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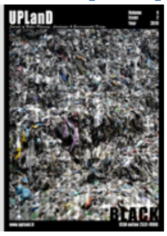

Research & experimentation
Ricerca e sperimentazione

Organic waste management through anaerobic digester technologies in urban areas. A multicriterial predesign tool to support urban strategies

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Highlights

- Waste recycle, reuse and reduction practices are crucial strategies in cities as alternative solution to landfilling.
- Micro-Anaerobic Digesters for urban bio-gas production show new possibilities in the reuse onsite of urban organic waste for energy production according a circular green economy strategy.
- Multi-criterial predesign tools could be nowadays essential resources for architects, city planners and urban managers to support Smart Biogas Grids.

Abstract

The daily production of waste within urban areas represents an opportunity to transform its organic fraction in biogas through anaerobic digestion, but until now it has not been studied and considered as an applicable urban solution. This paper presents a part of the results achieved in the research named "Smart Biogas Grid", study conducted with the aim to investigate the perspective for the realization of small-scale anaerobic digesters to produce biogas exploiting biowaste produced in urban areas. While the scientific technical literature on biogas is deeply investigated, experiences and literature for urban context are poor with only few cases and prototypes. Starting with the presentation of a case pilot of anaerobic digester realized in Camley Street Park in London, UK, the paper goes beyond the only technical and technological aspects, considering the role of non-technical features of anaerobic digester installation and providing a transversal analysis to focus on the architectural and urban planning consequences. It emerges the need for a multi and inter-disciplinary approach that can find in the support of early design tool and useful instrument to help in organizing and managing the contents proper of different disciplines; the tool presented in the paper has this purpose. Through a multi-criteria decision analysis, statistical data, features of the urban areas object of intervention, the tool defines a set of solutions, which can contribute in the activation of strategies of waste prevention, energy utilization and community awareness thanks to people/stakeholders engagement at different scales. The result is a decision-making tool useful to direct pathways for socio-technical transition from a district to the city scale, supporting the definition of urban local strategy to the creation of anaerobic digesters in urban areas, in existing as well as in new settlements.

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1. Introduction

The waste production and its management are among the most relevant topics within the scenario of sustainability. Since more than ten year, the European strategy with its regulatory framework and its policies, directs the promotion and the diffusion of solutions to contribute at the reduction of waste carbon footprint through waste recycle, reuse and reduction practices (European Parliament and Council, 2008). The waste becomes a source which can be exploited to introduce best practices for the whole chain and, in this scenario, it is crucial to define new approaches and strategies related to those areas that are waste producer: the cities. Indeed, being the most settled areas, urban territories are also the biggest waste producers and waste management is becoming an issue even more challenging, considering the need to provide alternative solution to landfilling.
With this purpose, the utilization of the organic fraction of the urban waste – the so-called biowaste – opens an interesting direction for the multiple aspects involved within urban areas as well as the possible energy uses. Urban areas are the most energy consumers – 75% of the whole world energy consumed – and the consequence is a total CO2 emission around 50-60% of the whole Green House Gas (GHG) emission on the Earth ("Energy – UN-Habitat," n.d.)("Energy – UN-Habitat," n.d.). Considering that in 2012 the urban settled population was at 52,25% and this amount is expected to grow until 66% by 2050 (United Nations, 2014), the definition of new waste management strategies within the city appears to be necessary. In this perspective, the anaerobic digestion is one of the most appealing solution for the bio-waste treatment thanks to its biodegradation process of the waste with an organic matrix – 46% of the whole amount of municipal solid waste (Baxter & Al Seadi, 2013) – that allows the production of biogas, a mix of gas with a high percentage of methane – 40/70% depending on the organic matter used – that can be used with different purposed as energy production in co-generative system or as fuel for vehicle. The utilization of the organic waste implies the installation of micro-Anaerobic Digester (micro-AD) at district scale that allows to manage locally the organic waste creating a network of distributed micro-ADs within the urban areas. Despite micro-AD solution seems to be very promising and in line with EU strategies, because it allows to support the development and the diffusion of solutions based on urban metabolism, circular economy and blue economy (European Commission, 2017), its application within urban area is not diffused.
To better focus on the possibilities opened by the application of micro anaerobic digester within urban patterns, the present paper presents more in detail the strategy of bio-waste management in urban district through the realization of micro-AD. In the first part, the pilot case of Camley Street Park in London (UK) (Walker et al., 2017) is presented with its technological application at district scale and the conclusions obtainable; in the second part, all the aspects involved in micro-AD are underlined presenting opportunity to use a predesign tool to support the decision making process and operative solutions for micro-AD realization.

2. The organic waste management within urban areas: the opportunity opened by micro-AD

Management of waste is a priority in the worldwide scenario and city represents a major issue for the recovery, recycle and reuse strategies. In 2015, 477 kg/capta (Eurostat, 2016) was produced inside urban areas in EU, and 247 kg have been incinerated or landfilled and to manage this huge amount of waste, European waste legislation is deeply challenging this handling of waste, setting targets for progressively, especially setting policies to reduce the amount of organic waste landfilled (European Parliament and Council, 2008) (Figure 1).

Figure 1: Bio-waste potential is currently dispersed in landfill disposal process, with a loss of biogas and money expenses for producers. *Source: the authors.*

Nowadays, bio-waste is an underestimated and unused source, but it represents a precious feedstock for anaerobic digestion process, because of the wide range of different substrates accepted by AD. Municipal Solid Waste (MSW) is composed by different waste – papers, plastic, glass, food waste, garden waste, etc. – and an estimation of the percentage of bio-waste contained is a challenging aspect to be evaluated, because there are many features that affect organic waste production – people density, activities in the district, local culture, standards of living, local policies, system collection. To have a precise evaluation of bio-waste amount is necessary a survey district by district to understand how the rate of organic waste produced in the area is, its typology and its energy potential. However, the organic fraction of MSW can be classified in three categories of urban biomass:

- food waste – it is composed by primary production, processing, wholesale and retail, food service, households, and its total is estimated to be 173 kg/capta/yr in EU (Åsa Stenmarck et al., 2016). It represents the major contributor in urban bio-waste because it is connected to human feeding. In particular householders have a crucial role because they provide the greatest contribution at food waste, 92 kg/capta/yr (53% of total food waste)(Åsa Stenmarck et al., 2016), marking an opportunity to engage citizens in reutilization of their discarded matter;
- wastewater – it is water that has been used in the home, in a business, or as part of an industrial process ("wastewater - definition of wastewater in English | Oxford Dictionaries," n.d.) and in urban areas it is generally collected in sewage systems. Collection of black water among wastewater is the most appealing because it is composed by only urine and faeces, human waste, and represents the most relevant part of whole wastewater. The average amount of urine produced by human is 1,40 l per person at day, 1,4 kg/capta/day, while the amount of faeces is 140 ml per person and day, 52 kg/capta/year (Hao et al.,2010);
- garden waste – It is produced in garden and park areas and it includes garden waste, trees waste, flowers and all waste derived by green area management. Its evaluation is maybe one of the most complex because it is affected by green design, vegetation adopted and management practices.

These bio-waste typologies underline the amount and the potential to use organic fraction of urban waste. To exploit properly this district bio-waste, new models of waste management need to be assessed, able to define strategies and action plans that connect expected results and policies at different institutional levels, from national to municipal one (Piippo, Saavalainen, Kaakinen, & Pongrácz, 2015) and micro-AD can represent a possible valuable strategy to be carried on.

Micro-AD process involves the breakdown of biodegradable material in absence of oxygen by micro-organisms called methanogens in a period that takes from two to five weeks, with a conversion of chemically bound of organic matters in two products:

- biogas – It is a mixture of different gases – methane (CH_4) and carbon dioxide (CO_2) and small amounts of nitrogen nitrous oxide (N_2O), and ammonia (NH_3), hydrogen, hydrogen sulfide (H_2S) and oxygen – mainly composed by methane and carbon dioxide which content is between a range of 55-70% and 30-45% (Tomperi, Luoma, Pongrácz, & Leiviskä, 2014). Its energy potential is dependent on methane yield and it can be used alternatively for energy specific needs as heating, Combined Heat and Power (CHP), upgrade and injected into the grid.
- digestate – a semi-liquid stabilized product rich of nutrients. During AD process, bio-waste degradation releases a semi-liquid component dehydrated and sanitized, deodorized and rotted without having lost original nutrients of feedstock (Tomperi et al., 2014). In fact, the process increases the nutrient efficiency of bio-waste by solubilizing nutrients (nitrogen) and, despite it is commonly considered as a secondary product of anaerobic digestion, its utilization is a valuable solution to be used as (Al Seadi, Drosg, Fuchs, Rutz, & Janssen, 2013): fertilizer – considered the most sustainable utilization for digestate, it is an alternative for artificial and mineral fertilizer in green and agricultural growing, but with the limit nitrate input maximum of 170 kg/ha per year for application; soil conditioner – obtained by the separation of solid fraction of digestate, it is a compost which can improve soil quality, improving water retention capacity.

Among the possibilities of anaerobic digestion processes – thermophilic and mesophilic (Banks & Heaven, 2013; Tomperi, Luoma, Pongrácz, & Leiviskä, 2014; WRAP, 2016) – the most interest-

Figure 2: waste treatment processes are part of possible circular economy strategies using urban micro-AD. *Source: Pracucci, 2018.*

ing AD process for urban biogas system is mesophilic one, because it needs lower temperatures and it uses as feedstock mainly household food waste with low solid material concentration, two conditions which appear to be more achievable and cost effective at district scale. However, the choice should be evaluated case by case by chemical and energy expertise, because of peculiar local feedstocks available – food or drinking facilities, large green areas, etc. – or context conditions favorable for thermophilic system – local heating system recovery (for instance wastewater treatment plant) with possibility to integrate digester heating demand with heating recovery.

Regardless of AD system applied, the anaerobic digestion process guarantees to organic waste processed to be used beyond its usual life, exploiting its potential suitable for energy production. For this reason, the implementation of a micro-AD plant in urban district opens three key operational strands, as expected by environmental EU strategy (European Commission, 2017):

- urban metabolism – micro-AD in urban district identifies a model to facilitate the analysis, description and utilization of organic waste flows and derived energy within cities;
- circular economy – micro-AD in urban district assesses an economy model which extends waste life thanks to reusing bio-waste to exploit its potential with the aim to close cycle of bio-waste nutrients where waste is produced;
- blue economy – micro-AD in urban district stimulate relative low investments using an innovative way local bio-waste to obtain multiple income streams, local job opportunities and ownership of new solutions adopted.

Micro-AD can work to develop these strategies in waste chain and urban waste treatment, adopting a non-conventional approach focused on reuse of bio-waste in a logic of green economy with people

that are aware participants in the waste management process. The key and winning factor of bio-waste utilization in micro-AD for waste management, is the creation of a local system that engages community to transform bio-waste in valuable products for their own needs. (Figure 2).
In this scenario of waste management strategies of bio-waste utilization at district scale through the products of anaerobic digestion, micro-AD in urban areas represent a solution not properly investigated yet. Only some rare pilot cases have been realized and, among them, the case of Camley Street Park is here presented.

3. The pilot case: the micro-AD in Camley Street Park, London, UK

3.1 The project and the adopted productive technologies

Camley Street Park is a green area located in north-west part of London, close to Pancras Square and King's Cross Railway Station. In 2013, a consortium composed by enterprises and researchers active in the realization of small scale anaerobic digester, named Local Energy ADventure Partnership (LEAP) (LEAP - Local Energy ADventure

Figure 3: Camley Street Park, London (UK). Picture of the building that hosts the micro-AD. *Source: photo by Pracucci, 2017.*

Figure 4: Camley Street Park, London (UK). Position of the micro-AD in the district. *Source: Pracucci, 2018.*

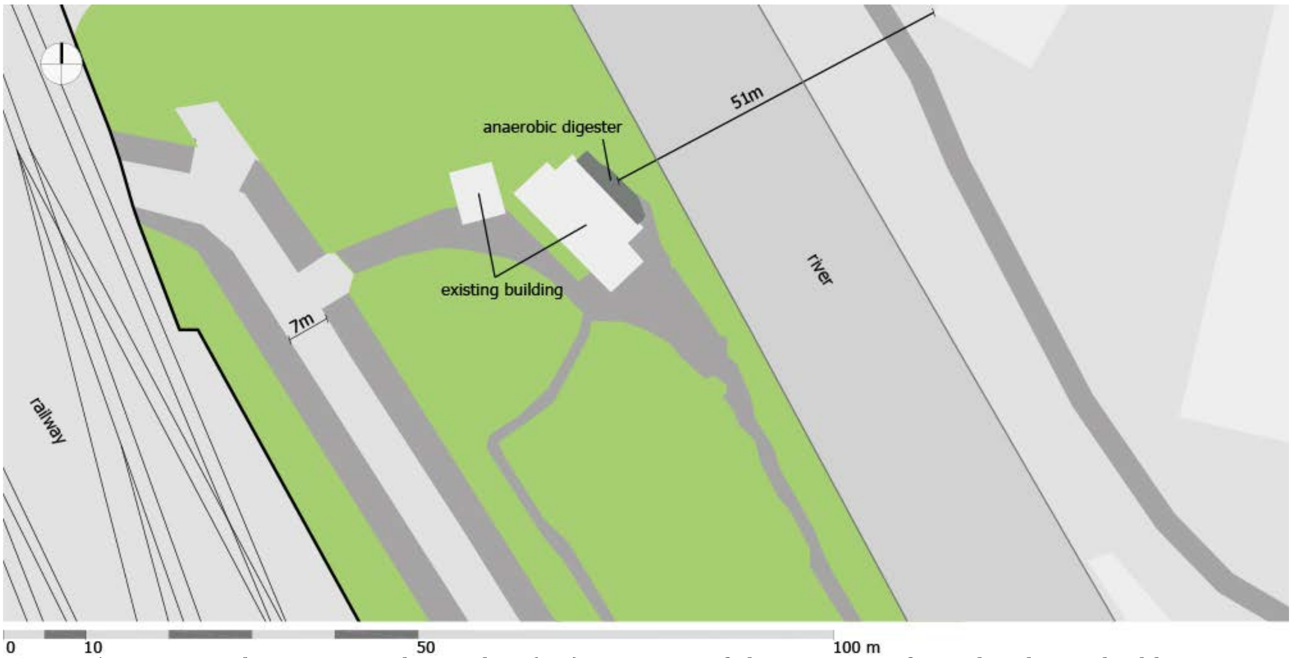

Figure 5: Camley Street Park, London (UK). Distance of the micro-AD from the closest buildings. *Source: Pracucci, 2018.*

Partnership, n.d.), promoted and guided the realization of this anaerobic digester inside the Park. The initial project aimed at creating a network of micro and small anaerobic digesters within the London urban area, to demonstrate the economic sustainability at urban scale of the whole anaerobic digestion process, considering the only treatment of food waste. Objective of the project was to direct strategies of circular economy in food waste management within the district, supporting the engagement of local communities providing biogas for energy issue and digestate useful to promote urban solutions of urban farm activities and green management.

For the purpose of this paper and the directions that the pilot case opens, some elements of this project are underlined:

- the demonstration of effectiveness of the applicability of anaerobic digester within urban areas – since the very beginning the anaerobic digester in Camley Street Park was designed with low cost technological components, to guarantee a cost-effective solution (Walker et al., 2017) easy to be replicated somewhere else

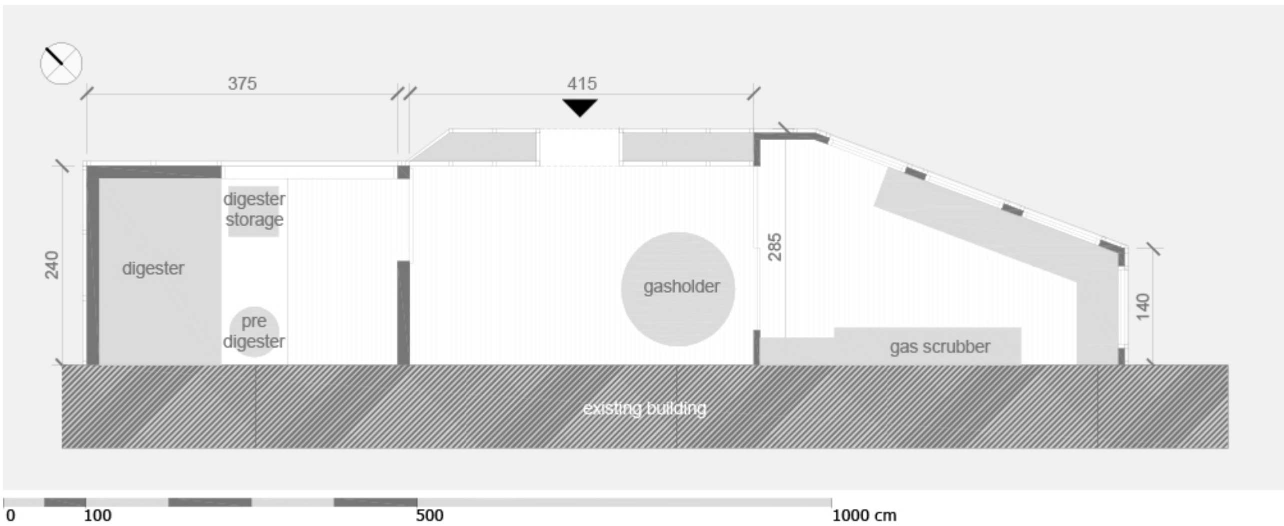

Figure 6: Camley Street Park, London (UK). The preliminary project of the micro-AD shows the dimenson of the technological components and the equipment designed. *Source: acknowledgment to Rokiah Yaman, Director of Community by Design, London, UK, for the material provided.*

Figure 7: Camley Street Park, London (UK). Cargo bike is used for food waste collection direct to Camley Street Park anaerobic digester. The cargo collects 100 kg of food waste has a speed of 15/20 km/h and is used in an area of 3,2 km of radius. *Source: photo by Pracucci, 2017.*

in an hypothetical network. Omitting in this work the detail of the components installed, it is interesting to highlight that the anaerobic digester in Camley Street park demonstrates how anaerobic digestion process can be conducted though a compact technological design and low investment solutions that can be easily integrated in a local green area within an urban district;

- the low impact solutions adopted for waste collection – LEAP realized a waste collection system to collect food waste coming from households and local food suppliers involved in the project, based on a low environmental impact solution using a cargo bike, capable to cover an urban area with a radius of 3,2 km and to collect 100 kg of food waste;
- the educational training to engage population – the local community has been engaged not on-ly through the waste collection process, but also with specific educational activities, promoted within the park's visitor center able to show the positive impact of the circular system food-waste-digestion-biogas/digestate introduced in the district with the anaerobic digestion process and its activities;
- biogas utilization as energy supplier – the biogas produced during the anaerobic digestion has been used in line with the specific necessities of the pilot case, showing its potential to replace nat-ural gas: biogas for hub for food cooking; biogas for boiler to heat the visitor center; biogas for cogeneration engine;
- reduction of Green House Gas emissions – considering the waste collection system adopted and the substitution of traditional fossil fuel by biogas, the total amount of GHG reduction was 2,95 kg CO_2eq for kWh of primary energy produced or 0,741 kg CO_2eq for kg of waste treated.

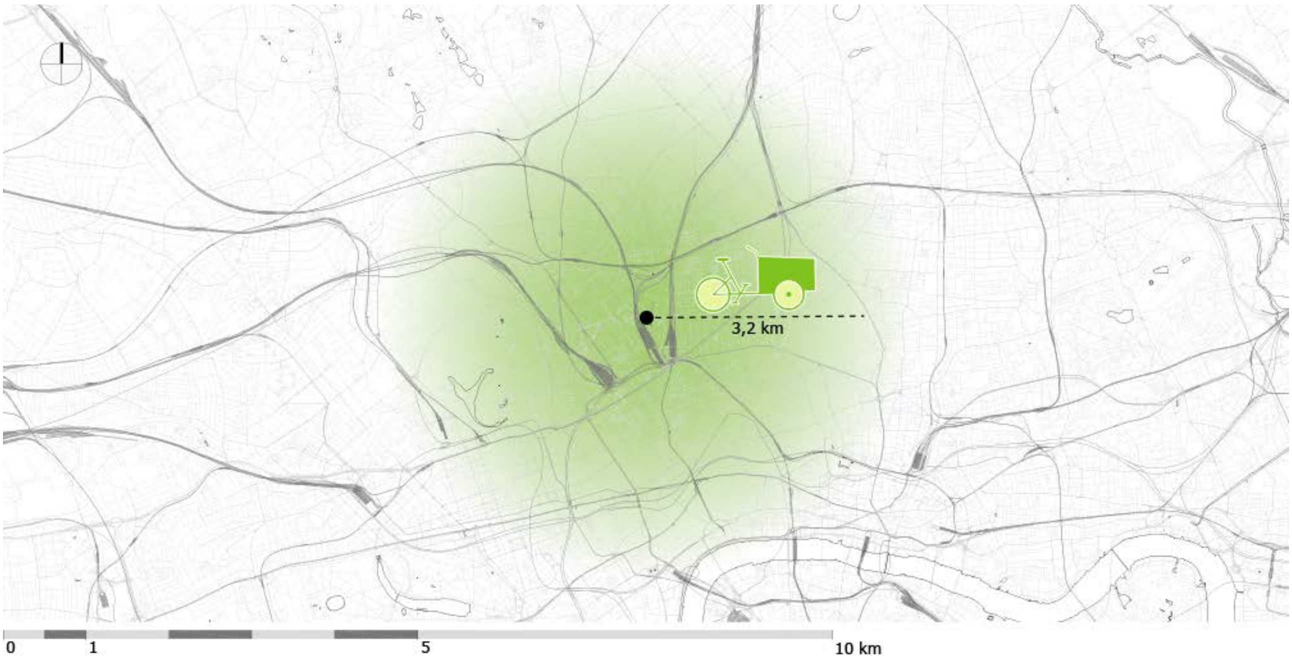

Figure 8: Camley Street Park's micro-AD covers an area of 2 miles radius (3,2 km). *Source: Pracucci, 2018.*

3.2 Conclusions achieved by the pilot case

The anaerobic digester in Camley Street Park was operational since October 2013, until 2017 and this 5 years experience direct some considerations for further steps:

- area of installation – the urban area to a micro-AD needs to guarantee full accessibility at the digester and the requested maintenance operations;
- digestate utilization – new specific norms for the use of digestate from micro-AD should be issued. In particular, demonstrated the safety digestate from micro-AD, selling permission could open new solutions in addition to the only utilization in local green areas in the urban areas;
- creation of user friendliness micro-AD – the anaerobic digester needs to be integrated in the district to be fully accepted by the population. At this aim, the phase of design is crucial for the aesthetical appraisal as well as to communicate the scope of work;
- odor control – urban population can be concerned about this possibility, but the design phase can direct properly the prevention of this matter, in complement of the right maintenance activities of the digester;
- training of the staff – despite micro-AD technologies is simple, a training phase for the staff of the micro-AD should be conducted, so to reduce the risk of failures in the different process phase: waste collection, bio-waste management, digestion and biogas/digestate utilization. If this training is well performed, the engineering know-how is not necessary in

a

b

Figure 9: (a) Regent's Canal at Camley Street Park, London (UK). Boat along Camley Street Park on Renget's Canal have been used as green surfaces for food production and for the utilization of the digestate from anaerobic digestion; (b) Camley Street Park, London (UK). The local community is engaged in activity for food production within the park. *Source: photo by Pracucci, 2017.*

the ordinary micro-AD activities;
- engagement of local actors – the micro-AD emerges as a technological part of a more complex project that needs to include citizens, associations, business activities and local community to achieve valuable and profitable results.

The pilot case shows how the micro-AD strategies is achievable in urban areas with good results, but in the same time it underlines the need to include multi and inter-disciplinary consideration into a systemic view to guarantee that the project could become profitable and have a long-lasting impact; the design and the utilization of predesign tool can work at this purpose.

4. The utilization of predesign tool to support micro-AD realization in urban areas

The conclusions deducted by Camley Street Park pilot case demonstrate how micro-AD is connected to all a set of aspects strongly related one with the other. Micro-AD realization in urban district emerges as a complex system to be realized, managed and operated and for this reason it appears interesting to define some tools to direct, support help the promotion of micro-AD solution. With this purpose, this paragraph presents an original predictive tool designed insiede "Smart Biogas Grid" research, to support the decision-making phase on micro-AD realization in urban areas.

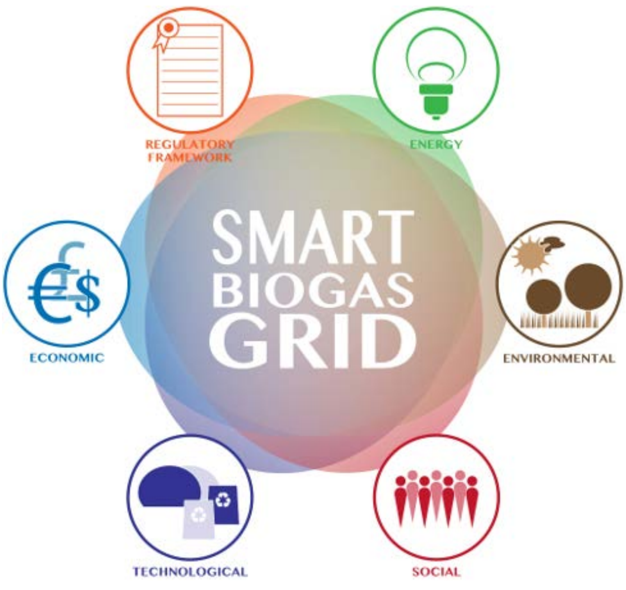

Figure 10: Multi and inter-disciplinary aspects for micro-AD in urban district need to be considered in a systemic view to join all different disciplines. *Source: Pracucci, 2018.*

4.1 Multi and inter-disciplinary aspects to design the predictive tool

First element to be considered to design a predictive tool for micro-AD realization in urban area, are the multi and interdisciplinary aspects involved. As presented in the pilot case, micro-AD does not only concern technological issues or urban areas boundary conditions for installation, but different features that are part of a more complex strategy for urban waste management and for the results to be achieved by the action plan assessed. For this reason, it is crucial for the success of micro-AD to consider the following outstanding aspects:
- environment – set of aspects related to environmental features: waste production, collection and management, digestate utilization, biogas utilization and dispersion prevention, emissions reduction;
- energy – set of aspects related to energy features: biogas energy potential, biogas utilization, energy saving;
- regulatory framework – set of aspects related to normative features: regulatory framework at different institutional scale (European, national, regional, local), policies, financial incentives;
- technological – set of aspects related to technological features: classification of technologies involved, applicability at district scales, evaluation of correlation between energy and urban morphology, technological legitimacy of biogas at district scale;
- social – set of aspects related to social features: social legitimacy of biogas among people, solutions of social innovation, behavior and engagement in SBG, community energy system;
- governance and economy – set of aspects related to governance and economic features: model of governance, not as usual business scenario, costs, incomes.

These six features are part of a holistic vision of waste management, helping to preserve a 'systemic view' on the perspective of micro-AD realization in urban district. In this way, it emerges as micro-AD is not only related to technical issues, but it involves and needs to be implemented going over the only organic matter for biogas

production, including also immaterial considerations – local expertise, social cohesion, restoring needs – typical of the district where the micro-AD system is realized. The disciplines involved need to be afforded and overlapped in a collaborative co-evolutionary frame directing specific features, projects, solutions, perspectives, in order to optimize the disciplinary outcomes and research in a multi-level perspective and common vision. Designing in such a way the predictive tool helps to find common strategies and solutions to develop new strategies for transition process, contributing in meeting ambitious performance goals assesses by public strategies and to overcome the current lack of joined-up actions. (Geels, 2002).
In line with multi and interdisciplinary aspects presented, the tool designed is based on a Multiple Criteria Decision-Making (MCDM), a methodology characterized by making preference decisions over the available alternatives that are characterized by multiple, usually conflicting, attributes (Yoon and Hwang, 1995). These methods are designed for problems that are concerned with the evaluation of different possibilities and alternatives and here applied for micro-AD. MCDM is an interactive and cumulative process in which opportunities are dynamic and consequently, the factors inducing actors participation or influencing actions are controlled by a variety of system components as well as factors that go beyond technology specific features. In this frame of reference some characteristics, common in MCDM (Yoon and Hwang, 1995) have been considered to design the predictive decision support tool on micro-AD:

- alternatives – finite number of alternatives are screened, prioritized, selected and ranked;
- multiple attributes – project has multiple attributes and a decision-maker must consider the most relevant. The number of attributes depends on complexity of the project, and higher this complexity is, higher is the number of attributes to consider. Theory of change is used to organize these attributes;
- multiple indicators – in relation to specific field of interest, attributes have different units of measurement and are assessed differently within the predictive tool;
- criteria weight – MCDM requires information to define the relative importance of each criterion; with this purpose Quality Function Deployment methodology is used to weight the importance of different criterias to evaluate outputs goodness.

4.2 The predictive tool for micro-AD in urban district

Following the consideration and the methodologies above presented, the predictive decision support tool has been designed in three phases parts:
- Input data phase – aspects the user must enter in the DST forms:

- process' actors and core group - stakeholders involved with their potential role in micro-AD project: community member, community group, business-SME, educational institution, government, NGO, other;
- context identification – set of limitations and opportunities typical of the district of application of micro-AD, characteristics requested to define which are the local elements for the success and/or failure of micro-AD realization. The context includes: statistical data on urban area, material sources – bio-waste from households and green area, existing systems useful for the project, network infrastructures, human capital – education in specific scientific and technological fields, entrepreneurship, management and finance –, financial capitals, people involved, boundary conditions as waste management or norms;
- requirements – actors' expectations on the micro-AD project useful to direct the decision process on the base of personal and social aspects.

- Evaluation phase – input data are analyzed by evaluation processes assessed in the predictive design tool using the following methodologies:

- theory of change – allows to connect elements on the base of analysis conducted and assumptions made on how actions/outputs/outcomes are logically connected. Theory of change operates in the decision support tool creating and/or excluding pathways made by 'actions' that actors and context activate assessing different possibilities for micro-AD development and implementation that are weighted with requirements through the utilization of Quality Function Deployment;
- Quality Function Deployment (QFD) – QFD in the predictive tool is developed on an evaluation matrix that crosses 'actions' activated by the context possibilities and theory of change, with 'requirements' expected by tool users. The best solution to be pursued is identified.

- Output data phase – results obtained by the predictive design tool, classified in:

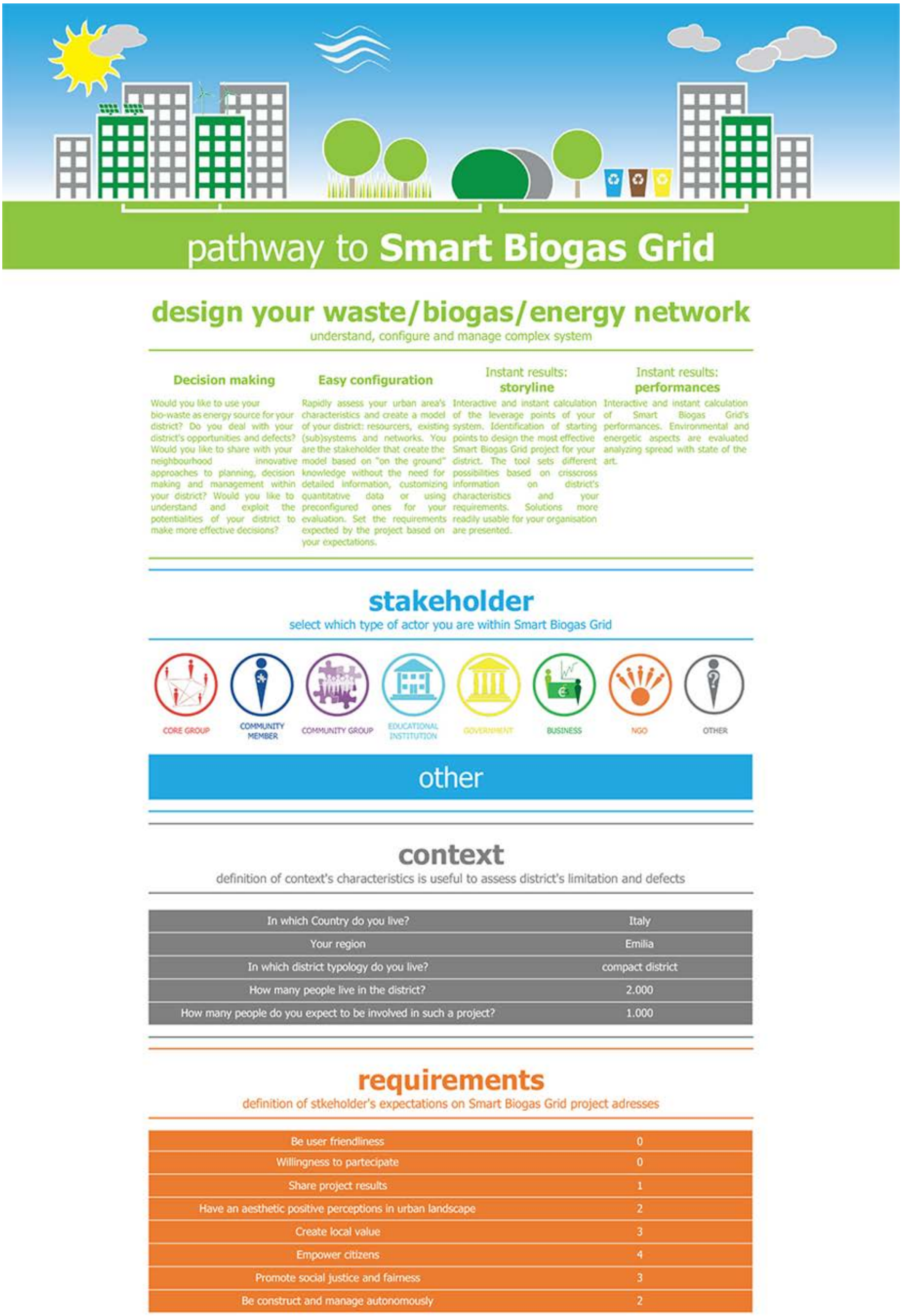

Figure 11: DST user interface with fields to enter input data.

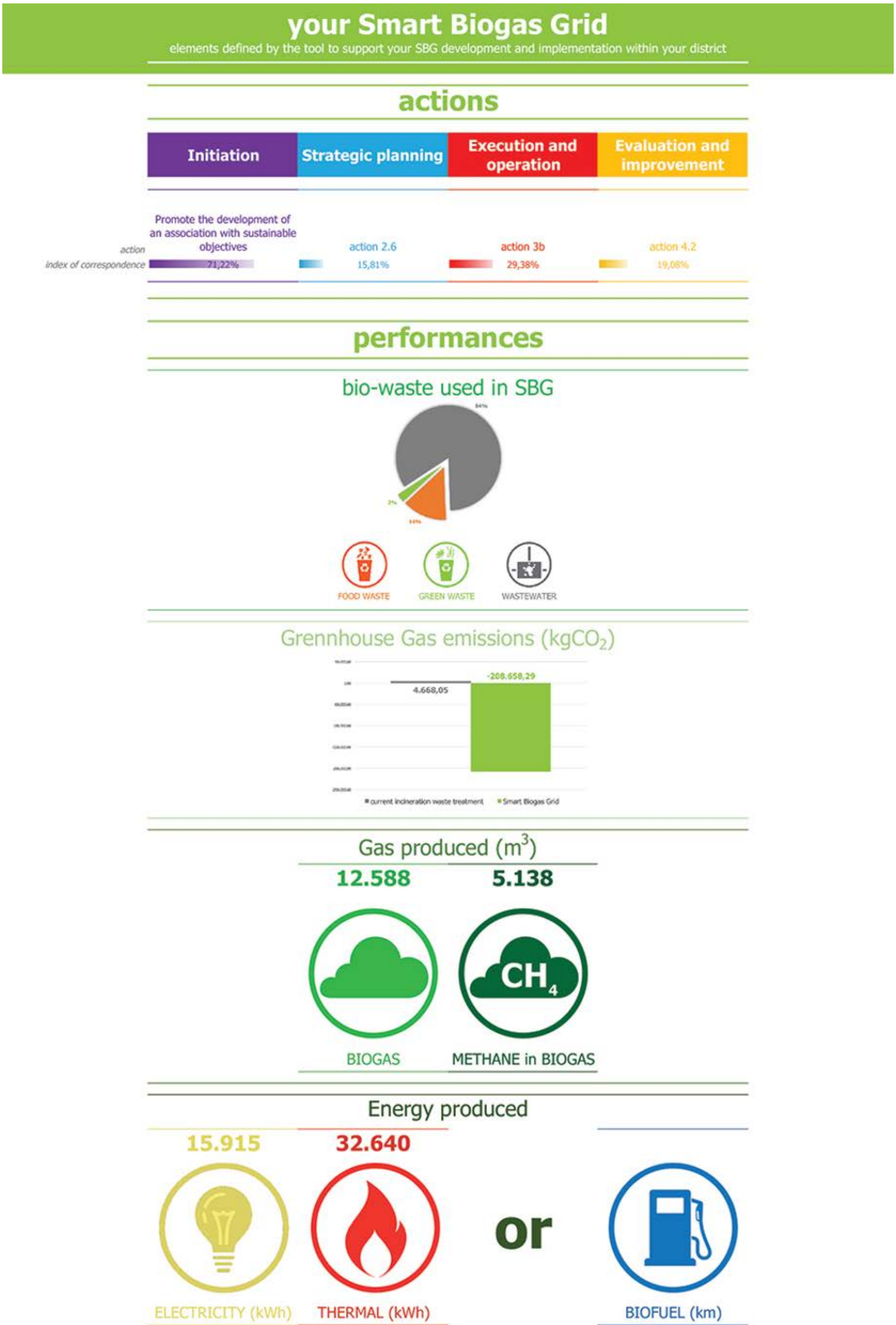

Figure 12: DST user interface with a screenshot that shows output data.

- micro-AD actions (qualitative output) – set of actions achievable by stakeholders, in line with specific context and requirement assessed. The actions can be divided in three transversal typologies: bio-waste collection – including collection and transportation, this step depends on waste collection typology and connected fuel energy consumption by the transport used; biogas production – including energy required for the operation of production; products utilization – including post-processing, transportation biogas and digestate can be used treated and used in different ways and therefore there are different energy consumptions expected. These actions provide a storyline that can fit different actors' ideas and expectations with the urban district potential, codifying micro-AD possibilities;
- SBG energy and environmental performances (quantitative output) – measurable results of waste management through micro-AD: amount of bio-waste treated, energy produced, greenhouse gas reduction, micro-AD minimum dimension.

The predictive tool has been presented to different stakeholders within international scientific groups active in triggering biogas community; at this moment, their evaluation is ongoing. After this preliminary evaluation, the further steps will predict to identify specific urban areas to evaluate the tool on the filed through and the direct involvement of the community and possible actors which could be involved in the realization of the micro-AD and its connected urban strategies.

5. Conclusions

Micro-AD in urban district appears to be a suitable alternative to traditional bio-waste management for urban areas. However, its realization needs to be part of strategies that go over the only traditional waste management practices. Indeed, the utilization of bio-waste in micro-AD does not only comprise technical and technological issues related to anaerobic digestion, but it includes a set of multi and interdisciplinary features that need to be considered as part of a systemic view. Micro-AD involves environmental, energy, normative, technological, social, economic aspects that need to be related since the very early phase to pursue holistic results, emerging as a socio-technical system useful to direct considerations at urban scale helpful to support strategies of technological and energy upgrade, social interrelation among actors and urban renovation, going over the only actions on waste management practices. This potential can be exploited only if all the features involved are considered in the early phase of micro-AD evaluation to avoid the missing of opportunities. The utilization of a digital platform as the predictive design tool presented in the paper works at this aim, supporting the decision-making process of the actors engaged, to manage all the aspects involved in micro-AD realization in urban district. The tool helps the players to manage a complex system using an only digital platform, meeting the expectations of the actors and anticipating possible actions. Despite the predesign tool is useful to anticipate a possible set of activities to be carried on and the results achievable, it represents only a predesign instrument useful to understand the potential of micro-AD in urban district, that cannot replace specific studies to be carried on by expertises of the different disciplines. The predesign tool operates to create a vision to work on defining a common base of discussion for the actors involved – citizens, district activities, local authorities, policy makers, waste companies, energy providers, etc. – that can participate in urban micro-AD realization. The predesign tool is useful to support the introduction of urban micro-AD at district scale, but it also opens the opportunity to create a network of micro-AD systems spread in the city. The micro-AD potential is not in a single system, but in the creation of a network of micro-AD that create and promote a new model of waste management inside city that supports a sustainable growth – waste is converted in an energy and environmental source –, local economy – waste is used locally, new expertise is created, educational activities are encouraged – and participation of a new generation of aware citizens – people are not only waste producers, but become producers/users/consumer of the waste as a source.

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