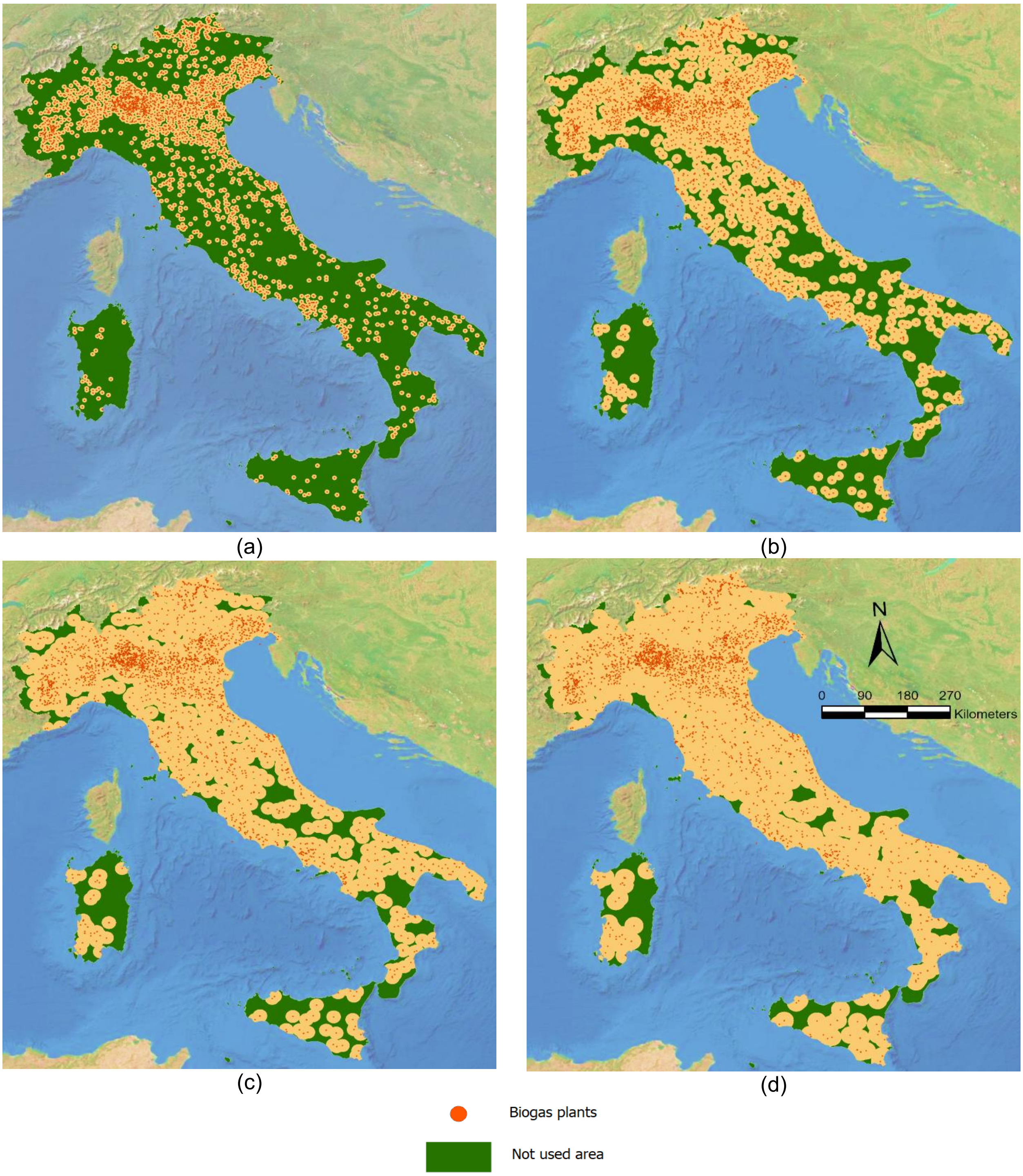


Figure 3-6. Biogas plants and unused areas in 5 km (a), 10 km (b), 15 km (c) and 20 km (d) radii

Table 3-6. Value and percentage of methane produced in the area at 5 km, 10 km, 15 km and 20 km from the biogas plant

Region	Methane	Methane used at 5 km		Methane used at 10 km		Methane used at 15 km		Methane used at 20 km	
	(m^3×10^6)	(m^3×10^6)	%	(m^3×10^6)	%	(m^3×10^6)	%	(m^3×10^6)	%
Piemonte	202.1	168.6	83.4	198.3	98.1	201.3	99.6	202.0	100.0
Valle d'Aosta	1.0	0.2	21.3	0.6	62.6	0.9	88.5	0.9	97.8
Lombardia	642.0	616.1	96.0	636.5	99.1	640.3	99.7	641.7	99.9
Liguria	1.7	0.1	6.1	0.5	27.0	0.9	56.0	1.3	79.1
North-west	846.7	785.0	92.7	835.8	98.7	843.5	99.6	845.9	99.9
Trentino-Alto Adige	34.9	21.3	61.1	32.8	93.9	34.9	99.9	34.9	100.0
Veneto	198.0	169.5	85.6	194.3	98.1	197.6	99.8	198.0	100.0
Friuli Venezia Giulia	43.3	36.8	85.2	42.2	97.5	43.1	99.5	43.2	100.0
North-east	276.2	227.6	82.4	269.3	97.5	275.6	99.8	276.2	100.0
Emilia-Romagna	220.9	162.5	73.6	214.1	96.9	219.7	99.5	220.9	100.0
Toscana	22.1	7.9	35.9	18.0	81.8	21.2	96.1	22.0	99.7
Umbria	24.7	13.1	53.1	22.5	90.9	24.6	99.4	24.7	100.0
Marche	16.3	7.3	45.0	13.5	83.1	15.5	95.5	16.2	99.5
Middle-north	284.0	190.9	67.2	268.2	94.4	281.1	99.0	283.8	99.9
Lazio	51.7	22.9	44.4	41.9	81.1	48.3	93.5	50.3	97.4
Abruzzo	16.0	4.3	26.7	9.2	57.3	12.0	75.4	14.0	87.8
Molise	10.7	1.1	10.6	3.2	29.5	6.1	56.8	9.8	91.9
Middle-south	78.3	28.3	36.2	54.2	69.2	66.4	84.8	74.2	94.7
Campania	103.4	61.1	59.1	87.6	84.7	97.3	94.1	102.3	99.0
Puglia	37.7	7.5	20.0	19.8	52.5	30.2	80.2	35.3	93.7
Basilicata	15.2	3.8	25.3	9.5	62.5	12.8	84.3	13.9	92.0
Calabria	18.4	3.5	18.9	8.5	45.9	12.0	65.0	14.2	77.0
South	174.6	75.9	43.5	125.3	71.7	152.3	87.2	165.8	94.9
Sicilia	54.3	4.3	7.9	14.3	26.4	27.1	49.9	40.6	74.8
Sardegna	49.6	10.5	21.1	18.4	37.2	24.9	50.2	30.8	62.1
Isles	103.9	14.8	14.2	32.8	31.5	52.0	50.0	71.4	68.7
Italy	**1,763.7**	**1,322.6**	**75.0**	**1,585.5**	**89.9**	**1,670.8**	**94.7**	**1,717.2**	**97.4**

3.4.3 Spatial analysis of livestock, nitrogen load and methane production

To analyze the spatial correlation between the heads per square kilometer, nitrogen load per hectare of UAA and methane potential per square kilometer of each municipality, global spatial autocorrelation analysis was performed by the tool "Spatial Autocorrelation (Global Moran's index)" (Table 3-7). For both the AU per square kilometer, the nitrogen load per hectare and CH_4 potential per square kilometer, the p-value passed the 1% significance level test. Therefore, AU density, nitrogen load and methane potential are spatially clustered at the global level.

Table 3-7. Moran's index analysis results

Parameter	Animal Unit (head per km^2)	Nitrogen load (kg/ha)	Methane potential (m^3/km^2)
Moran's Index	0.638226	0.351278	0.588694
expected value	-0.000127	-0.000127	-0.000127
variance	0.000029	0.000028	0.000029

z-value	118.97	65.92	109.95
p-value	0	0	0

LISA was used to locate the spatially clustered and isolated regions using the tool “Cluster and Outlier Analysis (Anselin Local Moran’s Index)”. The results are shown in Figure 3-7.

For the number of animal units (AU) per square kilometer (Figure 3-7a), 764 municipalities (9.7%) are located in “high-high” clusters, while the “low-low” cluster include 2,774 (35.1%) municipalities.

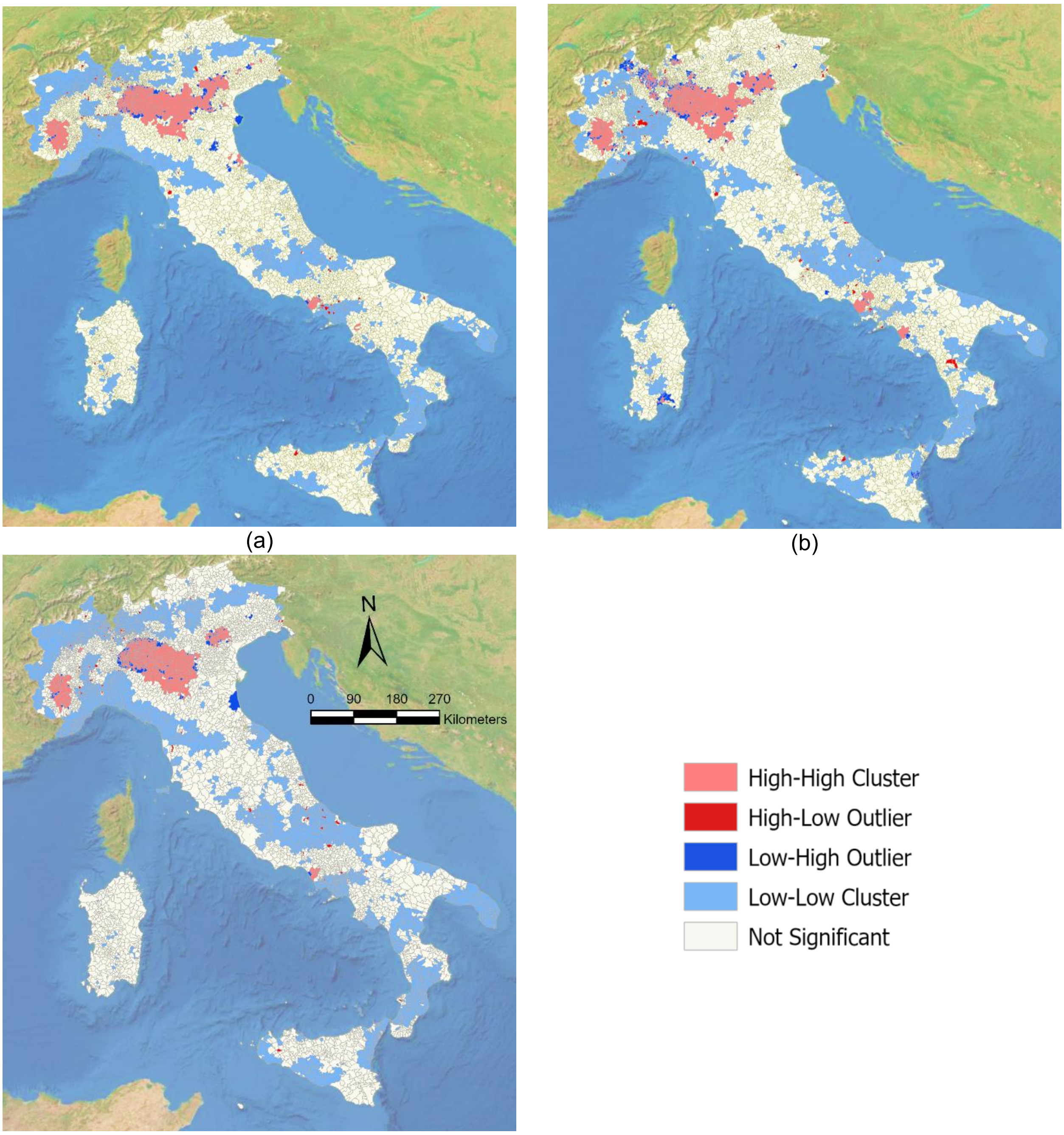
“High-high” clusters are located in the Po valley and in the south of the Piedmont region; medium clusters are also located in the Campania region. “Low-low” clustered regions are mainly distributed along the mountain chains, and there are several cluster areas in southern Italy, Calabria, Campania, Sicily and Sardinia. This cluster distribution accurately reflects the map of the distribution of livestock (Figure 3-4a).

“Low-low” clustered regions identify regions where intensive livestock is difficult because of the orographic features of the territory, the absence of water resources and the lack of a developed industrial framework. In these regions, extensive grazing is widespread and small farms are mainly managed at the family level. Finally, there are 67 municipalities with high-low outliers (0.8%) and 115 with low-high outliers (1.5%).

The results of the analysis of nitrogen load per hectare of AUU are shown in Figure 3-7b. “High-high” clusters are located in the same areas identified in the previous analysis, the Po valley, Lombardy (552 municipalities), Veneto (149) and Emilia-Romagna (50), the south of Piedmont region (90 municipalities), and Campania region (small clusters with 34 municipalities), and include 881 municipalities (11.1%). “Low-low” clusters with 2,353 municipalities (29.8%) mainly located in northwest Italy and in the Piedmont and Liguria regions. This distribution is deeply affected by the availability of agricultural areas; many regions, including Tuscany, Emilia-Romagna, and part of Veneto and Friuli-Venezia-Giulia, showed a low load of nitrogen in the field because the orographic condition is particularly suitable for agricultural activities and there is a wide area for nitrogen disposal. There are 72 municipalities with high-low outliers (0.9%) and 337 with low-high outliers (4.3%) that do not fall into any of the clusters.

In Figure 3-7c, the results of the analysis of the methane potential per square kilometer are reported. “High-high” clusters, 635 municipalities (8.0%), are in the areas where the previous analysis identified a considerable presence of livestock farms: the Po valley, south of Lombardy (410 municipalities), Veneto (78), north of Emilia-Romagna (62), and south of the Piedmont region (78). “Low-low” clustered areas, 3,265 municipalities (41.3%), are very scattered in the country, mainly located in mountain areas. Many municipalities are not included in any clusters, 77 high-low outliers (1.0%) and 121 low-high outliers (1.5%); in other words, livestock effluents are randomly scattered across these territories, which means that the exploitation of methane in these areas is possible because there are municipalities with high resources. However, the supply distance could increase;

therefore, the use of district plants that collect effluents from various areas may require greater distances and compromise the efficiency or profitability of their use.



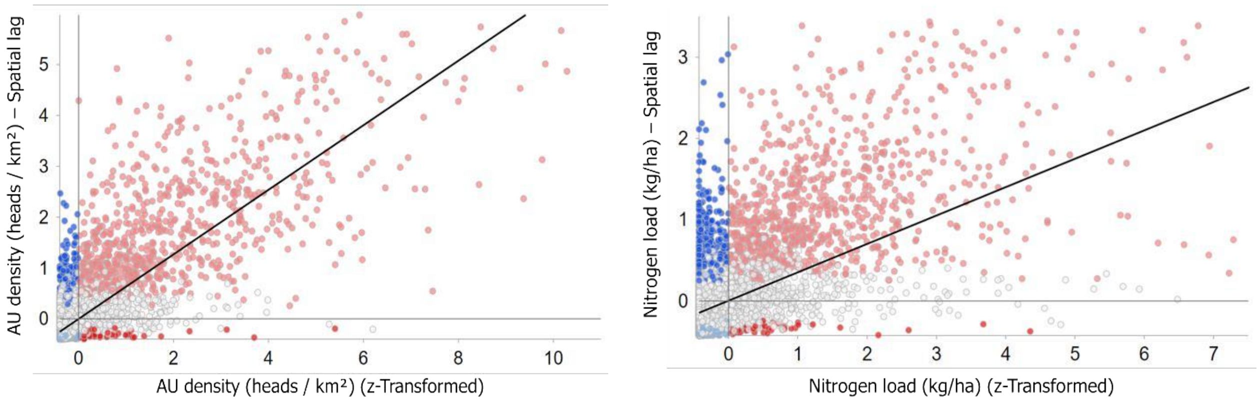
(a)

(b)

(c)

Figure 3-7. Local spatial autocorrelation pattern: Animal Unit (AU)per square kilometre (a), nitrogen load per used agricultural area (UAA) (b) and methane potential per square kilometre (c)

Anselin’s Moran scatter plots are shown in Figure 3-8. In particular, Figure 3-8a shows Moran’s index scatter plot of AU per square kilometre, Figure 3-8b shows Moran’s I scatter plot of nitrogen load per hectare and Figure 3-8c shows Moran’s I scatter plot of methane potential per square kilometer. The first and third quadrants show a positive spatial relationship; the other two quadrants show a negative spatial relationship. In the first quadrant, high-value municipalities are surrounded by other high-value municipalities (High-High). In the second and third quadrants, low-value areas are surrounded by high-value areas (Low-High), and vice versa (High-Low). The slope of the interpolation line represents Moran's I value. Graphs allow to identify the outlier and to have a visual distribution of the elements of the clusters.



(a) (b)

Figure 3-8. Anselin's Moran scatter plot: (a) Animal unit (AU) per km^2, (b) nitrogen load per hectare of UAA, (c) methane potential per km^2 in the Italian municipalities

3.5 Conclusions

The present paper investigated the livestock system in Italy and applied spatial statistical tools in order to describe the distribution of effluents and provide a cluster representation of nitrogen load and biogas potential.

The study forecasted a supply system with shorter distances than those reported by literature, particularly in areas characterized by a higher production of biomass. The analysis gave evidence that 75.0% of the bioresources are available within a distance of 5 km from the nearest biogas plant, and 89.9% within 10 km. These distances should be increased by roughly 35-40% (Gonçalves et al., 2014) due to the fact that they refer to Euclidean rather than road distances; nevertheless such values confirm that a proper biomass supply to the existing biogas plants could be reached with shorter distances than those reported by literature (15-50 km on average). In the spatial analysis, 5611 municipalities, 71.0% of the total, are in the same cluster regarding biomethane production and the nitrogen load, justifying a concurrent study. 635 municipalities lay in the cluster "high-high" for methane potential and 881 in the same cluster for nitrogen load; among these areas, 579 municipalities are in "high-high" cluster for both the two parameters demonstrating the existence of a good correlation between the two parameters.

Policy makers might intervene at local level, promoting district plants, and supporting the exploitation and management of effluents of the smaller farms. At national level, an incentive system could be implemented to stimulate the energy production by biomethane. Producers could be granted a tax bonus to reward energy production without the emission of carbon dioxide into the atmosphere.

Future research can define the specific location of plants for effluent combined management and assess the actual share of by-products that can be exploited by the existing plants. These spatial analysis tools can be applied in different regions or countries characterized by high heterogeneity, to support decision on macro-territorial scale.

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4 Land-Use Change and Bioenergy Production: Soil Consumption and Characterization of Anaerobic Digestion Plants

4.1 Abstract

The exploitation of bioenergy plays a key role in the process of decarbonising the economic system. Huge efforts have been made to develop bioenergy and other renewable energy systems, but it is necessary to investigate the costs and problems associated with these technologies. Soil consumption and, in particular, soil sealing are some of these aspects that should be carefully evaluated. Agricultural biogas plants (ABPs) often remove areas dedicated to agricultural activities and require broad paved areas for the associated facilities. This study aimed to (i) assess the surfaces destined to become facilities and buildings in ABPs, (ii) correlate these surfaces with each other and to the installed powers of the plants, and (iii) estimate the consumption of soil in bioenergy applications in Italy. Two hundred ABPs were sampled from an overall population of 1939, and the extents of the facilities were measured by aerial and satellite observations. An ABP with an installed power of 1000 kW covers an average surface area of up to 23,576 m^2. Most of this surface, 97.9%, is obtained from previously cultivated areas. The ABP analysis proved that 24.7 m^2 of surface area produces 1 kW of power by bioenergy. The obtained model estimated a total consumption of soil by ABPs in Italy of 31,761,235 m^2. This research can support stakeholders in cost-benefit analyses to design energy systems based on renewable energy sources.

Keywords: anaerobic digestion; biomethane; biogas plant; land use; spatial analysis

4.2 Introduction

Bioenergy is one of the most commonly used forms of renewable energy (World Bioenergy Association, 2018) because of both the wide range of suitable biomasses and the ease of energy production and storage (Ferrari et al., 2020; Yılmaz Balaman and Selim, 2016). However, studies are progressing in the field of optimising the benefits of biomass exploitation, especially regarding by-products (Mirkouei et al., 2017), in the optimal location of bioenergy plants (Delivand et al., 2015), in the consideration of bioenergy districts (Karschin and Geldermann, 2015), and in the maximization of economic profits by minimizing the transportation and processing costs (Bacenetti et al., 2013; Mohr et al., 2019; Singh et al., 2010).

Agricultural activities play a key role in developing and managing bioenergy systems (Valenti et al., 2018). This sector can be an integral part of rural community economies and of agricultural processes (Scarlat et al., 2015). The applications of bioenergy can contribute to reducing carbon emissions produced by agricultural activities (Castrillón Mendoza et al., 2018; Valentine et al., 2012) and by industrial and manufacturing activities (Mandova et al., 2018); this aspect could lead to an actual conversion of the energy system (Thrän et al., 2020). From economic and social points of view, bioenergy contributes to creating an energy system based on the local production of resources and an increased awareness in local communities (Pagliacci et al., 2020; Rossi and Hinrichs, 2011). Among the technical opportunities, the advantages of the treatment of livestock effluents in digesters should be considered; the digestate is a stable product for nitrogen removal and can be used as a fertilizer in agronomic activities (Provolo et al., 2017). Together with these opportunities, some issues must be carefully considered. It is essential to carefully consider all the implications, including both the benefits and problems, that can arise when using biomasses for energy purposes (Johnson and Altman, 2014). One of the most important problems is the competition between the energy and food destinations of crops (Ignaciuk et al., 2006).

Regarding the use of land for energy crops, preserving the soil conditions is a crucial issue (Kluts et al., 2017); many studies have discussed how to conjugate energy crops with environmental protection (Hattori and Morita, 2010) by considering areas not suitable for agricultural cultivations (Cronin et al., 2020), such as marginal lands (Liu et al., 2011; Shortall, 2013) and grasses harvested on riverbanks (Boscaro et al., 2018). However, on a large scale, it has been extensively explained that bioenergy systems based on energy crops are the basis of vast cultivated area losses (Sands et al., 2017) because of the depletion of organic carbon (Zhang et al., 2021), soil erosion (Wang et al., 2020), and the occupation of land that cannot be used for food production (Ignaciuk and Dellink, 2006; Valentine et al., 2012). For these reasons, the use of by-products allows the consideration of only the land area of a bioenergy plant as the land occupied for bioenergy production, thus not affecting agricultural production in the territory. This approach allows broad areas of cultivated land to be saved. Considering the most important crops used for energy purposes (Villa et al., 2020) and their yields per hectare and energy value, it can be determined that providing the diet for an agricultural biogas plants (ABP) with a power of 1000 kW requires a wide area of land (Table 4-1).

Table 4-1. Land area necessary to supply, with energy crops, an ABP with an installed power of 1000 kW.

Type of Crop	Area of Cultivation (ha)	References
Corn	310 ± 15	(Al Seadi et al., 2013; Murphy et al., 2011)
Sorghum	572 ± 78	(Garcia et al., 2019; Hammer and Broad, 2003; Murphy et al., 2011)
Triticale	707 ± 109	(Garcia et al., 2019; Murphy et al., 2011)
Wheat	718 ± 180	(Pöschl et al., 2010)
Barley	709 ± 57	(Murphy et al, 2020; Garcia et al., 2019; Hay, 1995)

When using by-products, the areas to be considered in estimating land use are only those areas that are necessary for the energy plants and the related facilities (Nathalie Bachmann, 2013) because soil consumption for primary crops does not lead to the direct loss of utilized agricultural areas (UAA) destined for food production. For these reasons, it is crucial to focus attention on by-products and waste products from agricultural activities to avoid detrimental competition. The use of by-products and livestock waste, which does not affect food production, can support the construction of a new energy system and represents a valid opportunity for new types of businesses in rural communities (Chiumenti et al., 2019; Statuto et al., 2019).

Currently, several types of agricultural by-products can be used for energy production: straw (Brosowski et al., 2020), grass (Mattioli et al., 2017), pruning residues (Pari et al., 2017), and livestock manure (Chiumenti et al., 2018; Finzi et al., 2020). However, even the use of by-products involves the consumption of soil because of the construction of anaerobic digestion plants. Soil provides a multitude of ecosystem services that are essential for environmental sustainability and, more broadly, for human survival (Pereira et al., 2018; Pulleman et al., 2012). However, soil is a limited and non-renewable resource and should only be consumed to the extent that is it needed (Congedo et al., 2017). A concrete signal aimed at the protection and sustainable consumption of soil has been launched by the European Commission, which has set challenging targets to limit, mitigate, and compensate soil sealing, the leading cause of degradation (European Commission, 2006). The permanent covering of soil by buildings, roads, or other impermeable anthropic materials causes soil sealing (Munafò et al., 2013; Pistocchi et al., 2015). This permanent condition entails severe consequences to soil functioning (Scalenghe and Ajmone-Marsan, 2009), including rising temperatures in the atmosphere near urban areas (Murata and Kawai, 2018), flooding caused by increasing volumes of stormwater (Jacobson, 2011), and reductions in hydraulic conductivity and the infiltration rate (Nciizah and Wakindiki, 2015).

The current literature presents some general studies that summarize the most common practices regarding the design and construction phases of bioenergy plants (Samer, 2012) and identifies the critical phases in biogas plant construction processes (Zareei, 2018). A standard scheme of a biogas plant includes the following components:

- Roads: both for the connection to the road network and inner traffic circulation. These roads include service areas for parking vehicles.
- Storage surface: where silage is stored. These components can be bunker silos, concrete enclosures filled, packed, and covered with plastic cloth to make them airtight, or silo-bags, polyethylene bags consisting of several co-extruded layers of plastic film.
- Digestion unit: this is where microbial activity occurs and where organic biomass is transformed into biogas.
- Other facilities: tanks, storage sites, and other buildings used for technical and administrative needs.

Several authors have broadly studied the structures and elements present in biogas plants to describe the differences among facilities based on the feedstock used (Benato and Macor, 2019). In recent studies, attention has been given to automatizing the production process to obtain flexible digester technology that is robust and suitable for handling variable feedstock characteristics (Theuerl et al., 2019).

Quantifying the surfaces covered by these structures allows the determination of the actual consumption of soil by bioenergy and permits the comparison of this value with those of other forms of renewable energy.

The present study aimed to analyze the impacts on land consumption that occur because of the construction of ABPs for producing renewable energy by providing information and quantitative details on the presence and characteristics of these plants in the Italian territory. In this analysis, the impact of the construction of new digesters on agricultural land was verified; the use of land dedicated to energy crops was not considered, but particular attention was focused on facilities and areas dedicated to anaerobic digestion systems.

The objective of this study was thus to provide a reliable parametrization of soil consumption of anaerobic digestion plants for biogas production, with specific reference to the Italian area. Analysis included identification of the different parts of digestion plants and proposed a modelling as a function of installed power. This value will allow a comparison with other renewable energy sources, to establish an effective environmental impact of bioenergy production.

4.3 Materials and Methods

4.3.1 Italian Biogas Plants

In 2008, there were 352 bioenergy plants in Italy, with an installed power of 1555.3 MW and a production capacity of 7631 GWh. In 2019, this number increased to 2835 bioenergy plants (Figure 4-1) in operation with a total installed power of 4119.7 MW (Terna Rete Italia, 2019a) and a production capacity of 19,562 GWh of electric energy (Terna Rete Italia, 2019b).

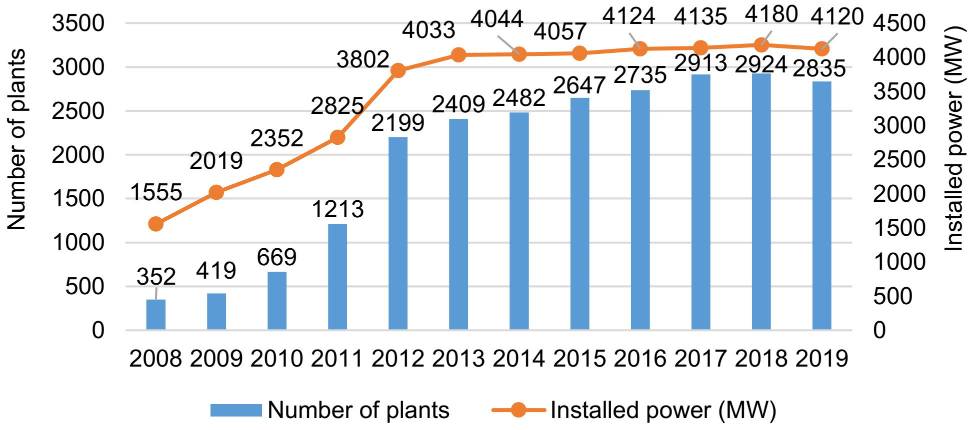


Figure 4-1. Number of bioenergy plants and amount of installed power in Italy from 2008 to 2019

4.3.2 Data Collection and Sampling

This research was performed using data supplied by the national database of biomass energy production plants, Atlaimpianti, made available by Gestore Servizi Energetici (GSE), which is the energy services managing authority. The database collects all the information for each registered plant: the bioenergy source (biogas, liquid biomass, solid biomass, waste), location, and installed power. The location of each plant is defined by its region (NUTS-2 level), province (NUTS-3 level), municipality, and coordinates.

Of the 2835 registered biomass plants, 1939 agricultural biogas plants were specifically identified for the analysis and subsequent sampling because they were supplied by agricultural products such as energy crops, by-products, or animal waste. Each ABP was analysed on the basis of both the declared power supply and the installed power.

In terms of the installed nominal power capacities, the distribution of the plants showed that most of them have installed power capacities up to 1000 kW (Table 4-2). This is due to the eco-incentive tariff that was enforced from 2008 until 2012, which provided an all-inclusive tariff of 0.28 €/kWh undifferentiated for ABPs up to 999 kW (Terna Rete Italia, 2019b).

Table 4-2. Frequency of digesters categorized by their power capacities

Class of Installed Power (kW)	Number of Plants	Total Installed Power (GW)
0–200	501	50.6
201–400	338	96.9
401–600	137	73.0
601–800	135	90.3
801–1000	714	704.5
>1000	114	307.5

The data show that the power class between 800 and 1000 kW is the most frequent; 36.8% of the plants fall within this range (714 plants), comprising 53.3% of the total installed power (704.5 GW). The percentage of digesters with powers between 990 and 999 kW is 28.4% (equal to 551 plants), with 41.6% of the installed power (550.2 GW); the threshold for incentives is exactly 999 kW, which has led to the adoption of many systems with powers within this range. There is a decreasing trend in frequency from small installations below 200 kW to those with powers of 800 kW. Larger plants, with more than 1000 kW of power output, are also much less frequent.

A random sampling selection was applied to the available dataset. Through this technique, of the 1939 biogas plants, a significant set of 200 Italian ABPs were selected and constituted the sample for this analysis. These digesters were selected randomly while respecting the distributional proportions of the plants in Italy to obtain a representative result of the actual situation with which to perform the desired analyses and to obtain conclusions with the lowest possible biases. In this work, ABPs with various powers were sampled, ranging in power capacity from 60 kW to 1156 kW (Figure 4-2). The biogas plants are represented with their installed power. Most of the ABPs are in northern Italy, and the distribution of the sampled plants is consistent with that of the entire sample; intensive agricultural activities are practised more intensively in these regions because there is a higher availability of resources for bioenergy production.

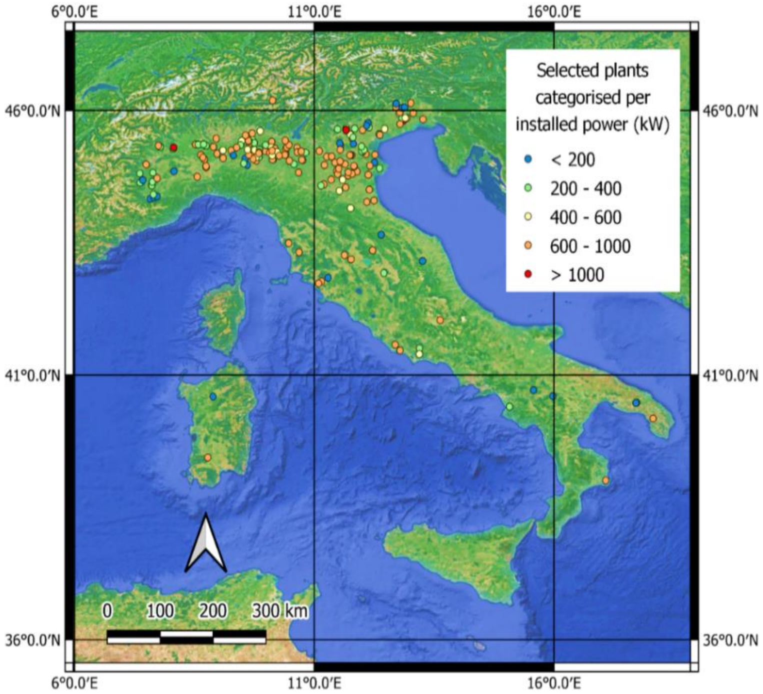


Figure 4-2. Map of biogas plants in Italy

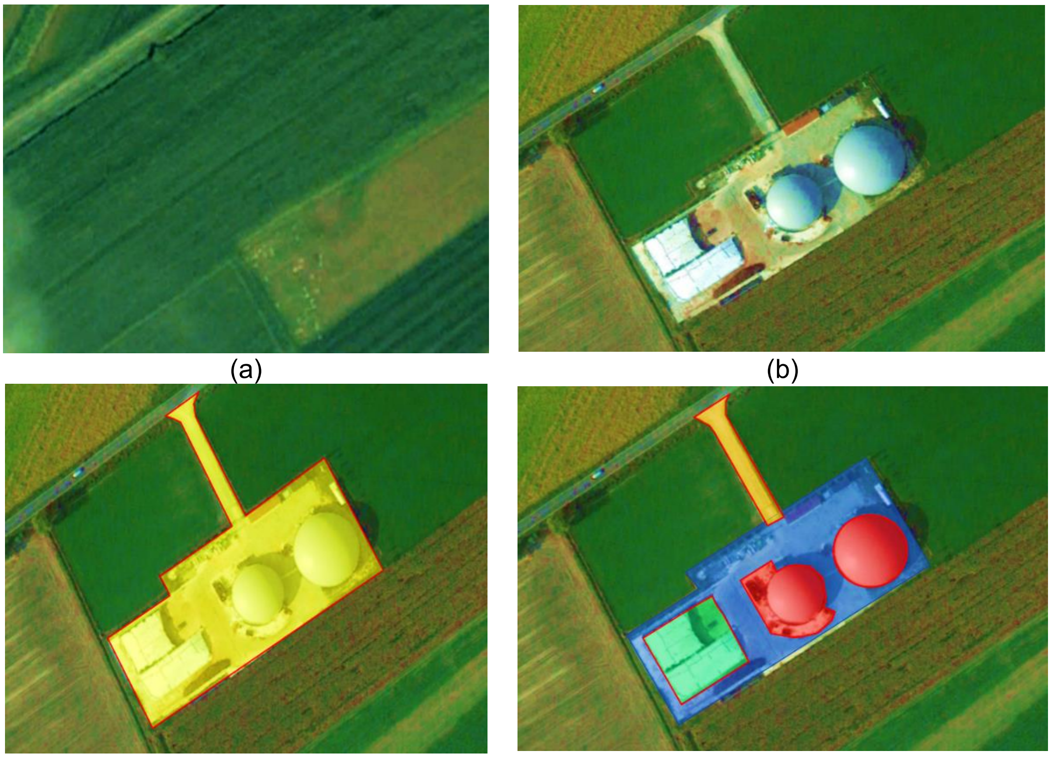
The distribution of the installed nominal power capacities of the studied plants is represented in Table 4-3. Most of the sample plants have an installed power between 800 and 1000 kW, comprising 94 plants (47.0% of the total), with an overall installed power of 93.5 GW (70.7% of the total). In the sample, there are 80 biogas plants (40.0% of the total) with an installed power between 990 kW and 999 kW, with a total installed power of 79.9 GW (60.4% of the total).

Table 4-3. Frequency of sampled digesters split by power capacity

Class of Installed Power (kW)	Number of Sampled Plants	Total Installed Power (GW)
0–200	25	2.7
201–400	44	12.6
401–600	20	10.9
601–800	14	9.4
801–1000	94	93.5
>1000	3	3.2

4.3.3 Data Processing and Analysis

To characterise the sizes and occupied areas of the studied plants, in addition to the information described above, in the present study, additional satellite and aerial imagery was included by the Google Earth Pro TM tool (Google Inc., Mountain View, CA), which provides detailed images of the entire surface of the globe (Figure 3), allowing extensive territorial analysis (Cogato et al., 2020). The software is equipped with two useful functions: i) it allows the measurement of areas from aerial images and ii) it makes available, for a given area, in addition to the most-updated images, images from the past, allowing their comparison and thus the evaluation of changes that have occurred in the territory over time. Once a national database system was selected, its nominal power (expressed in kW) was noted. Subsequently, its position was identified in Google Earth Pro using the latitude and longitude coordinates included in the database provided by GSE.



(a) (b)

(c) (d)

Figure 4-3. Before (a) and after (b) situation of a soil surface converted from agricultural cultivation land into a plant for anaerobic digestion with the scheme of the built structures. The total area occupied by the plant (c); the land surface occupied by digester structures (red), storage surfaces (green), new roads (orange), and other structures and remaining areas (blue) (d).

Then, once each plant was located, measurements of the following parameters were collected (Figure 4-3):

- Total area occupied by the biogas plant: the total surface area dedicated to the plant, including the maneuvering spaces, loading-unloading spaces, and other structures such as those used for storage or as sheds, as realised contextually with the biogas plant.
- Surface occupied by structures: the area occupied by digester structures, including the anaerobic digester, engine generator, and the technical space assigned to the plant.
- Surface occupied by storage areas: the surface occupied by storage facilities for the organic material destined to feed the plant.
- Surface occupied by new roads: the new roads specifically built to make the plant accessible.
- Remaining area: the remaining covered land dedicated to the plant that does not fall within the other categories, calculated by subtracting all the other surface areas from the total area. The remaining area includes yards, manoeuvring areas, and technical structures that are not

directly part of the digester but form part of the plant and are therefore built together with the plant; for example, stables or residential buildings are not included.

Using this combined analytical–visual method, data from 200 ABPs were integrated and analysed. The ABPs were analysed individually and aggregated per power class to reduce the noise due to outlier values.

4.4 Results and Discussion

4.4.1 Biogas Plant Area Analysis

The biogas plant-covered surfaces were correlated with the related technical and performance parameters (Figure 4-4). The 200 analysed digesters supply a total power of 132,263 kW and cover a total area of 3,259,663 m^2, divided as follows: 413,276 m^2 occupied by digester facilities (12.7% of the total); 730,200 m^2 occupied by storage surfaces (22.4% of the total); 2,096,534 m^2 comprising remaining areas (64.3% of the total); and 19,652.2 m^2 of new roads (0.6% of the total). On average, one ABP requires 16,380 m^2 of land.

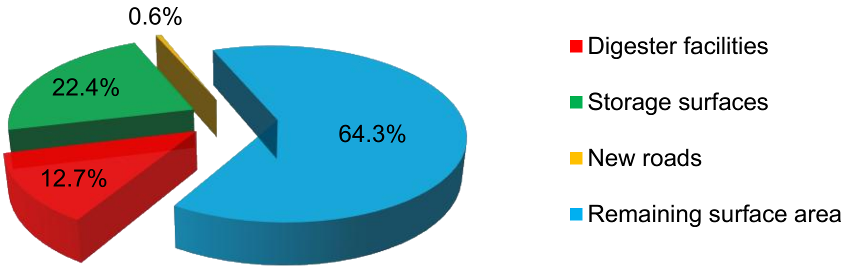


Figure 4-4. Percentage breakdown of the total area occupied by installations with their intended uses

On average, 64.3% of the covered surface area is free from any facility dedicated to anaerobic digestion. For 24 of the studied biogas plants, this percentage is above 75%, and for 18 of them, up to 2 hectares are allocated in this manner. These values demonstrate how crucial the proper planning of inner traffic circulation in biogas plants is for reducing soil sealing. The remaining 35.7% of the area is divided between areas occupied by the plant and areas dedicated to storage systems. The latter category occupies more than one-fifth of the total area because of the large volume of biomass that must be stored to allow the continuous and efficient operation of the anaerobic digestion process. In 58 ABPs, the surfaces occupied for storage exceed 5000 m^2. This value highlights the importance of an efficient supply of feedstock. The digester, the main element of each complex, occupies, on average, together with the technical installations, a relatively small portion of the total space, covering up to 0.5 ha only in 7 sampled plants. The surfaces converted from agricultural areas to new roads compose the remaining 0.6%. Only in 16 cases were new roads asphalted from scratch; all the other systems were installed in easily accessible areas thanks to existing roads.

4.4.2 Analysis of Punctual Trends

The results of the punctual trend analysis and its statistical significance inferred from the sample data analysed for Italian ABPs are reported and discussed. The correlation between the total surface areas and the areas occupied by digesters was studied (Figure 4-5). These digesters, mainly composed of digestion tanks or engine placement buildings, occupied 12.7% of the total area. The results showed that there is a correlation between the two considered measurements, with an R^2 value equal to 0.55, especially in cases where the surface area dedicated to digesters was below 3000 m^2, as in 162 cases; here, the areas dedicated to the digester structures and the total areas grow proportionally, and there is very low dispersion.

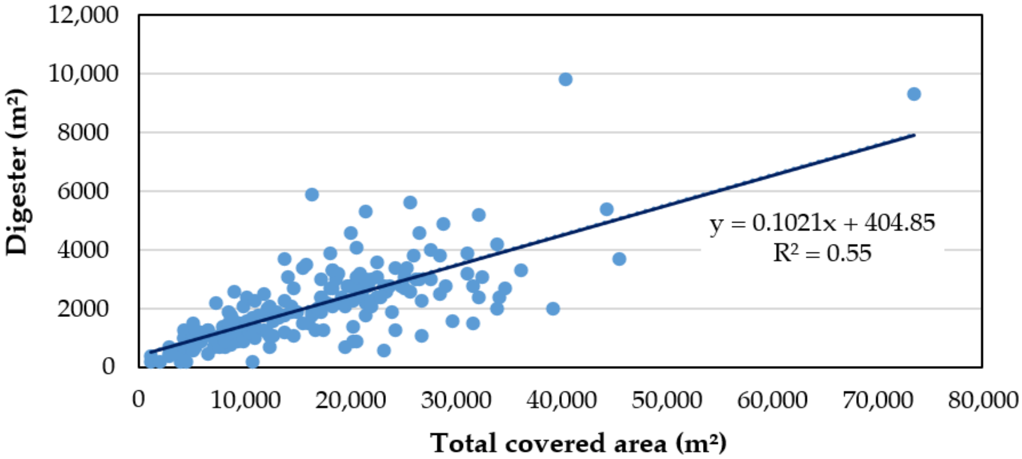


Figure 4-5. Correlation between digester facilities areas and total covered area

The relationship between the total surface areas and the areas intended for storage was also studied (Figure 4-6). On average, storage areas occupy 22.4% of the total surface area; the determination index was $R^2 = 0.56$ and the *p*-value < 0.0001, attesting to the high correlation between the two variables. Only in 33 plants did the area dedicated to the storage surface exceed 30% of the overall surface area, and in 11 cases, the storage surface area was less than 10% of the total covered area. The particular condition of the plants could have led to higher or lower values of the parameters; for example, the use of existing structures or service areas or the presence of multiple areas for bunker silos, due to a process of conversion, determined larger areas compared to the model. These plants were not excluded by the analysis because they represent actual situations that have to be considered in the general model.

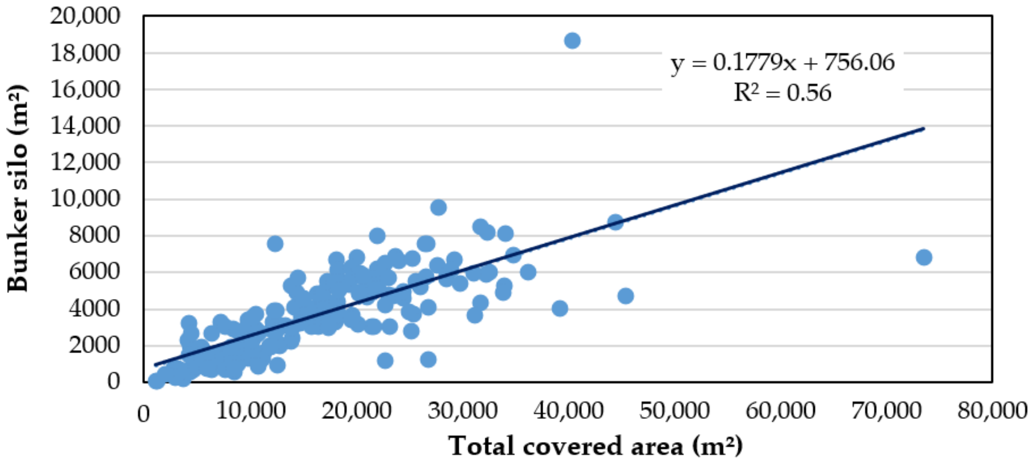


Figure 4-6. Correlation between storage areas and total covered area

4.4.3 Analysis of Aggregated Trends

The digesters were grouped into six power classes so as to have a less distributed and therefore more clear representation of the analysed data. The study of the classes allowed the identification of soil consumption for the different levels of installed power, including the two most frequent sizes in the Italian area: 300 kW and 999 kW. For each class, a different number of observations was reported, with almost half of the surveys reporting powers greater than 900 kW, which was coherent with the actual composition of the overall population of ABPs. The value of each class corresponds to the average of the observations that compose the class. The total area occupied by each ABP was reported as a function of its installed power (Figure 4-7).

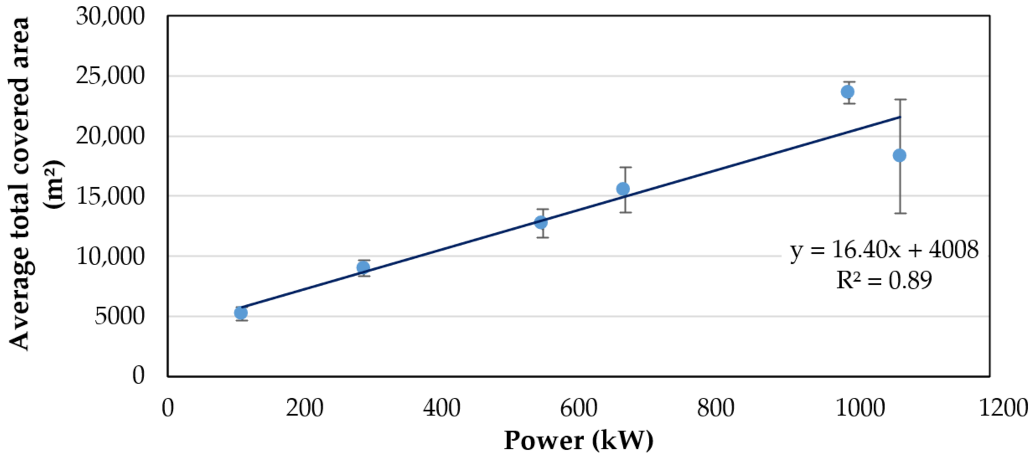


Figure 4-7. Relation between installed power and average total covered area (m^2).

The obtained model can be described by Equation 1 as follows:

$$TCA = 16.40 \cdot IP + 4008 \quad (2)$$

where:

TCA is the total covered area (expressed in square meters);

IP is the installed power (expressed in kilowatts).

The resulting coefficient of determination was $R^2 = 0.89$, providing evidence of a high correlation between the two parameters; the *p*-value = 0.004 also indicated a statistically significant correlation. Given the slope of the line, the model showed that the average consumption of soil increased by 16.4 m^2 per kilowatt-hour requested. The model indicated an intercept equal to 4008 m^2, which can be fixed as the minimum surface occupied by a plant facility. However, this value was highly correlated to the size of the plants and, to better clarify this point, the average land consumption (LC) of the ABPs was calculated based on different values of installed power. The relations between the average installed power and the LC per kilowatt installed were assessed. These relations considered the LC due to the digester unit, the bunker silo, and the total plant area.

In Figure 4-8, the relation between the installed power and the average LC per installed kilowatt is reported. The model indicated an increase in efficiency for larger plants: a biogas plant with an installed power ranging between 0 and 200 kW occupies on average 49 m^2 per kilowatt, whereas biogas plants with 801–1000 kW needs on average 24 m^2 per kilowatt. The resulting parameters and the *p*-value = 0.002 provide indication of a statistically significant correlation.

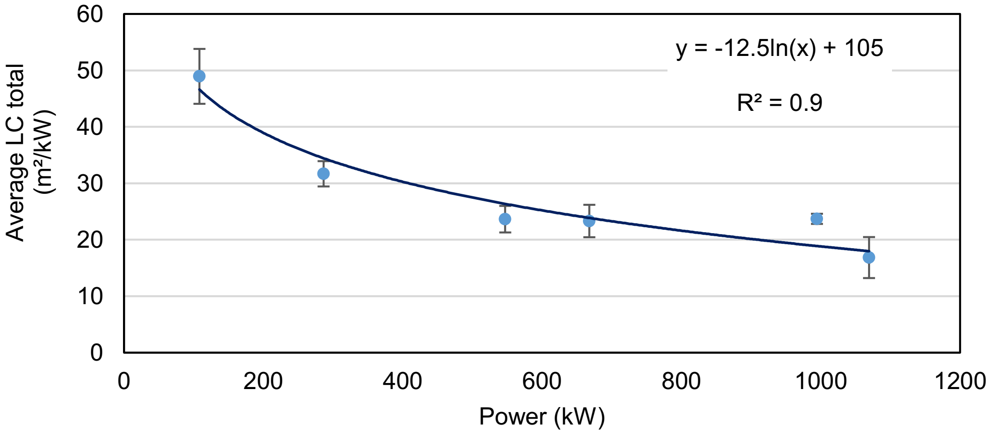


Figure 4-8. Relation between installed power and average total LC (m2/kW).

In order to define the influence of installed power on the size of different ABP structures, the installed power was studied along with the average LC of the digester (Figure 4-9a) and the bunker silo (Figure 4-9b). On average, biogas plants with an installed power lower than 200 kW had 6.6 m^2/kW occupied by the digester and 9.3 m^2/kW by the bunker silo. These values reduced to 2.9 m^2/kW and 5.5 m^2/kW, respectively, for biogas plants ranging between 801 and 1000 kW. The coefficient of determination as well as the p-value of the two models indicated a high correlation between the variables (installed power vs. average digester LC, $p < 0.001$; vs. average bunker silo LC, $p = 0.013$). The model can be thus implemented in order to reliably estimate the surface request of these bioenergy energy plants and predict soil consumption for a given value of plant power.

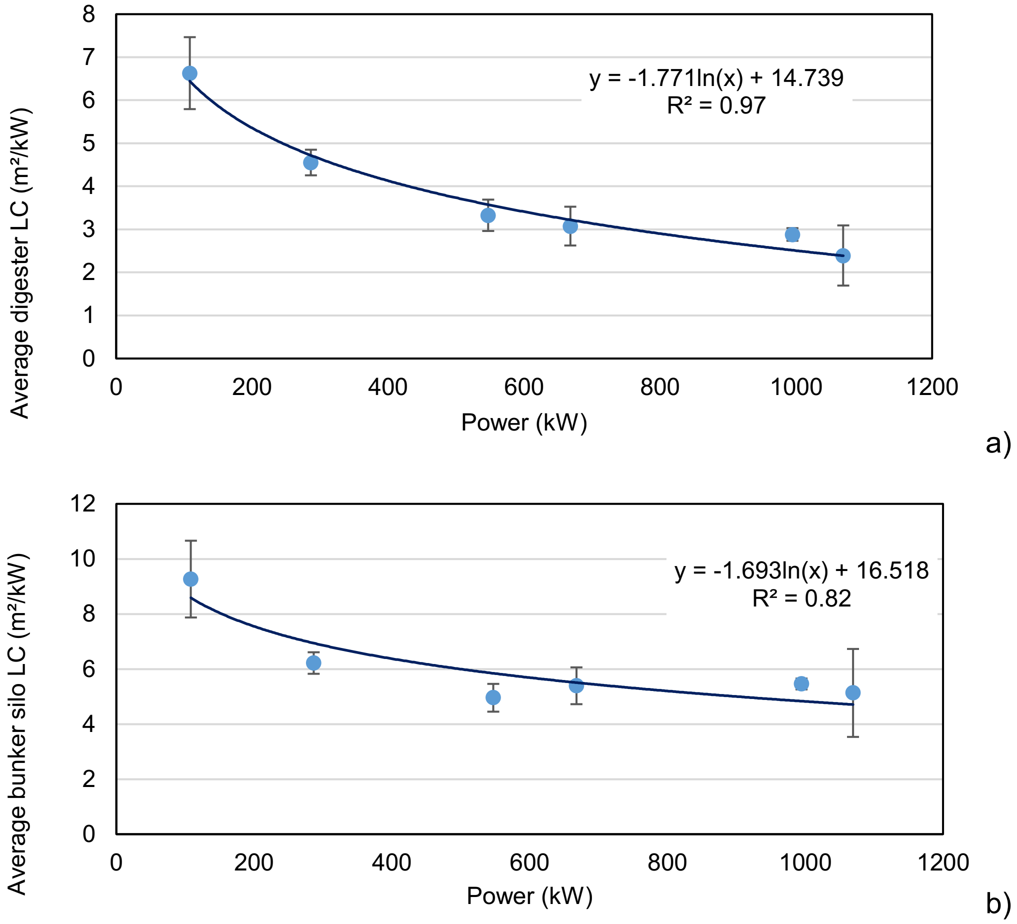


Figure 4-9. Relation between installed power and average digester LC (a) and average bunker silo LC (b).

4.4.4 Soil Consumption of Bioenergy

The study concluded that one ABP requires an average surface area of 16,380 m^2. Observing the aerial images of the studied ABPs, 97.9% of the plant surfaces were previously used as agricultural areas. Reporting these values to the overall population of biogas plants, with 1939 ABPs, it was assessed that 31.8 km^2 (i.e., 3176 ha) of land has been dedicated to ABPs in Italy, most of which (3109 ha) consisted of previously cultivated areas. To better understand this value, it should be kept in mind that between 2012 and 2017 in Italy, an average of 49.7 square km of land was consumed for new urbanization each year (ISPRA, 2018).

The energy productivity of these plants was assessed: at 40.5 W/m^2, to produce 1 kW of electric energy, an average surface area of 24.7 m^2 is necessary. These results can be compared with those derived from preliminary studies of other forms of electric energy production collected by the same authors (Table 4-4).

Table 4-4. Land use requirements for different energy plants

Technology	Average Area (m^2/kWe)
Biogas plant	23.7–48.9
Onshore wind	3.7–8.4
Solar photovoltaic	120–172

Thermal power	1.8–4.5

To produce 1 kW of electric energy with photovoltaic panels, on average, 144 m^2 of land surface is necessary, whereas to produce the same amount of energy with onshore wind systems, 5.6 m^2 of land surface is needed. Considering the largest thermal power stations operating in Italy, it was assessed that to produce 1 kW of electric energy, 2.63 m^2 must be occupied by the plant. The wide differences among these values reflect the huge differences among various energy production forms. Moreover, to achieve a reliable balance of the environmental impact of biogas plants, other features must be taken into consideration: polluting gas emissions, non-renewable resource consumption, and impacts on local communities.

4.5 Conclusions

In this study, the consumption of soil by anaerobic digestion plants in Italy was analysed. The analysis only considered ABPs and did not involve those using forest biomasses or municipal waste products. A sample of 200 ABPs was randomly selected for the analysis from the entire population of 1939 biogas plants operating in Italy. It was found that to produce 1 kW of electric energy power, it is necessary to cover 24.7 m^2 of the land surface. This surface is dedicated to the digesters and related machinery (3.1 m^2/kW), bunker silos and other storage areas (5.5 m^2/kW), new roads built for the plants (0.1 m^2/kW), and other covered areas related to the plants, such as yards, manoeuvring areas, and technical structures that are not directly part of the digesters but form part of the plants and are therefore built together with plants (15.9 m^2/kW).

This study assessed the proportionality among the areas of facilities and between these areas and the installed powers. This model makes it possible to estimate the total surface area covered by this type of renewable energy. Future research could compare the results achieved herein with other renewable energy sources to estimate the consumption of land and the extent of soil sealing. It would also be important to consider the consequences of the use of energy crops in land consumption and its effects on agricultural spatial planning.

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5 Environmental assessment of a two-stage high pressure anaerobic digestion process and biological upgrading as alternative processes for biomethane production

5.1 Abstract

Biomethane plays a key role in achieving decarbonization and sustainable development goals. According to the objectives that arise, choosing the most suitable production system allows optimization of production, thereby reducing CO_2 emissions. In this study, three biomethane production scenario life cycle assessments were compared to determine which would maintain the lowest CO_2 emissions. Conventional anaerobic digestion and an innovative process called two-stage high pressure anaerobic digestion were considered. These methods were combined with two upgrading processes: water scrubbing and biological upgrading. Cattle manure and sugar beets were used as substrates for the process. Emissions were 805.6 gCO_2eq/m^3CH_4 for the traditional biogas production process combined with water scrubbing and 450.3 gCO_2eq/m^3CH_4 for the two-stage anaerobic digestion process combined with biological upgrading. Furthermore, the analysis demonstrated that these values would be reduced by 29.5% and 48.0% if electrical energy were produced using only renewable energy sources.

Keywords: Life cycle assessment, biomethane, two-stage anaerobic digestion, water scrubbing, biological upgrading

5.2 Introduction

The Renewable Energy Directive (RED) (European Parliament, 2018) set the objectives of the EU Member States, committing to reach a 32% renewable energy share by 2030. Therefore, all renewable energy sectors need to be explored to implement innovative and effective solutions for achieving set goals.

Bioenergy production allows the exploitation of several types of biomass: agricultural (Murphy et al., 2011), forestry (Shabani et al., 2013), and urban organic waste (Bartocci et al., 2020). Several authors have described the benefit of agricultural by-products (Hejnfelt and Angelidaki, 2009) for energy purposes, valorizing waste products and avoiding competition with food crops. Likewise, the benefits of using cattle and pig manure have been demonstrated: mitigating pollution from their management (Holm-Nielsen et al., 2009), decreasing the costs related to the nitrogen disposal process (García-González et al., 2016), and obtaining digestate for fertilization (Hou et al., 2017). In addition to the wide range of exploitable biomass, bioenergy production using biogas can supply several types of energy, depending on the available biomass as well as energy system needs: electricity, heat, and once upgraded to biomethane, as gaseous or liquefied fuel, and biofuels. Nevertheless, it is also necessary to carefully identify the conditions that support the environmental sustainability of bioenergy production (Thornley et al., 2009) and develop innovative anaerobic digestion (AD) technologies to improve it.

AD consists of four main degradation steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. When occurring simultaneously, these contemporary activities can cause conflicts between acidogenic and methanogenic microorganisms due to different nutrient requirements, physiology, and environmental conditions (e.g., pH value) (Coats et al., 2013). Therefore, a two-stage process has been developed as a possible solution, splitting and independently optimizing the four steps in two subsequent digesters: first hydrolysis and acidogenesis, followed by acetogenesis and methanogenesis (Lindner et al., 2016). This system increases the cost of building a double reactor, however, it allows for better control of the process by establishing the optimal pH and temperature conditions for different types of microorganisms. In AD, the hydrolysis is the rate limiting stage. Decoupling the methane generation and pressurizing the reactor leads to a high reactor-specific methane yield. Since pressurized reactors are cost extensive, separating the digestion steps leads to an overall economic design. For many applications, such as injection into the natural gas grid or using biomethane as a transportation fuel, a further upgrading process is necessary to purify the gas, removing its carbon dioxide component.

The biogas upgrading increases the lower heating value (LHV) of the biogas, allowing its use as a standard fuel, as the produced biomethane (Kougias et al., 2017) reaches specifications comparable to natural gas. Depending on the adopted technology, the share of CO_2 in the biogas can either be removed or converted into biomethane (Fu et al., 2021). The most common methods for biogas upgrading are physical absorption using organic solvents (Bauer et al., 2013), pressure swing absorption (PSA) (Adelt et al., 2011), membrane separation (Baker, 2012), and water scrubbing (Cozma et al., 2014). The water scrubbing process is based on the different solubilities of CO_2 and CH_4 in water. The biogas is injected into an absorber column as a countercurrent of the water flow. The resulting upgraded biomethane has a purity of 98%.

An innovative and promising technology is chemoautotrophic biogas upgrading, where hydrogenotrophic methanogens utilize H_2 to convert CO_2 to CH_4 based on the Sabatier reaction. The necessary H_2 can be produced by electrolysis using excess current from renewable energy plants. This new technology is called power to gas (P2G) (Angelidaki et al., 2018) and can function as a storage system for energy generated by wind turbines and solar plants. There are two possible configurations for the process: in-situ and ex-situ. In the in-situ system, H_2 is injected directly into the biogas reactor and combined with CO_2. This option reduces the costs for new plants; however, it requires that operational parameters be fully monitored to avoid reducing methanogenesis (Luo and Angelidaki, 2012). The ex-situ system uses a separate reactor for the upgrading process, providing several benefits: the autonomy of the process guarantees the maintenance of the ideal condition, it is independent of the biomass supply, and CO_2 can be supplied from different sources. To identify the best solution for biogas production and upgrading, it is necessary to determine the environmental impact of the processes considering the energy requirements and greenhouse gas (GHG) emissions of all process steps. This analysis is developed by a life cycle assessment (LCA); by this method, it is possible to assess the environmental impact associated with the life cycle of a process, a product or a service. Many authors have applied LCA to biogas production processes or upgrading methods: conventional AD (Fusi et al., 2016), two-stage high pressure (TSHP) AD process (Chen et al., 2014), water scrubbing upgrading (Moghaddam et al., 2015), and ex-situ biological methanation (Alfaro et al., 2018). However, a complete calculation of the entire process chain, that allows comparison between alternative solutions, is currently lacking.

In this work, three alternative scenarios of biogas production and upgrading were compared, assessing the energy production of each phase and the related GHG emissions. In addition, a sensitivity analysis was conducted to determine how CO_2 emissions vary by changing the substrate used, cattle manure (CM) and sugar beet (SB), and the energy supply, renewable sources or fossil fuels. This study allowed the identification of the process phases that mainly contribute to GHG emissions; optimizing these critical phases is the most effective way to improve process efficiencies. Consequently, it is a key contribution to implementing a sustainable energy system.

5.3 Material and methods

The following paragraphs describe the research methodology standardized by the International Organization for Standardization (ISO) in the documents ISO 14040 and ISO 14044. LCA is carried out in four independent phases: *(i)* Goal and scope definition, *(ii)* Life Cycle Inventory (LCI), *(iii)* Life Cycle Impact Assessment (LCIA), *(iv)* Interpretation.

LCA allows quantifying the energy and material flows associated with a certain amount of product, the functional unit (FU). Therefore, by comparing the values of different processes that produce the same FU, it is possible to establish the most suitable one.

5.3.1 Goal and scope definition: alternative analysed scenarios

This study focused on assessing the GHG emissions associated with the production of 1 m^3 of CH_4 or the management of 1 t of CM and SB. The LCA lies between the transport of the substrates to the plant and the disposal of digestate in the field and the CH_4 injection into the natural gas grid. Three alternative scenarios have been analyzed (Figure 5-1).

- Conventional biogas production with one-stage digestion – Biogas upgrading with water scrubbing.
- Conventional biogas production with one-stage digestion – Biogas upgrading with ex-situ biological methanation.
- Biogas production with two-stage high pressure anaerobic digestion – Biogas upgrading with ex-situ biological methanation.

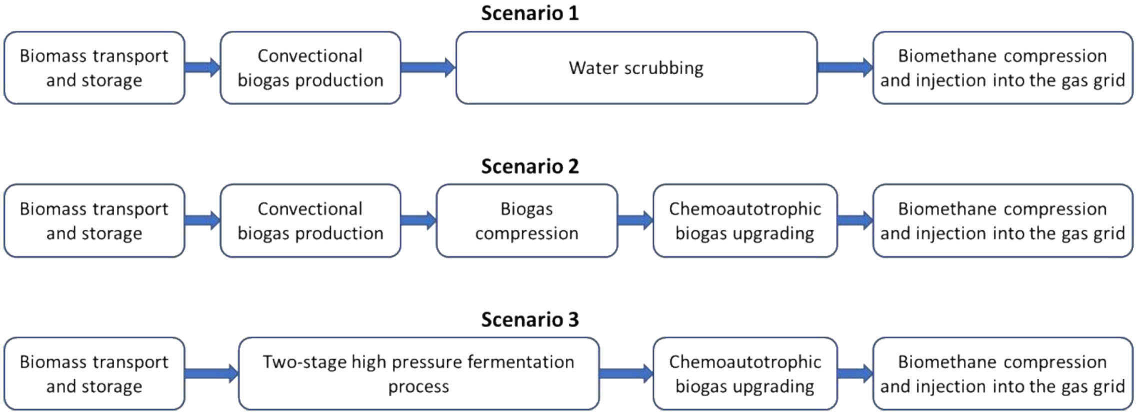


Figure 5-1. Alternative analyzed scenarios

Each scenario was divided into elementary phases; the energy demand or production and GHG emissions were assessed for each phase. Using the cubic metre of biomethane as a FU allowed for the establishment of the effectiveness of the three alternatives regarding energy production. The amount of biomass was also considered as a FU to compare the three alternative methods with the traditional treatment of CM as a fertilizer. This approach can be useful when the number of animal units is a fixed parameter.

GHG production was expressed in carbon dioxide equivalents (CO_2eq), i.e., the mass of carbon dioxide with the same global warming potential as the GHG produced. For CO_2, the related CO_2eq mass is naturally 1, while for the CH_4, it is 25, and for N_2O, it is 298.

5.3.2 Inventory analysis

5.3.2.1 Data collection

The fundamental data for the analysis were collected in the scientific and technical literature (Alfaro et al., 2018; Nock et al., 2014) and by specific measurements and research in the biogas plant of the University of Hohenheim (Naegele et al., 2012) (https://www.probiolng.de/). Previous studies led to the definition of the elementary phases: transport and storage of the substrates (Schnorf et al., 2021), conventional biogas production (Lübken et al., 2007), TSHP AD (Sun et al., 2019), traditional biogas upgrading with water scrubbing (Nock et al., 2014), ex-situ biological methanation (Alfaro et al., 2018), electrolysis (Götz et al., 2016), and alternative use of CM (Aguirre-Villegas and Larson, 2017). The articles thereby addressed different contexts: substrates, type of energy or scale of the plant (laboratory or full scale); therefore, a careful selection of the data was necessary to identify only suitable parameters for the present analysis. However, the literature review helped to collect a set of values to compare with those obtained in the current study. In particular, Naegele et al. (2012) evaluated the electric power consumption of the biogas plant “Unterer Lindenhof” of the University of Hohenheim. It is a full-scale plant comprising three different and independent traditional one-stage digesters. They measured the energy inputs of this biogas plant and described its operating scheme.

The technical parameters of the machinery and the energy (electricity and heat) demand were used to set the model for the LCA.

The alternative to the conventional AD method is the TSHP AD. One example for the application of this alternative process is the ProBioLNG project, carried out by the University of Hohenheim together with other partners from research. The ProBioLNG project, to which this work refers, involves the construction of an experimental two-stage digester. An acidification reactor (AR), operating under atmospheric pressure and thermophilic (55 °C) temperature, is followed by a fixed-bed methanogenesis reactor (MR) operating under pressures up to 9 bar and mesophilic (37 °C) temperature to produce biogas with a methane content of up to 75%. The ProBioLNG project parameters were used to describe the TSHP process and calculate its energy demand and GHG production. The system is then joined with an ex-situ biological methanation to convert the remaining CO_2 into biomethane by hydrogen injection. A significant amount of electricity is required to produce hydrogen by electrolysis. This electrical energy can be supplied by the national electrical distribution grid. The best alternative is the use of surplus electricity produced by photovoltaic and wind power plants to achieve a significant reduction in emissions (Figure 5-2).

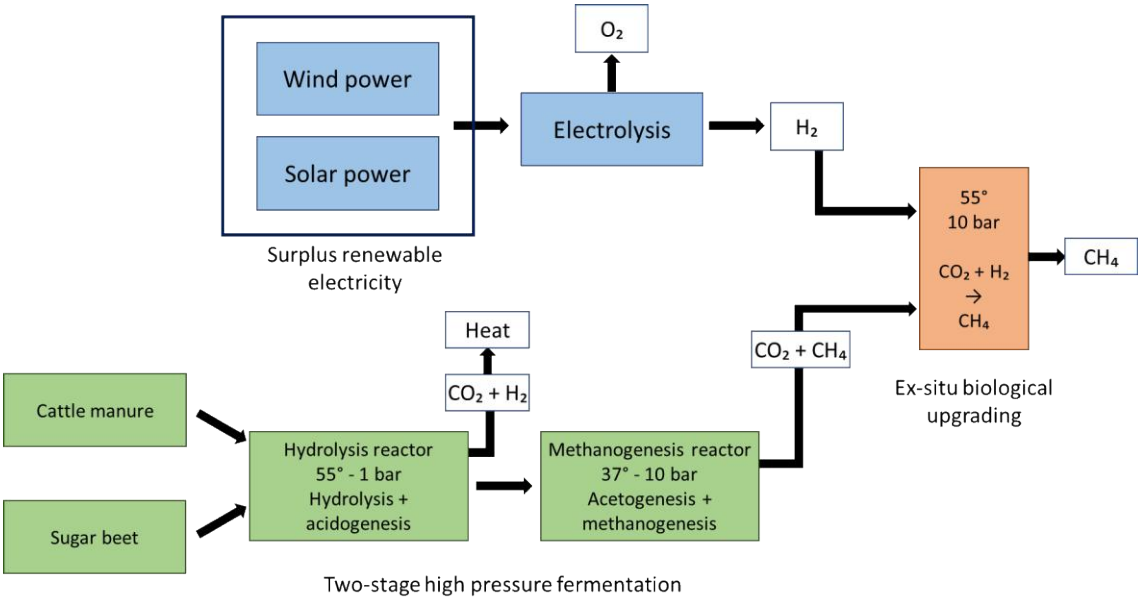


Figure 5-2. Scheme of two-stage high pressure anaerobic digestion, electrolysis with renewable electricity, and biological hydrogen methanation

Water scrubbing as an upgrading system is widely used, and the literature has provided robust results on energy consumption. On the other hand, the ex-situ biological upgrading is more recent. Nevertheless, it has experienced remarkable development thanks to its superior performance when increasing the amount of biomethane produced by converting CO_2 and the possibility of being used as a storage system for excess electricity from solar and wind power plants (Voelklein et al., 2019).

5.3.2.2 Single-stage assessment

An installed electrical power value of 250 kW was set to run the model. The constructional and technical parameters of the plants have been adjusted on this value to obtain a realistic dimensioning. The literature review and specific studies allowed to calculate the energy consumption for each step of the analysed process. In the following paragraphs, a summary description of the data and the calculation of the stages are provided. The most important parameters for the analysis are presented in Table 5-1.

Table 5-1. Summary of the most important parameters used in the analysis

Storage and transport			
VS loss during the storage of SB (%)	1.5	CH_4 loss during the storage of CM (%)	3
Conventional biogas production			
Retention time (d)	30	Temperature of the AD (°C)	37
Power of the mixer (kW)	13	Power of the agitator (kW)	15
Time for mixing (min/h)	6	Time for agitating (min/h)	6
Organic loading rate (kg_VS_added/(m^3_Reactor·d))	0.517	Volume of the digester (m^3)	4241
Two-Stage high pressure AD			
Temperature of HR (°C)	55	Temperature of MR (°C)	37
Retention time in HR (d)	10	Retention time in MR (d)	5
Technical power of the pump in HR (kW)	2.2	Technical power of the pump in MR (kW)	2.2
Running time of the pump in HR (min/d)	34	Running time of the pump in MR (min/d)	26
Power of the stirrer (kW)	2.2	Time for stirring (h/d)	8
Volume of the HR (m^3)	352	Volume of the MR (m^3)	156
Organic loading rate for HR (kg_VS_added/(m^3_Reactor·d))	6.232	Organic loading rate for MR (kg_VS_added/(m^3_Reactor·d))	14.101
Water scrubbing upgrading			
Electricity requirement-base (kWh/m^3biogas)	0.012	Electricity requirement-Flash tank and desorption coloumn (kWh/m^3biogas)	0.02
Electricity requirement-Compressor - Absorption coloumn (kWh/m^3biogas)	0.121	Electricity requirement-Water pump - absorption coloumn (kWh/m^3biogas)	0.084
Pressure of the methane in the grid (bar)	200	Methane loss (%)	6
Total electricity demand (kWh/m^3biogas)	0.237	Capacity of the system (m^3_Biogas/h)	41.115
Working pressure (bar)	1		
Ex-situ biological upgrading			
Total electricity demand (kWh/m^3biogas)	0.106	Methane Formation Rate (m^3 CH_4/(h·m^3_Reactor))	0.444
Working pressure (bar)	10	Electrolysis consumption (kWh/m^3H_2)	1.037
Volume of the reactor (m^3)	39.631	Pressure of the outlet biomethane (bar)	10
Biogas compression			
Starting pressure in conventional biogas production (bar)	1	Final pressure in conventional biogas production (bar)	1
Starting pressure in two-stage AD (bar)	1	Final pressure in two-stage AD (bar)	10
Required pressure in water scrubbing (bar)	1	Required pressure in biological upgrading (bar)	10

Biomass transport

The energy consumption for transport is related to distance and fuel type. The maximum capacity of a truck was fixed at 27 m^3 of biomass or 22 t (Equation (1)).

$$EC_{tr} = \frac{FC_{km} \cdot d_{tr} \cdot e}{M_{tot}} \qquad (1)$$

where FC_{km} is the fuel consumption of the truck per km (0.3 kg/km for methane and 0.45 kg/km for diesel); d_{tr} is the transport distance; e is the energy density of the fuel (55.52 MJ/kg for methane, 45.5 MJ/kg for diesel); and M_{tot} is the total mass carried by a load (22 t). Applying the coefficient of CO_2eq emission (2533 gCO_2eq/kg for methane and 3029 gCO_2eq/kg for diesel) and the methane potential of one ton of biomass, it was possible to determine the total emissions per ton of biomass and per cubic metre of produced biomethane.

Biomass storage

During the storage period, the biomass loses some of its organic matter content, which is released into the environment in the form of methane. This dispersion is strongly linked to many factors: type of storage, necessity of pretreatments, and environmental conditions. In this analysis, the use of gas tight storage was considered to lead to a 3% assumed loss of methane potential during the storage of CM (Schnorf et al., 2021).

Conventional biogas production

AD requires pumping of biomass into the digester and periodic stirring to prevent the agglomeration of biomass and allow uniform digestion of the substrate. In this work, the digester was provided with a mixer and an agitator to stir the substrate. The electricity consumption was assessed by Equation (2):

$$E_{el} = P_p \cdot t_p + P_m \cdot t_m + P_a \cdot t_a \qquad (2)$$

where P_p, P_m and P_a are the powers of the pump (11 kW), the mixer (13 kW), and the agitator (15 kW), respectively, while t_p, t_m and t_a are the running times during the day for the three types of machinery: pump (2 min/h), mixer (6 min/h), and agitator (6 min/h).

The AD runs at a mesophilic temperature of 37 °C that should be maintained in the digester. The feedstock must be heated from a temperature of 10 °C (average temperature of the site), and then further heating must balance the thermal loss through the digester walls. The heat loss by thermal conduction thereby depends on digester geometry and construction materials.

$$E_h = E_{heat} + E_{rad} \qquad (3)$$

$$E_{heat} = \frac{c \cdot Q_{in} \cdot (T_{dig} - T_{sub})}{3.6} \qquad (4)$$

$$E_{rad} = \frac{1}{W_{w1}/K_{t1} + W_{w2}/K_{t2}} \cdot (T_{dig} - T_{air}) \cdot (S_l + S_r + S_f) \qquad (5)$$

where E_{heat} (kWh/d) is the thermal energy loss for heating the substrate; E_{rad} (kWh/d) is the thermal energy loss for maintaining the constant temperature; c is the heat capacity of the substrate (4.186 kJ/(kg·K)), assumed equal to that of water; Q_{in} is the inlet flow (t/d); T_{dig} is the temperature inside the digester; T_{sub} is the temperature of the substrate, the wall consists of three layers, two of concrete and in between a layer of insulating material (polystyrene); K_{t1} is the thermal conductivity (0.8 W/(m·K)) for concrete; W_{t1} is the overall thickness of the concrete; K_{t2} is the thermal conductivity (0.05 W/(m·K)) for polystyrene; W_{t2} is the thickness of the insulation; T_{air} is the average temperature of the air (10 °C); and S_l, S_r and S_f are the lateral, roof and foundation surfaces, respectively. In the present model, the three surfaces were calculated for a 6 m high and 15 m radius digester, and they are supposed to be built with the same type of materials.

A methane loss of 1.37% has been considered (Whiting and Azapagic, 2014). In the LCA of the process, the management of the digestate obtained from the digester was considered. The methane loss during the storage period of the digestate was assumed to be 1% of the biomethane produced. It was assumed that the energy spent transporting the biomass from the farm to the digester was equal to that spent transporting the digestate to the field since the number of transport vehicles was the same. Finally, the energy spent on manure spreading, according to Aguirre-Villegas and Larson (Aguirre-Villegas and Larson, 2017), was 2169 gCO_2eq/t of digestate.

Biogas compression

Biogas exiting the conventional production process has a pressure of 1 bar; upgrading by the biological method requires a 10 bar pressure. Moreover, before being fed into the grid, biomethane must be compressed to a 200 bar pressure. Therefore, the energy expended to compress the gas, biogas or biomethane was obtained by the following equation:

$$E_{com} = 2.78 \cdot 10^{-2} \cdot P_{in} \cdot Biogas_{in} \cdot \ln\frac{P_{out}}{P_{in}} \qquad (6)$$

where E_{com} (kWh/d) is the energy for biogas compression; P_{in} (bar) is the inlet pressure; P_{out} (bar) is the outlet pressure; and $Biogas_{in}$ (m^3/d) is the biogas flow. The same equation has been used for biomethane compression, with the same definition for the symbols.

Two-stage high pressure anaerobic digestion

The second biogas production process analyzed in the study was the TSHP AD. First, biomass is pumped inside the AR, which consists of a 5 mm thick cylindrical steel chamber with 10 cm thick mineral wool insulation. The reactor has an overall height of approximately 7 m and a radius of 4 m; the operating volume for biomass is 311 m^3. The retention time in the AR was estimated to be 10 days. Here, a stirrer ensures biomass movement and proper mixing. The installed pump has a technical power of 2.2 kW and a working time of approximately 34 minutes per day. Hydrolysis and acidogenesis work at a thermophilic temperature of 55 °C, which needs to be maintained in the AR. After the first stage, the product called hydrolysate is pumped into the MR for the methanogenesis reaction. Due to its higher working pressure, the MR is smaller in size than the AR; it has a height of approximately 5.5 m and a radius of 3 m. The total working volume is approximately 155 m^3. The walls and insulation of the chamber are similar to those of the AR. The hydrolysate has a retention time of approximately 5 days within the MR. The working temperature is set to mesophilic temperatures of 37 °C, allowing the recovery of part of the heat from the liquid, which had a temperature of 55 °C when fed. The biogas produced has a pressure of 10 bar, alleviating the need for further compression before upgrading. The result of the TSHP AD is the production of biogas and digestate. Digestate is produced in semisolid form from the AR and in mostly liquid form from the MR, and it is then transported to production sites and used as fertilizer.

Biogas upgrading with water scrubbing

The upgrading process by water scrubbing requires feeding the biogas into an absorption column and pumping water in the opposite direction. Therefore, Equation (7) gives the energy consumed by the process:

$$E_{tot} = E_{el-b} + E_{pump-biogas} + E_{pump-H_2O} + E_{rec-H_2O} - E_{rec-CH_4} \quad (7)$$

where E_{tot} (kWh/d) is the total energy consumption, considering both electricity and heat; $E_{el\text{-}b}$ (0.012 kWh/m^{3}biogas) is the electrical energy required for base operations; $E_{pump\text{-}biogas}$ (0.121 kWh/m^{3}biogas) is the electrical energy necessary for feeding biogas into the absorption column; $E_{pump\text{-}H2O}$ (0.084 kWh/m^{3}biogas) is the electrical energy required for feeding water into the absorption column; $E_{rec\text{-}H2O}$ (0.02 kWh/m^{3}biogas) is the electricity for water recovery and passage to the Flash Tank and Desorption Column; and $E_{rec\text{-}CH4}$ is the thermal energy generated by the combustion of the unrecovered methane remaining in the biogas (6% of the total biomethane). The efficiency of heat recovery from biomethane is 80%.

Ex situ biological upgrading

In this process, the produced biogas is fed into an external reactor in combination with H_2. Therein, methanogenic microorganisms combine CO_2 and H_2 to form CH_4, adding to the biomethane already present in the biogas.

The following equation gives the energy required for the process:

$$E_{tot} = E_{heat} + E_b + E_{pump-H_2} + E_{prod-H_2} - E_{rec-microb} \quad (8)$$

where E_{heat} (0.25 kWh/m^{3}biogas) is the thermal energy to reach and maintain the constant process temperature (55 °C); E_b (0.012 kWh/m^{3}biogas) is the electricity for the base operations of the process; $E_{pump\text{-}H2}$ (4.800 kWh/Nm^{3}H$_2$) is the electricity for the electrolysis; $E_{prod\text{-}H2}$ (0.081 kWh/Nm^{3}H$_2$) is the electricity for pumping water for electrolysis, its purification, and compression of hydrogen to 10 bar; and $E_{rec\text{-}microb}$ (0.22 kWh/m^{3}biogas) is the thermal energy obtained from the exothermic Sabatier reaction, which can be recovered for the needs of the process. Although the literature (Alfaro et al., 2018) suggests a value of 0.41 kWh/m^{3}biogas for biogas compression, in this analysis, this energy is not needed in this analysis because one of the advantages of the TSHP AD is to have an equal pressure with the reactor where the biological upgrading takes place. Considering the difficulty of heat estimation, the value is taken from the literature as it is more reliable; once the plant is operating, a specific value will be measured. Furthermore, in this analysis, the need for heat is balanced entirely by microbial activity. To produce hydrogen, water is purified and then pumped into the electrolyzer. Finally, the hydrogen is dried from the residual steam. Due to the large quantity of hydrogen, it is possible to exploit large plants that optimize energy consumption and are able to limit emissions.

Biomethane compression

Biomethane produced with the traditional upgrading method has an outlet pressure of 1 bar, while if methane is produced with the biological method, the outlet pressure is 10 bar. The feed-in pressure of the natural gas grid depends on the regulations of the country where the plant is located. In this study, a methane feed-in pressure of 200 bar was considered. The equation used to calculate the energy required for methane compression was the same as that used to calculate the energy for biogas compression (Equation (6)).

5.3.3 Impact assessment: overall calculation

The environmental impact of the alternative scenarios for biomethane production were compared; precisely, the amount of GHG emitted from each process step was calculated.

Once the overall results for each scenario were obtained, they were compared to the baseline values provided in the 2018 RED. This step allowed validation of the model and certification of its congruence with the reference values. Then, based on the final values, a twofold analysis was performed to evaluate the following questions.

- Which steps were the most significant in the overall GHG emissions balance?
- Which were the most environmentally beneficial processes?

5.3.3.1 Sensitivity analysis

The results of emissions in the three different scenarios depended on the parameters used for the calculation. In particular, the need to study two aspects arose. i) How do the results change using different biomasses? ii) What results would be obtained if the needed electricity was produced only by renewable energy sources? To answer these questions, a sensitivity analysis was carried out. The results of the described scenarios were compared with those obtained using SB instead of CM. Finally, emissions were calculated for the two biomass alternatives with three different ways of producing electricity.

- Energy sources in the German national energy system in their actual proportions.
- Fossil fuels are excluded from the energy mix, and renewable energy sources and nuclear energy are retained.
- Only renewable sources are kept and fossil fuels and nuclear power are excluded.

If the electricity derives from the national grid, GHG production can be estimated based on the energy sources in the electric system. In 2020, in Germany, 37.0% of electricity was produced from fossil fuels (24.5% coal and 11.9% natural gas), 12.7% from nuclear power, and 50.3% from renewable energy sources (24.7% wind power, 10.5% solar, 9.2% biomass and 4.0% hydroelectric).

GHG emissions from a power source must consider all stages, from construction and operation to decommissioning of a plant. Various authors have conducted numerous studies to determine GHG levels related to power generation from various energy sources. The following values were used in this analysis: 66 gCO_2eq/kWh_{el} nuclear power (Raadal et al., 2011), 659 gCO_2eq/kWh_{el} natural gas (Davis and Socolow, 2014), 1090 gCO_2eq/kWh_{el} coal (Davis and Socolow, 2014), 34.1 gCO_2eq/kWh_{el} wind (Nugent and Sovacool, 2014), 49.9 gCO_2eq/kWh_{el} solar (Nugent and Sovacool, 2014), 73.8 gCO_2eq/kWh_{el} biomass (European Commission, 2021), and 160 gCO_2eq/kWh_{el}

hydroelectric (Hertwich, 2013). The heat needed for the process is supplied by the combustion of the biomethane produced in the plant, providing 1816 gCO_2eq/m^3CH_4.

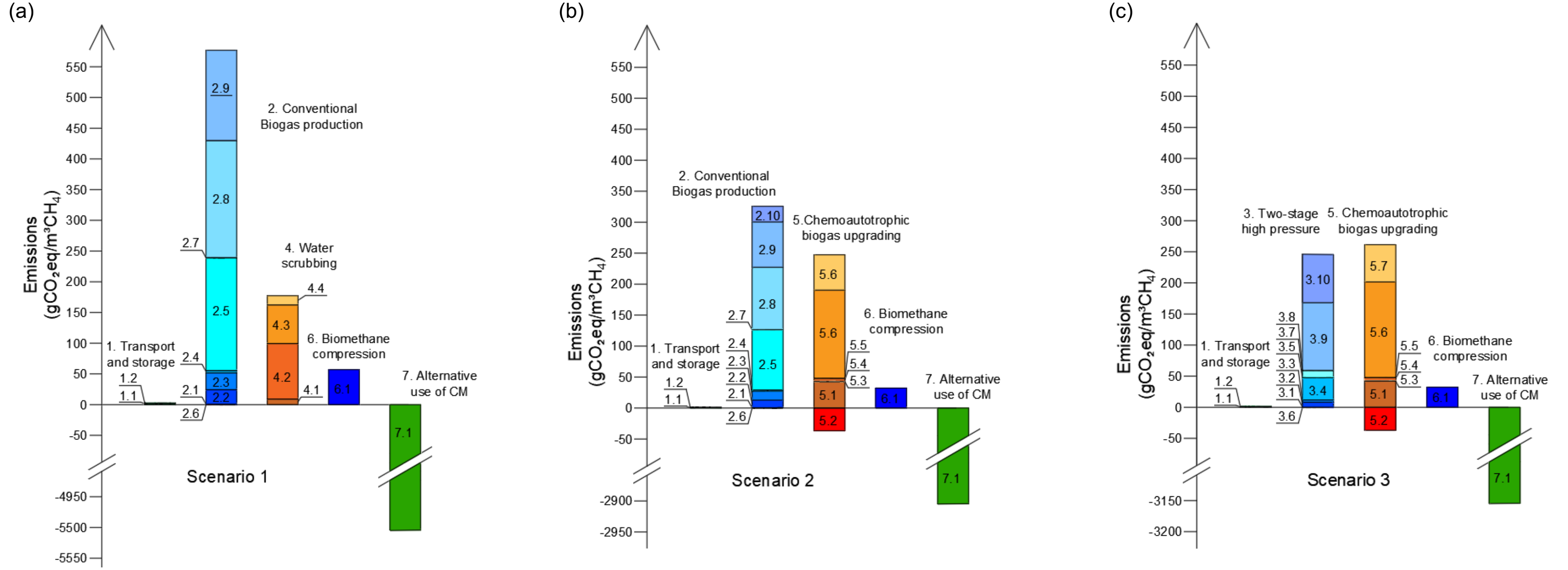
5.3.4 Interpretation

In the last part of the analysis, the results and the model were subjected to critical analysis to identify improvement points and possible critical issues. A critical analysis is necessary to compare alternative techniques, as they operate under different biomass loading conditions. Then, the sensitivity analysis allowed the identification and discussion of which process steps had the most significant impact on the final GHG balance. The conclusions summarized the results obtained and identified potential study developments.

5.4 Results and discussion

5.4.1 Conventional Biogas Production - Conventional Biogas Upgrading

In the first scenario, biogas was produced by the conventional AD, and upgrading was conducted by water scrubbing. This system is the most common and can be considered the base scenario. Under these conditions, 805.6 gCO_2eq is emitted to produce 1 m^3 of methane and manage the digestate, equivalent to 20.2 gCO_2eq/MJ. This resulted was the outcome of the production of 510.2 m^3CH_4/d. The biomethane production required 668.5 gCO_2eq/m^3CH_4, equivalent to 16.8 gCO_2eq/MJ, close to the RED value of 11.9 gCO_2eq/MJ (Figure 5-3a).



1. Transport and storage
1.1 Biomass transport
1.2 Biomass storage
2. Conventional biogas production
2.1 Substrate pumping
2.2 Substrate mixing
2.3 Substrate agitating
2.4 Substrate heating
2.5 Thermal energy loss in the reactor
2.6 Energy production by microbial activity
2.7 CH_4 loss during the process
2.8 CH_4 loss during digestate storage
2.9 Digestate management
3. Two-stage high pressure anaerobic digestion
3.1 Substrate pumping in the AR
3.2 Substrate stirring
3.3 Substrate heating
3.4 Thermal energy loss in the AR
3.5 Substrate pumping in the MR
3.6 Thermal energy recovery in MR
3.7 Therma energy loss in the MR
3.8 CH_4 loss during the process
3.9 CH_4 loss during digestate storage
3.10 Digestate management
4. Water scrubbing
4.1 Base operations
4.2 Biogas compression in absorption coloumn
4.3 Biogas and water injection in absorption coloumn
4.4 CH_4 recovery and water regeneration
5. Biological upgrading
5.1 Biogas heating
5.2 Microbial activity in upgrading process
5.3 Base operations
5.4 Water purification
5.5 Water pumping in electrolyser
5.6 Electrolysis
5.7 Hydrogen purification
6. Biomethane compression
7. Alternative use of CM

Figure 5-3. Calculated CO_2 emissions using CM as a substrate and considering electricity production with the actual German energy system of a) conventional biogas production and water scrubbing biogas upgrading; b) conventional biogas production and biological upgrading; and c) two-stage high pressure anaerobic digestion process and biological upgrading

The biogas plant in this model is close to the farm where the biomass was collected, 1 km distance, so transport costs are negligible. As a result, biomass transport and storage contributed very little to CO_2 production, only 2.8 gCO_2eq/m^3CH_4.

The most significant production of CO_2, 431.5 gCO_2eq/m^3CH_4, occurred in the biogas production phase. The emissions were mainly due to the thermal energy loss to maintain the digester's temperature (37 °C), 183.5 gCO_2eq/m^3CH_4, and the methane loss during the digestate storage, 190.6 gCO_2eq/m^3CH_4, before its transfer and use as a fertilizer. The electrical energy used to set the mixer and agitator in motion caused emissions of 23.6 gCO_2eq/m^3CH_4 and 27.3 $gCO_2eq/m^3CH_{4,}$ respectively. These values depend not only on the technical characteristics of the machinery (power and working time) but also on how electricity is produced in the national electrical energy system. Substrate pumping and heating, methane loss during the process and digestate transport showed a much smaller impact on overall CO_2 emissions. Digestate disposal resulted in the emission of 137.1 gCO_2eq/m^3CH_4.

The biomethane upgrading phase caused the emission of 234.2 gCO_2eq/m^3CH_4. Emissions were mainly due to the electrical energy spent for biogas compression in the absorption column, 90.5 gCO_2eq/m^3CH_4, and water and biogas injection, 62.8 gCO_2eq/m^3CH_4. The CH_4 recovery and water regeneration for absorption resulted in 15.0 gCO_2eq/m^3CH_4. Additional energy consumption for all basic process operations has been estimated to result in 9.0 gCO_2eq/m^3CH_4. Finally, it was necessary to consider a significant energy consumption for methane compression, which must be fed into the network at a high pressure set by the network operator. An emission of 56.9 gCO_2eq/m^3CH_4 was calculated to achieve the required pressure of 200 bar.

The assessment of emissions for the alternative use of CM resulted in a savings of 5509 gCO_2eq/Nm^3CH_4, or 138 gCO_2eq/MJ. This value is confirmed by the RED, which set a credit for using CM of 111.9 gCo_2eq/MJ.

5.4.2 Conventional Biogas Production - Chemoautotrophic Biogas Upgrading

In the second scenario, biogas was produced by the conventional process, and for biogas upgrading, the biological ex-situ method was used. In this scenario, an output of 569.9 gCO_2eq/m^3CH_4 was obtained to produce 1 m^3 of methane and manage the digestate, which was 14.3 gCO_2eq/MJ. The biomethane production required 497.4 gCO_2eq/m^3CH_4, equivalent to 12.5 gCO_2eq/MJ, thereby very close to the value reported in the RED. This system allowed for an estimated methane production of 964.6 m^3CH_4/d, higher than that obtained in the previous scenario with water scrubbing upgrading (Figure 5-3b).

In this scenario, biogas transport and storage still played a minor role in CO_2eq production, 1.5 gCO_2eq/m^3CH_4 and 0.04 gCO_2eq/m^3CH_4.

Biogas production accounted for most of the emissions in this scenario as well. The values were proportionally the same but changed due to different methane production. During this phase, 97.1

gCO_2eq/m^3CH_4 was emitted to maintain the digesters temperature, while emissions due to methane loss during digestate storage were 100.8 gCO_2eq/m^3CH_4. The mixer and agitator electricity consumption inside the digester was also significant in this scenario; the emissions from these machines were 12.5 gCO_2eq/m^3CH_4 and 14.4 gCO_2eq/m^3CH_4, respectively. The other process steps showed a minor impact on the total emissions: substrate pumping, 0.4 gCO_2eq/m^3CH_4; substrate heating, 2.0 gCO_2eq/m^3CH_4; methane loss, 0.1 gCO_2eq/m^3CH_4; and digestate handling, 1.2 gCO_2eq/m^3CH_4. The upgrading process demanded a biogas injection pressure of 10 bar, which required the work of an electric pump, which caused the emission of 25.3 gCO_2eq/m^3CH_4. Finally, digestate disposal entailed the emission of 72.5 gCO_2eq/m^3CH_4.

In this scenario, biogas upgrading is performed with ex-situ biological methanation. Preheating the biogas (55 °C) resulted in 42.0 gCO_2eq/m^3CH_4 emissions. These emissions increased by 4.7 gCO_2eq/m^3CH_4 due to the electricity consumption for all other basic reactor equipment operations. The produced biomethane has a pressure of 10 bar, so it is necessary, as in the previous case, to use a pump to raise the gas pressure to 200 bar to feed it into the distribution network, resulting in an emission of 32.2 gCO_2eq/m^3CH_4. The reaction between CO_2 and H_2 inside the reactor allowed the recovery of a considerable amount of energy, leading to a savings of 37.0 gCO_2eq/m^3CH_4. The emissions caused by the electrolysis heavily depend on how electricity is supplied. Hydrogen is produced with electricity from renewable sources, so the emissions were 200.4 gCO_2eq/m^3CH_4.

Due to the increased methane output, an emission saving for carbon credits of 2913.7 gCO_2eq/m^3CH_4, or 73.2 gCO_2eq/MJ, was calculated. This value is lower than that proposed by the RED, probably due to the higher efficiency of this system, which allows obtaining higher methane values with the same amount of CM.

5.4.3 Two-Stage High Pressure anaerobic digestion - Chemoautotrophic Biogas Upgrading

In the third scenario, biogas was produced using the TSHP AD and upgraded using the biological method. This combination made it possible to obtain 892.6 m^3CH_4/d with the same amount of biomass; the quantity was lower because the methane produced in the first stage of the biogas process, the AR, was burnt to obtain thermal energy for the process (Figure 5-3c).

Biomass transport and storage caused emissions of 1.2 gCO_2eq/m^3CH_4 and 0.4 gCO_2eq/m^3CH_4, still having little effect on the overall balance.

In the two reactors, AR and MR, a constant temperature must be maintained (55 °C and 37 °C), causing the highest emissions: 35.7 gCO_2eq/m^3CH_4 and 11.2 gCO_2eq/m^3CH_4, respectively. In case of mesophilic temperature in AR, the heat loss would be less, and the difference between two reactors would only be due to geometrical and construction characteristics. The pump for feeding the substrate into the AR (0.5 gCO_2eq/m^3CH_4), the stirrer (7.6 gCO_2eq/m^3CH_4), and the pump for feeding the hydrolysate into the MR (0.4 gCO_2eq/m^3CH_4) need an electricity supply. Substrate heating resulted in the emission of 3.6 gCO_2eq/m^3CH_4. The highest emissions occurred at the end of the process, during digestate storage, when 109.0 gCO$_2$eq/m^{3}CH$_4$ was emitted. Finally, spreading digestate on the field resulted in the emission of 78.4 gCO$_2$eq/m^{3}CH$_4$.

The steps for biogas upgrading were the same as those described in the previous chapter. The phase causing the highest emissions was the biomethane compression for injection into the grid, leading to 32.2 gCO$_2$eq/m^{3}CH$_4$ in electricity consumption. Electricity was also used for basic process operation, with estimated emissions at 4.6 gCO$_2$eq/m^{3}CH$_4$. Biogas heating at the beginning of the process as well as maintaining a stable process temperature of 55 °C caused 40.3 gCO$_2$eq/m^{3}CH$_4$. Energy recovery due to the biological reaction between H_2 and CO_2 allowed the reduction of 35.5 gCO$_2$eq/m^{3}CH$_4$ emissions. One of the advantages of the TSHP AD is the autogenerative pressure increase to 10 bar via microbial activity, superseding the consumption of additional energy to reach the pressure required for biological upgrading.

In this scenario, hydrogen production resulted in significant emissions due to the energy sources supplying the necessary electricity, resulting in 21.8 gCO$_2$eq/m^{3}CH$_4$.

Savings of 3148.6 gCO$_2$eq/m^{3}CH$_4$, equivalent to 79.1 gCO$_2$eq/MJ, were quantified for carbon credits; again, a lower value than reported in the RED, due to the higher productivity of this scenario compared to the conventional biogas production and upgrading process.

5.4.4 Sensitivity analysis

The results of the sensitivity analysis are shown in Figure 5-4 and Table 5-2.

Table 5-2. Results comparison of the alternative scenarios

		Heat (kWh/m^{3}CH$_4$)	Electricity (kWh/m^{3}CH$_4$)	Fuel (kWh/m^{3}CH$_4$)	Emissions (gCO$_2$eq/m^{3}CH$_4$)
Scenario 1	Biomass supply	0.000	0.000	0.013	2.826
	Anaerobic digestion	1.138	0.133	0.013	568.642
	Biogas Upgrading	-0.565	0.458	0.000	177.214
	Biomethane compression	0.000	0.147	0.000	56.941
	Alternative use of feedstock	0.000	0.000	0.000	-5509.033
	Total consumption	0.573	0.739	0.027	-4703.410
Scenario 2	Biomass supply	0.000	0.000	0.007	1.495
	Anaerobic digestion	0.602	0.136	0.007	326.070
	Biogas Upgrading	0.031	0.600	0.000	210.44
	Biomethane compression	0.000	0.083	0.000	32.195
	Alternative use of feedstock	0.000	0.000	0.000	-2913.729
	Total consumption	0.632	0.733	0.014	-2260.736
Scenario 3	Biomass supply	0.000	0.000	0.008	1.615
	Anaerobic digestion	-0.029	0.022	0.008	192.334
	Biogas Upgrading	0.029	0.567	0.000	224.189
	Biomethane compression	0.000	0.083	0.000	32.195
	Alternative use of feedstock	0.000	0.000	0.000	-3148.636
	Total consumption	0.000	0.656	0.015	-2698.303

Figure 5-4a shows the emission values for 1 m^3 of produced biomethane, which did not change significantly by varying the biomass. Under almost all conditions, the differences in emissions between CM and SB were less than 5% using the same process and electricity supply. Only scenario 3, with electricity directly from the grid, showed an increase in emissions of 6.2%. However, it must be considered that the carbon savings due to manure management must be added to these emissions if CM is used. This factor made CM more cost-effective than SB from an emissions point of view. CO_2eq production decreased using the TSHP process for biogas production and biological upgrading.

Using different electricity supplies, a considerable decrease occurred with the utilization of renewable energy sources. This decrease was more distinct in scenarios 2 and 3 due to the consumption of electricity for hydrogen production, which had a high impact on the total emission balance. With CM and supplied electricity only from renewable and nuclear sources, emissions decreased by 29.5% for scenario 1, 42.3% for scenario 2 and 48.0% for scenario 3. Without nuclear power, there were even greater reductions: -30.5% for scenario 1, -43.7% for scenario 2 and -49.7% for scenario 3. With SB, similar values occurred with the same general trend.

Figure 4b shows the emission for 1 ton of FM. Considering the higher specific methane yield of SB compared to CM, the emission values for SB were much higher if one ton of biomass was used as a reference parameter. The calculation of carbon credits increased the convenience of using CM. Again, the use of electricity from renewable sources, substantially reduced carbon equivalent emissions, particularly in scenarios 2 and 3 (the reduction percentages are the same as in the previous case). Scenario 2, given the higher methane production, showed the highest CO_2eq emissions per ton of biomass. However, the emission increase could be mitigated by using electricity from renewable sources.

The developed analysis showed that the most significant contribution to energy consumption and GHG emissions in the conventional AD was the heat loss in the digester (32.3% of the GHG emissions). Insulating materials, e.g., polystyrene or mineral wool, significantly reduced heat flow. Another important factor was the emissions caused when digestate was stored between AD and the field, accounting for 33.5% of the GHG emissions. Therefore, the use of covers and efficient logistics organization to minimize storage time to reduce emissions is advised. Electricity was used to operate pumps, control instruments, agitators and mixers at 0.133 kWh_{el}/m^3CH_4.

Similar considerations are valid for the TSHP process. Substrate and digestate storage resulted in the highest GHG emissions. The authors discussed this point extensively; the final decision was to assume this value based on the literature, but a reduction is expected as various solutions, such as digestate coverage, that allow to contain it are adopted. In addition, the TSHP AD is expected to produce a digestate with a lower residual methane potential and therefore lower emissions. The heat loss in the AR was more relevant than that in the MR, both because of a longer retention time (10 and 5 days, respectively) and therefore a larger reactor and because the process temperature was higher, 55 °C in HR and 37 °C in MR.

Upgrading with water scrubbing consumes 0.606 kWh_{el}/m^3CH_4, with the highest share in the biogas and water pumping phase in the absorption column. Additionally, considering water recycling once it has passed through the absorption column, the relative energy consumption had to be examined; however, the water savings that would have to be constantly introduced justified this choice from an environmental point of view. On the other hand, upgrading biogas with the biological method required considerable electrical energy consumption; therefore, even with this method, a significant reduction in emissions can be achieved using renewable energy, 71.4% with CM, for example. The resulting values of methane formation rate (0.444 m^3 $CH_4/(h·m^3$_Reactor)) and gas hourly space velocity (1.037 h^{-1})) are comparable with those found by other authors; the values of these parameters in a study by Ullrich and Lemmer (2019) were 0.23 m^3 $CH_4/(h·m^3$_Reactor) and 1.16 h^{-1}, respectively. Hydrogen production by electrolysis was the most sensitive process regarding the energy supply. However, this technology can be used as a storage system for excess electricity produced by wind and photovoltaic plants. Indeed, one of the main issues to be addressed in planning a 100% renewable energy system is managing excess energy production due to the inconstancy of winds and solar irradiance. Biomethane can serve as a form of storage for this excess energy, which can be used during peak demand periods. The use of methane requires its compression to be injected into the natural gas distribution grid.

Biomethane compression before being introduced into the grid involved an important energy expenditure and high GHG emissions: 8.5% in scenario 1 (56.9 gCO_2eq/m^3CH_4), 6% in scenario 2 (32.2 gCO_2eq/m^3CH_4) and 8.7% in scenario 3 (32.2 gCO_2eq/m^3CH_4). These percentages decreased using renewable energy sources: 1.9% (8.0 gCO_2eq/m^3CH_4), 1.8% (4.5 gCO_2eq/m^3CH_4), and 3.0% (4.5 gCO_2eq/m^3CH_4). In scenario 1, the final compression brought the pressure from 1 bar to 200 bar. In scenario 2, 25.3 gCO_2eq/m^3CH_4 was added to bring the biogas pressure from 1 bar to 10 bar before the biological upgrading process (3.6 gCO_2eq/m^3CH_4 with renewable sources). In scenario 3, no additional energy increases were required because 10 bar was reached in the biogas production by the TSHP.

Comparing the biogas production scenarios, the analysis demonstrated (Fig. 3) that if energy supply derives from renewable sources, using the two-stage system and biological upgrading improved the performance of the process, thereby reducing emissions.

The consideration of carbon credits for the use of manure requires further investigation. If the RED was considered, which provides a credit value (111.9 gCO_2eq/MJ) based on the energy produced, the convenience of scenarios 2 and 3 still increased because of a higher biomethane production. Otherwise, if the CO_2 savings were calculated based on the CM mass used, scenario 2 became the least convenient: -4703.4 gCO_2eq/m^3CH_4 in scenario 1, -2260.7 gCO_2eq/m^3CH_4 in scenario 2, and -2698.3 gCO_2eq/m^3CH_4 in scenario 3, with energy from the national electrical distribution grid. This approach would be correct if the reference point were only biomethane production. If, on the other hand, the reference was the CM to be disposed of, the analysis performed showed that scenario 3 was the most efficient, -74.7 gCO_2eq/tFM, followed by scenario 1, -74.4 gCO_2eq/tFM, and by scenario 2, -70.1 gCO_2eq/tFM. These values became 80.9 gCO_2eq/tFM for scenario 3, 78.3 gCO_2eq/tFM for scenario 1, and 77.6 gCO_2eq/tFM for scenario 2 if only renewable energy sources were used. Under this condition, scenarios 1 and 2 became very close, -1.0% (Fig. 4), involving different evaluations of the scenario's efficiency.

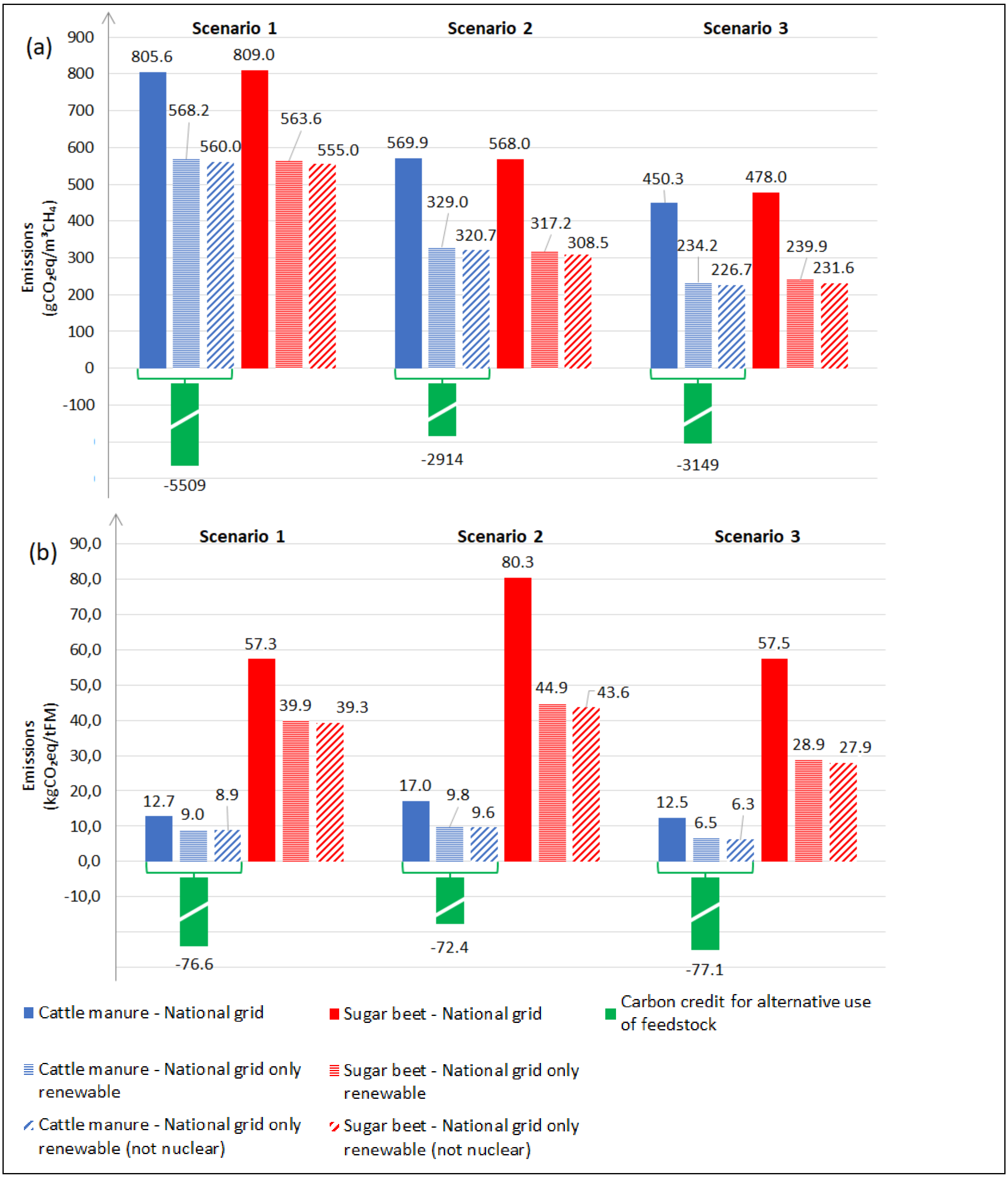


Figure 5-4. Sensitivity analysis: substrates and electricity production. Values refer to (a) 1 m^3 of CH_4 and (b) 1 t of FM

5.5 Conclusion

TSHP process and biological upgrading method allowed energy savings and a significant reduction in GHG emissions with equal biomethane produced. The use of renewable sources to produce electricity reduced CO_2 emissions up to 51.5%, while the use of CM allowed the acquisition of carbon credits of RED. A comparison of alternative biomethane production methods must consider conditions external to the system itself, mainly the electricity generation system, production capacity of renewable energy plants, and demand characteristics. Future researches may focus on the analysis of the consumption of innovative plants and their variations according to the biomass used.

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6 Where and how? A comprehensive review of multicriteria approaches for bioenergy plant siting

6.1 Abstract

The growing interest in renewable energies requires increased consciousness regarding their impact on the territory and communities. For this reason, several researchers have studied the conditions that influence the balance between the benefits and costs of new bioenergy plants, producing a wide-ranging review of studies regarding the optimal location of plants. This process is based on several economic, social and environmental conditions. One of the most valuable and useful tools to evaluate the criteria and attribute the proper weight is the multicriteria decision model/analysis (MCDM/A). This review summarizes the studies of the last 20 years to describe the criteria that influence the location of bioenergy plants and how the authors compared and categorized the alternatives. In total, 40 papers were reviewed, studying *i)* the adopted criteria and multicriteria decision model/analysis and *ii)* the environmental and social conditions that influence this type of analysis. As a result, 55 criteria, divided into 13 subgroups and three main groups (social, economic, and environmental), are identified and studied. This research can support future studies that address the territorial management of energy sources and integrate different types of renewable energies.

Keywords: Bioenergy, Multicriteria, MCDM/A, Decision Model, Plant location.

Abbreviations

AA	Agricultural activities	IEA	Influence on economic activities
AAA	Anthropic activities or artefacts	MCDM/A	Multi-Criteria Decision Model/Analysis
AUA	Avoid urban areas	NE	Natural elements
BCT	Biomass collection and transport	NEP	Negative effect on population
BLC	Benefits for local communities	NH	Natural hazard
BP	Biomass Plant(s)	OT	Other
FC	Financial consideration	RES	Relation with the energy system
IA	Industrial activities		

6.2 Introduction

“Affordable and clean energy” and “Sustainable cities and communities” are two of the 13 goals set by the UN to promote prosperity while protecting the planet. However, how can energy production be combined with the safety and security of communities and the protection of natural environments? The production of energy, even from alternative energy sources, entails a series of critical decisions that must be carefully considered. Problems in storage (Trainer, 2017), economic viability (Moriarty and Honnery, 2016), end-of-life disposal of the main components (Rocchetti and Beolchini, 2015), impact on the local natural environment (Ouyang et al., 2011), and awareness and maturity of local producers, are just some of the issues that have to be dealt with when addressing the issue of renewable energy.

Bioenergy is one of the most promising forms of renewable energy for the future (Ferrari et al., 2020); however, its exploitation still needs careful consideration of the technical and economic aspects of production and the environmental and social impacts and benefits (Ferrari et al., 2021a). Numerous projects and agreements have also been drawn up internationally, and many authors have dedicated their research to studying these aspects. The transport of biomass on road vehicles involves the emission of polluting gases (Shu et al., 2017), particularly raw material with variable energy values scattered across the territory. Thus, it is essential to consider the transport network in a bioenergy production system's economic and environmental balance. Soil sealing is another critical problem to face (Pistocchi et al., 2015): biomass plants (BP) could cause local waterproofing problems (Ferrari et al., 2021b) for large covered areas. Soil overexploitation can also originate from the use of energetic crops that subtract lands from food cultivation (Valentine et al., 2012). Furthermore, a relevant issue is the location of the plants, which has to contend with potential negative consequences on the environmental and economic context and not-in-my-backyard (NIMBY) beliefs in local communities.

Several authors have studied the impact of these facilities on local communities and carried out studies regarding the social acceptance of this energy source (Liebe and Dobers, 2019). Authors typically discriminate the issues related to the plant location problem in three main fields: (i) social, (ii) economic and (iii) environmental.

The presence of biomass facilities usually entails direct or indirect negative consequences on local communities. BP are a source of noise and odour due to the biodigestion process (Chinese et al., 2014) and to the agricultural and livestock activities that supply the feedstock (Kampman et al., 2020); moreover, problems for tourism and traffic have been considered in the latest studies (Babalola, 2018; Vlachokostas et al., 2020). These problems concern a limited area with proximity to the plants, and the affected population is restricted. In general, communities in the proximity of the plant can suffer to varying degrees depending on the distance from the energy production site, especially if impacted by inefficient solutions implemented by BP. Complementary technical and management solutions have been developed to address this problem. First, various chemical and/or biological systems and processes have been designed to reduce emissions and noise from BP (Ren et al., 2019). Second, solutions can include installing the facilities as far as possible from communities (Kythreotis et al., 2019). Therefore, the fundamental elements to be protected and the distances to be respected to preserve them from the adverse effects of BP must be identified. In addition to preventing the problems above, this approach allows for most of the benefits offered by installing BP.

New bioenergy facilities are usually excellent economic opportunities (Lyytimäki, 2018), allowing the creation of job sites and stimulating the local circular economy. Knowledge of the economic context of the area in which the plants are planned to be located is essential, for example, to exploit the heat produced in the plants (Soltero et al., 2018). In cogeneration plants, part of the heat is used for the production processes, and the remainder can be used to heat buildings near the plant. Furthermore, it should be considered that many aspects can contribute to the economic sustainability of such an investment (Gebrezgabher et al., 2010). The availability of bioresources is a critical factor in implementing a profitable bioenergy production system (Valenti and Porto, 2019). Furthermore, collecting byproducts and waste can constitute an additional income and a positive externality for the environment. Such is the case of biogas production of urban waste (Picardo et al., 2019) and livestock effluent treatment: collecting and treating livestock waste in biogas plants facilitates the control of nitrogen emissions (Provolo et al., 2017).

Environmental conditions and issues greatly influence BP location and characteristics (Paolini et al., 2018). The analysis must consider anthropic elements, such as land use, cultivated crops in the area, cultural and historical sites, and natural features, such as hydrographical networks, natural spaces, and climate conditions (Börjesson and Berglund, 2007). Environmental risks play an essential role in the process; areas with high hydrological risk, susceptible to flooding and earthquakes, should be avoided.

Every situation requires consideration of additional criteria, with proper importance ascribes to each of them. Multicriteria decision model/analysis (MCDM/A) is the usual methodology to model and solve such problems. Decision analysis is the process of designing or choosing the best alternatives based on the preferences of the decision-maker and the conditions of the case study (Zarghami and Szidarovszky, 2011). Usually, it is necessary to identify as many of these alternatives as possible and choose the one that best fits goals and requirements (Rikalovic et al., 2014).

Decision-making is rarely a linear process. First, decision-makers must consider conflicting criteria simultaneously: economic, social, and environmental criteria deal with needs that conflict by nature. Moreover, these criteria are differently assessed: quantitative or qualitative, with different scales, numerical or verbal categories. Second, when environmental issues are considered, it is necessary to meet the present communities' needs without compromising the possibility or future generations to meet their own needs (Vera and Langlois, 2007). Third, the evaluation of alternatives could be imperfect or inconsistent. For example, the assessment could be uncertain, incomplete, or subjected to the personal point of view of the analyst. Finally, authors and policy-makers increasingly need to involve stakeholders within a participatory and cooperating will to make decisions. However, the heterogeneity of the opinions of stakeholders and, in some cases, the incomplete knowledge of the problems, especially the technical aspects, can increase the problem complexity.

MCDM/A is suitable to evaluate a group of alternatives that consider a set of multiple and conflicting criteria. Several authors have felt the need to review and summarize the application of MCDM/A models in various research fields. (Kandakoglu et al., 2019) reviewed 342 sustainable development articles that used MCDM/As. This approach allowed them to describe the temporal evolution and spatial distribution of the articles and the types of MCDM/A applied. The authors also performed other specific analyses, providing editorial details and defining the fields of application. Given the breadth of the subject matter, the authors did not perform a critical analysis of each article but provided studies of a primarily statistical nature. A different approach was followed by (Hajkowicz and Collins, 2007), who reviewed the studies that have applied MCDM/A to water resource planning and management. With a more specific topic and only 113 articles, the authors were able to conduct more detailed analyses, including discriminating articles based on the application. This type of analysis allowed the authors to examine the rationale behind the adoption of MCDM/A in water management problems and express considerations for future research directions.

In the last 20 years, several authors experimented with different types of MCDM/A to find the best sites to install a biomass facility (Babalola, 2018; Jeong and Ramírez-Gómez, 2017a; Silva et al., 2014). Depending on the condition of the study area and the goals of the authors, different sets of criteria have been considered, resulting in a broad range of literature; however, a comprehensive review of the studies directly applicable to future scientific research in technical and application fields is lacking. For this reason, a careful review of state-of-the-art research is necessary to implement new methodologies and to perform further studies in specific areas.

Unlike previous reviews on the general topic of bioenergy, the focus of this work is on the specific issue of siting new biogas plants. This approach allowed the study of the relationship between bioenergy plants and territory and between plants and local communities. The results can also be compared with similar studies on alternative energy sources and provide additional elements of comparison and discrimination in a sustainable energy system setting. This review aims to summarize the conclusions reached in the articles regarding the application of MCDM/A to the optimal location of BP. Furthermore, the research describes the types of MCDM/A applied based on the studied region. Finally, criteria used in the studies have been collected and analyzed to show which parameters the authors have considered more decisive and for which conditions.

6.3 Material and Methods

The methodology applied in this research includes three steps (Figure 6-1). First, the definition of the field of study, with the fundamental concepts of the research (Section 6.3.1). Second, the research methodology on the Scopus database (Section 6.3.2). Third, the performed analysis on the selected articles, with a description of the studied characteristics of the works (Section 6.3.3).

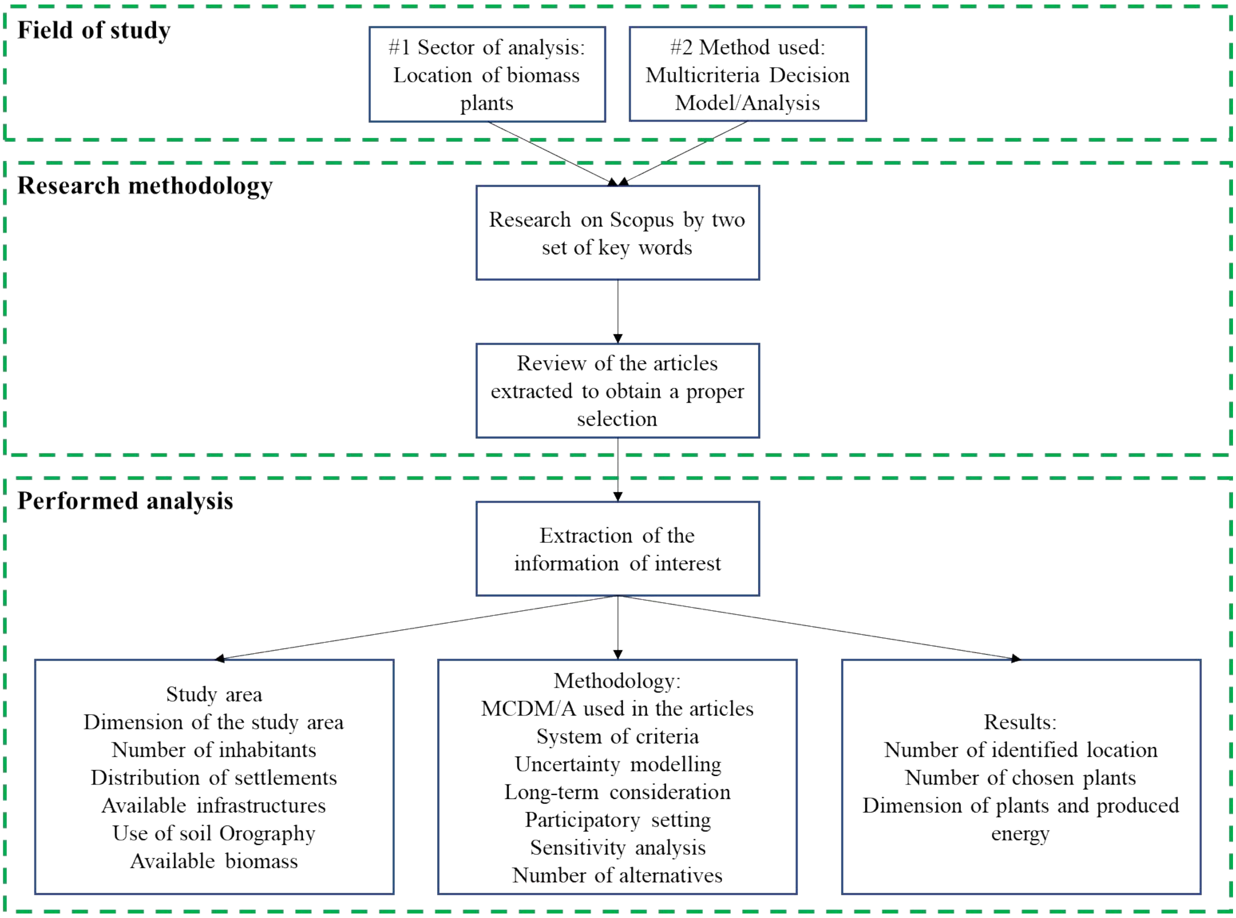

Figure 6-1. Flow chart describing the operating steps of the methodology

6.3.1 Definition of the field of analysis

In the present review, studies applying MCDM/A to BP location are investigated. Therefore, the study is focused on (i) description of the study area of the analysis, (ii) analysis of the criteria utilized by the authors to select and rank the alternatives, (iii) description of the MCDM/A chosen by the authors and (iv) type of analysis conducted to describe the problems and the aims.

Articles that applied MCDM/A to other phases of bioenergy production, such as selecting the proper feedstock or choosing the type and size of the facility, were not considered in this work. Again, articles that deal with BP location but do not use MCDM/A for the analysis have not been selected; for example, articles that only apply a set of constraints determined by GIS software to exclude parts of the study area are not included.

6.3.2 Research methodology

Based on the objectives of the work, two guiding concepts have been established: (i) bioenergy regarding the study area and (ii) *multicriteria analysis* regarding the study methodology (Table 6-1). The two concepts have been converted into a set of terms for the research of the articles. The algorithm required the presence of at least one of the terms related to both main concepts in the title-abstract keywords.

The search resulted in 385 articles. The articles were analyzed individually, and only those relevant for the review were selected and analyzed. To determine the relevance of the analysis, the following exclusion criteria were applied:

- Articles selected based on the presence of the terms but not covering the topic at hand (308 articles);
- Articles selected based on the presence of the terms but not applying the methodology under study (19 articles);
- Work done by the same authors and on the same case study, presented in stages; for example, as a preliminary analysis in a conference paper and then as a full journal article (3 articles).
- Review articles that do not feature case studies or book chapters (15 articles).

At the end, 345 were discarded and 40 were suitable for the analysis.

Table 6-1. Concepts for extraction of research papers

Concept	Search terms used for extraction	Search terms not used for extraction
#1 Sector of analysis: Bioenergy	anaerobic digester*, anaerobic digestion, biodigester, biogas, biomass facility*, biomass plant*, biomass resource*, biomethane, biomethane.	Renewable energy, waste, biogas plant location
#2 Methods used: Multicriteria analysis	multicriteria, multicriteria, mcda, mcdm, multiple criteria, multiple attribute, multiattribute, multiattribute, AHP/ANP, direct weights direct rating, equal weights, entropy weights, swing method, dematel, delphi, random weights, topsis, vikor, topsis/vikir, multiobjective programming, weighted sum, electre, promethee, MAUT/MAVT, fuzzy analysis, MOORA, MULTIMOORA, WASPAS, EDAS, CODAS, SECA, MULTIMOOSRAL, ARAS, PIPRECIA.	Decision-making, decision analysis, constraints.

6.3.3 Review approach

The most critical information was extracted from the selected articles. In particular, the study area, methodology and results were used to categorize the articles.

6.3.3.1 Study area

Anthropic and geographical conditions deeply influence the potential bioenergy system. Each study area of the analyzed articles was described according to the following parameters: size, population, number, size and distribution of settlements present, orography of the area, presence and distribution of road infrastructure, land use (urban, agricultural or forest), and type of biomass used.

The number of inhabitants in the area and the resulting population density were recorded. Articles were divided into 4 classes depending on the dimensions of the study area: very small (<500 km^2), medium-small (between 500 km^2 and 5000 km^2), medium-large (between 5000 km^2 and 40,000 km^2) and very large (>30,000 km^2). Furthermore, urban settlements and their distribution and the available infrastructures, such as roads, gas networks, electricity networks and other facilities, were examined. Finally, the available biomass, the use of the soil, the distribution between forests and cultivated land, and the presence of reliefs and hilly or mountainous areas were observed and catalogued.

6.3.3.2 Study methodology

The following steps were followed to extract, organize, and present the studied methodologies.

i) Number of alternatives for the BP position

Two categories of methods can be used for the optimization problems:

Discrete decision space - Optimization with few alternatives: To investigate the feasibility of each option by determining whether it satisfies all restrictions and assess how much they reach the established goals.

Continuous decision space - Optimization with many alternatives: Continuous variables characterize the decision alternatives. The alternatives satisfying all constraints are acceptable, and the set of all acceptable alternatives is the decision space. In the decision space, the point that maximizes the level of achievement of established objectives must be found.

ii) Criteria analysis

A uniform linguistic definition was applied to the various criteria because, in different papers, many criteria were expressed with different words, aggregating or disaggregating several aspects. For example, Sultana and Kumar, 2012 expressed the constraints: "*Rivers, lakes and other water bodies: Sites within buffer zone of 200 m are avoided*", while Delivand et al., 2015a reported the same constraint but specified two situations: "*Lake bordering areas: buffer of 300 m*" and "*Rivers, streams and waterways: buffer of 150 m*". Then, criteria were gathered depending on their sector of interest; for example, "Flooding risk, avoid areas", "Geomorphology, Physiography and related risk" and "Seismic areas" constitute the "Natural hazard" group. Finally, the groups were included in the three main sectors of criteria: social, economic and environmental. MCDM/A can be combined with other specific analyses that have been considered in this work: uncertainty modelling, long-term consideration, participatory setting, and sensitivity analysis.

iii) Feedstock-based relation analysis

The choice of criteria to be used also depends on the biomass available for the plants. To better understand this relationship and to set up subsequent analyses based on prior research, criteria was chosen based on the distinguishing characteristics of the various biomass types. The articles were divided into three groups according to the type of substrate used: agricultural forest, livestock, and urban industrial. The distribution of criteria used in each of these groups of articles was compared to the overall distribution to understand how and how much the use of a biomass influences the choice of location criteria.

iv) MCDM/A analysis

The most important points were the type of MCDM/A used in the articles. Two steps involve the MCDM/A: to represent preferences and aggregate the alternatives. In addition, some articles performed more than one analysis applying two or more methodologies to compare the results. Finally, a critical analysis of articles was completed to standardize the processes to extract the information regarding the applied methodologies.

6.3.3.3 Study results

The results include a description of suitable sites for plant placement and sites selected, number and size of the BP expressed by the amount of biomass or the installed power, and level of uncertainty of local community involvement.

Depending on the article, analysis has provided only the available areas that have not been excluded by constraints or chosen areas and, consequently, the number and size of plants. This information was collected and correlated with the features of the study areas and the adopted methodology.

6.4 Results and Discussion

6.4.1 Study area

The characteristics of the study areas are reported in Table 6-2. The heterogeneity of the case studies in the articles required categorizing the features into classes that were as homogeneous as possible.

Most articles considered medium-dimensional study areas, with a surface area between 500 km^2 and 5000 km^2 (32%) and between 5000 km^2 and 40,000 km^2 (32%). The same considerations apply concerning the population in the study area; 29% of the articles considered study areas with a resident population between 50,000 and 500,000 people, and 37% considered a population between 500,000 and 4,000,000 people (Figure 6-2).

Economic and geographical conditions have a decisive influence on the types of biomasses available for bioenergy production (Table 6-3). Most of the articles considered agricultural and forestry biomass as the source of bioenergy, 47% of the articles. Several types of biomass were included in this category: energetic crops (Ghose et al., 2019; Jeong and Ramírez-Gómez, 2018; Smyth et al., 2011), byproducts (Chiumenti et al., 2019; Perpiña et al., 2013; Rodríguez et al., 2017; Saladaga et al., 2015) or other particular biomasses. The authors developed models of district plants supplied with particular biomass collected in a medium-large region (Delivand et al., 2015; Waewsak et al., 2020). For this type of study, medium and large areas were necessary (Delivand et al., 2015; Saladaga et al., 2015; Smyth et al., 2011; Villamar et al., 2016), and 71% of the articles that used agricultural biomass were in the classes “medium-large” and “very large” regarding the dimensions of the study area.

The use of forestry biomass is typical in rural areas; many of these study areas were characterized by a low and medium density of infrastructures (Jeong and Ramírez-Gómez, 2017b; Quinta-Nova et al., 2017; Recanatesi et al., 2014). Livestock manure is one of the most promising bioenergy sources due to its positive impact on the management and disposal of this raw material; 29% of the articles referred to this biomass. Sixty-four percent of these works referred to “medium-small” and “very small” study areas (Coura et al., 2021; Dao et al., 2020; Díaz-Vázquez et al., 2020; Franco et al., 2014). This biomass has a low energetic value and very localized production; these factors entail short transport distances between sites of production and BP.

In urban contexts (Akther et al., 2019; Babalola, 2018; San Martin et al., 2017; Thiriet et al., 2020), organic and industrial waste were usually the most important sources of energy (22% of the articles). These areas are characterized by small sizes, high population density and a high presence of infrastructures and facilities. The significant demand for energy and the difficulties caused by proximity to urban buildings influenced the decision to choose large plants to reduce plant numbers, minimize their impact on the population and maximize their yield (Akther et al., 2019; Jesus et al., 2021; Yalcinkaya, 2020; Yalcinkaya and Kirtiloglu, 2021).

6.4.2 Study methodology

6.4.2.1 Alternatives for the BP position

Discrete decision space - Optimization with few alternatives

The alternatives were listed as a set of candidates and were based on existing plants or best site selection (Panichelli and Gnansounou, 2008; Vlachokostas et al., 2020) or resulted from a discretization of the study area in homogeneous subareas (De Carlo and Schiraldi, 2013). Panichelli and Gnansounou, 2008, considered the process of locating plants as a location-allocation problem to tackle resource competition between facilities. They identified a set of potential sites, allocated the biomass resources in a least-cost way, and selected the best energy facilities locations based on marginal delivery costs. Vlachokostas et al., 2020 developed an easily adaptable methodology to other study areas. The goal of the work was to reduce the gap between bioenergy and non-renewable sources from an economic and efficiency point of view.

De Carlo and Schiraldi, 2013, categorized and divided an entire region into homogeneous areas to choose the best location for a BP. The authors considered four possible alternative scenarios according to the different priorities that decision-makers can have. The analysis considered a system of incentives that could make economically convenient large biogas plants, more than 5 MWe.

The established sites could be a set of city candidates to hold BP: Yücenur et al., 2020 proposed a model consisting of 12 criteria for determining the best city to place a biogas plant supplied by municipal solid waste in Turkey. The authors used SWARA and COPRAS methods to rank the feasibility of the plant in the selected cities.

Continuous decision space - Optimization with many alternatives

Most of the research admitted the positioning of plants throughout the territory of the study area, thus considering an infinite number of alternatives. The authors perfected the analysis systems, added case studies, modified the MCDM/A, and applied different criteria or data collection methods. One of the most adopted tools to perform spatial analysis is geographic information system (GIS) software. Ma et al., 2005, and Jesus et al., 2021, explored the bioenergy potential and the geographical condition of Tompkins County, New York and the state of Paraná, Brazil. Their studies focused on economic and social benefits for farmers and the resident population, aiming to identify the areas where there was an interest in producing bioenergy through a community digester. GIS software can be helpful in the mitigation of the environmental impacts of bioenergy production. Villamar et al., 2016, explored the bioenergy potential of the Bío Region, Chile. The region covers 36,000 km^2, and it includes 7,000 km^2 of protected areas covered with native forest and located in mountainous regions (the Andes and Coast Range). Despite the vast protected areas, there are many signs of human intervention, with industrial, agricultural, livestock, forestry, fishery, and residential activities. The heterogeneous conditions required careful integration of the natural and anthropic constraints. Specific activities can cause a significant environmental impact; the primary objective of anaerobic digestion in the study of Dao et al., 2020a, was not energy production but mitigation of the environmental impact caused by pig farms in Hanoi, Vietnam. GIS software allowed the authors to consider specific needs related to infrastructures and facilities. Rodrigues et al., 2019, studied the sites that have the best characteristics to place a biogas plant considering the minimum distance from the cattle farms, the electricity grid and the roads in Barcelos municipality (Portugal). Díaz-Vázquez et al., 2020, stressed the importance of waste treatment in anaerobic digestion plants to mitigate the environmental impact of livestock farms distributed in the Jalisco region (Mexico).

An interesting aspect of spatial modelling to locate bioenergy plants is spatial observation using satellite systems. Saladaga et al., 2015, proposed a model that used the LandSAT 8 image to classify the land cover. They produced a thematic map showing the suitable areas for biomass power plants in Nueva Ecija, Philippines. Rodríguez et al., 2017, developed an integrated GIS-based fuzzy AHP methodology that combined spatial and nonspatial factors, such as technical and geographic restrictions, transport cost indicators, and logistics factors, in the study area. These regions are characterized by high population density, with many spread out urban settlements and a heterogeneous orography. These studies focused on high-resolution satellite imagery to produce biomass resource maps. Land cover can be appropriate for economic and environmental optimization and for identifying buildings, facilities and human activities. Thiriet et al., 2020, considered the wet fraction of solid urban waste currently not recovered in Grand Lyon Metropole, France. They minimized the distances travelled to deliver the products to the digester and transfer the digestate to the fields at the end of the process based on micro anaerobic digestion plants spread throughout the territory. Yalcinkaya, 2020, and Yalcinkaya and Kirtiloglu, 2021, in Izmir, Turkey, conducted an economic assessment to compare the unit cost of electric energy and the current incentive rate for biogas plants.

6.4.2.2 Criteria analysis

Usually, authors identify two types of criteria: constraints and actual criteria. Constraints are rules that determine the available areas for the facilities. They can be administrative or technical and only allow two answers: “yes” or “no”. Therefore, they exclude or admit the territories directly. They are most important because the areas that do not respect a constraint cannot be evaluated as available sites. Unlike the criteria, in this evaluation, the compensation between different constraints is not allowed: a land must satisfy the requirements of all the constraints, failing even one determines the exclusion of the area. Authors usually applied them as the first analysis phase to identify only the soils that can be evaluated and then exclude the others. The criteria determine how well an area is suitable for hosting a BP in the second analysis phase. Different criteria are usually associated with different weights, which expresses their relative importance compared with the others. Combining the scores of the weighted criteria makes it possible to classify the various areas for the installation of the systems. Unlike the constraints, a site can score very low in one criterion but high in the others; therefore, these scores offset each other while still determining a sufficient level of acceptability.

In the examined articles, the authors expressed the criteria and constraints very differently; therefore, the different formulations were homogenized to be compared in the first phase. Subsequently, the criteria were grouped into subgroups representing areas of interest. Finally, in the third step, these subgroups were divided into three thematic fields: social, economic, and environmental (Table 6-4).

6.4.2.3 Feedstock-based relation analysis

The distribution of the different criteria based on various feedstock systems was studied (Figure 6-3) (Table 6-3). In some cases, authors focused their works on very specific biomasses. For example, Smyth et al., 2011, considered the annual grass production in Ireland in a county-by-county analysis. The vast area dedicated to pasture in the country allowed a high output of biomethane that could be used by the transport sector. Sultana and Kumar, 2012, developed a methodology for determining the optimal locations, sizes and number of pellet plants through transport cost optimization in the Province of Alberta, Canada. The methodology included computation of the cost of pellet production, consideration of road networks and spatially varied biomass, and the presence of existing facilities. Considering the vast area and the energetic value of pellets, the transport distance was very high, and the road network was critical. Zubaryeva et al., 2012, proposed an integrated methodology to support local-scale design, aiming to construct small and medium anaerobic digesters with a total electrical power of 500 and 1000 kW. The study area, the Apulia region, in southern Italy, does not offer a high amount of biomass, so the author considered several types of feedstocks: urban waste, livestock manure and agricultural residues, in particular viticulture residues, olive orchard residues and byproducts of wine and olive oil production. Delivand et al., 2015b, developed alternative scenarios with increasing BP supplied by straw and tree pruning. The logistic costs were analyzed to keep the feedstock supply risk at a minimum level. As a result, optimal plant locations were found for each scenario by minimizing the total transportation distance.

In the urban context, municipal waste is a valuable source of energy. Its use as a source of energy can constitute an effective treatment and management of the organic fraction of waste (Joshi et al., 2015). San Martin et al., 2017, used the framework of the Life GISWASTE project, an MCDM/A tool developed to help decision-makers (private or public) implement food waste enhancement projects in the Basque Country region (Spain). The feedstock considered for supplying biogas plants was dairy, vegetable and meat waste from the food industry and retail sector. Khademalhoseiny et al., 2017, used the fuzzy analytic hierarchy process (FAHP), fuzzy analytic network process (FANP), and GIS to determine the optimal location for biogas plants supplied by urban waste in Najaf Abad city, Iran. According to the FAHP method, approximately 10% of the study area was suitable for biogas plants.

In comparison, approximately 11% of the study area was suitable for constructing biogas plants based on the FANP method. The reduction of the available sites for biogas plants was also demonstrated by Babalola, 2018, and Akther et al., 2019. They applied MCDM/A to locate BP supplied with urban waste in two highly urbanized contexts, Oita City, Japan, and Dhaka City, Bangladesh. In this background, the suitable areas were considerably reduced due to the environmental and social constraints imposed. The authors claimed that the valorization of the wet fraction of urban solid waste through anaerobic digestion would have reduced waste management costs.

Almost all published papers implemented criteria belonging to at least two dimensions. The most important fields of interest for each category were “Negative effect on population” (Social, 60% of the articles), “Biomass collection and transport” (Economic, 85% of the articles) and “Natural elements” (Environmental, 88% of the articles) (Figure 6-3a).

The use of agricultural and forestry biomasses was associated with a high interest in interaction with natural elements (95% of the articles), probably due to the location of the plants in a rural area (Figure 6-3b). On the other hand, the location of BP supplied by livestock has been determined to benefit the population (33% of the articles, compared with 15% as an average), probably due to the positive externality that this use involves (Figure 6-3c).

The location of BP supplied by urban and industrial feedstock was not hugely affected by criteria related to existing energy systems (RES, 20% of the articles, compared with 40% as an average) and natural hazards (NH, 0% of the articles, compared with 25% as an average) (Figure 6-3d). These plants are located near cities and urban areas in areas with a high density of energy networks. Therefore, it is reasonable that there are no particular natural hazards near already urbanized areas and that there are no substantial differences between different sites in this context.

6.4.2.4 Type of MCDM/A used

The most commonly used MCDM/A to represent preference was AHP, 58% of the articles (Table 6-5). Our results are consistent with other authors who demonstrated that AHP is the most applied MCDM/A in sustainability (Kandakoglu et al., 2019). The method offers a hierarchical representation of the problems, explicit calculation and pairwise comparison matrix; these factors explain the success of this method in multicriteria problems. Furthermore, AHP allows the participation of experts and communities in the decisional process, assigning the weights, hence the importance, to the criteria. The second most commonly used method was direct weights (20%); in this method, the weights are assigned by experts or by the community in the form of a score and are usually standardized. Equal weights were used in 8% of the articles, and DEMATEL was used in 5%. Interestingly, in 2 articles, weights were not applied to the criteria; in these studies, the focus was on the constraints and optimization of transport cost. In the “Other” category were included LLSM, SWARA and ANP.

AHP was the preferred MCDM/A to aggregate the alternatives in 55% of the articles (Table 6-6). Weighted linear combination was used in 9 papers, or 22%; this method was presented slightly differently by the authors because it was used with different preference representations. In the “Other category”, COPRAS, weighted overlap dominance, fuzzy weighted overlap dominance, simple sum, and available area from constraints were included.

6.4.3 Study results

The results of these analyses generally consist of descriptions of areas suitable for plant siting, those selected, and the number and size of the planned plants (Table 6-7). In addition, some authors have described community and expert involvement in the decision-making process and provided a value of uncertainty in the conclusions.

Some authors have demonstrated the importance of many constraints that reduce the available areas for BP placement. For example, in Bojesen et al., 2015, only 4–6% of the municipal area was suitable for biogas facilities. In some cases, Perpiña et al., 2013, this percentage was even lower at only 1.5% of the initial area.

Authors were often faced with the problem of uncertainty due both to the survey in the field and the attribution of precise measurements to large areas. Overall, 35% of the articles considered the uncertainty in measuring the parameters, and fuzzy logic was the most commonly used tool to manage this problem. Franco et al., 2015, 2014, in the region of Ringkøbing-Skjern, Denmark, examined a selection of 13 biogas plant locations and analyzed the potential location of new biomass facilities using measurements taken in interval form, expressing the natural imprecision of public data. The fuzzy weighted overlap dominance (FWOD) procedure was applied for aggregating and exploiting this kind of data, obtaining a suitability ranking for every alternative. The data were classified into four classes depending on whether they were strongly favorable, semiformal, semirejectable, or strongly rejectable, considering several environmental reasons and legislative planning restrictions. Jeong et al., in a series of articles (Jeong and González-Gómez, 2020; Jeong and Ramírez-Gómez, 2018, 2017b, 2017a), implemented a process with the case study region rasterized into 10 m × 10 m grid cells. The fuzzy logic set was used to standardize the criteria and subcriteria data with the extensively selected criteria. The studies primarily focused on optimal locations of biomass facilities in long-period sustainability and resilience. They used several MCDM/A techniques to assess the bioenergy potential of the region: AHP, weighted linear combination (WLC), and F-DEMATEL.

Problems and benefits for the resident population in areas close to BP are fundamental. The opposition or the support of the inhabitants and political decision-makers can determine the feasibility of the project. Supporting the decision-making process with the involvement of the population, politicians, and technicians is crucial to maximize the benefits and limit the problems to prevent frequent NIMBY effects. Ferrer-Martí et al., 2018, worked on a development program in rural areas of Peru. The authors proposed a model to determine the location of a biogas plant, the best digester model, and the optimal feedstock and size. The model was validated in three study areas in the rural areas of the Peruvian Andes with the involvement of local communities. In other research, participatory settings involved technicians and politicians who established, through survey, the priority among the criteria (Perpiña et al., 2013). In conclusion, 55% of the models and projects included participation, either in the decision phase of the criteria weights or in the estimation of the scores of the criteria themselves.

6.5 Conclusions

In this review, 40 articles dealing with the localization of BP with MCDM/A were examined. The adopted MCDM/A and the criteria used by the authors were analyzed and correlated with the types of biomasses used. Criteria related to adverse effects on the population, biomass collection and transport, and the protection of natural elements were considered the most by the authors. Numerous types of biomasses were considered in the studied articles: agricultural, forestry, livestock, urban and industrial.

Most of the article study areas are in Europe (52%), followed by Asia (28%), North America (4%) and South America (4%) (Figure 6-4). The studied areas are small to medium in size: 53% of the studies involve an area of less than 5000 km^2, while 21% have an area of less than 500 km^2. Only 16% of the study areas are larger than 40,000 km^2.

Based on the observation of the results, the following considerations and future research could be concluded:

- Criteria in the social sphere are still secondary to those in economic and environmental fields. However, current trends on the involvement of local communities in decision-making processes, particularly in the energy sector, will require modifying this approach, reserving increasing importance to the social rather than the technical sphere.
- Future research on plant location may be concerned with the participation of communities in the decision-making process to exploit bioenergy not as an independent sector but as an element of integrated development in the territory.
- In addition, although other authors have used MCDM/A for plants siting in other renewable energy domains, there is a lack of sufficient literature on integrated studies among various forms of energy. Therefore, future research should be directed towards incorporating different forms of energy into the area in an integrated manner.
- Finally, another issue not considered in this study is the effect of climate change on plant potential. These changes are significant for agricultural and forestry activities. Future research should evaluate the cost-benefit ratio, not limiting the current state of the climate but simulating future environmental scenarios.

Acknowledgement

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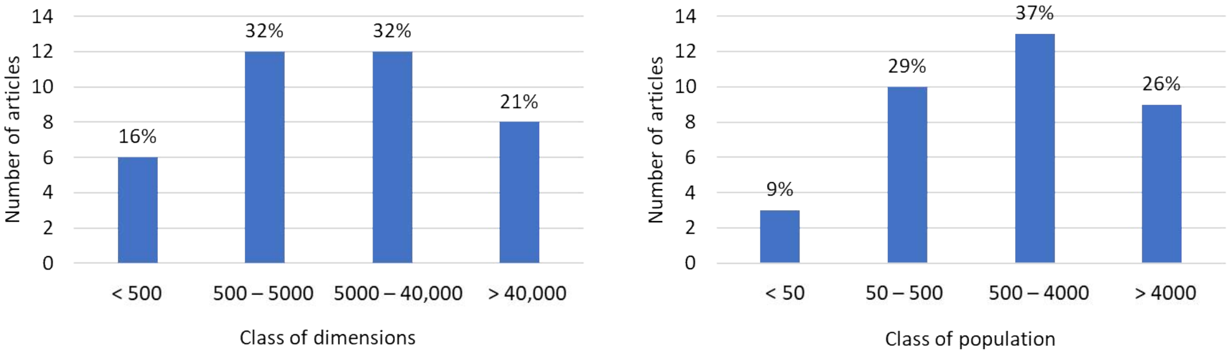
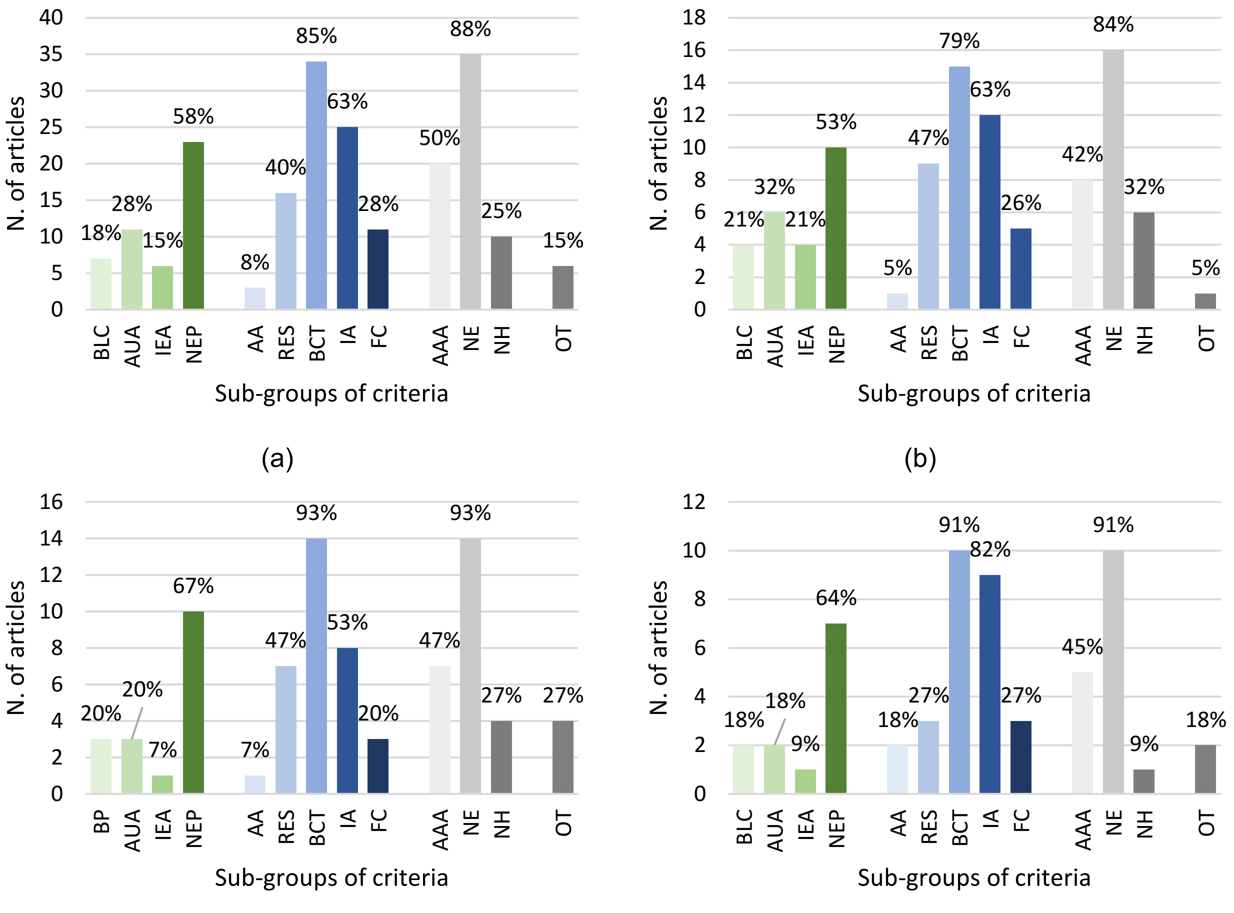


(a) (b)

Figure 6-2. Article distribution based on study area dimensions (a) and resident population (b)



(a) (b)

(c) (d)

Figure 6-3. Number of papers that use criteria related to the various subgroups of interest and specified for each type of biomass for feedstock: (a) Total (b) Agricultural and forestry (c) Livestock (d) Urban/industrial waste

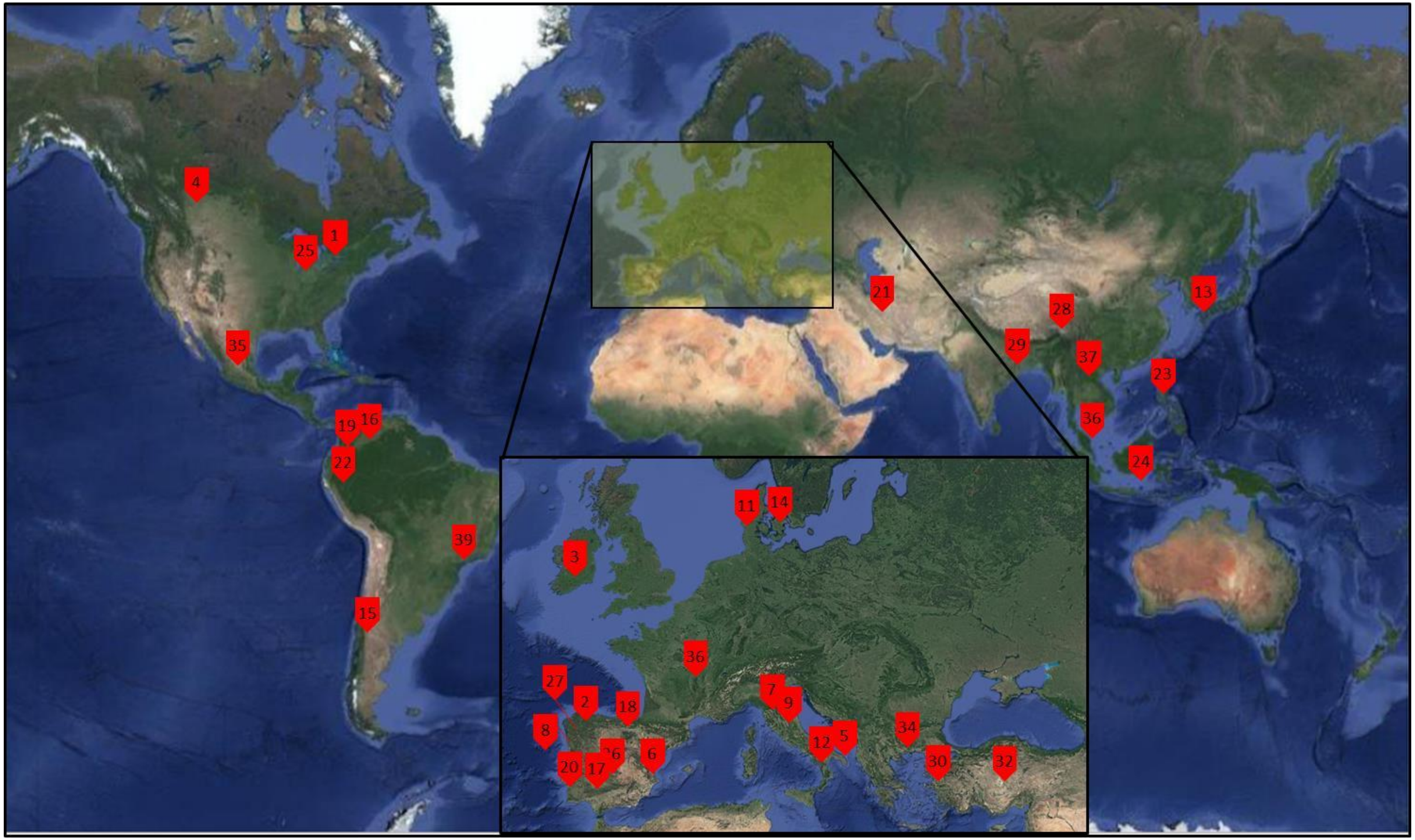


Figure 6-4. Geographical distribution of the analysed studies: 1) Ma et al., 2005; 2) Panichelli and Gnansounou, 2008; 3) Smyth et al., 2011; 4) Sultana and Kumar, 2012; 5) Zubaryeva et al., 2012; 6) Perpiña et al., 2013; 7) De Carlo and Schiraldi, 2013; 8) Silva et al., 2014; 9) Recanatesi et al., 2014; 10) Franco et al., 2014; 11) Franco et al., 2015; 12) Delivand et al., 2015; 13) Saladaga et al., 2015; 14) Bojesen et al., 2015; 15) Villamar et al., 2016; 16) Escalante et al., 2016; 17) Jeong and Ramírez-Gómez, 2017b; 18) San Martin et al., 2017; 19) Rodríguez et al., 2017; 20) Quinta-Nova et al., 2017; 21) Khademalhoseiny et al., 2017; 22) Ferrer-Martí et al., 2018; 23) Babalola, 2018; 24) Sahoo et al., 2018; 25) Meidiana et al., 2018; 26) Jeong and Ramírez-Gómez, 2018; 27) Rodrigues et al., 2019; 28) Ghose et al., 2019; 29) Akther et al., 2019; 30) Yalcinkaya, 2020; 31) Jeong and González-Gómez, 2020; 32) Yücenur et al., 2020; 33) Yalcinkaya and Kirtiloglu, 2021; 34) Vlachokostas et al., 2020; 35) Díaz-Vázquez et al., 2020; 36) Thiriet et al., 2020; 37) Waewsak et al., 2020; 38) Dao et al., 2020; 39) Jesus et al., 2021; 40) Coura et al., 2021

Table 6-2. Concepts for extraction of research papers

Concept	Search terms used for extraction	Search terms not used for extraction
#1 Sector of analysis: Bioenergy	anaerobic digester*, anaerobic digestion, biodigester, biogas, biomass facility*, biomass plant*, biomass resource*, biomethane, biomethane.	Renewable energy, waste, biogas plant location
#2 Methods used: Multicriteria analysis	multicriteria, multicriteria, mcda, mcdm, multiple criteria, multiple attribute, multiattribute, multiattribute, AHP/ANP, direct weights direct rating, equal weights, entropy weights, swing method, dematel, delphi, random weights, topsis, vikor, topsis/vikir, multiobjective programming, weighted sum, electre, promethee, MAUT/MAVT, fuzzy analysis, MOORA, MULTIMOORA, WASPAS, EDAS, CODAS, SECA, MULTIMOOSRAL, ARAS, PIPRECIA.	Decision-making, decision analysis, constraints.

Table 6-3. Study area characterization

Reference	Dimension of study area (km^2)	Population in the study area (thousand)	Cities in the study area	Orography in the area	Infrastructure	Land use
Ma et al., 2005	1233	102	One city - Medium density of rural communities	Mainly plan, partly hilly	Medium density	Mainly forestry, partly agricultural
Panichelli and Gnansounou, 2008	41,956	4079	Several cities - Medium density of rural communities	Mainly hilly, partly plan	Medium density	Mainly forestry, partly agricultural
Smyth et al., 2011	70,273	4762	Several cities - High density of rural communities	Plan	Medium density	Mainly agricultural, partly forestry
Sultana and Kumar, 2012	661,848	3632	Several cities - Low density of rural communities	Plan	Low density	Agricultural and forestry
Zubaryeva et al., 2012	590	189	Several cities - Very urbanized area	Plan	High density	Intensive farming and urban

Perpiña et al., 2013	1831	41	No cities - Medium density of rural communities	Hilly	Medium density	Mainly agricultural, partly forestry
De Carlo and Schiraldi, 2013	22,987	3668	Several cities - Medium density of rural communities	Mainly hilly, partly mountainous	High density	Mainly agricultural, partly forestry
Silva et al., 2014	7293	250	Several cities - Medium density of rural communities	Hilly	Medium density	Mainly agricultural, partly forestry
Recanatesi et al., 2014	720	78	No cities - Medium density of rural communities	Hilly	Low density	Mainly agricultural, partly forestry
Franco et al., 2014	1485	57	No cities - High density of rural communities	Plan	High density	Agricultural
Franco et al., 2015	1485	57	No cities - High density of rural communities	Plan	High density	Agricultural
Delivand et al., 2015	7000	988	Several cities - High density of rural communities	Mainly hilly, partly mountainous	Medium density	Mainly agricultural, partly forestry
Saladaga et al., 2015	5751	1955	Several cities - High density of rural communities	Plan	High density	Agricultural
Bojesen et al., 2015	3994	221	Several cities - High density of rural communities	Plan	High density	Agricultural
Villamar et al., 2016	23,890	1557	Several cities - Low density of rural communities	Mainly hilly, partly plan	Mixed	Agricultural and forestry
Escalante et al., 2016	30,537	2185	One city - Low density of rural communities	Mainly mountainous, partly hilly	Low density	Mainly forestry, partly agricultural
Jeong and Ramírez-Gómez, 2017b	41,635	1065	No cities - Medium density of rural communities	Mainly mountainous	Low density	Agricultural and forestry
San Martin et al., 2017	7234	2190	Several cities - Medium density of rural communities	Mainly hilly, partly mountainous	Medium density	Mainly forestry, partly agricultural
Rodríguez et al., 2017	30,537	2185	One city - Low density of rural communities	Mainly mountainous, partly hilly	Low density	Mainly forestry, partly agricultural
Quinta-Nova et al., 2017	4615	84	No city - Medium density of rural communities	Hilly	Medium density	Mainly forestry, partly agricultural
Khademalhoseiny et al., 2017	88	274	One city - Very low density of rural communities	Plan	Very low density	Desertic

Ferrer-Martí et al., 2018	807	217	No cities - Low density of rural communities	Mountainous	Low density	Mainly forestry, few agricultural areas
Babalola, 2018	502	479	One city - Very urbanized area	Hilly	High density	Urban
Sahoo et al., 2018	116,096	11,689	Several cities - High density of rural communities	Plan	Medium density	Mainly agricultural, partly forestry
Meidiana et al., 2018	< 10	< 1	No cities - Low density of rural communities	Plan	Medium density	Agricultural
Jeong and Ramírez-Gómez, 2018	42	4	No cities - Medium density of rural communities	Mainly mountainous	Low density	Agricultural and forestry
Rodrigues et al., 2019	379	120	One city - High density of rural communities	Mainly hilly, partly plan	Medium density	Agricultural and forestry
Ghose et al., 2019	7096	619	No cities - Low density of rural communities	Mountainous	Very low density	Forestry
Akther et al., 2019	23	1003	One city - Very urbanized area	Plan	Very high density	Urban
Yalcinkaya, 2020	11,891	4321	One city - Medium density of rural communities	Hilly	Medium density	Mixed
Jeong and González-Gómez, 2020	42	4	No cities - Medium density of rural communities	Mainly mountainous	Low density	Agricultural and forestry
Yücenur et al., 2020	783,562	85,038	n.s.	Mixed	Mixed	Mixed
Yalcinkaya and Kirtiloglu, 2021	11,891	4321	One city - Medium density of rural communities	Hilly	Medium density	Mixed
Vlachokostas et al., 2020	3968	200	One city - Very high density of rural communities	Plan	High density	Agricultural
Díaz-Vázquez et al., 2020	78,588	8100	Several cities - High density of rural communities	Mainly mountainous	High density	Mainly agricultural, partly forestry
Thiriet et al., 2020	534	1371	One city - Very urbanized area	Mainly hilly, partly plan	Very dense	Urban
Waewsak et al., 2020	13,941	3148	Several cities - Low density of rural communities	Mainly plan, partly hilly	Low density	Mainly forestry, partly agricultural
Dao et al., 2020	3345	8053	One city - High density of rural communities	Plan	High density	Urban and agricultural
Jesus et al., 2021	92	< 1	No cities - Low density of rural communities	Plan	Low density	Agricultural and forestry
Coura et al., 2021	149	80	One city - High density of rural communities	Plan	Very dense	Agricultural

Table 6-4. Number of articles per type of biomass used

Category	Biomass type	Number of articles	References	Percentage (%)
Agricultural and forestry raw material	Crop residues	11	Delivand et al., 2015; Escalante et al., 2016; Ghose et al., 2019; Jeong and Ramírez-Gómez, 2018; Jesus et al., 2021; Perpiña et al., 2013; Rodríguez et al., 2017; Sahoo et al., 2018; Saladaga et al., 2015; Villamar et al., 2016; Vlachokostas et al., 2020	46
	Forest residues	4	Jeong and Ramírez-Gómez, 2017b; Panichelli and Gnansounou, 2008; Perpiña et al., 2013; Quinta-Nova et al., 2017	
	Tree pruning	3	Delivand et al., 2015; Waewsak et al., 2020; Zubaryeva et al., 2012	
	Forest biomasses	3	Ghose et al., 2019; Jeong and Ramírez-Gómez, 2018; Recanatesi et al., 2014	
	Energetic crops	2	Ghose et al., 2019; Jeong and Ramírez-Gómez, 2018	
	Grass	1	Smyth et al., 2011	
	Wood Chips	1	De Carlo and Schiraldi, 2013	
Livestock residues	Livestock manure (multiple sources)	9	Bojesen et al., 2015; Díaz-Vázquez et al., 2020; Ferrer-Martí et al., 2018; Franco et al., 2015, 2014; Meidiana et al., 2018; Villamar et al., 2016; Yalcinkaya, 2020; Zubaryeva et al., 2012	30
	Cattle manure	5	Coura et al., 2021; Ma et al., 2005; Rodrigues et al., 2019; Silva et al., 2014; Yücenur et al., 2020	
	Livestock byproducts	1	Díaz-Vázquez et al., 2020	
	Swine manure	1	Dao et al., 2020	
Urban and industrial biomasses	Urban waste	8	Akther et al., 2019; Babalola, 2018; Coura et al., 2021; Khademalhoseiny et al., 2017; Thiriet et al., 2020; Yalcinkaya, 2020; Yalcinkaya and Kirtiloglu, 2021; Zubaryeva et al., 2012	22
	Agro-industrial wastes and byproducts	3	San Martin et al., 2017; Vlachokostas et al., 2020; Zubaryeva et al., 2012	
	Pellet	1	Sultana and Kumar, 2012	
Other	Not specified	1	Jeong and González-Gómez, 2020	2

Table 6-5. Summary of used criteria (in brackets the acronym used throughout the paper)

Dimension	Subgroup	Criteria	Description	References
Social	Benefits for the population (BP)	Beneficiary population	Minimize the distance to urban settlements, to increase the number of potential beneficiaries	Babalola, 2018; Díaz-Vázquez et al., 2020; Ferrer-Martí et al., 2018; Ghose et al., 2019; Jeong and Ramírez-Gómez, 2018; Villamar et al., 2016; Vlachokostas et al., 2020
		Social acceptance	Maximize the level of population awareness and/or number of successful projects previously implemented, avoiding NIMBY effects	
	Avoid urban areas (AUA)	Build up areas	Maximize the distance to build up areas to not interfere with the human activities	Akther et al., 2019; Dao et al., 2020; Delivand et al., 2015; Jeong and Ramírez-Gómez, 2018; Perpiña et al., 2013; Rodrigues et al., 2019; Sahoo et al., 2018;
		Important place, building or facility	Maximize the distance from important places or public buildings	

		Military areas	Maximize distance from military areas	Saladaga et al., 2015; Silva et al., 2014; Thiriet et al., 2020; Waewsak et al., 2020
	Influence on economic activities (IEA)	Drovers’ path	Maximize the distance to guarantee their conservation	Babalola, 2018; Bojesen et al., 2015; De Carlo and Schiraldi, 2013; Delivand et al., 2015; Ghose et al., 2019; Perpiña et al., 2013
		Job creation	Maximize job creation potential, particularly in peripheral areas	
		Tourism	Safe distance for any tourist centres and protected and cultural areas	
	Negative effect on population (NEP)	Population affected	Minimize the impacts on local populations by a surrounding safety area	Akther et al., 2019; Bojesen et al., 2015; Coura et al., 2021; Dao et al., 2020; De Carlo and Schiraldi, 2013; Ferrer-Martí et al., 2018; Franco et al., 2015; Jeong and González-Gómez, 2020; Jeong and Ramírez-Gómez, 2018, 2017b; Khademalhoseiny et al., 2017; Ma et al., 2005; Perpiña et al., 2013; Recanatesi et al., 2014; Rodrigues et al., 2019; Sahoo et al., 2018; Sultana and Kumar, 2012; Thiriet et al., 2020; Villamar et al., 2016; Vlachokostas et al., 2020; Waewsak et al., 2020; Yücenur et al., 2020; Zubaryeva et al., 2012
		Sensitivity to noise and smell	Minimize air pollution, odours, noise pollution	
		Traffic generated	Minimize the traffic and the effect on population	
		Visual impact	Minimize the visibility for aesthetic reasons	
		Welfare	Minimize the interference with parks and recreational areas, the impact of pollution on the local population	
Economic	Agricultural activities (AA)	Alternative fertilizer	Access to alternative fertilizer (e.g., chemical or biological fertilizer)	Akther et al., 2019; Ferrer-Martí et al., 2018; Vlachokostas et al., 2020
		Land cost	Minimize the costs of land	
	Relation with the energy system (RES)	Alternative sources of energy	Access to alternative fuels (e.g., natural gas, firewood, propane)	Bojesen et al., 2015; Coura et al., 2021; Ferrer-Martí et al., 2018; Franco et al., 2015; Ghose et al., 2019; Jesus et al., 2021; Ma et al., 2005; Perpiña et al., 2013; Rodrigues et al., 2019; Rodríguez et al., 2017; Sahoo et al., 2018; Saladaga et al., 2015; Smyth et al., 2011; Sultana and Kumar, 2012; Waewsak et al., 2020; Zubaryeva et al., 2012
		Heating plants distance	Minimize the distance to heating plants	
		Pipeline in the area or distance to the gas grid	Accessibility to natural gas grid in the area but guaranteeing a safe distance from the pipelines	
	Biomass collection and transport (BCT)	Biomass cost	Prefer areas where operation costs for biomass collection are lower	Akther et al., 2019; Bojesen et al., 2015; Coura et al., 2021; Dao et al., 2020; De Carlo and Schiraldi, 2013; Delivand et al., 2015; Díaz-Vázquez et al., 2020; Escalante et al., 2016; Ferrer-Martí et al., 2018; Franco et al., 2014, 2015; Ghose et
		Biomass resources	Maximize the bioenergy resource availability density (urban and rural)	
		Dispersion of biomass	Prefer areas where biomasses are concentrated in a reduced space	

	Livestock Unit of beef on total LU	Maximize the number of beefs compared to the other livestock units	al., 2019; Jeong and González-Gómez, 2020; Jeong and Ramírez-Gómez, 2018, 2017b; Jesus et al., 2021; Ma et al., 2005; Panichelli and Gnansounou, 2008; Perpiña et al., 2013; Quinta-Nova et al., 2017; Rodrigues et al., 2019; San Martin et al., 2017; Silva et al., 2014; Smyth et al., 2011; Sultana and Kumar, 2012; Thiriet et al., 2020; Villamar et al., 2016; Vlachokostas et al., 2020; Waewsak et al., 2020; Yalcinkaya, 2020; Yalcinkaya and Kirtiloglu, 2021; Yücenur et al., 2020; Zubaryeva et al., 2012
	Seasonability	Maximize the stable supply of feedstock during the year to reduce storage spaces and costs	
	Sinuosity	Measure how much a road (or other linear feature) deviates from being straight	
	Transport cost	It includes the tools and expenses necessary for the supply of raw materials from supplier to energy facility. It depends on the distances to be covered and the accessibility to the road network	
Industrial activities (IA)	Airports and heliports	These sites need a safety area to guarantee the safety of air traffic	Akther et al., 2019; Babalola, 2018; Coura et al., 2021; Dao et al., 2020; Delivand et al., 2015; Escalante et al., 2016; Jeong and González-Gómez, 2020; Jeong and Ramírez-Gómez, 2018, 2017b; Jesus et al., 2021; Khademalhoseiny et al., 2017; Ma et al., 2005; Perpiña et al., 2013; Quinta-Nova et al., 2017; Rodrigues et al., 2019; Rodríguez et al., 2017; Sahoo et al., 2018; Saladaga et al., 2015; San Martin et al., 2017; Silva et al., 2014; Sultana and Kumar, 2012; Villamar et al., 2016; Yalcinkaya, 2020; Yalcinkaya and Kirtiloglu, 2021; Zubaryeva et al., 2012
	Economic and industrial context	Avoiding conflicts with industrial activities and maximize potential benefits derived from the combination biomass plants-industries	
	Electricity grid	Easy access to electricity grid but guarantee of a safe distance to the electrical lines	
	Other installations and infrastructures	Safe distance to other important installations and infrastructures, e.g., caves, valleys, sewage plants, fuel and water tanks, filling stations, aqueducts, dams, bus stations	
	Railways	Plants must be at least this distance from railways	
	Safety area by roads	Guarantee a safe distance from any passages, roads, or highways	
	Type of road	Prefer areas with a modern and efficient road network	
Financial consideration (FC)	Investment ratio (EUR/kW)	Investment cost compared to energy produced	De Carlo and Schiraldi, 2013; Ferrer-Martí et al., 2018; Jeong and González-Gómez, 2020; Jeong and Ramírez-Gómez, 2018, 2017b; Meidiana et al., 2018; Perpiña et al., 2013; San Martin et al., 2017; Thiriet et al., 2020; Vlachokostas et al., 2020; Yücenur et al., 2020
	Labour cost	It includes expenses for workers such as transportation, eating and drinking, education.	
	Maintenance cost (EUR/kW)	Presence of skilled workers in the community for biomass facility construction, processing biomass, administrative issue	
	Revenues and costs from the sale of energy	Maximize the potential demand within the municipal area in accordance with energy consumption and the distribution of settlements	
	Revenues and costs from other reasons	Income for the management of food waste, selling digestate, gas. It includes farmers capability	

Social, economic, and environmental	Anthropic activities or artefacts (AAA)	Agricultural land use	Land use classification to conserve certain areas and avoid overuse of land consumption	Akther et al., 2019; Delivand et al., 2015; Ferrer-Martí et al., 2018; Franco et al., 2014; Ghose et al., 2019; Jeong and González-Gómez, 2020; Jeong and Ramírez-Gómez, 2018, 2017b; Jesus et al., 2021; Meidiana et al., 2018; Perpiña et al., 2013; Rodrigues et al., 2019; Rodríguez et al., 2017; Saladaga et al., 2015; San Martin et al., 2017; Silva et al., 2014; Smyth et al., 2011; Sultana and Kumar, 2012; Thiriet et al., 2020; Yalcinkaya, 2020; Yücenur et al., 2020
		Tons of CO2 avoided and environmental benefits	Minimize soil and water pollution due to organic waste disposal	
		Water availability and consumption	Guarantee water availability during the year and minimize water consumption	
	Natural elements (NE)	Coast areas	Guarantee safe distance from coast areas	Akther et al., 2019; Babalola, 2018; Bojesen et al., 2015; Coura et al., 2021; Dao et al., 2020; Delivand et al., 2015; Díaz-Vázquez et al., 2020; Escalante et al., 2016; Ferrer-Martí et al., 2018; Franco et al., 2014, 2015; Ghose et al., 2019; Jeong and González-Gómez, 2020; Jeong and Ramírez-Gómez, 2018, 2017b; Khademalhoseiny et al., 2017; Ma et al., 2005; Perpiña et al., 2013; Quinta-Nova et al., 2017; Recanatesi et al., 2014; Rodrigues et al., 2019; Rodríguez et al., 2017; Sahoo et al., 2018; Saladaga et al., 2015; Silva et al., 2014; Sultana and Kumar, 2012; Thiriet et al., 2020; Villamar et al., 2016; Vlachokostas et al., 2020; Waewsak et al., 2020; Yalcinkaya, 2020; Yalcinkaya and Kirtiloglu, 2021; Yücenur et al., 2020; Zubaryeva et al., 2012
		Hydrographical network and water masses	Respect a safe distance from rivers, lakes, wetlands, channels, and other water bodies	
		Lithology	Lithological classification to determine industrial lithological capacity and detention capacity	
		National heritage items	Monuments, cultural heritage places and archaeological sites need a protective ring to prevent degradation	
		Natura 2000 and specially protected areas	Areas classified as National Ecological Reserve, Protected Areas and Natura 2000 are excluded from the analysis and need a safe area to be preserved	
		Natural spaces	Areas classified as natural and protected spaces are excluded from the analysis and need a safety area to be preserved	
		Natural vegetation cover	Classification of vegetation covers to conserve certain types during biomass collection, in particular preserving forests	
		Slopes, height, and orientation of the land	Areas with slopes larger than a specific value (usually 15%) are avoided. Lower elevations were assumed to be most capable because of the relatively flat slope than mountainous regions.	
		Temperature and climatic condition	Suitability of ambient temperature (for a proper digester operation) and conditions that do not facilitate corrosion	
	Natural hazard (NH)	Flooding risk, avoid areas	The biomass plants must avoid areas liable to flooding and must respect a safety distance from these areas	Coura et al., 2021; Dao et al., 2020; Delivand et al., 2015; Jeong and Ramírez-Gómez, 2018; Ma et al., 2005; Perpiña et

	Geomorphology, Physiography, and related risk	Determination of morphological characteristics of slopes about instability and danger of landslides. Identification of areas susceptible to erosion and landslides	al., 2013; Rodríguez et al., 2017; Sahoo et al., 2018; Saladaga et al., 2015; Yücenur et al., 2020
	Seismic areas	Minimize seismic risk of the chosen areas	
Other (OT)	Minimum area	Potential sites must have a minimum area (usually at least 1 ha) for implementation of a biomass plant	Bojesen et al., 2015; Sahoo et al., 2018; Silva et al., 2014; Yalcinkaya, 2020; Yalcinkaya and Kirtiloglu, 2021; Yücenur et al., 2020
	Shape of the territory	Exclude polygons that do not satisfy a minimum of compactness (ratio between the two sides of a rectangle), usually 0.25	
	Terrorist attack	Minimize the risk in the chosen areas	

Table 6-6. Most frequently used methods to represent preference

Methods to represent preferences	N. of papers	Percentage (%)	References
AHP	23	58	Akther et al., 2019; Babalola, 2018; Bojesen et al., 2015; Coura et al., 2021; Dao et al., 2020; Escalante et al., 2016; Ghose et al., 2019; Jeong and Ramírez-Gómez, 2017b; Jesus et al., 2021; Khademalhoseiny et al., 2017; Ma et al., 2005; Meidiana et al., 2018; Perpiña et al., 2013; Quinta-Nova et al., 2017; Rodrigues et al., 2019; Rodríguez et al., 2017; Saladaga et al., 2015; Sultana and Kumar, 2012; Villamar et al., 2016; Waewsak et al., 2020; Yalcinkaya, 2020; Yalcinkaya and Kirtiloglu, 2021; Zubaryeva et al., 2012
Direct weights	8	20	Delivand et al., 2015; Díaz-Vázquez et al., 2020; Ferrer-Martí et al., 2018; Franco et al., 2014; Recanatesi et al., 2014; San Martin et al., 2017; Silva et al., 2014; Vlachokostas et al., 2020
Equal weights	3	8	Sahoo et al., 2018; San Martin et al., 2017; Smyth et al., 2011
DEMATEL	2	5	Jeong and González-Gómez, 2020; Jeong and Ramírez-Gómez, 2018
No weights	2	5	Panichelli and Gnansounou, 2008; Thiriet et al., 2020
Other	3	8	De Carlo and Schiraldi, 2013; Franco et al., 2015; Yücenur et al., 2020

Table 6-7. Most frequent methods for the aggregation of the alternatives

Methods to aggregate the alternatives	N. of papers	Percentage (%)	References
AHP	22	55	Akther et al., 2019; Babalola, 2018; Coura et al., 2021; Dao et al., 2020; Delivand et al., 2015; Escalante et al., 2016; Ghose et al., 2019; Jesus et al., 2021; Khademalhoseiny et al., 2017; Ma et al., 2005; Meidiana et al., 2018; Quinta-Nova et al., 2017; Rodrigues et

			al., 2019; Rodríguez et al., 2017; Saladaga et al., 2015; San Martin et al., 2017; Sultana and Kumar, 2012; Villamar et al., 2016; Waewsak et al., 2020; Yalcinkaya, 2020; Yalcinkaya and Kirtiloglu, 2021; Zubaryeva et al., 2012
Weighted Linear Combination	9	22	Bojesen et al., 2015; Díaz-Vázquez et al., 2020; Jeong and González-Gómez, 2020; Jeong and Ramírez-Gómez, 2018, 2017b; Perpiña et al., 2013; Recanatesi et al., 2014; Sahoo et al., 2018; Smyth et al., 2011
ANP	2	5	De Carlo and Schiraldi, 2013; Khademalhoseiny et al., 2017
ELECTRE	2	5	Silva et al., 2014; Vlachokostas et al., 2020
Ideal point method (IPM)	2	5	Ferrer-Martí et al., 2018; Perpiña et al., 2013
Other	5	13	Franco et al., 2015, 2014; Panichelli and Gnansounou, 2008; Thiriet et al., 2020; Yücenur et al., 2020

Table 6-8. Resulting areas and plants in the analysed plants.

Reference	Number of chosen sites	Size of plants
Ma et al., 2005	20	n.s.
Panichelli and Gnansounou, 2008	2	~22 MWe
Smyth et al., 2011	25	Medium and small
Sultana and Kumar, 2012	13	150,000-250,000 t of pellet per year
Zubaryeva et al., 2012	n.s.	0.5-1 MWe
Perpiña et al., 2013	1.5% of the study area	n.s.
De Carlo and Schiraldi, 2013	1	5-50 MW
Silva et al., 2014	73	n.s.
Recanatesi et al., 2014	n.s.	n.s.
Franco et al., 2014	n.s.	n.s.
Franco et al., 2015	20	25-32 MW
Delivand et al., 2015	From 1 to 5	7-135 MWe
Saladaga et al., 2015	n.s.	n.s.
Bojesen et al., 2015	4%-6% of the study area	n.s.
Villamar et al., 2016	n.s.	8.5 MW
Escalante et al., 2016	29	n.s.
Jeong and Ramírez-Gómez, 2017b	9.25% of the study area	n.s.
San Martin et al., 2017	250	n.s.
Rodríguez et al., 2017	12	5.4-15.2 TJ
Quinta-Nova et al., 2017	n.s.	n.s.
Khademalhoseiny et al., 2017	10%-11% of the study area	n.s.
Ferrer-Martí et al., 2018	3	n.s.
Babalola, 2018	3-5	n.s.
Sahoo et al., 2018	25	5000 t of energy crops
Meidiana et al., 2018	66	n.s.

Jeong and Ramírez-Gómez, 2018	n.s.	n.s.
Rodrigues et al., 2019	n.s.	n.s.
Ghose et al., 2019	2	~51 MWe
Akther et al., 2019	1	26-40 MW
Yalcinkaya, 2020	8	~92 MWe
Jeong and González-Gómez, 2020	n.s.	n.s.
Yücenur et al., 2020	1	n.s.
Yalcinkaya and Kirtiloglu, 2021	1 selected, 4 potential	~117 MWe
Vlachokostas et al., 2020	1	0.036 MWe
Díaz-Vázquez et al., 2020	n.s.	53.6-85.9 MWe
Thiriet et al., 2020	143-273	n.s.
Waewsak et al., 2020	12-25	9.5 MW
Dao et al., 2020	5	3-4 MW
Jesus et al., 2021	Up to 30	n.s.
Coura et al., 2021	Two scenarios: 3 or 8 plants	0.032-0.146 MW

6.6 References

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7 Network analysis for optimal biomethane plant location through a multidisciplinary approach

7.1 Abstract

Bioenergy production from agricultural biomass is considered a key opportunity for achieving the sustainable development goals set by various international institutions. This sector must combine efficiency and profitability with environmental protection and territorial integration. For this reason, plants location should consider the natural and anthropic characteristics of the areas where they are supposed to operate. In this paper, a multicriteria analysis is introduced for optimal location of biomass plants in a region of Northern Italy. The study was based on a detailed set of 8 constraints and 15 criteria, and eventually identified 93 potential sites for plant location. The distribution of biomass from the territory to the plants was carried out with the specific Location-Allocation algorithm that allowed considering both the attractiveness of the plants and the maximum acceptable power. This result was compared with the current bioenergy production system: three alternative scenarios were developed, considering existing plants and the natural gas distribution network. Finally, a sensitivity analysis was conducted, to study the consequences of various decision-makers decisions. The results showed the possibility of installing between 90 and 199 plants in the different scenarios, resulting in a biomethane production between $246.8 \cdot 10^6$ Nm^3 and $503.6 \cdot 10^6$ Nm^3.

Keywords: biomethane, modelling, location allocation, multicriteria, spatial analysis

Abbreviations

SRR	Sustainable removal rate
FM	Fresh material
DM	Dry material
VS	Volatile solid
HI	Harvest index
NVZ	Nitrogen Vulnerable Zone
MCDM/A	Multicriteria decision model/analysis
AHP	Analytic hierarchy process
AD	Anaerobic digestion
Nm^3	Normal cubic meter (273 K and 1 bar)

7.2 Introduction

Over the past few years, national and international institutions have set ambitious goals regarding environmental protection and sustainable development (United Nations, 2015). Therefore, many public and private institutions have invested considerable resources in the development of renewable energy (Moriarty and Honnery, 2016). The Renewable Energy Directive set targets for EU member states, committing to reach a 32% share of renewable energy by 2030 (European Parliament, 2018). This target was further raised to 40% (European Parliament, 2021). A specific renewable energy share target of 14% was set for the transport sector and, in particular, a 2.2% share of the total is set aside for biofuels; this proves the interest and importance of this resource in EU plans. As a result, 11.9 GWe of electricity from biogas were installed in the EU in 2020, with a total production of 55.8 TWhe of energy. In 2020, the European countries with the largest share of renewable energy were Sweden (60.1%), Finland (43.8%) and Latvia (42.1%); in absolute terms, Germany has the largest installed renewable electricity capacity, 141.03 GW (Eurostat, 2020). Some countries have devoted considerable resources to this sector. In Germany, the system has been defined by the Renewable Energy Act (EBA, 2019), starting in 2000, which has enabled the construction of a large number of plants (9500 in 2018). On the other hand, also a number of problems arose: dependence on energy crops, lack of efficiency of the implemented technology, or low utilization of produced heat (Brémond et al., 2021). These initiatives showed that competition from other renewables in power generation can be overcome with the development of biomethane upgrading plants, which reached 200 units in Germany in 2018 (REGATRACE, 2020). France has included biomethane in its energy development policies. In 2019, 107 biomethane plants were active, potentially producing 1.3 TWh of energy per year. Several simulations demonstrated the importance of biomethane and biogas in achieving emissions neutrality of the energy system by 2050, however all of these scenarios consider a reduction of biomethane production cost (Brémond et al., 2021). Italy is currently one of the European countries that is most focusing on biomethane production development. Since 2008, bioenergy production has been directed to the production of biogas for electricity generation; by 2021, 2010 biogas plants were operating in Italy (GSE, 2021). This situation has led to a lack of attention to biomethane, so that in 2017 only one plant was operating in the country. With the entry into force of the Biomethane Decree in 2018, the situation has radically changed: from 2019 to 2021, 25 new biomethane plants came into operation, with a total theoretical capacity of 18.2 tCH_4/h. An important point in the decree concerns the feedstock of biomethane plants; only livestock waste, second-crop crops, agricultural by-products and organic fractions of municipal solid waste can be used. In this way, energy crops are explicitly discouraged in order to protect food production. Recent studies have shown how the incentives of the Biomethane Decree can make investments in upgrading technologies profitable for existing plants but not for new plants (Barbera et al., 2019). Based on these considerations, it appears necessary to move beyond the paradigm of the classic biogas plant, which is fed by energy crops produced specifically by the company itself (De Corato et al., 2018). The development of a profitable and environmentally sustainable bioenergy system must necessarily rely on waste biomass, to reduce costs and produce marginal gains, and move toward advanced forms of biofuels, especially biomethane. The use of agricultural by-products poses the problem of transportation costs, due to their dispersion over land; therefore, careful spatial analysis is necessary, to optimize the entire supply chain.

The possibility of accessing renewable energy sources has spread throughout the territory, meeting the need to create increasingly self-sufficient energy communities (Rossi and Hinrichs, 2011). Moreover, it can be regulated based on the energy demand of communities, balancing the deficit or surplus of other renewable energies, thus minimizing the influence of meteorological factors that cannot be controlled by humans (Szarka et al., 2013). In addition, there has been a growing interest on integration of bioenergy with other forms of renewable energy -solar and wind- in rural areas (Ferrari et al., 2022b; Poggi et al., 2018). In fact, it is possible to harness the surplus electricity produced by photovoltaic and wind power plants for the production of hydrogen and methane (Lecker et al., 2017). In this way, biomethane and biohydrogen provide a type of energy storage that can be easily used when needed. In order to implement this technology, however, it is necessary to continue the development and deployment of biomethane production facilities, especially in rural areas (Brémond et al., 2021).

To date, most agricultural biomass plants are organized to produce electricity through the combustion of biogas, resulting from anaerobic digestion (AD) (Balussou et al., 2018). Such production system operates with relatively low efficiency, approximately 40%, thus reducing the main potential advantages of this energy (Nock et al., 2014). For this reason, national and international institutions are encouraging biomethane production (Brémond et al., 2021): as a result, biomethane plants in the EU increased from 305 in 2015 (Scarlat et al., 2018) to 465 in 2017 (Prussi et al., 2019). This gas is obtained through biogas upgrading, which separates methane from CO2, obtaining a product with a purity above 95% (Angelidaki et al., 2018). In this way, the produced gas is fully comparable to natural gas and, therefore, suitable for use as vehicle fuel or introduced into the distribution network. However, the production of biomethane is a complex process, requiring a careful analysis of resources and planning of production centers (Baccioli et al., 2018). Many financial and environmental costs must be considered by analyzing locations and sizes of biomass and upgrading plants. The installed power must allow efficient and sustainable exploitation in rural areas, with land consumption compatible with environmental needs. It has been demonstrated that plants with power ranging between 0 and 200 kW occupy, on average, 49 m^2/kW; plants with power between 800 and 1,000 kW require an average of 24 m^2 per kilowatt installed (Ferrari et al., 2021b). Among the benefits to be gained from biomethane production is the possibility of using this gas as a form of storage for excess energy produced by other forms of renewable energy, particularly solar and wind (Lecker et al., 2017). Such use requires advanced and expensive technologies, so it requires a detailed cost-benefit analysis, which must be carried out in cooperation with policymakers to establish the environmental and energy goals to be achieved (Ferrari et al., 2022b).

Furthermore, road network analysis and the distribution of biomass in the territory reduce transport distances; this aspect is particularly relevant when dealing with very dispersed biomass, such as byproducts, or with large plants supplied by different operators (Schnorf et al., 2021). The road system is crucial when biomass is concentrated in specific locations, as is the case with animal waste; Rodrigues et al., 2019, studied the sites that have the best characteristics to locate a biogas plant considering the minimum distance from cattle farms, the power grid and roads. The locations of these plants impact in different ways on local communities; for this reason, it is advisable to prefer locations which are far from densely populated areas in order to minimize the impact on communities and avoid dangerous NIMBY effects (Batel et al., 2013). At the same time, the involvement of the local population allows citizens to be included in the decision-making process, explaining the positive effects of these plants and identifying shared choices (Walker and Devine-Wright, 2008). One option is to place plants close to settlements to take advantage of the heat produced for district heating systems; in this way the inconvenience of hosting the biomass plant is offset by the benefits of district heating (Leduc et al., 2010). This complex decision-making process must consider several criteria that have variable effects on the final decisions and are partly subjective.

In those processes where it is necessary to choose among a number of alternatives considering various decision criteria and/or in the presence of different evaluations for the same criterion (e.g., in the case of a plurality of decision-makers), it is common to implement Multicriteria decision models/analysis (MCDM/A). These models make it possible to solve multi-objective problems by aggregating different evaluations for various parameters and then ranking the alternatives according to an order of preference. Some of the most popular MCDM/A systems are (Hajkowicz and Collins, 2007): Dominance Method, e-Constraint Method, Simple Additive Weighting (SAW), Distance-Based Methods (DBM), Analytic Hierarchy Process (AHP), ÉLimination et Choix Traduisant la REalité (ELimination Et Choice Translating REality) (ELECTRE), Multiple Attribute Utility Theory (MAUT), Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE), and Sequential Optimization (SO). The choice of a method to be used depends on the objectives set by the decision-maker and the technicians' resources (data and technical tools) (Kandakoglu et al., 2019). Among these methods, AHP is one of the most widely used in the environmental and agronomic fields (Ferrari et al., 2022a). It is also the most commonly used for the location of biomass plants, applied in approximately 55% of the works that address this issue (Ferrari et al., 2022a). These papers involve different types of biomass: food waste (San Martin et al., 2017), forest residues (Jeong and Ramírez-Gómez, 2017), livestock manure (Bojesen et al., 2015) and agricultural byproducts (Delivand et al., 2015). These and other works have addressed specific aspects of the process; however, an analysis that considers all these aspects and that applies these resources to the conversion of plants from biogas based to biomethane production is currently lacking.

The set of candidate sites can be based on a list of existing plants to be developed, or on a discretization of the study area into homogeneous sub-areas. One of the most important issues is the preliminary selection of candidate sites, where biomass plants can theoretically be installed, and whose actual suitability must be quantified. De Carlo and Schiraldi, 2013, categorized and zoned an entire region to choose the best location for a biomass plant. The authors considered four possible scenarios based on the priorities of policy makers. To make large biogas plants larger than 5 MWe economically viable, the analysis also considered an incentive system. Alternatively, candidate sites could be a set of cities: Yücenur et al., 2020, proposed a model using the SWARA and COPRAS methods consisting of 12 criteria to determine the best city in which to locate a biogas plant fueled by municipal solid waste in Turkey. The alternative approach is to admit the location of the plant on the whole territory of the study area, thus considering an infinite number of alternatives. In these cases, a widely used tool is GIS software. Ma et al., 2005, and Jesus et al., 2021, explored the bioenergy potential and geographic conditions of Tompkins County, New York, and Parana State, Brazil. The authors focused on the economic and social benefits to farmers and residents, identifying areas where there is interest in producing bioenergy through a community digester. GIS software can be useful in mitigating the environmental impacts of bioenergy production. Villamar et al., 2016, explored the bioenergy potential of the Bío Bío region of Chile. The region covers 36,000 km^2 and includes 7000 km^2 of protected areas covered by native forests and located in mountainous regions (the Andes and the Cordillera). The use of spatial analysis software was necessary because, despite the vast protected areas, there is also a lot of anthropogenic infrastructure: industrial, agricultural, livestock, forestry, fishing, and residential activities. Many studies have been directed toward analyzing various aspects of the plant siting process, but in most of the work there is a lack of careful sensitivity analysis with respect to the priorities of decision makers, who may assign different weights to the various criteria established. In addition, many of these analyses are carried out without considering the facilities already in the area, making the studies useful only for comparison with the current situation. It therefore appears necessary to study how to work on the existing scenario, in a study area that is already developed but over which the energy system has evolved in an uncoordinated way.

One of the issues emerging from the literature review is the supply chain of biomass to produce bioenergy (De Meyer et al., 2014). Some authors tend to target studies toward very specific biomasses, which are particularly characteristic of the study area where they operate. (Smyth et al., 2011, considered annual grass production in Ireland in a county-by-county analysis. The special conditions of the study area, large areas in the country dedicated to grassland, allowed for high biomethane production; other studies have shown that exploiting this biomass requires a careful analysis of the territory (Boscaro et al., 2015). In a recent study by (Valenti and Porto, 2019), the bioenergy potential of citrus pulp and olive pomace in a province in Sicily, Italy, was examined. Again, the particular conditions of the area determine the high availability from biomass that would be difficult to find in other contexts. These approaches lead to a high exploitation of the resource with an efficient transport system; however, they limit the possibilities for the development of the bioenergy system. A comprehensive study in an agricultural area is necessary, to understand the actual possibilities of this sector in a fully renewable energy system.

This paper presents a plan for converting bioenergy production from a biogas-based system for electricity production to one for biomethane production. The conversion must also include biomass, shifting from a system conventionally based on energy crops to one based solely on agricultural and livestock byproducts, thus avoiding using agricultural land for energy crops competing with food ones. Furthermore, a multicriteria analysis allowed us to identify the best sites to locate the new plants among 693 candidates, considering environmental, social and economic parameters. Finally, the model enabled the realization of different scenarios to describe the integration of new plants with the 129 existing ones that can be converted or upgraded for biomethane production. In this study, the biomass considered is only that of agricultural and livestock by-products. The other typical sources are not considered: forest biomass, municipal organic waste and energy crops. In some scenarios the possibility for the decision maker to act on existing plants is assumed, modifying the powers and excluding them from the biomass supply, not considering the constraints due to their ownership. This type of analysis is fundamental to estimating the effects of energy policies to coordinate resources, choices, and district investments.

The paper presents a first methodological part, with a description of the study area, the used databases, and where the steps of the study are detailed: the definition of the available areas, the functioning of the multi-criteria analysis, the network analysis with the identification of the most suitable areas for plant installation; finally, the sensitivity analysis with the alternative scenarios is explained. In the second part, the results of the study accompanied by the related discussion are presented: the base scenario, the alternative scenarios considering the existing plants, and the analyses with the different policy guidelines of the decision makers.

7.3 Materials and methods

7.3.1 Case study and spatial database design

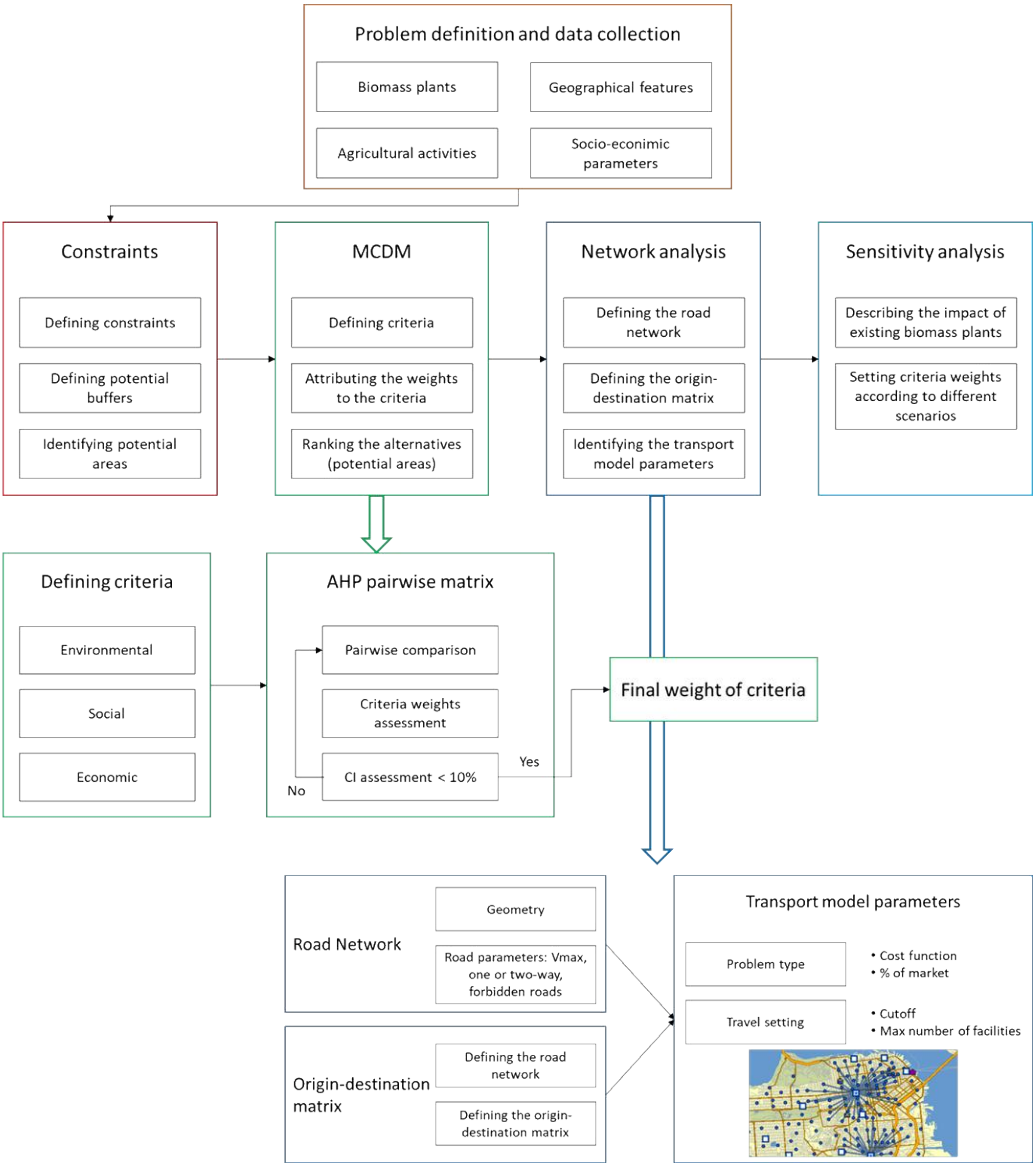


Figure 7-1. Methodology flowchart

The study area where the methodology is applied corresponds to the Veneto region (NUTS 2). The region, located in north-eastern Italy, has an area of 18,345 km^2 and a population of approximately 4.9 million inhabitants. From the orographic point of view, it is clearly divided into two main subareas: in the south and east, there is the Po Valley; in the northern part, there is the mountainous chain of the Alps. Most of the settlements are located in the flat area; therefore, it is strongly anthropized, with a high population density and productive activities. Agricultural and industrial activities are concentrated in the same area. Under these conditions, the area has developed into one of the most productive in Europe (Eurostat, 2020). The high density of population and industrial activities leads to a high demand for energy. At the same time, the geographical characteristics of the region are not the ideal ones for solar and wind power production. For these reasons, and due to very high agricultural production, bioenergy is particularly important in the perspective of autonomous renewable energy production.

Table 7-1 summarizes the spatial data used for the analysis. Most of the contributions are openly accessible online; others were provided by the offices responsible for conducting this analysis. The organization and processing of the data were performed with QGIS (QGIS, 2022) software, while ArcGIS Pro (ESRI, 2022) software was used for the subsequent network analysis.

Table 7-1. Spatial resources

Data	Description	Source
Railway network	Polyline vector file of the railway network with the properties of the lines.	(Regione Veneto, 2020)
Road network	Polyline vector file of the railway network with the properties of the roads: category, one/two-way, max speed.	(Regione Veneto, 2020)
Water body	Polygon and polyline vector file with the lakes, rivers, canals, and other water bodies with the properties: type, name.	(Regione Veneto, 2020)
Natura 2000	Polygon vector file of the Natura 2000 network sites.	Rete 2000, 2019)
Corine Land Cover	File with land cover and uses. Urban, industrial, agricultural, and infrastructure areas are shown. The data is provided in raster or vector format, depending on the use.	(CORINE Land Cover, 2018)
Slope	Raster file showing terrain slope at 100 m resolution.	(ARPAV, 2020)
Agricultural resources	Polygon vector file showing cropland in the region. It identifies the type of crop.	(AGEA, 2020)
Livestock waste	Polygonal file with the number of animals raised in each municipality, categorized by species, breeding mode and production type.	(Anagrafe Zootecnica, 2020)
Organic carbon	Polygonal vector file showing carbon content per hectare (t/ha) and percentage of organic carbon in the soil.	(Regione Veneto, 2020)
Natural gas grid	Polyline vector file showing methane distribution network.	(Regione Veneto, 2020)
Nitrogen Vulnerable Zones	Polygon vector file showing nitrate vulnerable areas. It reports location and extent.	(ISPRA, 2021)
Hydrogeological risk	Polygonal vector file with hydrogeological risk areas. They are classified into three groups according to the probability of the adverse event.	(ISPRA, 2021)
Landslide risk	Polygonal vector file with landslide risk areas.	(ISPRA, 2021)
Population density	Polygon vector file with a 1 km mesh grid with the population density value for each area.	(ISTAT, 2021)
GDP per capita	Polygonal vector file with per capita income defined at the municipal level.	(MEF, 2020)

One of the assumptions underlying this work was the exploitation of biomass that must not compete with other sectors, particularly the food sector. Therefore, no energy crops were considered, including only agricultural or livestock byproducts. Table 7-2 summarizes the livestock biomasses with their physical and energetic parameters. Livestock information was obtained from the National Livestock Registry, which provides the number of animals by type and productive orientation for each municipality. Only farms with a minimum size of 20 cattle, 20 pigs, or 4000 poultry were considered. Farming methods that do not allow manure collection were excluded (e.g., wild, transhumant).

Finally, an availability coefficient of 60% was applied to estimate the actual contribution of these biomasses (Meyer et al., 2018).

Table 7-2. Available livestock bioresources and potential bioenergy assessment

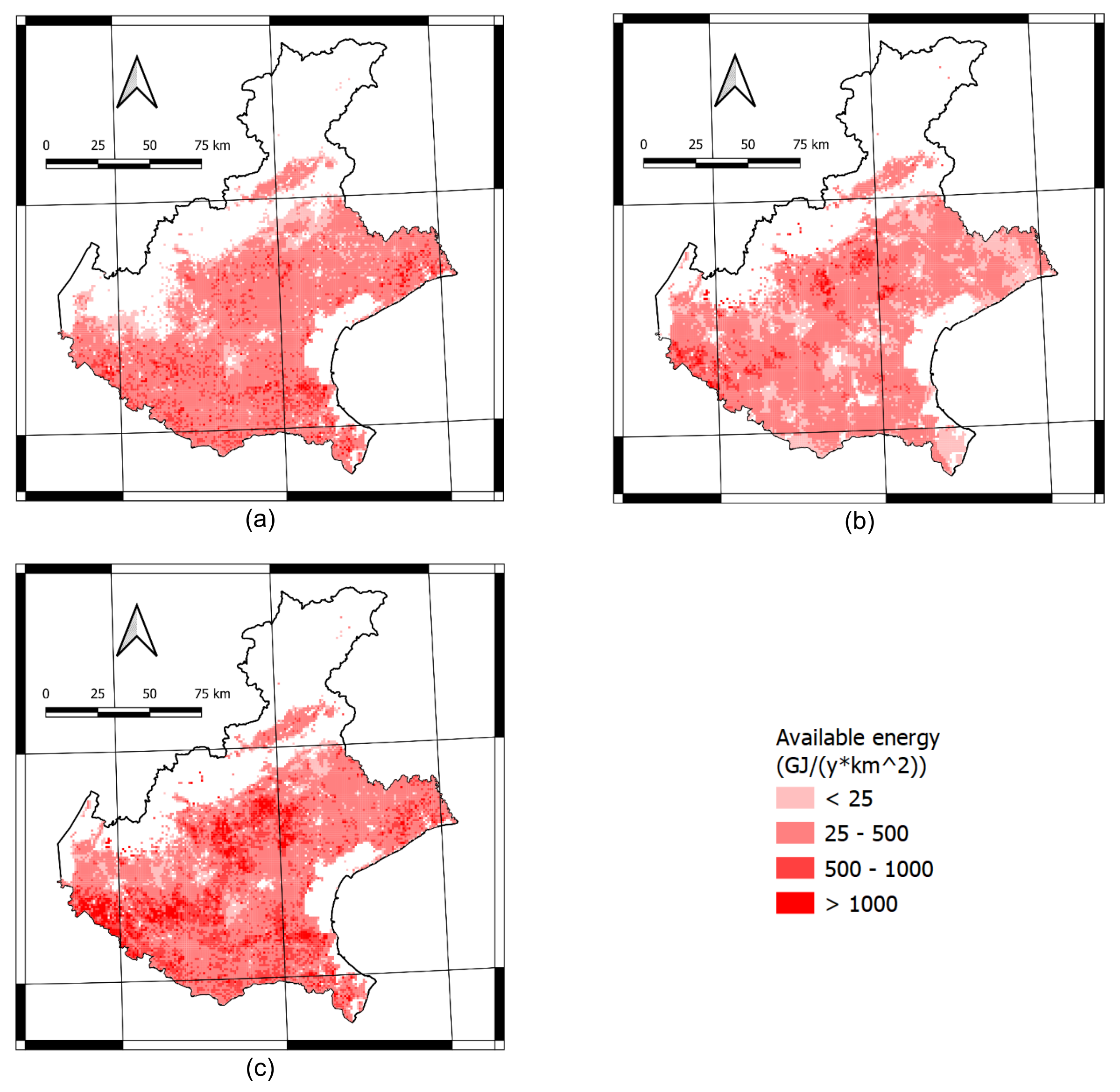
	Slurry				**Manure**				**Reference**
	FM t/head/y	**DM %FM**	**VS %DM**	**CH_4 m^3/tVS**	**FM t/head/y**	**DM %FM**	**VS %DM**	**CH_4 m^3/tVS**	
Dairy Cow	9.8	8	80	200	10.8	20	80	100	(Allen et al., 2016; Browne et al., 2013; Caliskan et al., 2020; Garcia et al., 2019; Kouas et al., 2017; Tańczuk et al., 2019)
Beef Cattle	5	8	80	200	5.40	20	80	100	
Pig Sow	6	5	80	300	1.89	20	80	300	
Pig Swine	5	5	80	300	1.89	20	80	300	
Poultry	-	-	-	-	0.015	20	80	300	

Table 7-3 summarizes the agricultural biomasses used for the calculation, along with the necessary physical parameters and their energy content. The data were provided by AGEA, the Agency for Payments in Agriculture, which collects cultivation data for each land property in the country. A number of coefficients were applied to simulate the production phases to ensure that the calculation adhered to the actual situation. First, only fields of at least 2000 m^2 have been considered; smaller fields are considered economically disadvantageous in terms of mechanisation and working efficiency to collect the byproducts to be sent to the digester. In addition, a 40%-50% sustainable removal rate (SRR) was applied to ensure an adequate supply of organic matter to the field while avoiding land depletion and maintaining soil fertility (Scarlat et al., 2010). Finally, the byproduct potential was further reduced by 84% to account for competing uses, such as livestock activities (Scarlat et al., 2010).

Table 7-3. Available livestock bioresources and potential bioenergy assessment

	FM yield (t/ha)	**DM (%)**	**HI (%)**	**VS (%$_{DM}$)**	**SRR (%)**	**Methane yield (m^3/t_{VS})**	**Reference**
Cornstalk (*Zea mays*)	10.86	87	52	95	50	239	(Einarsson and Persson, 2017; Fan et al., 2017; Ge et al., 2016; Lamani, 2019; Lozano-García et al., 2020; Monlau et al., 2015; Murphy et al., 2011; Tian et al., 2017)
Durum wheat (*Triticum durum*)	5.78	85	48	93	40	200	
Rapeseed (*Brassica napus*)	3.33	74	30	95	50	209	
Sunflower (*Helianthus annuus*)	3.51	93	27	93	50	159	
Sugar beet (*Beta vulgaris*)	65.58	27	85	90	50	300	
Oats (*Avena sativa*)	3.92	80	52	93	40	200	
Wheat (*Triticum aestivum*)	6.63	85	48	93	40	200	
Barley (*Hordeum vulgare*)	6.16	66	53	93	40	200	
Sorghum (*Sorghum vulgare*)	7.09	87	52	95	50	239	
Ryegrass (*Lolium perenne*)	24.89	45		90		400	
Triticale (*Triticosecale Wittmack*)	39.50	30		92		440	

An availability map was created, consisting of a grid with meshes of 1 km based on the potential energy values from agro-livestock byproducts. Each mesh is associated with its energy availability value (Figure 7-2).



(a)

(b)

(c)

Figure 7-2. Distribution of bioresources in the study area: (a) agricultural byproducts (AGEA, 2020), (b) livestock manure (Anagrafe Zootecnica, 2020) and (c) total.

7.3.2 Available areas definition

The first step in decision-making is the definition of the theoretically available plant location areas. These areas are obtained by applying a series of territorial constraints and directly subtracting the areas that cannot be exploited for environmental or social reasons. These conditions are the most important ones, since sites that do not respect a constraint cannot be considered available. Unlike the criteria, compensation between different constraints is not allowed: a site must meet the requirements of all constraints, as lacking even one results in the exclusion of the site. Table 7-4 summarizes the constraints applied in this work (Ferrari et al., 2022a). Some constraints, including water features, roads, or railways, are accompanied by a buffer, a distance that determines a protection belt.

Table 7-4. Constraints considered in biomass plant candidate site selection

Constraint	Description	Buffer distance (m)	Reference
Road network	Exclude areas that contain or are too close to roads and highways.	40 (local road) 60 (highway)	(Ma et al., 2005; Silva et al., 2014)
Railway network	Exclude areas that contain or are too close to railways.	100	(Zubaryeva et al., 2012)
River	Exclude areas that contain or are too close to rivers and other watercourses.	150	(Silva et al., 2014)
Lake	Exclude areas that contain or are too close to lakes.	300	(Delivand et al., 2015)
Natura 2000	Exclude areas classified in the Natura 2000 program.		(Zubaryeva et al., 2012)
Urban, industrial	Exclude areas that contain or are too close to urban and industrial areas.		(Jeong and Ramírez-Gómez, 2018; Sultana and Kumar, 2012)
Slope	Avoid areas with a slope greater than 15%.		(Delivand et al., 2015)
Landslide and hydrological risk	Avoid landslide and hydrogeological risk areas.		(Delivand et al., 2015)

7.3.3 MCDM by AHP

The calculation of the suitability of sites and their ranking were performed using the AHP method. This choice is supported by a robust literature, with many studies having applied this method to similar decision-making processes. Moreover, when applied to GIS techniques, the AHP allows considering both spatial distribution of elements/information and their physical relations, which are paramount for the analysis of interventions about landscape, biodiversity, etc. The advantages offered by AHP are:

- Possibility of using both quantitative and qualitative information. Conversion using Saaty's (Saaty, 1987) method allows for comparison of attributes expressed in different units of measurement.
- Possibility of analyzing phenomena described by criteria that are themselves related to attributes and sub-attributes, thus enabling the hierarchical representation of complex problems.
- Comparison of the performance of alternatives according to alternative policy objectives. In the case of integrating AHP with GIS techniques, the result of the analysis is usually a characterization of space by dividing it into homogeneous domains with regard to the objectives of the analysis.

A set of preference criteria was chosen to determine the best sites for locating biomass plants based on previous studies (Ferrari et al., 2022a). The criteria were related to three macrogroups: environmental, social, and economic. These groups represent the areas of concern that are usually thought to be affected by plant placement and are evaluated in the project framework. Table 7-5 lists the criteria adopted for the analysis, their macrogroups and a brief explanation.

Table 7-5. Criteria and subcriteria considered in locating a biomass plant

Category	Criteria	Weight	Description	References
Environment	Nitrate Vulnerable Zone (NVZ)	0.3363	Maximise the presence of NVZ to maximise the positive effect of livestock manure treatment.	(Ferrari et al., 2021a)
	Water bodies	0.2487	Maximise distance from waterbodies.	(Silva et al., 2014)
	Hydrogeological risk	0.2122	Minimise the presence of hydrogeologic risk areas near potential areas.	(Perpiña et al., 2013)
	Slope	0.0636	Minimise the slope of potential areas.	(Silva et al., 2014)
	Natura 2000	0.1392	Maximise distance from sites belonging to the Natura 2000 network.	(Jeong and Ramírez-Gómez, 2018)
Social	Population density	0.5678	Minimise the number of people residing within a distance of 2 km.	(Perpiña et al., 2013)
	Urban areas	0.1789	Maximise distance from urban areas.	(Sultana and Kumar, 2012)
	GDP per capita	0.1922	Minimise GDP to facilitate less wealthy areas. Installation of facilities can have positive effects on employment.	(Bojesen et al., 2015)
	Visual impact	0.0611	Minimise visual impact to protect the landscape.	(Bojesen et al., 2015)
Economic	Road network density	0.2771	Maximise the presence of roads to make bioresources transport more economical.	(Sultana and Kumar, 2012)
	Harvesting cost	0.1986	Minimise the cost of bioresources harvesting to make bioenergy production more profitable.	(Perpiña et al., 2013)
	Biomass seasonality	0.2263	Minimise seasonality of bioresources supply to decrease storage space and costs.	(San Martin et al., 2017)
	Organic carbon	0.1394	Minimise the percentage of organic carbon in the soil. The most carbon-poor soils are the ones that have the most benefit from using the digestate produced in the plants.	(Ferrer-Martí et al., 2018)
	Gas grid	0.1070	Minimise distance from the natural gas distribution network to facilitate biomethane input for possible future upgrading of facilities.	(Sultana and Kumar, 2012)
	Industrial areas	0.0515	Minimise distance from industrial areas to avoid mutual interference.	(Zubaryeva et al., 2012)

Once the criteria to be used were established, the relative weights were calculated and the importance of a given criterion compared to the others was established. Finally, the various sites were ranked by applying the AHP method. Participatory approaches have been included either through information based on the perception of the value of indicators (criteria) and by providing weights on the relative importance of the elements included in each hierarchical level. So, a questionnaire was submitted to a group of experts to assign weights to the criteria. These experts work in different sectors of the agronomic and environmental field; with this heterogeneous composition, it was possible to collect different experiences that allowed us to consider various aspects. Each respondent was to answer by making a numerical judgement indicating the importance of each criterion relative to the others. The judicial system is as described by (Saaty, 1987). The comparison was carried out between criteria belonging to the same macrogroup. This combination of homogeneous criteria regarding the topic simplified pairwise comparisons. In addition, these are the three major fields of interest for stakeholders; distinguishing them allows for targeting the analysis to a particular field, as evidenced in the subsequent sensitivity analysis. Once the judgements of the experts were obtained, the average of each pairwise comparison was calculated. The result is the matrix of criteria weights (Equation (1)).

$$K = \left[K_{ij}\right]_{n\times n} = \begin{bmatrix} K_{11} & K_{12} & \cdots & K_{1n} \\ K_{21} & K_{22} & & K_{2n} \\ \vdots & & \ddots & \vdots \\ K_{n1} & K_{n2} & \cdots & K_{n,n} \end{bmatrix} \tag{1}$$

where K_{ij} expresses the importance (the weight) of criterion *i* relative to criterion *j*.

The second step is the normalization of the pairwise comparison matrix: i) calculating the sum of each column; ii) dividing each item by the sum value of its column; and iii) calculating the mean of each row to obtain the relative criterion weight.

The consistency of ratings could be significantly affected by assigning importance ratings to one pair at a time. The consistency ratio is calculated to assess the consistency of the pairwise weight matrix (Equation (2) and Equation (3))

$$CI = \frac{\lambda_{max} - n}{(n-1)} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

where n represents the number of criteria, λ_{max} is the largest eigenvalue of the pairwise comparison matrix, CI is the consistency index, and RI is the random index that depends on the number of alternatives (Zarghami and Szidarovszky, 2011).

If the CR is less than 10%, the test is passed, and the matrix of weights is consistent. However, if the test results in a value greater than the threshold, the weight matrix cannot be accepted. Several authors have examined this situation; in general, decision-makers are required to revise their initial judgements.

After obtaining the weights of each criterion, it was possible to calculate the suitability score. Then, each area was associated with the score related to all selected criteria based on environmental, social and economic characteristics. Finally, the overall score for each area was calculated as the sum of the scores for the relative weight. In this way, it was possible to identify the most suitable sites to locate the plants.

7.3.4 Network analysis and potential plant sites

The final step of the analysis identified the best sites among those extracted for the location of the plants. The process considered the scores obtained with MCDM, the existing plants and the distribution of bioresources in the territory. ArcGIS Pro software provides a specific extension for this type of analysis: Network Analyst.

The extension provides a specific tool, Location-Allocation, which calculates the best layout of a set of facilities based on demand points. The tool requires the input of three elements.

1) The road network interconnects the different points and the geometry and the necessary technical parameters must be defined: maximum speed, one-way traffic, and forbidden roads.

2) A demand point is typically a location representing the people or things requiring the facilities' goods and services. Each demand point is assigned a “weight”, i.e., a value that indicates the importance of that point; it can represent the number of customers to be served by a supermarket. In this case, the potential energy of the corresponding territory can supply the digester.

3) Facilities are the candidate sites to host facilities. They can be of three types: “candidates”, if they are potential sites; “required”, if they are sites to be included in the results and contribute to the final result; and competitors, if they are alternatives to the sites that the solver wants to find. The potential sites were those found in the previous analysis. The requested sites were the current facilities, computed along with the potentials in one step of the sensitivity analysis. There were no competing sites because the created model represented a coordinated system, and it did not include competing elements of each other.

After defining the points of the origin-destination matrix and the road network, the analysis parameters must be specified. The first is the cut-off value, the maximum biomass travel distance; this work set a cut-off of 30 km and a linear cost function. Next, the Maximize Attendance model was used for the base case and the sensitivity analysis regarding the existing facilities management. This algorithm chooses facilities such that as much demand weight is allocated to facilities while assuming the demand weight decreases with the distance between the facility and the demand point. With this choice, attention was given to the effect of space between facilities and between facilities and production areas. For the analysis of the environmental, social and economic scenarios, on the other hand, the Maximize Market Share was applied, which assigns the weight (biomass in this work) of the demand point in proportion to the attractiveness of the potential sites. This algorithm permits evaluation of the effects of a different attractiveness of potential sites, assessing the impact of the interest of the decision-makers towards a specific area and certain criteria.

7.3.5 Sensitivity analysis

During the development of this model, two questions in particular arose: how does the distribution of new facilities change considering the presence of existing plants and the natural gas grid?; and how does the overall outcome vary if the decision-maker adopts a particular interest in a specific topic? A sensitivity analysis was conducted to answer these questions. The analysis allowed at individuating spatial ambits that are homogeneous as regards relevant criteria. Indeed, ex post analyses of the effects of policies impacting on agriculture and environment have highlighted that AHP spatial models are more suitable to achieve an effective policy, if compared to non-spatial regression models.

In the base scenario, existing facilities were not considered. New plants have all of the available biomass in the region at their disposal. Therefore, the first analysis evaluated the consequences of a different approach to existing facilities and to the natural gas grid. Three scenarios were developed:

1) Existing facilities without their current powers were considered. Only existing plants located in suitable areas were selected in accordance with the previous spatial analysis. These were loaded as “required” sites on the software and combined with the new plants to be installed.

2) Existing facilities were prioritized. In the first analysis, all these plants were assigned the necessary biomass supply to maintain their current power (consistent with availability and distances). Then, the location of the new plants was determined, considering only the biomass remaining that was available after the previous assignment.

3) Only potential areas within 1 km of the primary natural gas distribution grid were considered for plant locations. These sites minimize the construction costs of the infrastructure needed to feed the produced biomethane into the grid. This scenario determines the best distribution of plants for an energy system oriented to biomethane production.

The sensitivity analysis regarding the preferences of decision-makers was performed by applying the Maximize Market Share method, which allows an attractiveness value to be assigned to the facilities. First, the environmental, social and economic macrogroups had the same weight in the neutral scenario—33% each. Then, in the environmental scenario, 50% of the total score was attributed to the criteria of the environmental macrogroup, while the other two macrogroups contributed 25%. Similarly, 50% of the final weight was attributed to the social and economic macrogroups in the social and economic scenarios, respectively.

7.4 Results and discussion

7.4.1 Spatial distribution of bioresources

The distribution of available resources is concentrated in two macroareas of the region. Agricultural byproducts, mostly maize stalks and wheat straw, allow the high availability of biomass in the south of the region, in the middle of the Po Valley. On the other hand, the intense zootechnical activity determines the highest availability of animal waste near the mountainous part (Fig. 4). Overall, the estimated potential of plant byproducts reached 8,923,811 GJ/year, equal to 867,662 MWh/year of potential CH_4. A total of 67.9% of this potential is represented by corn stalks, and 17.9% is represented by wheat straw. The remaining area, just 14.2%, is made up of all other crops: ryegrass (5.4%), barley (2.4%), sugar beet (1.4%), sunflower (1.0%), and others (3.9%). Most of the energy potential from livestock activities derives from cattle farms, 3,166,708 GJ/year, or 58.7% of the total, with a population of 734 thousand heads. Swine farms produce 1,313,821 GJ/year of energy potential, 24.4%, with a population of 637 thousand heads. The remainder, 910,172 GJ/year, comes from poultry farms, representing 43,698 thousand heads. The distribution of resources is linked to environmental, geographical and climatic factors. It is also a consequence and cause of human development in the territory. Corn and cereal crops in the southern part favored the presence of scattered settlements on the territory, low population density and infrastructure. Widespread livestock farming in the western part of the region, bordering the most industrialized region in Italy, favored the presence of product processing industries, and benefited from the presence of a higher density of road infrastructure and manufacturing centers. As a result, the distribution is very heterogeneous over the territory and shows sudden variations both within the region and lower administrative areas (provinces in Italy, NUTS 3). Compared with other work, this result indicates that the analysis of biomass distribution over the territory needs to have a greater level of detail, using statements from farm centers or aerial and satellite surveys rather than aggregate statistical data.

7.4.2 Available areas for biomass plant location

The application of the constraints produced the map of available areas. A threshold of 2 ha (20,000 m^2) was applied to this result to remove areas too small to accommodate a facility. The constraints have greatly influenced the final result; in fact, at the end of the selection process, 18,466 available areas covered 5619.54 km^2, 30.6% of the original area (Figure 7-3a). Each constraint had a very different impact in the different areas of the region, depending on geographical characteristics and human activities. There are 1400 km of railways in the region, in addition to the urban parts, distributed almost evenly over the entire territory. The road network stretches over 74,000 km (considering both urban and suburban roads), thus registering a density of 4.04 km/km^2; having a buffer of 40 m (60 m from motorways), the infrastructure leads to the exclusion of approximately 5060 km^2. However, the situation is very heterogeneous; in the northern provinces, in the mountainous area, the density of roads decreases to only 2.04 km/km^2, while in the central part, in the Po valley and in an industrialized area, a value of 5.44 km/km^2 is found. The main water network stretches for about 5200 km and is distributed fairly evenly throughout the region. The 150 m buffer reduces the available territory for installations by 1550 km^2. Protected areas cover 5625 km^2, or 30.7% of the territory; these areas are very localized: the Venice lagoon, the Po delta, the mountainous part. Urban areas are an important constraint, covering about 1245 km^2 of territory, especially in the central and western part; while industrial areas occupy an area of about 379 km^2. Overall, constraints regarding the slope, hydrogeological risk and protected areas led to the exclusion of much of the mountainous territory. In the central part, with high population density and intense industrial activity, many areas have been excluded for their proximity to urban or industrial areas and the presence of road infrastructure. In the plains, the main constraints were the buffer zone along roads and the protection of urban and industrial areas. For these reasons, the presence or absence of certain constraints must be carefully considered in light of careful territorial analysis.

7.4.3 MCDM and ranking of areas

The MCDM made it possible to prioritize among the various criteria. The interviews conducted to determine the weight of the criteria were validated by calculating the CI. Among the environmental criteria, protection of NVZ, at 33.6%, was the most important, followed by protection of rivers and lakes, at 24.9%. Among the social criteria, the distance from urban areas was the most considered criterion, at 56.8%. Finally, among the economic criteria, decision-makers favored the presence of road network infrastructure, 27.7%, and the constant availability of biomass throughout the year, 22.6%. As an alternative to this methodology, the process can be developed by completing or replacing expert judgement with population interviews. Involving local communities will take longer and probably entail more work to harmonize opinions and needs. However, it also leads to solutions that are more accepted by the community and, therefore, that are more feasible.

Applying the criteria scores and their respective weights produced the suitability map shown in Figure 7-3b. The top scores, and thus the most suitable sites, are gathered in three areas: 1) In the south, in the flat area along the Po River. 2) In the central part, close to the upland area and 3) In the northern part, where population density is lower. In general, currently installed facilities are concentrated in these areas (Figure 7-3c).

The process led to selecting the 693 most suitable sites in these three macroareas by score and size. These sites were used as “candidate” areas in the subsequent network analysis (Figure 7-3d). Overall, the MCDM has proven to be successful and consistent with the geographic and anthropogenic features of the study area. Numerous criteria and different expert opinions allowed a sort of fuzzy logic to be applied to an otherwise deterministic process. Moreover, the use of a grid with 1-km meshes made it possible to achieve a high level of detail in the spatial analysis, managing to consider many constraints and criteria. At the same time, it allowed the study to be conducted over a relatively large area, which made it possible to plan a logistics model over distances compatible with actual ranges.

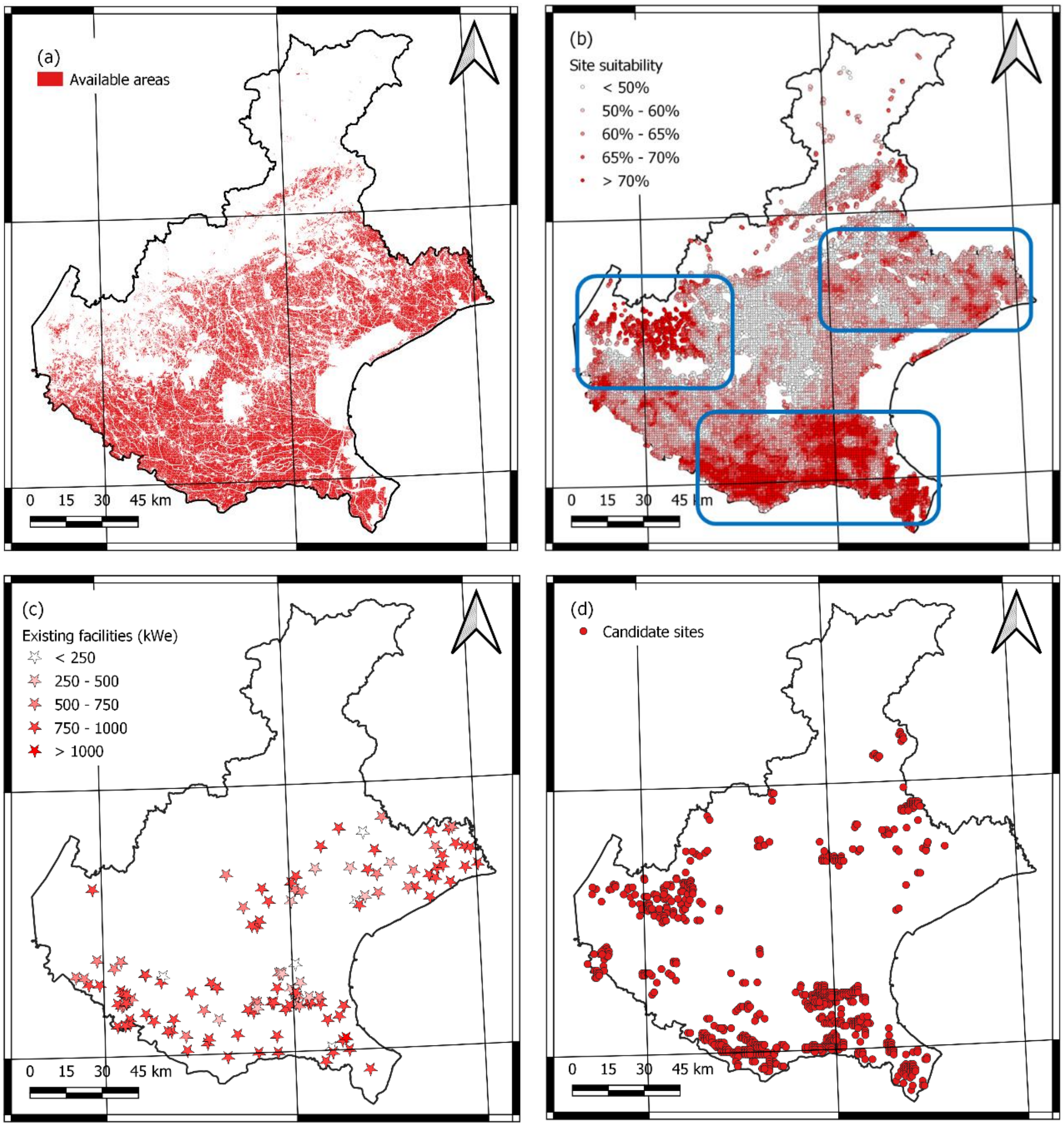


Figure 7-3. (a) Available areas for biomass plant location, (b) site suitability according to the MCDM, (c) Existing plants, and (d) Selected candidates for biomass plant location.

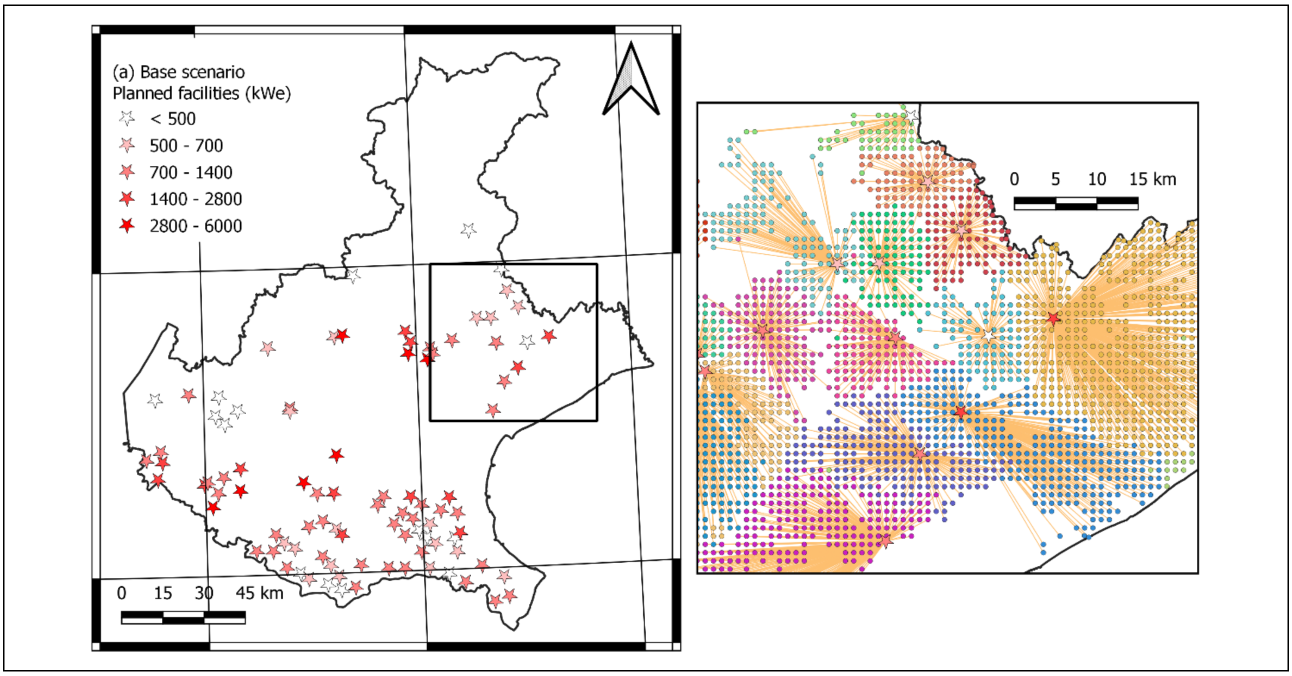
7.4.4 Network analysis and plant site selection

The network analysis located the plants considering the mutual influence of the candidate sites and simulated the actual conditions. The analysis was performed by adopting an iterative procedure with the Location-Allocation tool. The Maximize Attendance function requires the a priori definition of the number of plants to be identified; increasing this number tends to decrease the biomass allocated to each plant and, therefore, its potential power. Instead, the resulting power tends to increase by reducing the number of plants. In this work, a minimum threshold of 200 kWe and a maximum of 6000 kWe have been considered. The result was the location of 93 biomass plants and the allocated demand points for each plant (Figure 7-4a). The plants are located in almost all areas of the regional territory, allowing broad coverage of the territory. The potential capacity ranged from 232 kWe to

4006 kWe, with a predominance of plants between 500 kWe and 1000 kWe (Figure 7-4b), the same mode observed in the power categorization of existing facilities. The total capacity of the plants is 103 MWe, and the expected production is 866.7 GWhe, which would be sufficient to supply 3.0% of regional consumption. If the system were not based on electricity production from biogas combustion but on biomethane production, these outputs would potentially produce $246.8\cdot10^6$ Nm^3 of biomethane, which corresponds to 6.3% of the civil methane consumption of the region.

The power of the planned plants can be compared with that of the plants currently installed in the region. This comparison reveals that the technical analysis identifies as the ideal dimension of the plants, a higher power size than the average one currently adopted. Authorization procedures and incentives provided by institutions, which have proven to be crucial for the development of the sector, should also be based on territorial analyses and energy models. Investments should consider the territory as a set of integrated and interconnected components, encouraging models of integration and coordinated operation of plants. A careful cost-benefit analysis, not only of the financial but also of the social and environmental factors, may be able to balance the different interests and produce a resilient energy system over an extended period.

The Location-Allocation tool has shown that it can also be used for the location of biomass plants by setting the biomass available in the various areas as the product demand to be distributed. However, in the case of further applications of the tool for similar purposes, the authors recommend that much attention be paid to the choice and control of the parameters: location method, cut-off distance, weights, and the types of plants needed. Indeed, these specifications are crucial to the final result.



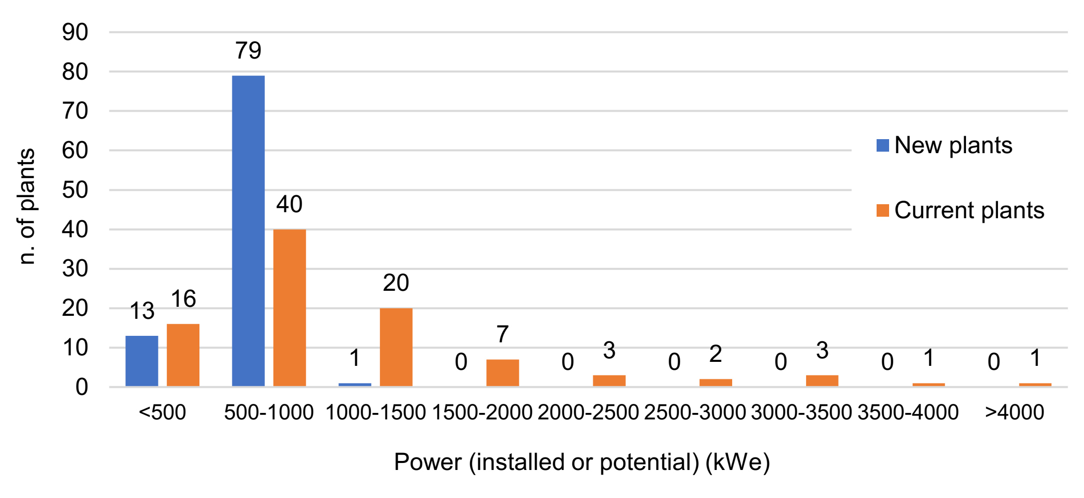


Figure 7-4. (a) Sites selected for biomass plant location and domain area of each plant (example) and (b) Categorization of new biomass plants by potential power.

7.4.5 Sensitivity analysis

The sensitivity analysis results related to the management of existing plants are presented in Figure 7-5. In fact, the different management of existing plants determined different results in the distribution of facilities and their powers.

The first scenario is the "base case" described in the previous chapter (Figure 7-4). The base scenario involved a complete replacement of the existing plants with new plants located in the most suitable sites; this approach was based on social and environmental needs, which aimed to minimize the disturbance caused by the energy production plants to people and the environment.

In the second scenario, new facilities are installed considering the presence of existing facilities. It was the most articulated and closest to an actual hypothetical situation, in which attempts are made to maintain the plants currently in operation; this is for economic reasons to avoid building new plants and upsetting the current productive reality. To simulate this condition, each existing plant was assigned the average suitability value of the available areas at a 2 km distance resulting from the MCDM. Then, the 56 plants with the highest suitability value were selected. The process of locating new facilities allowed identification of 34 new sites; these were added to the existing 56. Therefore, 90 facilities were identified with the associated powers, both those of the new facilities and the recalculated powers of the current facilities (current powers were not considered) (Figure 7-5a). The plants ranged in capacity from 271 kWe to 5758 kWe. This scenario also confirms that the most common size is between 500 kWe and 1000 kWe. The total capacity of the plants is 129.8 MWe. In this scenario, the potential electricity production would be 1090.65 GWhe, 3.7% of the regional consumption, while with a system based on biomethane, the estimated production would be $310.6 \cdot 10^6$ Nm^3 of gas, 8.0% of the regional civil consumption.

The differences between the results of this scenario and the base case support the decision to consider existing facilities. The results demonstrate the need to supplement the literature on the topic with an analysis that integrates the layout of new plants with existing ones. For this reason, the authors recommend that technical and political stakeholders determine from the beginning of the decision-making process how existing facilities and resources should be managed.

In the third scenario (Figure 7-5b), existing plants had priority. Biomass resources are allocated primarily to these plants to maintain or enhance their current capacity. Then, with the remaining biomass, new plants are located. Due to the higher number of facilities that will be obtained, it can be considered an "energy" approach. Because of the lower amount of resources, the lower threshold of acceptability has been raised to 200 kW_e. The result is the placement of 70 new plants, with a capacity between 199 kW_e and 3219 kW_e. These plants would complement the 129 existing plants. In this scenario, the potential electricity production was calculated to be 1768.5 GWhe, with a capacity of 210.5 MWe, equal to 6.1% of the annual consumption of the region. Alternatively, up to $503.6 \cdot 10^6$ Nm^3 of biomethane could be produced, 12.9% of the annual civil consumption of the region. Such high production values were due to the large number of plants considered, more than twice as many as in the other scenarios. In fact, all existing plants remained operational, and more were added to cover the remaining areas of the region. These high production levels were achieved at the expense of efficiency and associated operating costs, which, for such a large number of plants and with structures of smaller average size, will be more onerous. The results obtained by considering existing plants, with and without prioritizing them, in the second and third scenarios are very different from the base case. The authors discussed extensively whether and how to consider existing plants. Ultimately, the choice was to assume that existing facilities deserved a dedicated analysis, and this result supports that choice. Furthermore, this result demonstrates the importance of applying this methodology in full-scale applications.

The fourth scenario located the plants to facilitate biomethane production while reducing feed-in costs (Figure 7-5c). In the network analysis, only areas within 1 km of the natural gas distribution grid were considered candidate sites. The grid is well spread regionally but is particularly developed in the industrial part of the south and along the coast. A minimum limit of 500 kW of expected installed capacity was set to support the costs of plant upgrading. The result was the location of 90 plants with a capacity ranging from 524 kWe to 5124 kWe. The system has a biomethane production potential of $255.1 \cdot 10^6$ Nm^3 of biomethane, equal to 3.1% of regional consumption. Although this value is lower than the previous ones, it is obtained with fewer facilities and could increase by inserting upgrading plants even at greater distances from the grid. Furthermore, one possible solution to increase biomethane production to be fed into the distribution grid is to use the upgrading plants as hubs, transporting the biogas produced to the other sites. This option would be the only one designed to ensure high production of biomethane from biogas instead of its use as fuel for cogenerator power generation.

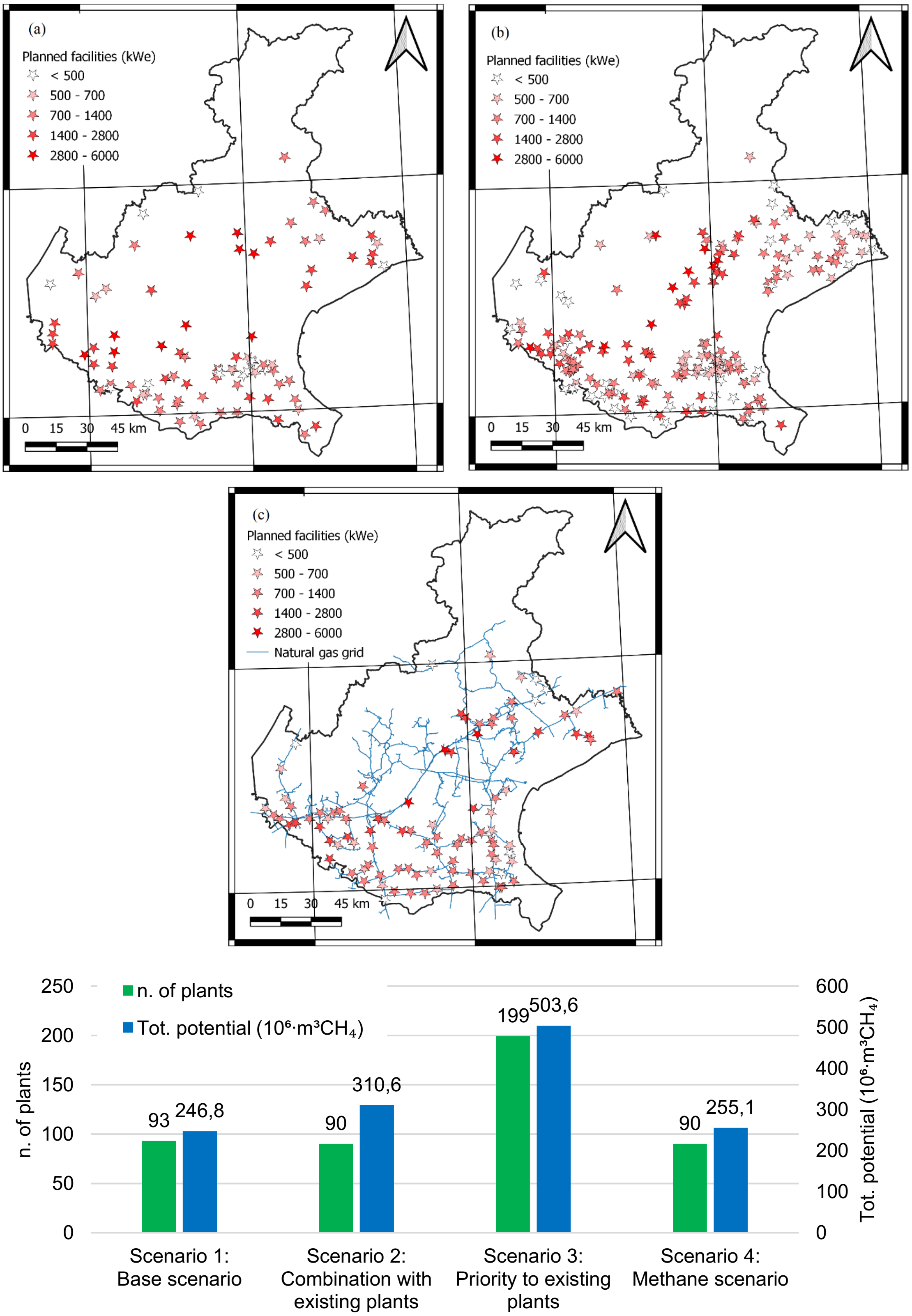


Figure 7-5. Sites selected in three scenarios of development: (a) in combination with existing plants, considering their location but without considering the current installed power; (b) considering the presence of existing plants and assuming the priority of their supply; (c) installing the new plants at a maximum distance of 1 km from the primary methane distribution grid; and (d) comparison of the number of plants and total potential of the four scenarios

For these reasons, it is reasonable to recommend an integrated approach in the planning phase, possibly integrating the various scenarios and setting up a mixed system that considers the various needs. In any case, it seems increasingly clear that the best use of biogas is upgrading to biomethane; efficiency is greatly increased, and a gas is produced that is suitable for storage and thus suitable to serve as an energy storage system.

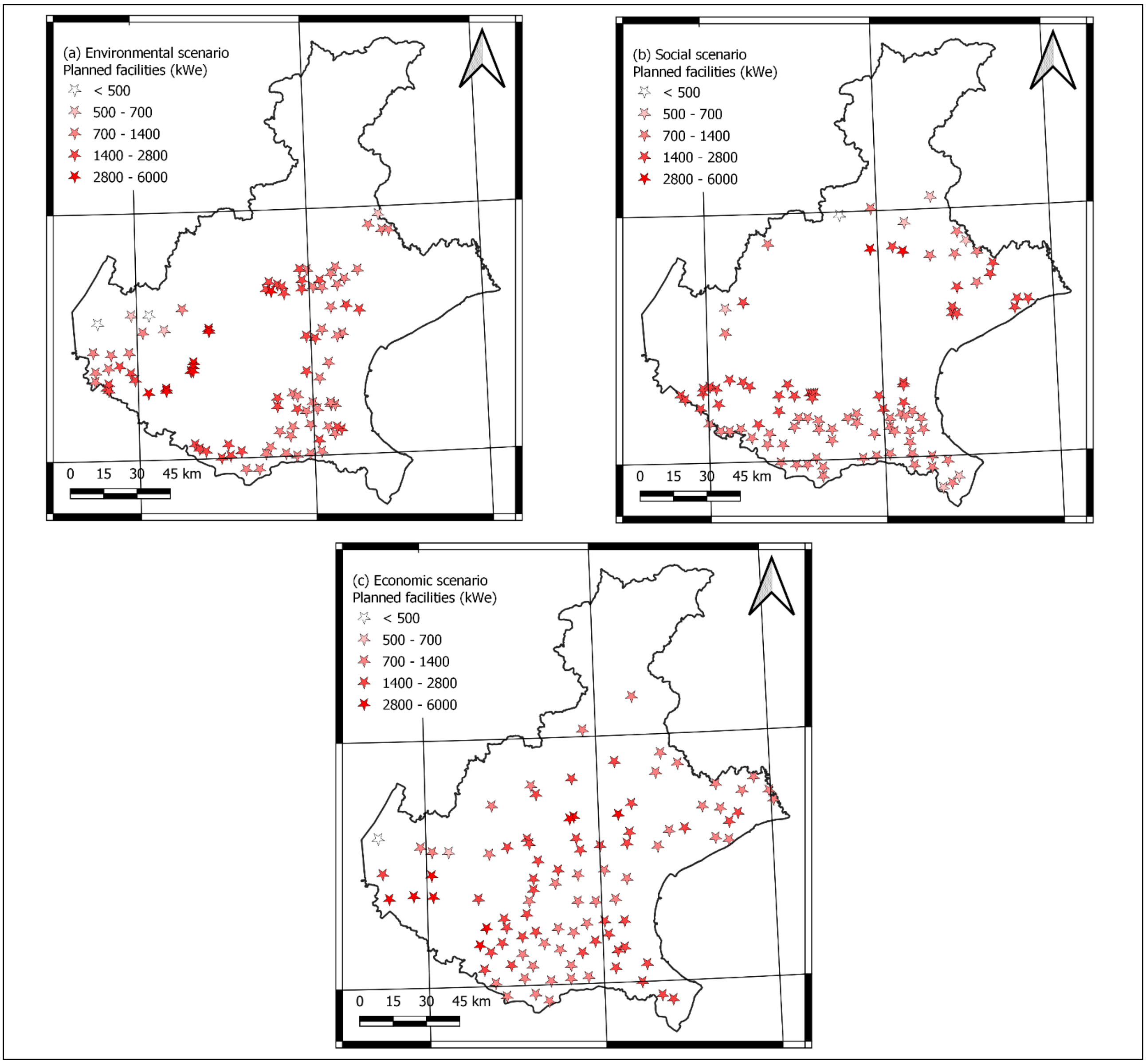
The last sensitivity analysis examined the consequences of a specific policy direction in the definition of the criteria. Three alternative situations were considered, where the importance (i.e., weights) of the three groups of criteria were alternately increased. Figure7- 6 reports the sensitivity analysis results regarding the preferences of decision-makers.

In the environmental scenario (Figure 7-6a), the distribution of plants clearly reveals the presence of constraints along the coast and in the mountainous and some protected areas in the middle of the region. The result was a heterogeneous distribution of plants, concentrated in some areas with high levels of anthropization: agricultural areas in the south, farms in the west and industrial areas in the middle. In this scenario, 95 plants have been located, with an installed capacity between 400 kWe and 3428 kWe. The total electrical power is estimated at 145.8 MWe, with a production of 1225.0 GWhe, 4.2% of regional consumption, $348.8 \cdot 10^6$ Nm^3 of biomethane, and 9.0% of regional consumption for civil uses.

The distribution of facilities in the social scenario (Figure 7-6b) traces the distribution of the population. The plants are concentrated in the southern part, along the Po valley and in the area close to the mountains where the population density is lower. The localized plants were 98, with an installed capacity between 410 kWe and 6735 kWe. The total electrical power is estimated at 140.0 MWe, with a production of 1176.3 GWhe, 4.0% of regional consumption, $334.9 \cdot 10^6$ Nm^3 of biomethane, and 8.6% of regional consumption for civil uses.

The economic scenario (Figure 7-6c) is particularly influenced by the presence of infrastructure and the type of biomass available, characterized by greater or lesser ease, and therefore cost, of collection, and by the different availability during the year. The entire flat area benefits from a widespread presence of infrastructure. Even the distribution of biomass, although heterogeneous, does not leave areas completely devoid of livestock or agricultural activities. Only the mountain area, for obvious reasons, has a lower density of roads and shows higher costs of collection and exploitation. For these reasons, the economic scenario shows a more homogeneous distribution of plants throughout the flat area of the region. A total of 98 plants was identified, with an installed capacity between 407 kWe and 5213 kWe. The total electrical power was estimated at 162.7 MWe, with a production of 1366.4 GWhe, 4.7% of regional needs, or $389.1 \cdot 10^6$ Nm^3 of biomethane, 10.0% of regional consumption for civil uses.

The three scenarios showed a similar distribution of the power of the planned plants; the most common size was between 1000 kWe and 1500 kWe for all three. Small sizes were more frequent in the environmental and social scenarios, between 500 kW_e and 1000 kW_e. In the economic scenario, in part due to the greater distribution throughout the territory, the plants tended to be larger: between 1500 kW_e and 2000 kW_e and even between 2000 kW_e and 2500 kW_e (Figure 7-6d). As previously explained in the literature review, sensitivity analysis on decision makers' choices and priorities has not been sufficiently studied. Instead, different results obtained by changing the importance assigned to different sets of criteria show that this aspect needs careful study. Authors recommend that this methodology might be considered both for scientific analyses, including those in different but assimilated areas of research, for example, the placement of other renewable energy facilities, and for actual technical applications. The different distributions of plants across the territory and the different installed capacities show that dialogue with policy makers is critical to establishing desired goals, and designing the energy system to achieve them.



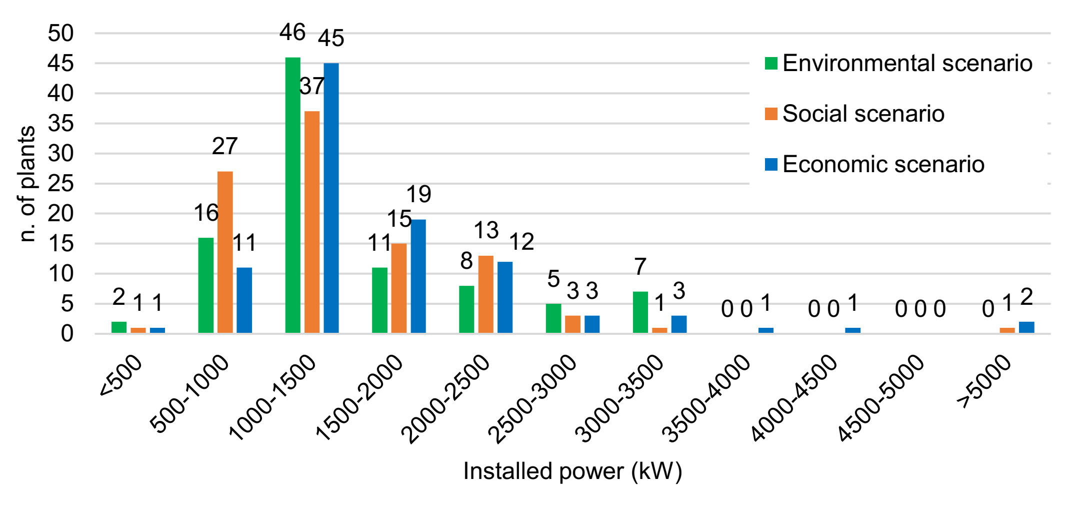


Figure 7-6. Installed power categorisation of sites selected in three different scenarios: (a) Environmental; (b) Social; (c) Economic; and (d) Comparison of installed power of the plants in the three scenarios.

7.5 Conclusions

This study proposes a MCDM for biomass plant locations. To define the model, 8 constraints and 15 territorial criteria were identified. A series of scenarios were developed using such criteria to simulate various development approaches. In the base scenario, 93 plants were located, allowing production of 103 MWe, or $246.8 \cdot 10^6$ Nm^3 of biomethane. Then, a set of scenarios was developed to assess how the result would change based on the management of existing plants, the natural gas distribution grid and the use of different criteria weights to simulate different policy interests. The combination of new plants with existing ones resulted in two different placement schemes of 90 and 199 plants, respectively, with potential biomethane production ranging from $310.6 \cdot 10^6$ Nm^3 to $503.6 \cdot 10^6$ Nm^3. The scenarios where the criteria weights are modified based on different policy decisions show three different plant distributions and three different values of potential bioenergy: from $334.9 \cdot 10^6$ Nm^3 to $389.1 \cdot 10^6$ Nm^3 of biomethane. These values support the need to pursue further research in bioenergy. The multi-criteria analysis produced many results, but carefully studying the selected criteria was necessary. In the case of similar research, or full-scale applications, authors recommend selecting criteria and limitations based on a critical analysis of the literature, that is, selecting case studies similar to the case study under consideration. The presented research did not explore two crucial aspects of energy policy: biomethane production and the integration of bioenergy with other renewable energy sources. Future research can analyze the possible solutions for biomethane production and their integration in the area. Moreover, the energy potential of the territory can be investigated with a holistic approach, integrating the various forms of renewable energy. In this way, it is possible to design a diffuse system, in which each area contributes to energy production according to its own characteristics and needs.

7.6 References

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8 Discussion

This thesis describes the scientific course followed during the doctoral program to improve techniques for exploiting biomass from livestock manure and agricultural by-products.

The project's primary purpose was "To study each step in the chain leading from the production of by-products to their valorization as energy, bio-fuels, and biomaterials, and to optimize the process with the use of mathematical software tools." The study started with the definition of the available biomasses and their distribution over the territory and ended with the location of the plants and the possibilities of using biogas and biomethane. Attention was paid to the logistics and management aspects and the process's interactions with the surrounding area.

Chapter 2 is devoted to the first article published in these three years, "Bibliometric Analysis of Trends in Biomass for Bioenergy Research". This review presents a meta-analysis of approximately 10,000 articles published in the past 20 years on bioenergy. Through a process of text mining, research trends over the past two decades were analyzed. The results showed a growing research interest in bioenergy. The most significant research has been done in the U.S., Canada, Germany, and the U.K., while the most significant growth in recent years has been in China. The textual analysis identified the most recurring themes and areas of work in the articles and their respective interactions. The most studied work areas were those related to the production process and the characteristics of the biomass used. In addition, two themes were identified that have had less research space but have grown in interest in recent years: environment and land. In 2001, only 7.3% of the articles directly or indirectly addressed environmental issues. However, this interest has grown significantly, and the percentage of articles reached 11.8% in 2019. Despite the growth, this value is still lower than that of the other topics studied; this consideration, combined with the growing interest in sustainable development, leads one to assume further growth in future years. This growth in interest has also included the topic of agricultural by-products, livestock manure, and waste in general. The authors believe this proves the awareness of the need to embed bioenergy production in a comprehensive view of the production system. Using manufacturing waste makes it possible to develop a sustainable circular economy that respects the environment and local communities. A final aspect that has been relatively little explored is the integration of bioenergy with other forms of renewable energy. The concept of energy communities, which produce as much of their energy as they need, is relatively new. Developing these communities requires an organic analysis of all possible energy resources and community needs. With this in mind, bioenergy can play a crucial role, along with other renewable energies, in achieving the goals of environmental protection and human well-being that institutions and communities have established.

The review, therefore, demonstrated the research interest in this area and justified the work done. The study also suggested many themes for further work, allowing the doctoral program to focus on some objectives better.

The first specific objective of the research is summarized in the question, "What methods can be adopted to evaluate and quantify bio-resources, with a focus on agro-livestock by-products?" This objective circumscribes the study to agro-livestock; neither waste from industrial activities, organic fraction of municipal waste, nor forestry by-products were considered. Furthermore, it is specified that agricultural biomass must be by-products; energy crops are not considered in this work. In this way, it is possible to assume the incorporation of bioenergy into the existing agricultural framework, using only biomass that would be produced anyway and not interfering with food crops. The objective was developed in two steps: *i*) evaluation of the energy potential of the resources, *ii*) distribution of the resources over the territory.

The choice of resources was made by considering the most widespread crops in the study area. The scientific literature has widely explored the energy potential of agro-livestock products; therefore, it was possible to establish very reliable values for different crops and livestock manure productions. Data provided by ISTAT (Italian Institute of Statistics), AGEA (Agency for Agricultural Payments), and the National Livestock Registry were used to determine the distribution of resources over the territory. These data are very reliable and have a high level of detail.

The first analysis was presented at the EUBCE 2020 conference: "Valorisation of agricultural by-products in different agro-energy districts: a case study in northeast Italy." This study demonstrated the high potential of bioenergy resources in Veneto and, thus, the suitability of the area for the research project. In subsequent work, plant diets were studied to determine the possibility of adopting a mixed diet consisting of by-products and livestock manure. The result was presented at the Venice 2020 conference: "A comparison of performance indices of biogas plant feedstock." The study showed that a mixed diet is feasible and better than one with only one type of biomass, as it provides greater reliability in the supply.

The analysis of available biomass was then extended to the entire Italian territory with the article, "An assessment of nitrogen loading and biogas production from Italian livestock: A multilevel and spatial analysis," reported in Chapter 3. This article focuses on livestock manure (cattle, pigs, and poultry); in addition, the problem of distribution of nitrogen produced by animals with related issues for vulnerable areas are addressed.

The first interesting result was the theoretical volume of biomethane obtainable from livestock manure; a potential of $1764 \cdot 10^6$ m^3 CH_4 was calculated, equivalent to 6.1% of national electricity consumption, a result that fully justifies the interest in this product. The regions with the most significant potential are those in northern Italy: Lombardy, $642 \cdot 10^6$ m^3 CH_4; Emilia-Romagna, $221 \cdot 10^6$ m^3 CH_4; Piedmont, $202 \cdot 10^6$ m^3 CH_4; and Veneto, $198 \cdot 10^6$ m^3 CH_4. The analysis showed that 75% of these resources ($1322 \cdot 10^6$ m^3 CH_4) are within 5 km of at least one plant. This value increases to 89.9% ($1585 \cdot 10^6$ m^3 CH_4) considering a linear distance of 10 km from the plants. The availability of biomass within a short distance from the plants reduces the environmental and economic costs of transportation.

Numerous researchers (Provolo, 2005) have demonstrated the effectiveness of anaerobic digestion as a pretreatment on digestate to improve soil nitrogen uptake capacity. Although anaerobic digestion does not reduce nitrogen levels, the resulting product, digestate, is more stable than the starting effluent, which allows for better nitrogen uptake. Therefore, the relationship between the presence of livestock farms, and thus the biogas potential, and the nitrogen load to the field was studied, considering both the slurry produced and the nitrogen-vulnerable zones. It is necessary to mention that in nitrogen-vulnerable zones, the legislation prescribes a maximum field nitrogen value of 170 kg/ha, while the limit is 340 kg/ha in other zones. LISA, Local Indicator of Spatial Analysis, was used to test the spatial correlation between municipalities with high methane potential. The results showed high spatial autocorrelation between areas with high biomethane potential and areas with high nitrogen load to the field.

Moreover, many of these areas, 579 municipalities, fall in a cluster of both high biomethane production and high nitrogen load to the field. These results first demonstrate the existence of many areas that would benefit from a biodigester for digestate pretreatment. In addition, since many farms are medium or medium-small in size, careful consideration should be given to providing district plants, which can collect effluent from these smaller farms as well.

The described analyses investigated the first aspect related to the effects, both positive and negative, of bioenergy production. This investigation merited further investigation with the second specific analysis objective, "What are the benefits and costs related to the exploitation of agricultural and livestock by-products?" As a result, three areas of study were identified: *i*) Environmental costs due to land consumption; *ii*) Environmental costs due to CO_2 emissions; *iii*) Social costs mainly due to the NIMBY effect.

Chapter 4 addresses the first of the listed costs, soil consumption. This topic was analyzed and discussed in the article "Land-Use Change and Bioenergy Production: Soil Consumption and Characterization of Anaerobic Digestion Plants," published in the journal Energies. This article analyzed a sample of 200 biogas plants randomly selected from the 1939 installation in Italy. The soil occupied by the plant was measured through satellite imagery, divided by the various structures. Soil provides several ecosystem services essential for environmental sustainability and, more generally, for human well-being (Pereira et al., 2018; Pulleman et al., 2012). However, permanent land cover by buildings, roads, or other impermeable anthropogenic materials causes soil sealing (Munafò et al., 2013; Pistocchi et al., 2015). This permanent condition leads to severe consequences for soil functioning (Scalenghe and Ajmone-Marsan, 2009), including increased temperatures in the atmosphere near urban areas (Murata and Kawai, 2018), flooding caused by increased volumes of rainwater (Jacobson, 2011), and reduced hydraulic conductivity and infiltration rate (Nciizah and Wakindiki, 2015). In the study, the area occupied by the facilities is divided into four areas:

- Roads: both for connection to the road network and internal traffic. These roads include service areas for vehicle parking. The total space occupied is 19,652.2 m^2 (0.6%).

- Storage area: where silage is stored. This can be bunker silos, concrete containers filled, packed, and covered with plastic sheeting to make them airtight, or silo-bags, polyethylene bags made of several coextruded layers of plastic film. The total area occupied is 730,200 m^2 (22.4%).
- Digestion unit: this is the place where microbial activity takes place and where organic biomass is transformed into biogas. The total area occupied is 413,276 m^2 (12.7%).
- Other facilities: tanks, storage sites, and other buildings used for technical and administrative needs. The total area occupied is 2,096,534 m^2 (64.3%).

A significant result came from the comparison between occupied area and installed power. The model indicated an increase in efficiency for larger plants: a biogas plant with an installed capacity between 0 and 200 kW occupies an average of 49 m^2/kW, while biogas plants with 801-1000 kW need an average of 24 m^2/kW. These results encourage the choice of medium- to large-scale plants to limit land consumption. This choice would also be functional in exploiting economies of scale for upgrading plants for biomethane production.

The biomethane production process and environmental effects are the subject of the research published in Bioresource Technology journal under the title, "Environmental assessment of a two-stage high-pressure anaerobic digestion process and biological upgrading as alternative processes for biomethane production." In this work, three LCAs of three alternative biomethane production processes were implemented. Specifically, the objective of the work was to investigate the environmental sustainability of the experimental plant implemented by the University of Hohenheim and other partners as part of the ProBioLNG project. The plant consists of a two-stage high-pressure anaerobic digester and a biological upgrading plant. The analysis is justified by the fact that although bioenergy is undoubtedly renewable energy, it still causes emissions of CO2 and other polluting gases. Therefore, these emissions must be calculated and considered in an overall energy system evaluation.

Three alternative processes were analyzed:

- Conventional biogas production with one-stage digestion - Biogas upgrading with water scrubbing.
- Conventional biogas production with one-stage digestion - Biogas upgrading with ex-situ biological methanation.
- Biogas production with two-stage high-pressure anaerobic digestion - Biogas upgrading with ex-situ biological methanation.

The LCA is developed between substrate transport and digestate disposal to the field. Therefore, the phases analyzed were: biomass transport, biomass storage, electricity consumption for the machinery operating in and around the digester, digester heating, biogas compression, biogas upgrading with water scrubbing method, upgrading with ex-situ biological system, biomethane compression, storage, transport, and digestate disposal. In addition, carbon credits from using livestock manure and emissions for conventional manure management were also considered. The first process, the conventional one, requires 805.6 gCO_2eq/m^3CH_4; the second process 569.9 gCO_2eq/m^3CH_4. The third process, the one chosen for the experimental plant, generates 450.3 gCO_2eq/m^3CH_4. The results demonstrate the effectiveness of the latter solution in terms of emission reduction. The subsequent sensitivity analysis shows that using livestock manure brings a further definite increase in environmental convenience. Although these biomasses produce much less energy than sugar beet, their use provides access to carbon credits under European regulations. This result again proves the convenience of using by-products and wastes for bioenergy production over energy crops.

An essential aspect of this technology is the possibility of obtaining biomethane by using hydrogen produced by water electrolysis with excess electricity generated by photovoltaic and wind power plants. In this way, bioenergy can serve the critical function of an electricity storage system.

Bioenergy production must integrate with other renewable energies, the environment, and the productive and social framework. This consideration is expressed in the third and final objective, "How can energy production facilities be integrated in a way that maximizes benefits while reducing social and environmental impacts?" The two articles that addressed this objective are intended as consecutive phases of the same work.

Chapter 6 consists of the article "Where and how? A comprehensive review of multicriteria approaches for bioenergy plant siting." This review summarizes the methodology and results of 40 articles published over the past 20 years to describe the criteria that influence the siting of biomass plants and how the authors compare and choose alternatives.

The information extracted from the articles was the characteristics of the area under analysis (area, population, orography, infrastructure, urban fabric), the biomass used, the criteria chosen to locate the plant, and the decision-making models adopted to determine the location of the plants. In most articles, social standards were less important than economic and environmental criteria. In addition, local communities were rarely involved in the decision-making process; an aspect, however, that must consider is that these are scientific studies and not approved and implemented projects.

An important aspect is the relative lack of sensitivity analysis about the criteria used. As a result, a careful assessment of the importance and impact of the criteria on the final decision was lacking; this consideration was particularly considered in the last and final paper.

The last chapter includes the final article of the doctoral program: "Network analysis for optimal biomethane plant location through a multidisciplinary approach", published in the Journal of Cleaner Production.

The study area chosen was the Veneto Region, an area where bioenergy is already highly developed. Two sets of constraints and criteria were used to determine the usable and most suitable places for plant location. The AHP method was used to aggregate the scores of the various criteria across the available sites and rank the results.

The results showed a very heterogeneous distribution of available biomass compared to much previous work. In addition, the application of constraints reduced the available areas to only 5615 km^2 or 30.6% of the regional area. For this reason, for future studies and projects, the authors recommend that much attention be paid to defining the constraints to be applied. At the end of classifying the results with the AHP method, 693 ideal sites for plant locations were identified. With the network analysis performed with the Location-Allocation tool of ArcGIS, it was possible to identify the base scenario with the 93 best sites and describe the biomass distribution pattern to these plants. The plants have a potential capacity of 866.7 GWhe/y or, alternatively, a production of $246.8 \cdot 10^6$ Nm^3 of biomethane per year, 6.3% of regional civilian consumption.

Two alternative scenarios with these plants were developed to account for the presence of existing plants. The results show that in environments such as the study area, with many plants already in service, it is impossible to disregard the analysis of these facilities, as a total redistribution of plants is not conceivable.

The last sensitivity analysis examined the consequences of a specific policy direction in setting the criteria. Three alternative situations were considered, in which the importance (i.e., weights) of the three sets of criteria were alternately increased. The distribution of facilities across the territory and the different installed capacities show that dialogue with policymakers is crucial in establishing the desired goals and designing the energy system to achieve them.

The management of energy resources and facilities imposes serious consideration for all stakeholders. Policymakers must adopt decision-making protocols that combine the technical assessments provided with the democratic methods necessary for consensus building. Administrators must not reject discussions with citizens and must promote virtuous practices for the common welfare. The technicians involved must be able to find solutions appropriate to policy directions; they must also not refuse dialogue with administrations and ordinary citizens to explain suggested solutions and increase awareness and accountability. Finally, citizens must strive to adapt to the new solutions that technological advances offer, grasping the importance of the problems they are trying to address, above all, climate change.

9 Conclusions

In recent years, interest in bioenergy has grown significantly and has covered all aspects of the production process. Research has explored both the production of biomass, particularly agricultural biomass, and the processing and production phase of biogas and biomethane. However, the consequences of bioenergy on the local population and social fabric have not yet been adequately studied. This thesis aims to contribute to understanding what social, environmental and economic factors are affected by the location of biomass plants.

The results of the analyses carried out allowed for the study of some environmental and economic aspects of biomass and plants. Land consumption, nitrogen production and CO_2 emissions were studied. Finally, the factors of mutual influence between bioenergy plants and the economic and social fabric were studied.

Despite the extensive work, the study did not directly involve local people. However, people's involvement can prevent the occurrence of NIMBY effects and facilitate the organization of a new and sustainable energy system.

In addition to people's involvement, future developments may consider the interactions of bioenergy with other forms of renewable energy. Another aspect to consider is the possible contribution of biomass plants in building independent energy communities.

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