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Designing the biomethane production chain from urban wastes at the regional level: An application to the Rome Metropolitan Area☆

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ABSTRACT

This paper proposes a methodology to design the biomethane production chain from MSW at the regional level and to assess the environmental and economic performance of the chain. In the design phase, the following parameters are considered: number and production capacity of biomethane plants, localization of plants, waste flows among municipalities and plants. The model is adopted to design the biomethane chain in the Rome Metropolitan Area (Italy). Several structures of production chain are designed and their performances are assessed. The economic factors mostly able to affect the performance of the chain are waste disposal tariff, biomethane selling price, and the economic incentive provided to biomethane producers. Their impacts are discussed through sensitivity analyses.

Results show that the structure maximizing the economic performance has the worst environmental performance and *vice versa*. Hence, a new structure of the economic incentive is proposed, aimed at re-aligning economic and environmental performance.

1. Introduction

In the last decades, although renewable energy production has increased significantly, such growth has been unable to reduce the energy production by fossil fuels, which is responsible for more than 60% of the CO_2 emissions worldwide (International Energy Agency, 2017). With the growing concern about the impact of CO_2 emissions on climate change (e.g., IPCC, 2014), policymakers at the global level have committed to reduce them by 80% until 2050 (European Commission, 2011; Rogelj et al., 2016). Hence, the production of renewable energy must be further promoted. A well-known example in this context concerns biomethane production from the organic fraction of municipal solid wastes (MSW) (e.g., Borowski, 2015; Fan et al., 2018; Zhang et al., 2012).

Although many European countries make large use of biomethane from MSW, in other countries the biomethane chain is still scantly developed (Prussi et al., 2019; Scarlat et al., 2018). For instance, in Italy only 4.8% of organic MSW is exploited for biomethane production (ISPRA, 2019a). Aimed at supporting the transition towards the circular economy, policymakers are pushed towards designing biomethane production chains from MSW at the regional level – i.e., a given area where independent municipalities are located. Designing the biomethane production chain in a given region means (1) defining the structure of the chain (in terms of number and location of production plants) and (2) designing the waste flows from municipalities to production plants.

The design of bioenergy production chains is a topic not new in the literature. For instance, Jensen et al. (2017) developed an optimization model aimed at finding the optimal production and investment plan for biogas supply chains, as well as the optimal waste flows. Wu et al. (2015) developed a model aimed at determining the optimal location of a production plant and at allocating the waste flows to the plants, so as to maximize the economic performance of the production chain. Optimization models concerning the location of multiple production plants have been proposed by Park et al. (2019) and Mayerle and Neiva de Figuereido (2016)[1]. The literature, however, has focused on energy

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☆ The views and opinions expressed in this article are those of Mario Spagnoli and do not reflect the official policy or position of Gestore dei Servizi Energetici S.p.A.

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[1] The literature cited is not exhaustive of the topic. Some papers are mentioned to introduce the gap of the literature addressed by this paper.

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production chains from agricultural and animal wastes (e.g., manure) – and not energy production from MSW, which is the focus of this paper[2]. Furthermore, these studies focus on optimizing economic performance. Nevertheless, when designing a bioenergy chain that involves urban areas, the development of models able to integrate different decision levels, as well as to consider different performances simultaneously, aimed at incorporating a broader view of the impacts related to implementing sustainability practices, is recommended (Barbosa-Póvoa et al., 2018).

In this context, the structure of the production chain can strongly impact both the economic and environmental performance of the chain. Production chains can be characterized by a centralized structure (i.e., one or few big-scale production plants) or by a more distributed structure (i.e., multiple small- or medium-scale plants) (Mangoyana and Smith, 2011). While a centralized structure allows to exploit the economies of scale minimizing both investment and operational costs of the plant(s), *ceteris paribus* (Bekkering et al., 2010; Brown et al., 2007; Hengeveld et al., 2014), a decentralized structure allows to optimize the truck routing, so as to reduce the kilometers overall run by trucks moving wastes from municipalities to plants, thus minimizing the GHG emissions due to waste transportation and the waste transportation costs (Höhn et al., 2014). When deciding which structure to implement, policymakers should explore both these perspectives, considering that the best solution might depend on the specific case.

This paper is aimed at developing a methodology that can assist policymakers to design the organic MSW management chain towards the biomethane production from MSW at the regional level, as well as to measure the performance of the overall chain. The proposed methodology is applied to the case study of Rome Metropolitan Area (Italy), to explore the following two issues related to the case analyzed: (1) quantifying the extent to which the structure of the production chain impacts the economic and environmental performance of the chain; and (2) highlighting which other factors are mainly able to affect the above-mentioned performances.

The remainder of the paper is organized as follows. Section 2 presents the technical background. Section 3 concerns the model proposed to design the biomethane production chain and to assess the environmental and economic performance. Section 4 addresses the case study of the Rome Metropolitan Area. Section 5 presents results and discussion. The paper ends with conclusions in Section 6.

2. Technical background

Biomethane comes from the purification of biogas, a renewable gas produced by anaerobic digestion (AD). The AD is a microbiological fermentation process that breaks down complex molecules of organic matter into simpler molecules, in an anaerobic environment using bacteria. Bacteria can process almost any organic material, such as industrial organic waste (Xie et al., 2017), wastewater streams (Harris and McCabe, 2015), organic fraction of MSW (Breitenmoser et al., 2019; Browne et al., 2014), food waste (Browne and Murphy, 2013; Choi, 2020), agricultural residues (Surra et al., 2019). The main output of AD process is biogas, which contains approximately 50–60% methane (CH_4). The biogas can be used in the power sector and the heat and cooling sector, as well as it can be transformed into biomethane through an upgrading process, which removes all the impurities such as CO_2, H_2O, and H_2S (Angelidaki et al., 2018; Ryckebosch et al., 2011). Upgrading biomass into biomethane is preferred because considered more environmentally sustainable than the burning process (Uusitalo et al., 2014). Producing biomethane requires an upgrading plant to be added downstream of the AD plant. After the upgrading process, the biomethane so obtained can be injected into the natural gas grid or liquefied to be used as a fuel for transportation (Gustafsson et al., 2020). Finally, the by-product of AD is a degraded biomass (digestate), which can be used as organic fertilizer (compost) in agriculture (Chiew et al., 2015). Fig. 1 shows the overall biomethane chain that considers multiple potential waste producers.

Biomethane production from MSW is recognized as one of the best technologies to produce energy from urban wastes, from an environmental perspective (Ardolino et al., 2020). Such a practice can be considered as a form of urban-industrial symbiosis (Albino et al., 2015; Fan et al., 2021; Van Berkel et al., 2009), i.e., a strategy of urban waste exploitation able to create environmental benefits for the collectivity while providing the involved companies with economic advantages. In particular, such production can contribute to reduce the dependence on fossil fuels such as natural gas, as well as it can drive the reduction of CO_2 emissions due to energy production (Cherubini, 2010), which is one of the most pollutant processes – in terms of CO_2 emissions – in all countries (Fraccascia and Giannoccaro, 2019). Hence, biomethane production from MSW is fully consistent with the principles of the circular economy.

From the policy perspective in the Italian context, the Integrated National Energy and Climate Plan (INECP) – which aims at achieving at least 22% of renewable energy source in the gross final consumption of energy in the transport sector by 2030 – identifies biomethane production from MSW as the most important strategy to decarbonize the transport industry. The Decree of March 2, 2018 issued by the Minister of Economic Development promotes the use of advanced biomethane – i.e., biomethane produced using feedstocks such as manure and sewage sludge, biowaste from households and industry, agriculture and forestry residues, algae, and energy crops – in the transport sector, setting the goal of 1.1 billion m^3 per year of biomethane used. The decree also introduces economic incentives to bust the production of advanced biomethane: accordingly, producers of advanced biomethane are allowed to receive 375€ per 5 Gcal of fuel produced. Additional economic incentives can be achieved if biomethane producers install liquefaction and/or distribution plants, aimed at promoting the direct selling of the fuel[3].

3. Materials and methods

This Section is divided into two subsections. Section 3.1 concerns designing the organic MSW chain towards biomethane production (which, for the sake of simplicity, is called “biomethane chain” in the following sections). Section 3.2. concerns assessing the performance of the chain.

3.1. Designing the biomethane chain

This section presents the methodology that can be used to design the biomethane chain for MSW at the regional level. When designing such a chain, the following steps need to be addressed: (1) assessing the overall production capacity of the chain; (2) deciding the degree of centralization, i.e., how many plants to build; (3) identifying the localization of the plants; and (4) designing the allocation of wastes from the municipalities to the plants (Fig. 2).

The first step concerns assessing the production capacity of the chain, i.e., the amount of organic MSW to treat. This requires collecting data on the amounts of organic MSW produced yearly in each municipality, together with the main production drivers, such as the number of

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[2] Peculiar dynamics can characterize these bioenergy production chains, e.g., specific constraints related to building new production plants close to urban areas.

[3] The incentive mechanism is managed by Gestore dei Servizi Energetici S.p.A., an Italian company designed by the Italian Government to manage the transition towards achieving the energy efficiency goals. The company is also responsible for the withdrawal of biomethane from producers, if they prefer not to install a fueling station.

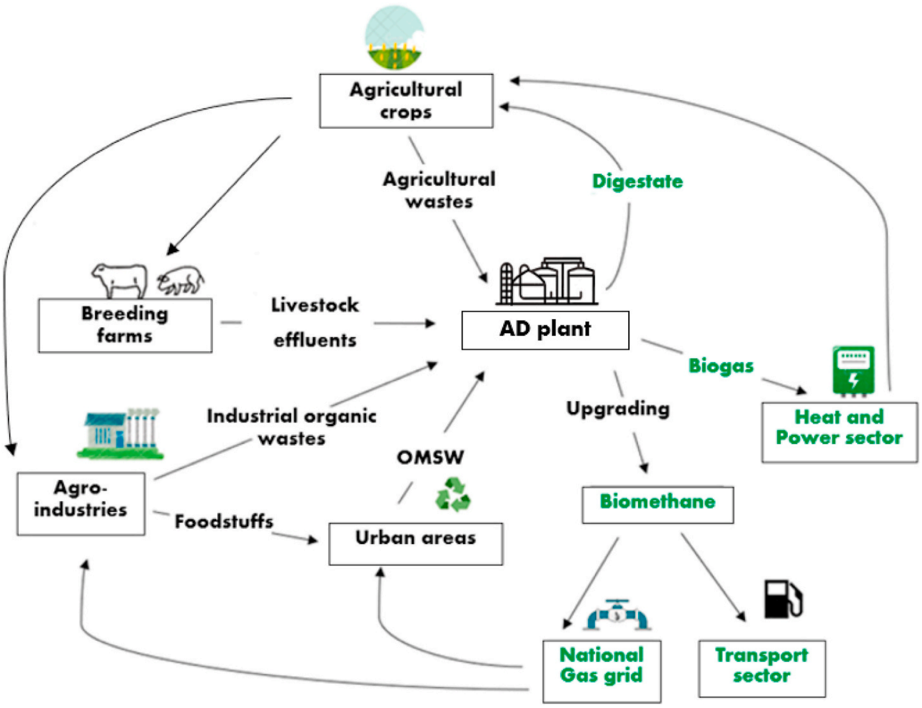

Fig. 1. Biomethane chain that considers multiple potential organic waste producers.

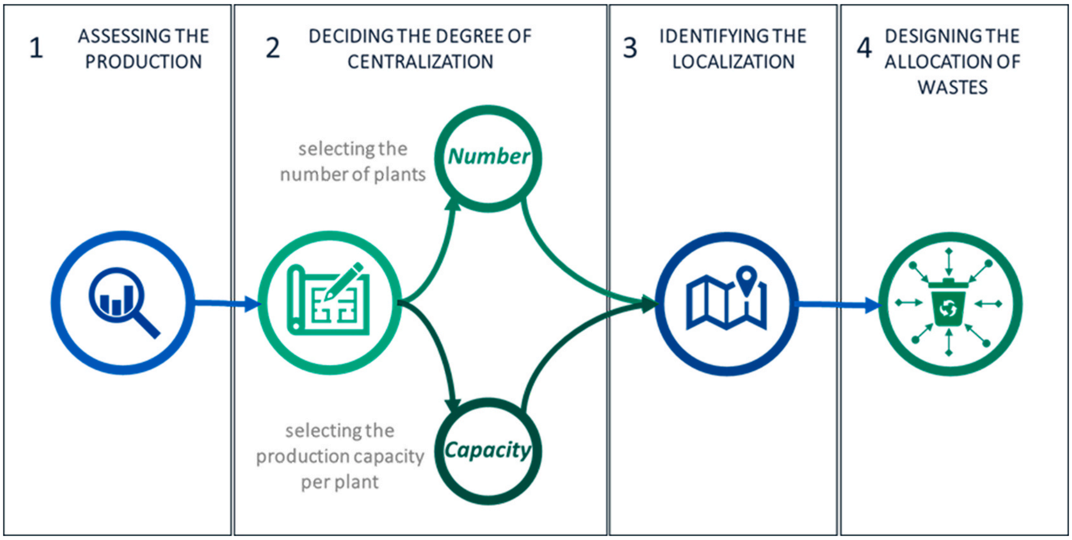

Fig. 2. Steps of the biomethane production chain design.

inhabitants, the amount of total MSW produced per capita, and the percentage of sorted collection. These drivers can be used to predict the amounts of wastes that will be produced in the upcoming years.

The second step concerns deciding the degree of centralization of the chain, i.e., the number of plants and their biomethane production capacity. In principle, two strategies can be adopted: (1) selecting the production capacity per plant *a priori* and then assessing the number of required plants, or (2) selecting the number of plants *a priori* and then assessing their production capacity.

The third step concerns identifying where to locate the production plants. The localization of plants must comply with the legislation on emissions, odor, or noise (Langeveld et al., 2010). To this aim, the regional government could have identified specific areas where building new biomethane plants is allowed; the choice must comply with this constraint.

The final step concerns designing the waste flows among municipalities and plants. Such a process can be done by solving a mathematical optimization problem (Gold and Seuring, 2011; Lo et al., 2021; Mansoornejad et al., 2013). In particular, a deterministic model can be used, since waste production is not affected by significant fluctuations over time (e.g., Abylkhani et al., 2019). Let us suppose that M municipalities belong to a regional area, where P plants need to be built. The objective function used to design the waste flows is described as follows:

$$\min f = \sum_{i=1}^{M} \sum_{j=1}^{P} \frac{q_{i \to j}}{TC} \cdot d_{i \to j} \tag{1}$$

subjected to the following constraints:

$$\sum_{j=1}^{P} q_{i\to j} = q_i^{MSW} \quad \forall\, i = 1, \ldots, M \tag{2}$$

$$\sum_{i=1}^{M} q_{i\to j} \le k_j^{MSW} \quad \forall\, j = 1,\ \ldots,\ P \tag{3}$$

$$q_{i\to j} \ \ge 0 \tag{4}$$

Here, $q_{i\to j}$ denotes the annual amount of waste transferred from the *i*-th municipality to the *j*-th plant, $d_{i\to j}$ the distance between the *i*-th municipality and the *j*-th plant, *TC* the truck capacity, q_i^{MSW} the amount of organic MSW produced by the *i*-th municipality, and k_j^{MSW} the maximum amount of waste the *j*-th plant can accept yearly. Hence, the problem minimizes the number of total Km run by trucks transporting wastes in one year, *ceteris paribus*. In turn, this allows to minimize the waste transportation costs and the CO_2 emissions due to the waste transportation process. The first constraint imposes that for each municipality the overall amount of organic wastes produced is collected and sent to a plant. The second constraint imposes that each plant cannot accept more wastes than its capacity. The last constraint imposes the non-negativity of waste flows. This step allows also to: (1) highlighting the number of trucks required and the Km run per year; (2) computing the waste transportation costs. Both of them will be used to assess the performance of the production chain (see Section 3.2).

3.2. *Assessing the performance of the biomethane chain*

The biomethane chain is characterized by environmental (Cherubini, 2010) and economic (Mangoyana and Smith, 2011) performances.

From the environmental point of view, the main performance concerns the GHG emissions along the overall chain. Since biomethane production is considered carbon-neutral, the main source of GHG emissions is waste transportation from municipalities to plants. Hence, in this paper the environmental performance assessment is given by considering the Km run by trucks transporting wastes from municipalities to plants – which is proportional to the amounts of GHG emitted. These data come as the output of the optimization model described in the previous section.

To assess the economic performance, the overall chain must be analyzed in terms of costs and revenues from required investments and daily operations. The theoretical model that we have developed to this aim is described as follows. The model is based on the Discounted Cash Flow (DCF) method; equation (5) shows the net present value (NPV) computed for the overall chain, considering P plants operating for N years:

$$NPV = \sum_{p=1}^{P}\left[-C_{0,p} + \sum_{t=1}^{N}\frac{R_{t,p} - C_{t,p}}{(1+r)^{t}}\right] \tag{5}$$

where $C_{0,p}$ denotes the initial investment costs to build the *p*-th plant, $R_{t,p}$ the revenues from the *p*-th plant at time *t*, and $C_{t,p}$ the operating costs of *p*-th plant at time *t*.

Eqs. (6)–(8) show the revenues and costs structure for the *p*-th plant. The meanings of all the revenue and cost terms are presented in Table 1.

$$C_{o,p} = C^{inv}_{a.d,p} + C^{inv}_{up,p} + C^{inv}_{compost,p} + C^{inv}_{fue,p} + C^{inv}_{OFMSW,p} + C^{inv}_{el,p} + C^{inv}_{gas\ grid,p} + C^{inv}_{other,p} \tag{6}$$

Table 1
Elements of Eqs. (6)–(8).

Symbol	Description	Unit of measure
$c^{inv}_{a.d,p}$	Unitary investment cost (anaerobic digestion)	[€ /Sm^3 /h]
$c^{inv}_{up,p}$	Unitary investment cost (upgrading process)	[€/Sm^3/h]
$C_{o,p}$	Initial investment	[€]
$C_{t,p}$	Annual costs	[€/year]
$C^{inv}_{OFMSW,p}$	Investment cost (pre-treatment wastes plant)	[€]
$C^{inv}_{a.d,p}$	Investment cost (anaerobic digestion plant)	[€]
$C^{inv}_{compost,p}$	Investment cost (compost treatment plant)	[€]
$C^{inv}_{el,p}$	Investment cost (electrical system)	[€]
$C^{inv}_{gas\ grid,p}$	Investment cost (gas grid connection)	[€]
$C^{inv}_{fue,p}$	Investment cost (fuelling station)	[€]
$C^{inv}_{up,p}$	Investment cost (upgrading plant)	[€]
$C^{inv}_{other,p}$	Other investment costs	[€]
$C_{fin,p}$	Amount of investment cost financed by third parties	[€]
$C_{ins,t,p}$	Insurance cost	[€/year]
$C_{man,t,p}$	Maintenance cost	[€/year]
$C_{el,t,p}$	Energy consumption cost	[€/year]
$C^{tax}_{t,p}$	Cost of taxation	[€/year]
$C^{debt}_{n,p}$	Cost of debt	[€/year]
c^{u}_{lab}	Unitary cost of labour	[€/year]
$c^{u}_{tr,p}$	Unitary cost of transport	[€/Km]
$d_{t,p}$	Annual km per truck	[Km/year]
DCF	Discounted Cash Flow	[€]
$f_{compost}$	Conversion factor organic MSW	[t/t]
i_{debt}	Interest rate of debt	–
r	Discount rate	–
$I_{n,p}$	Annual debt installment	[€/year]
$p^{biom.}_{t}$	Unitary price of biomethane	[€/Sm^3]
$p^{comp.}_{t}$	Unitary price of compost	[€ /t]
p^{CIC}_{t}	Unitary price of CIC	[€]
p^{OFMSW}_{t}	Unitary price for organic MSW disposal	[€/t]
$n^{CIC}_{t,p}$	Number of annual CIC	–
$n^{CIC_{ex}}_{t,p}$	Number of annual extra CIC	–
$n_{w,p}$	Number of workers	–
$n_{h,p}$	Number of operative hours	–
$Q^{biogas}_{t,p}$	Quantity of biogas	[Sm^3/year]
$Q^{biom.}_{t,p}$	Quantity of biomethane	[Sm^3/year]
$Q^{comp.}_{t,p}$	Quantity of compost	[t/year]
$Q^{OFMSW}_{t,p}$	Quantity of organic municipal wastes disposed	[t/year]
$R_{t,p}$	Annual revenues	[€/year]
Y_{biogas}	Organic MSW's biogas yield	[Sm^3/t]
$\%_{CH_4}$	Percentage of methane in biogas	–
$\%_{up}$	Percentage of methane loss in the upgrading process	–
$\%_{V.M.}$	Percentage of volatile matter	–
$\%_{D.M}$	Percentage of dry matter	–
$\%_{debt}$	Debt percentage of total investment cost	–
$\%_{man}$	Percentage of maintenance cost	–
$EBIT_{t,p}$	Earnings before interest and taxes	[€/year]

$$C_{t,p} = \left(n_{w,p}\cdot c^{u}_{lab}\right) + \left(c^{u}_{tr,p}\cdot d_{t,p}\right) + C_{el,t,p} + C^{tax}_{t,p} + C^{debt}_{t,p} + C_{ins,t,p} + C_{man,t,p} \tag{8}$$

$$R_{t,p} = \left(p^{biom.}_{t}\cdot Q^{biom.}_{t,p}\right) + \left(p^{comp.}_{t}\cdot Q^{comp.}_{t,p}\right) + \left(p^{OFMSW}_{t}\cdot\ Q^{OFMSW}_{t,p}\right) + \left(n^{CIC}_{t,p}\cdot p^{CIC}_{t}\right) + \left(n^{CIC_{ex}}_{t,p}\cdot p^{CIC}_{t}\right) \tag{7}$$

Investment costs $C_{o,p}$ – Equation (6) – include the realization of all plant's structures, i.e., anaerobic digestion ($C^{inv}_{a.d,p}$), biomethane upgrading ($C^{inv}_{up,p}$), compost treatment[4] ($C^{inv}_{compost,p}$), as well as the costs for the connection to the gas grid ($C^{inv}_{gas\ grid,p}$), the installation of the electrical system ($C^{inv}_{el,p}$), and the installation of the fuelling station ($C^{inv}_{fue,p}$). Furthermore, since the organic fraction of MSW always contains plastics residues that need to be disposed of before the anaerobic digestion, the cost for organic MSW pre-treatment plant has been considered ($C^{inv}_{OFMSW,p}$). Others initial costs that do not fall into the above categories, such as the initial costs of developing the initiative, are also considered ($C^{inv}_{other,p}$). Investment costs of anaerobic digestion plant ($C^{inv}_{a.d,p}$) and biomethane upgrading plant ($C^{inv}_{up,p}$) can be computed by the hourly methanogenic capacity of the plants themselves, as follows:

$$C^{inv}_{a.d,p} = \frac{Q^{biogas}_{t,p}}{n_{h,p}} \cdot c^{inv}_{a.d,p} \tag{9}$$

$$C^{inv}_{up,p} = \frac{Q^{biom.}_{t,p}}{n_{h,p}} \cdot c^{inv}_{up,p} \tag{10}$$

where $Q^{biogas}_{t,p}$ denotes the quantity of biogas yearly produced by p-th plant, $n_{h,p}$ the number of operative hours per year of the p-th plant, $c^{inv}_{a.d,p}$ the unitary investment cost for the anaerobic digestion of the p-th plant, $Q^{biom.}_{t,p}$ the quantity of biomethane yearly produced by the p-th plant, and $c^{inv}_{up,p}$ the unitary investment cost for the upgrading process of the p-th plant. In turn, $Q^{biogas}_{t,p}$ and $Q^{biom.}_{t,p}$ can be computed as follows:

$$Q^{biogas}_{t,p} = \%_{V.M.} \cdot \%_{D.M} \cdot Y_{biogas} \cdot Q^{OFMSW}_{t,p} \tag{11}$$

$$Q^{biom.}_{t,p} = Q^{biogas}_{t,p} \cdot \%_{CH_4} \cdot (1 - \%_{up}) \tag{12}$$

where $\%_{V.M.}$ and $\%_{D.M}$ denote the percentages of volatile matter and dry matter, respectively, Y_{biogas} the organic MSW's biogas yield, $Q^{OFMSW}_{t,p}$ the quantity of organic MSW treated by the p-th plant, $\%_{CH_4}$ the percentage of methane in biogas, and $\%_{up}$ the percentage of methane loss in the upgrading process.

The main sources of revenues shown in Equation (7), all of them referring to the p-th plant, are the following:

- Selling the biomethane produced by urban wastes, denoted as ($p^{biom.}_t \cdot Q^{biom.}_{t,p}$), where $p^{biom.}_t$ denotes the unitary selling price of biomethane at time t.
- Selling the compost obtained the anaerobic digestion process ($p^{comp.}_t \cdot Q^{comp.}_{t,p}$), where $p^{comp.}_t$ denotes the unitary selling price of compost at time t and $Q^{comp.}_{t,p}$ the quantity of compost produced by the p-th plant at time t. According to D'Adamo et al. (2019), the biomethane chain includes the recovery of compost that can be properly treated and then sold, promoting the principles of industrial symbiosis (Chertow, 2000). $Q^{comp.}_{t,p}$ can be computed as follows:

  $$Q^{comp.}_{t,p} = Q^{OFMSW}_{t,p} \cdot f_{compost} \tag{13}$$

  where $f_{compost}$ is the conversion factor for organic MSW.
- The price paid by municipalities for the waste disposal service, denoted as ($p^{OFMSW}_t \cdot Q^{OFMSW}_{t,p}$), where p^{OFMSW}_t denotes the unitary price for organic MSW disposal.
- The economic incentives provided by the Italian government to companies producing biomethane from organic MSW, denoted as ($n^{CIC}_{t,p} \cdot p^{CIC}_t$). The term $n^{CIC}_{t,p}$ denotes the number of CIC issued by the GSE and p^{CIC}_t the unitary price of CIC at time t. Each CIC is issued for 5 Gcal of biomethane released for consumption, where 1 Gcal = 1230 Sm^3. Therefore, since the biomethane quantity is calculated in Sm,[3] the number of CIC is computed as follows

$$n^{CIC}_{t,p} = \frac{Q^{biom.}_{t,p}}{1230} \tag{14}$$

In case of new distribution plant installation (fuelling station), the current legislation provides extra CIC ($n^{CIC_{ex}}_{t,p}$) so as to cover 70% of the distribution plant investment up to a maximum of € 600.000. The number of extra CICs is computed as follows:

$$n^{CIC_{ex}}_{t,p} \cdot p^{CIC}_t \leq \min\left\{ 600.000; 70\% \cdot C^{inv}_{fuel,p} \right\} \tag{15}$$

Finally, consider the operating costs shown in Equation (8), which include labor costs ($n_{w,p} \cdot c^{u}_{lab}$), energy consumption cost ($C_{el,t,p}$), organic MSW transport ($c^{u}_{tr,p} \cdot d_{t,p}$), taxes payment ($C^{tax}_{t,p}$), insurance cost ($C_{ins,t,p}$), maintenance cost ($C_{man,t,p}$), and the cost of debit[5] ($C^{debt}_{t,p}$). All these terms are described in Table 1. The waste transportation costs are related to the number of total annual km run by trucks determined in Section 3.2. The taxes payment ($C^{tax}_{t.p}$) – Equation (16) – includes both the payment for IRAP ($\%_{IRAP}$) and IRES ($\%_{IRES}$) taxes[6] ad is assessed as follows:

$$C^{tax}_{t,p} = (\%_{IRAP} + \%_{IRES}) \cdot EBIT_{t,p} \tag{16}$$

where $EBIT_{t,p}$ denotes the earnings before interests and taxes of the p-th plant. The maintenance cost $C_{man,t,p}$ is computed as a percentage of the total investment cost. It follows that:

$$C_{man,t,p} = \%_{man} \cdot C_{o,p} \tag{17}$$

Finally, let $C_{fin,p}$ be the share of investment cost financed by third parties, computed as a percentage of the total investment cost ($C_{o,p}$):

$$C_{fin,p} = \%_{debt} \cdot C_{o,p} \tag{18}$$

The annual cost of debt ($C^{debt}_{t,p}$) is assessed through the annual financial charges, as shown in the following equation:

$$C^{debt}_{t,p} = i_{debt} \cdot \left[\left(C_{fin,p} - \sum_{n=1}^{t-1} I_{n,p} - C^{debt}_{n,p} \right) \right] \tag{19}$$

where i_{debt} denotes the interest rate of the debt and $I_{n,p}$ the annual debt installment. $I_{n,p}$ can be computed through the Capital Recovery Factor (CRF), as follows:

$$I_{n,p} = C_{o,p} \cdot CRF \tag{20}$$

where

$$CRF = \frac{i_{debt} \cdot (i_{debt} + 1)^n}{(i_{debt} + 1)^n - 1} \tag{21}$$

Here n is the number of years for the debt recovery.

4. Case study: designing the biomethane chain in the Rome Metropolitan Area

This section is divided into two subsections, presenting the case study and the scenario settings, respectively.

4.1. The Rome Metropolitan Area

The Rome Metropolitan Area (Fig. 3a) counts for 121 municipalities,

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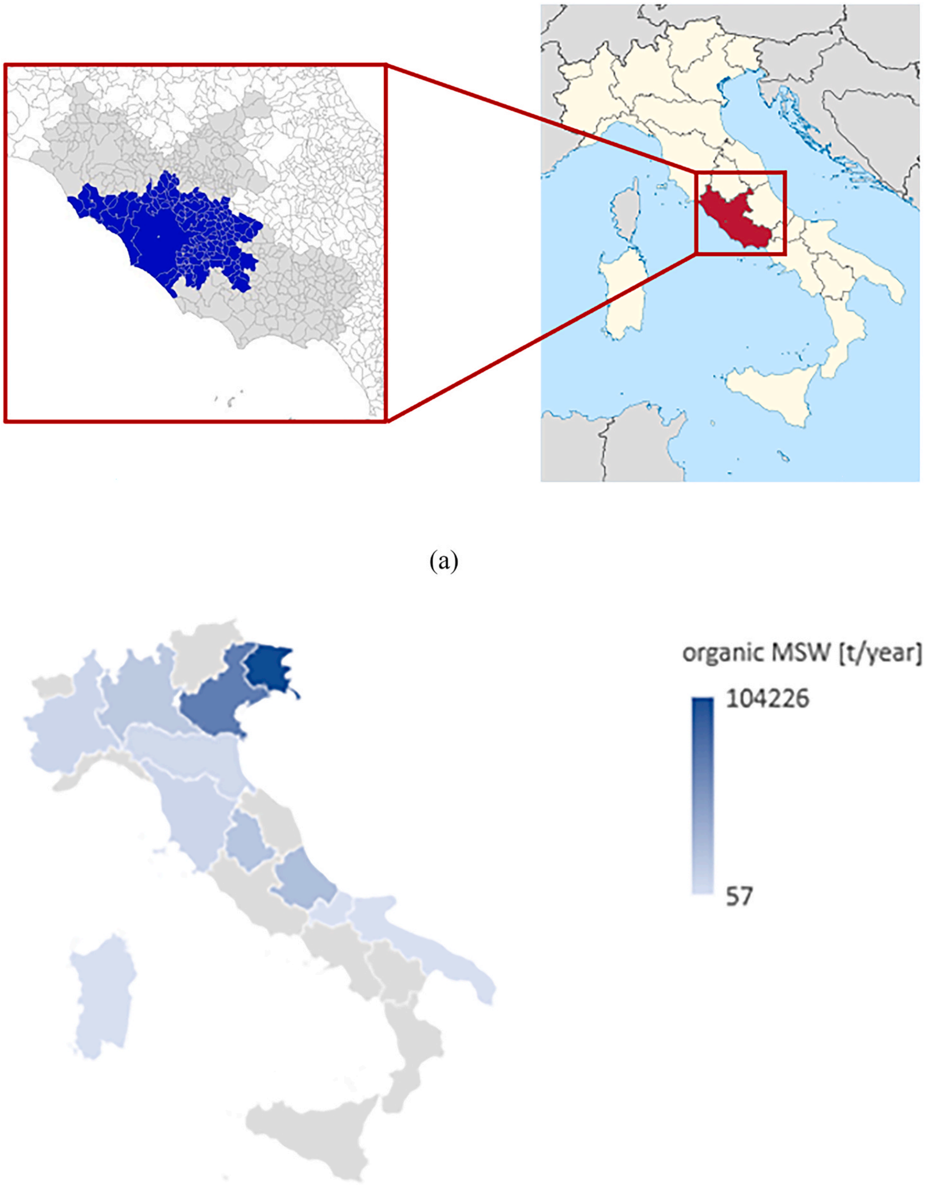
[4] If the biomethane plant is designed by converting an existing composting plant, companies do not need to pay the investment cost for compost treatment.

[5] The cost of debit needs to be considered whether (part of) the investment is financed by third parties.

[6] IRAP and IRES are two Italian taxes on the company revenues and profits.



(a)

(b)

Fig. 3. (a) On the right, the map of Italy, where the Lazio region is highlighted. On the left, the map of the Lazio region, where the Rome Metropolitan Area is highlighted; (b) Amounts of organic MSW sent from Lazio Region to the other Italian regions.

among which Rome (the Italian capital), 5.363 Km^2, and 4.3 million inhabitants[7]. Around 400.000 t of organic MSW are produced yearly in the area, resulting from a 45.6% rate of separated waste collection. According to the national target, this rate is expected to increase to 65% by 2030; hence, the amounts of organic wastes produced in the area will increase consequently. Currently, there are no plants for producing biomethane from MSW located in the area; part of organic wastes is exploited for compost production and 250.000 t per year are sent to plants out of the region[8] (Fig. 3b). This results in economic disadvantages for the citizens, who are required to pay the transportation costs for these wastes, as well as for the environment, due to the additional CO_2 emitted by the waste transportation. Nevertheless, the expected increase in the amounts of organic MSW produced will exacerbate this problem in the upcoming years.

4.2. Scenarios setting

First, we collected data on the amounts of organic MSW yearly produced in each municipality, together with the number of inhabitants for each municipality and the percentage of separated collection in 2018 (the last year when all the above-mentioned data were available) (ISPRA, 2019b). Then, according to the target level of separated collection fixed by the Italian government, i.e., 65% in 2023 and 70% in 2025, we assessed the amounts of wastes that will be produced in the upcoming years[9]. Notice that, for municipalities with a percentage of

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[7] https://ugeo.urbistat.com/AdminStat/it/it/demografia/dati-sintesi/roma/58/3.

[8] http://www.regione.lazio.it/binary/rl_main/tbl_documenti/RIF_DGR_49_31_01_2019_Allegato1.pdf.

[9] Changes in the number of inhabitants have been considered negligible.

separated collection higher than the target one, the 2018 amount of organic wastes has been assumed to be constant. These data are shown in the Supplementary Materials.

Based on them, several scenarios have been defined, according to the following criteria: (1) three different structures of biomethane chain, ranging from a centralized to a more distributed structure; (2) different locations of production plants, which accomplish with the areas identified by the regional government as potential locations of biomethane production plants[10] – see Table 2. Scenarios 1 and 2 are characterized by a centralized structure, i.e., one big-scale plant, able to process 450.000 t of organic MSW per year, located in the municipalities of Cerveteri and Magliano Romano (Fig. 7). Scenario 3 is characterized by three small-scale plants, each of them able to process 150.000 t of organic MSW per year, located in the municipalities of Cerveteri, Magliano Romano, and Riano. Scenarios 4 and 5 are characterized by an even more distributed structure, characterized by the co-existence of four small-scale plants: one plant able to process 150.000 t/year and three plants able to process 100.000 t/year each. Plants are located in the municipalities of Riano, Magliano Romano, Cerveteri, and Castel Madama in scenario 4 and in the municipalities of Aprilia, Cerveteri, Castel Madama, and Riano in scenario5[11]. The plant locations (see Fig. 4) have been decided according to the available locations defined by the regional government. We do not have considered plants with a production capacity lower than 100.000 t/year because the investment related to such plants has been proven not to be economically profitable (e.g., D'Adamo et al., 2019).

All the scenarios are characterized by the same biomethane production capacity,[12] i.e., almost 39 million Sm^3 per year[13]. For each scenario, first the optimization model described in Section 3.1 has been solved by using ILPG CPLEX Optimization Studio Version 12.10. Subsequently, the economic analysis of each scenario has been conducted using the model described in Section 3.2., under the following assumptions:

- The analysis has been conducted over ten years (2022–2032), corresponding to the period when the governmental incentives are given to biogas producers, according to the current Italian normative framework. It has been assumed that all the municipalities would reach the separated collection targets for 2023 and 2025 defined by the Italian law (i.e., at least 65% until 2023 and at least 70% until 2025) –the amounts of wastes assumed to be treated are reported in the Supplementary Materials.
- The unitary price of biomethane, the unitary price for organic MSW disposal, and the unitary price of CIC were considered constant during the ten years.
- The investment costs of the anaerobic digestion plant and the upgrading plant were considered proportional to the plant size[14]. Alternatively, economies of scale have been considered for all the other investment costs.
- The investment cost for the fuelling station has not been considered because the biomethane produced is withdrawn by Gestore dei Servizi Energetici S.p.A – see footnote 3.
- 80% of the investment is financed by third-parties[15].
- A 2.7% discount rate (r) was considered.
- The capacity of trucks used to transport wastes is 15 t.

The values of technical and economic parameters used for the analysis[16] are reported in Table 3, according to the different plant sizes considered.

Table 2
Scenarios analyzed in the paper.

Scenario	Plants	Location (municipality)
1	1 plant by 450.000 t/year	Cerveteri
2	1 plant by 450.000 t/year	Magliano Romano
3	1 plant by 150.000 t/year	Cerveteri
	1 plant by 150.000 t/year	Magliano Romano
	1 plant by 150.000 t/year	Riano
4	1 plant by 150.000 t/year	Riano
	1 plant by 100.000 t/year	Magliano Romano
	1 plant by 100.000 t/year	Cerveteri
	1 plant by 100.000 t/year	Castel Madama
5	1 plant by 150.000 t/year	Aprilia
	1 plant by 100.000 t/year	Cerveteri
	1 plant by 100.000 t/year	Castel Madama
	1 plant by 100.000 t/year	Riano

5. Results and discussion

5.1. Numerical results

Fig. 5 shows the revenues of the overall chain, computed by summing the revenues for each plant, highlighting the different revenue sources – see equation (7). Since the amounts of organic wastes treated are equal, all the scenarios have the same revenues per year.

Alternatively, costs are different for each scenario because of different (1) management costs for a different number and size of plants and (2) transportation costs. Fig. 6 shows the yearly costs, computed by summing the costs for each plant – see equation (8).

For each scenario, Table 4 displays the Km run by trucks for transporting wastes from municipalities to plants, considered as the environmental performance, as well as the net present value (NPV) and the payback period, both considered as measures of economic performance.

The first result that can be noted concerns the economic feasibility of all the five scenarios analyzed. In all cases, the investment is economically profitable and fully recovered within 5 years, i.e., 50% of the life of the investment considered for the analysis. The best scenarios from the economic perspective are scenarios 1 and 2, although they are characterized by the highest number of Km run. Alternatively, the worst cases are scenarios 4 and 5 (whose NPV is 35% lower compared to scenarios 1 and 2), although they are characterized by the lowest number of Km run (which are over 30% lower compared to scenarios 1 and 2). Hence, it can be observed that the higher the number of plants, the lower the Km run but also the NPV, *ceteris paribus*. Accordingly, the reduction in the operational costs thanks to a decentralized structure is not enough to

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[10] The regional government has identified several areas where to potentially locate biomethane production plants, defined according to several environmental criteria (e.g., proximity to urban areas, impact of the production plant to the natural ecosystem).

[11] These two scenarios differ from the fact that in scenario 4 plants are all located in the North of Rome whether in scenario 5 one plant is located also in the South of Rome.

[12] This allows to highlight the specific impact the structure of the biomethane chains plays on the economic and environmental performance of the overall chain.

[13] Assuming the percentage of volatile matter ($\%_{V.M.}$) and the percentage of dry matter ($\%_{D.M.}$) of organic MSW – see Table 1 – equal to 23% and 81%, respectively, and that the biogas yield (Y_{biogas}) is equal to 732 Sm^3/t, the maximum amount of biomethane that can be produced from 450.000 t of organic MSW is almost 39 million Sm^3.

[14] Such assumption is due to the lack of primary data. Hence, we have decided to consider a more conservative scenario. We have however conducted sensibility analyses to investigate the impact of potential economies of scale on these investment costs – see the Supplementary Materials. We found that the main results are not affected by this assumption.

[15] Such assumption is due to the high investment costs required for these projects and is consistent with primary data obtained by business operators.

[16] These data have been obtained from Italian business operators.

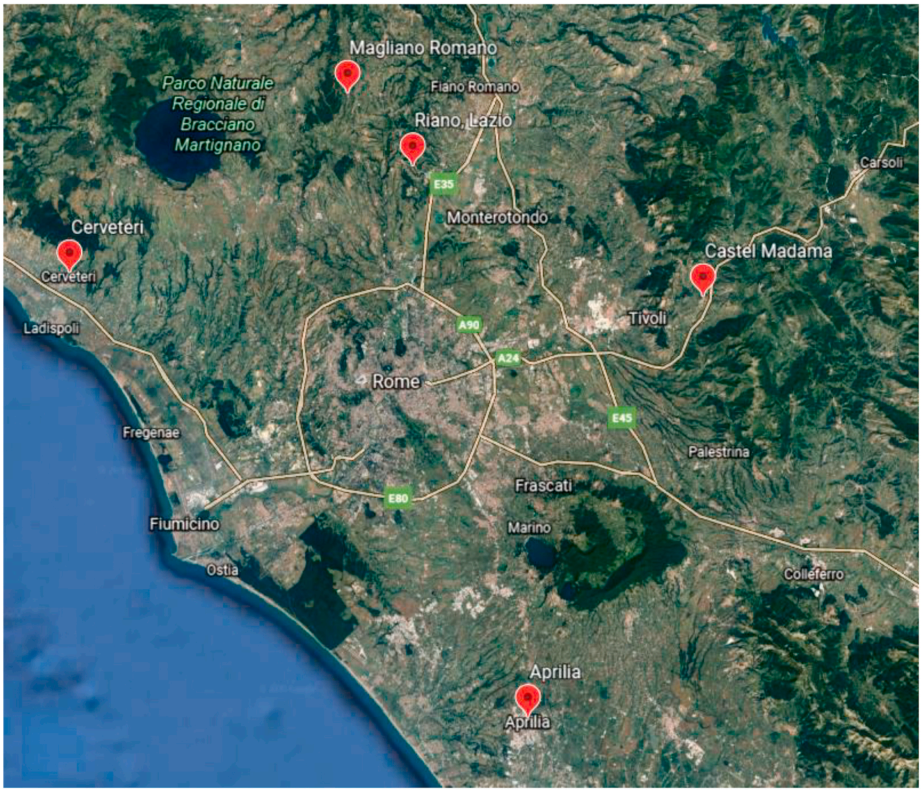


Fig. 4. Locations of biomethane production plants considered in the investigated scenarios.

Table 3
Numerical value of parameters used for computations.

	Plant size		
	100.000 t/year	150.000 t/year	450.000 t/year
$\%_{CH_4}$	65%	65%	65%
$\%_{up}$	1,5%	1,5%	1,5%
$f_{compost}$ [t/t]	0,30	0,30	0,30
C^{inv}_{other} [€]	1.500.000	2.500.000	6.000.000
C^{inv}_{OFMSW} [€]	1.000.000	1.500.000	4.000.000
$c^{inv}_{a.d.}$ [€/ Sm^3/ h]	3.700	3.700	3.700
c^{inv}_{up}[€ /Sm^3 /h]	3.200	3.200	3.200
C^{inv}_{el} [€]	3.000.000	3.500.000	10.500.000
$C^{inv}_{gas\ grid}$ [€]	1.500.000	2.000.000	5.000.000
$C^{inv}_{compost}$ [€]	4.000.000	4.500.000	15.500.000
$C_{el,t}$ [€/ year]	2.750.000	3.000.000	5.000.000
n_w	10	15	30
c^{u}_{lab} [€/ year]	60.000	60.000	60.000
$c^{u}_{tr,p}$ [€ /km]	0,60	0,60	0,60
$C_{ins,t,p}$ [€ /year]	70.000	80.000	150.000
n_h [h/ year]	8.400	8.400	8.400
$\%_{man}$	8%	8%	10%
$p^{biom.}_t$ [€/ Sm^3]	0,16	0,16	0,16
$p^{comp.}_t$ [€/t]	5	5	5
p^{CIC}_t] [€]	375	375	375
p^{OFMSW}_t [€/t]	70	70	70
i_{debt}	3%	3%	3%

cover the higher costs due to building multiple plants.

Furthermore, several differences in NPV and Km run can be noted between scenarios 1 and 2, as well as between scenarios 4 and 5, although these couples of scenarios are characterized each by the same number and size of plants – one big-scale plant for scenarios 1 and 2, four small-scale plants for scenarios 4 and 5. Building one big-scale plant in the municipality of Magliano Romano (scenario 2) instead of the municipality of Cerveteri (scenario 1) would save 51.710 Km/year (−3.3%). Similarly, implementing scenario 5 instead of scenario 4 would save 45.961,67 Km/year (−4.3%).

Regarding the factors able to affect the economic profitability of the overall chain, Fig. 6 shows that the main revenue sources come from the price paid by municipalities for the waste disposal service (currently accounting for 70 €/t), the economic incentives provided by the Italian government (currently accounting for 375 €/5 Gcal of fuel produced), and the selling price of biomethane (currently accounting for 0.16 €/Sm^3), which account for 62%, 24%, and 12% of the overall revenues, respectively. However, it should be observed that these parameters are not under the control of biomethane producers, but rather they depend on the market and normative dynamics. Hence, as a result of these dynamics, the values of the above-mentioned parameters could change over time, even unexpectedly. For this reason, the impact of the above-mentioned factors on the economic profitability of the chain has been further investigated.

Fig. 7 shows the results of sensitivity analysis. *Sic stantibus rebus*, the parameter potentially most impactful is the price of waste disposal service (Fig. 7a). *Ceteris paribus*, values lower than 30€/t for scenarios 1 and 2, values lower than 37 €/t for scenario 3, and values lower than 45 €/t for scenarios 4 and 5 make the investment no more profitable. Also the incentive provided by the government impacts significantly the economic feasibility of the chain. Fig. 7b shows that, without economic incentives, *ceteris paribus*, scenarios 4 and 5 would be no more economically convenient. Finally, Fig. 7c shows that the price of biomethane is not able to impact the economic feasibility of any scenario, *ceteris paribus*.

From Fig. 8, which refers to scenario 1, it can be appreciated the extent to which the economic feasibility of the biomethane chain depends on the combination of the three above-mentioned parameters. For

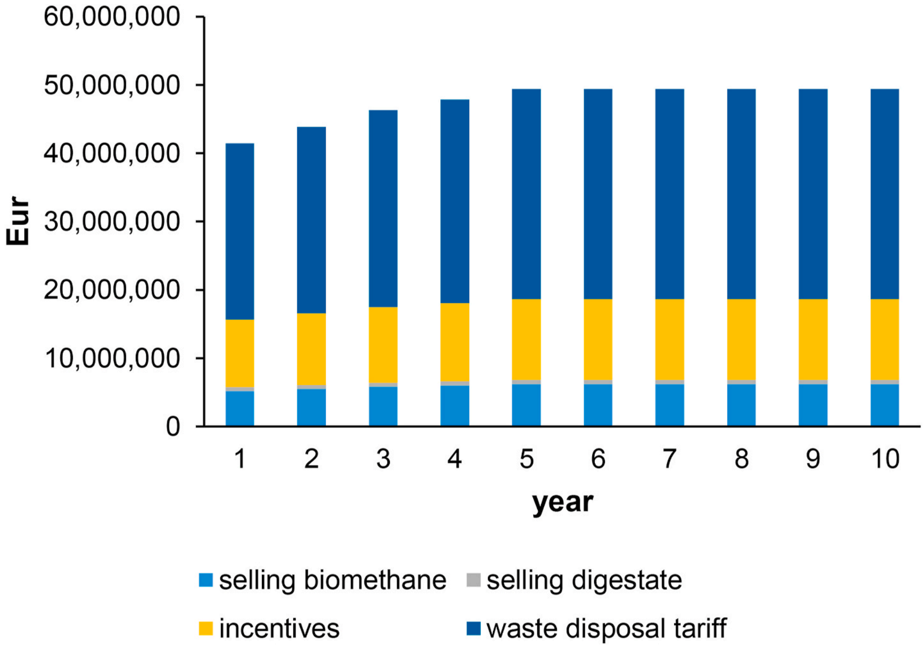


Fig. 5. Revenues of the overall biomethane chain for all the considered scenarios.

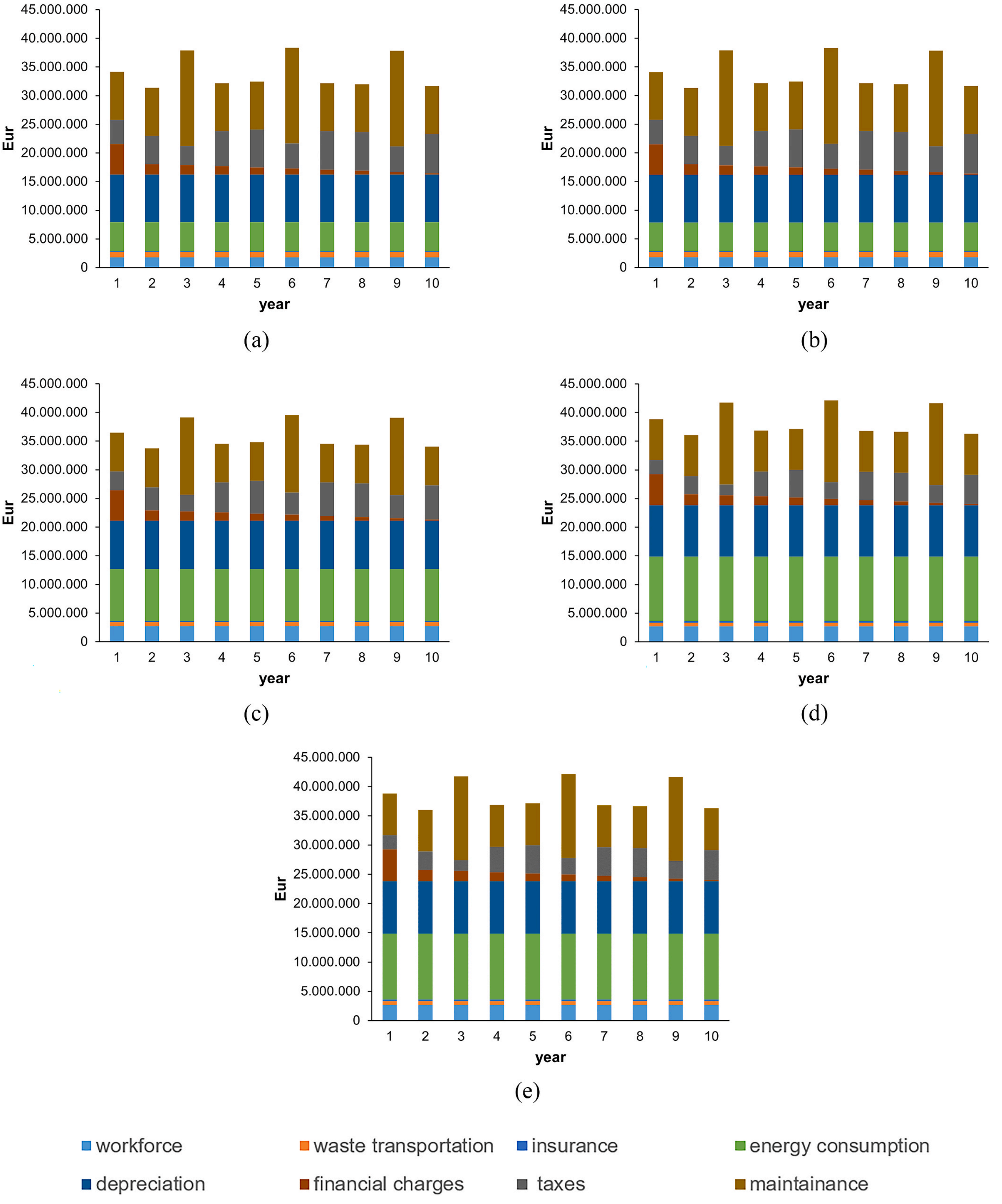
instance, it can be noted that, for a waste disposal tariff equal to 30 €/t, the biomethane chain is economically feasible in case of economic incentive equal to 375 €/5 Gcal and biomethane selling price equal to 0.16 €/m^3. However, if the economic incentive is reduced to 350 €/5 Gcal (−6.67%) or the biomethane selling price is reduced to 0.14 €/m^3 (−12.5%), the biomethane chain becomes no more profitable.

5.2. Discussion

Results are discussed with reference to the structural features of the biomethane chan, plant locations, potential uses of biomethane, and role of economic incentives. Advances, assumptions, and limitations, as well as practical applications and future research perspectives, are also discussed.

5.2.1. Structural features of the biomethane chain

Results show that all the investigated scenarios are feasible from the economic perspective. This is consistent with the other contributions aimed at exploring the economic feasibility of biomethane production from MSW in Italy (Cucchiella et al., 2019; D'Adamo et al., 2021), as well as in other countries (e.g., Martín-Pascual et al., 2020). Results also highlight that the scenarios with the highest economic performance (NPV) are those characterized by the lowest environmental performance (Km run, which is strongly related to the amounts of GHG emitted by trucks for the waste transportation process, *ceteris paribus*). This outcome emerges because the savings in waste transportation costs thanks to building multiple plants are lower than the additional investment and operational costs due to these multiple plants. This result is consistent with Yue et al. (2014), who highlight that, in a regional area, a centralized structure might be more economically profitable than a distributed structure, and with Elghali et al. (2007), who state that the plant scale is a decisive parameter for the design of the overall chain. Furthermore, our results show a decouple between the economic and the environmental performance, which is particularly relevant in the bioenergy business model aimed at creating environmental and economic benefits simultaneously. This pattern is consistent with the work by Lyng et al. (2018), who analyze several structures of biomethane value chains, in terms of different levels of sector integration, and highlight that the chains with the highest GHG emission reduction have the lowest economic profit. A similar pattern is also highlighted by Fraccascia et al. (2020), who analyze several operational scenarios of industrial symbiosis and show that the scenario maximizing the economic benefits does not necessarily maximize the environmental benefits. All in all, this happens because the profitability analysis does not consider the costs of the negative externalities, i.e., the GHG emissions. Concerning the structural features, it can be highlighted that the scenarios most economically promising, i.e., those characterized by one big-scale plant, are the scenarios more vulnerable and less resilient to perturbations. In fact, in case of a disruptive event – e.g., technical failures, natural disasters, terroristic attacks – affecting the big-scale plant, the overall production chain is interrupted (Craighead et al., 2007; Patriarca et al., 2018). Alternatively, in case of a disruptive event affecting one small-scale plant, the production chain would keep partially active. This result is consistent with the literature that highlights a trade-off between efficiency and resilience in industrial (Berger et al., 2004; Chopra and Sodhi, 2004; Ivanov et al., 2014; Tang and Tomlin, 2008) and natural ecosystems (Ulanowicz et al., 2009). Accordingly, making a structure resilient has its own price, which reduces the overall efficiency of the structure. Policymakers should take into account both the above-mentioned issues when assessing which structure is better to support with economic incentives. In this regard, if policymakers would prefer a more resilient structure, they could subsidize small-scale plants more than big-scale plants. Indeed, *ceteris paribus*, if all the plant sizes are equally subsidized, it is reasonable that companies would prefer investing in big-scale plants. Similarly, if policymakers would aim at maximizing the environmental benefits at the regional level (i.e., the minimization of GHG emissions from the chain), they could provide small-scale plants with higher incentives than big-scale plants. In our case, assuming that the average equivalent carbon emissions of diesel and biomethane trucks are 36 g CO_2 eq./(t × Km) and 8,05 g CO_2 eq./(t × Km) (Madhusudhanan et al., 2020), respectively, implementing scenario 4 (four small-scale plants) would produce 267,99 t CO_2 eq. per year and 59,92 t CO_2 eq. per year less than implementing scenario 1 (one big-scale plant). Nevertheless, policymakers should consider that, *ceteris paribus*, higher incentives could be required to ensure the profitability of small-scale plants. A final consideration concerns the social externalities of the different structures of the chain: accordingly, the higher the Km run, the greater the volume of traffic generated (Gold and Seuring, 2011). This aspect should be also considered by policymakers.



(a)

(b)

(c)

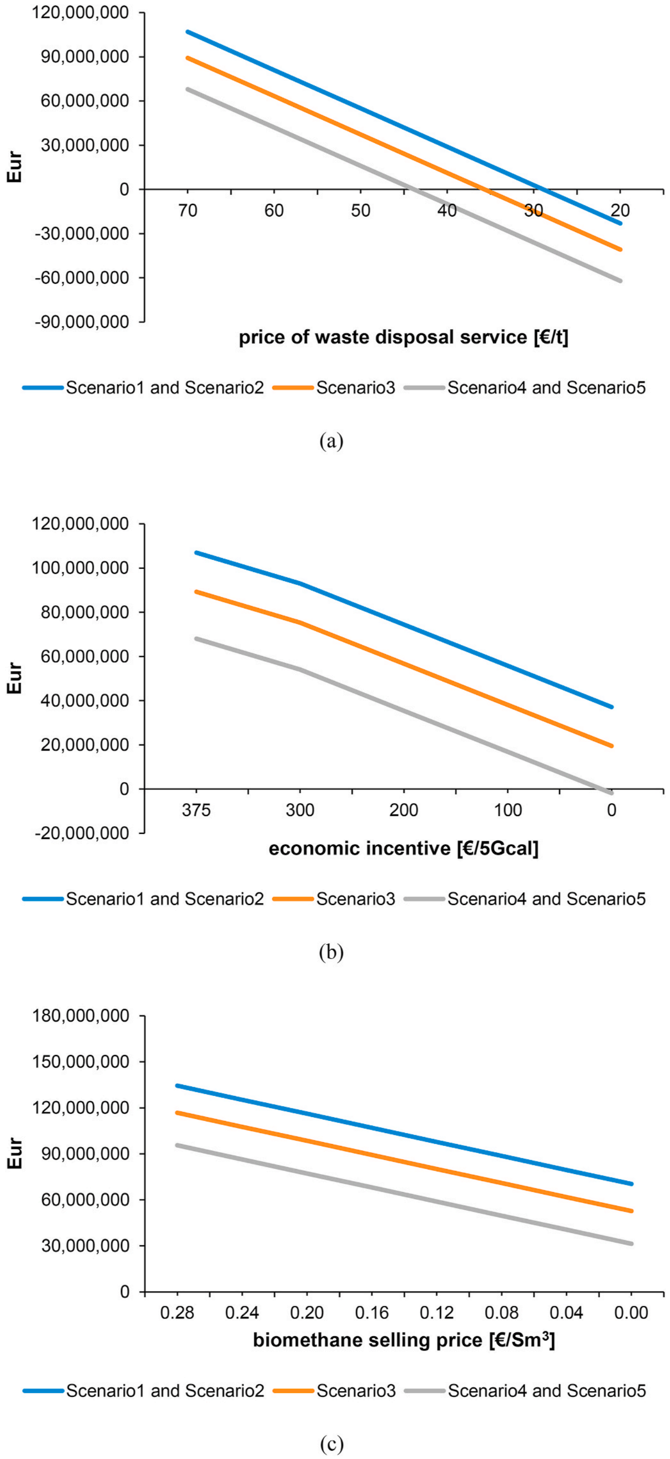
(d)

(e)

Fig. 6. Sources of costs for: (a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4, and (e) scenario 5. The legend is valid for all the scenarios.

5.2.2. Plant location

Results show that the plant location might affect both the economic and environmental performance of the chain. In this regard, *ceteris paribus*, the plant location matters because impacting on the total Km run and, in turn, on (1) the operational costs for waste transportation and (2) the GHG emissions by waste transportation. Assuming that the average equivalent carbon emissions of diesel and biomethane trucks are 36 g CO_2 eq./(t × Km) and 8,05 g CO_2 eq./(t × Km)



(a)

(b)

(c)

Fig. 7. Results of sensitivity analysis on NPV for the following factors: (a) price of waste disposal service, (b) economic inventive from the government, (c) selling price of biomethane. The curves of scenarios 1 and 2, as well as of scenarios 4 and 5, result overlapped, since the values for the above-mentioned couples are much similar.

Table 4
Environmental and economic performance for the scenarios analyzed.

Scenario	Km run per year	Net present value [€]	Payback period [years]
1	1.570.166,67	106.944.723,76	4
2	1.518.546,67	107.137.858,03	4
3	1.182.551,67	89.277.190,94	4
4	1.073.895,00	68.026.893,66	5
5	1.027.933,33	68.112.875,56	5

(Madhusudhanan et al., 2020), respectively, moving from scenario 1 to scenario 2 would allow to save 29,9 t CO_2 eq. per year, in the case of diesel trucks, or 6,24 t CO_2 eq. per year, in the case of biomethane trucks. Similarly, moving from scenario 4 to scenario 5 would allow to save 24,8 t CO_2 eq. per year, in the case of diesel trucks, or 5,55 t CO_2 eq. per year, in the case of trucks using biomethane. The importance of plant location is consistent with several works in the literature (e.g., Franco et al., 2015; Höhn et al., 2014; Patrizio et al., 2015; Rentizelas and Tatsiopoulos, 2010), which developed optimization models to identify optimal locations of plants producing biogas from agricultural wastes. However, to the best of our knowledge, other studies on biomethane production from urban wastes do not consider the location of plants. Hence, this is a further original contribution of this work.

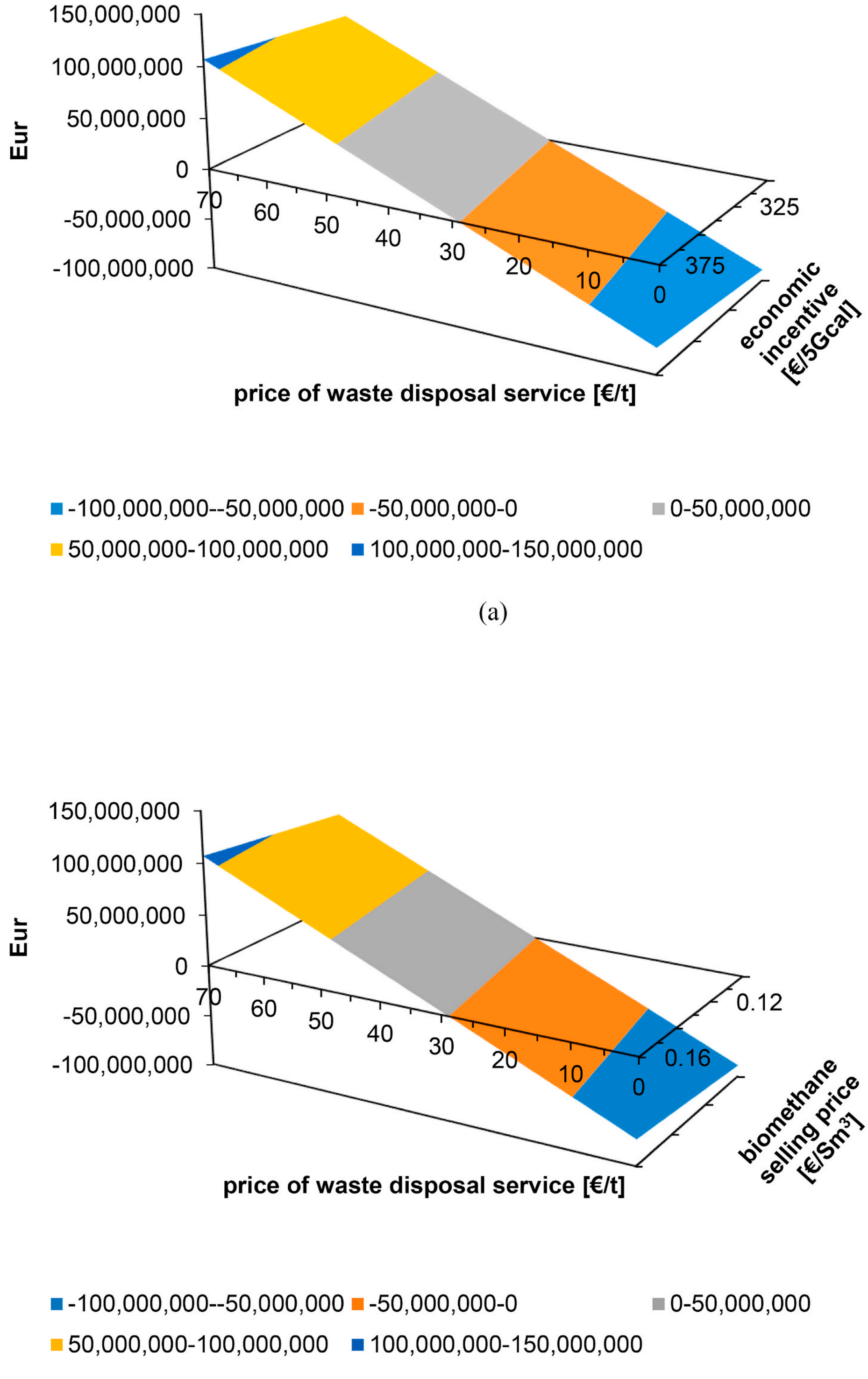
The optimal location of plants might depend on several spatial variables, such as the extension of the regional area, the location of municipalities and how the MSW production is spread among them, different waste production rates per municipality, the selected number of plants, the available locations of plants allowed by the regional government (Yazan et al., 2011). While some aspects are not under the control of policymakers (e.g., the extension of the regional area), other aspects can be directly managed. All in all, our work suggests that policymakers carefully assess the areas deputed to the construction of new plants taking into account the considerations above-mentioned.

5.2.3. *Potential uses of biomethane*

Biomethane produced from urban wastes can be injected into the natural gas grid or liquefied to be used as a fuel for transportation (Gustafsson et al., 2020). In the second case, two potential uses are discussed here. First, the biomethane could be used as a fuel for the trucks that collect MSW and transport them to the biomethane production plants. This use would contribute reducing the environmental pressure of the waste transportation process because biomethane trucks are less pollutant than diesel trucks (Ferreira et al., 2019; Madhusudhanan et al., 2020) and it would make the "circular business model" adopted even "more circular". One more potential use is related to public transport within the municipality of Rome. Currently, they are 239 bus lines that cover 1.300 Km^2 and a network of 1.852 Km; in 2018, more than 80 million Km were run by urban buses (Atac, 2019). Hence, one of the potential uses of the biomethane so produced could be related to fueling urban buses of Rome. For instance, according to Chan Gutiérrez et al. (2018), a 60.000 t/year co-digestion plant could fuel 136 urban buses per year. Both these uses would require a significant change in infrastructure, in terms of biomethane vehicles and the provision of biomethane gas service stations. Initially high incentives would be required to allow that the transition starts, but these subsidies can be reduced over time (Rajendran et al., 2019). The benefits of replacing diesel buses with biomethane buses in urban areas are known in the literature (Murphy and Power, 2009; Nanaki et al., 2014; Ryan and Caulfield, 2010), in terms of environmental and social advantages (e.g., the reduction in the GHG emissions in the urban area might positively impact on the quality of life of citizens).

5.2.4. *The role of economic incentives*

The results show that the economic incentives are the second source of revenues for the biomethane chain, whose economic profitability might depend on them. This result is consistent with other contributions in the literature analyzing the Italian context (Ferella et al., 2019), as well as other European (Eker and van Daalen, 2015; Larsson et al., 2016; Rajendran et al., 2019) and extra-European countries (Chan Gutiérrez et al., 2018; Hoo et al., 2020). According to Larsson et al. (2016), the development of biogas production in Sweden depends on continued tax exemptions. Eker and van Daalen (2015) highlight that subsidization is crucial to develop biomethane production in the Netherlands. Similar



(a)

(b)

Fig. 8. Results of sensitivity analysis on NPV for the following factors: (a) price of waste disposal service and economic incentive; (b) price of waste disposal service and biomethane selling price. Numerical results refer to scenario 1.

results are found by Yazan et al. (2018). However, many of the above-mentioned studies refer to biomethane production from agricultural wastes, for which biomethane producers usually do not receive any disposal tariff and, in some cases, they even pay a purchasing price to buy wastes. Different from these works, in this study we consider that biomethane producers are paid for disposing of organic MSW. Nevertheless, it can be highlighted that the economic incentives play an important role and, in some cases, can determine the profitability of the production chain. Hence, policymakers should carefully design the economic incentives that will be provided to biomethane producers, even with the aim to ensure a better alignment between the economic and environmental performance of the biomethane chain. In this regard, according to the numerical results, as well as to the considerations above-mentioned, we suggest that the structure of economic incentives for biomethane producers is revised. In particular, *ceteris paribus*, we propose that the current economic incentive – currently fixed to 375 € per 5 Gcal of fuel – is reduced and, simultaneously, associated with two new extra incentives: (1) the former provided to companies that accept only organic wastes generated in municipalities located into a given radius from the production plant, in order to favor more distributed structures that can minimize the Km run for waste transportation; (2) the latter provided to companies that use biomethane trucks for waste transportation, which can further reduce the GHG emissions due to the transportation process.

5.2.5. Advances, assumptions, and limitations

Compared to the existing literature, this paper proposes some advances. Concerning the Italian context, the few existing studies (e.g., Cucchiella et al., 2018) are limited to investigate the profitability of small-scale plants (e.g. 50–150 m^3/h), without considering bigger-scale plants. Hence, this paper provides a novel contribution. From the technical perspective, the proposed model considers the biomethane production rate dependent on the waste chemical characteristics, in particular as a function of the percentage of volatile matter, the percentage of dry matter, and the organic MSW's biogas yield. Hence, it provides a more accurate estimation of the amount of biomethane producible. From the economic perspective, the model considers the overall detailed structure of economic incentives provided by the Italian government to the biomethane producers. Finally, the model considers the economic impact of third-part financing, assessing the additional financial costs dependent on the structure of the capital invested. The optimization model proposed in this paper is a simple model, which can be easily and quickly used to assess the performance of multiple scenarios, even without the need to use a complex optimization software.

Concerning the assumptions and the limitations, we highlight that the numerical results described in Section 4, in particular the waste transportation cost and the Km overall run by trucks transporting wastes, are dependent on the truck capacity considered. Both these results would be different if a different capacity were used. Nevertheless, this issue does not change the outcome of the model. In fact, from an economic perspective, waste transportation costs account for a small percentage of the total costs (see Fig. 8). Furthermore, from an environmental perspective, changing the truck capacity would increase/decrease the total Km run of all the considered scenarios by the same rate, thus not impacting the sustainability ranking of the considered scenarios. Finally, we recognize that the model developed considers only one bioenergy producer, whereas multiple producers could be interested to contribute to developing the biomethane production chain.

5.2.6. Practical applications and future research perspectives

This paper can support companies and policymakers towards the development of the biomethane production chain at the regional level. Companies can adopt the economic model presented in Section 3.2 to assess the economic feasibility of investing in biomethane production, as well as to explore the extent to which the economic profitability can be affected by changes in the value of technical and economic variables. Policymakers can use the proposed model to design different structures of biomethane chain and assess the economic and environmental performance of each structure.

As the future research perspectives, a more accurate forecast of MSW production can be integrated into the model proposed in this paper, e.g., to consider changes in the number of inhabitants and the overall amount of MSW produced per municipality, highlighting the respective drivers. The optimization model described in Section 3.2 could be improved to address the equilibrium problem among multiple biomethane producers (Lo et al., 2021). The optimization model could be further integrated with additional models aimed at optimizing the waste collection and stocking processes, which have been not optimized in this work.

6. Conclusions

This paper proposes a methodology to design the biomethane production chain from organic MSW in regional areas, according to the principles of circular economy and the urban-industrial symbiosis concept. The case study highlights that biomethane production from organic MSW provides economic profits, depending on waste disposal tariff, selling price of biomethane, and the economic incentive provided. The centralized structure is the most economically profitable solution but also the structure that maximizes the number of Km run by trucks transporting wastes. To re-align the misalignment between the economic and environmental performance of the production chain, this paper proposes that the economic incentive provided to biomethane production is revised, aimed at rewarding companies that produce biomethane from municipalities located close by the plants and companies that use biomethane trucks for waste transportation. For these reasons, the policy implications of this paper should be carefully assessed by national and local governments.

Credit author statement

Luca Fraccascia: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing. Mario Spagnoli: Conceptualization, Methodology, Investigation, Writing – review & editing. Laura Riccini: Methodology, Investigation, Writing – review & editing. Alberto Nastasi: Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113328.

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