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A circular economy model based on biomethane: What are the opportunities for the municipality of Rome and beyond?

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ABSTRACT

This paper defines the roles of biomethane for a double-green transition, through the integration of an effective management of renewable energy and municipal waste. The authors perform an assessment of the potential transition of the municipality of Rome to a more sustainable transport system, based on the economic feasibility of production of biomethane as analysed with the Discounted Cash Flow methodology. The potential reduction of emissions is quantified considering biomethane, to be used as vehicle fuel instead of natural gas. The provision of subsidies is found to be an essential condition to support the development of the biomethane sector. The subsidies must be coordinated with other policies such as the construction and operation of new fuelling stations and the increase of vehicles fuelled by biomethane. Several economic indicators are used to support investors by defining the conditions in which the profitability and economic opportunities are quantified. The transformation of bio-wastes into clean energy, closes the loop and helps societies to make progress toward becoming circular economies, which can contribute to decarbonizing the transport sector. Results of these analyses are applicable in other municipalities, which are currently under-utilizing their organic wastes and by-products.

1. Introduction

Equitable, sustainable and liveable societies must increasingly be based on the effective usage of materials embedded in waste's flows and on the production of energy and other by-products from these natural resources [1,2]. Urban-level initiatives are essential for successfully managing and utilizing waste streams and thereby, contributing to transitioning to more effective and efficient Circular Economy (CE) models at the local, regional, national and global levels [3]. To make progress toward the CE, it is essential to prepare accurate estimates of the environmental/economic and ethical dimensions of proposals to support this transition [4].

The recovery of energy from wastes in CE models is integral to helping to close the materials and energy loops [5]. Among the potential energy forms to be derived from bio-wastes, biogas is of great interest due to its ability to transform organic feedstocks into biomethane and to produce a fermentate that can be used as a valuable agricultural/horticultural fertilizer [6,7].

The production and usage of biomethane can provide new opportunities for society at multiple levels [8]. However, some challenges and barriers can be linked to non-technical issues such as the lack of public acceptance for the biogas-biomethane plants and the current inadequacies in legislative and normative management guidance and support [9].

Currently, the transport sector is responsible for a third of global energy demand and one-sixth of global Greenhouse Gas (GHG) emissions [10]. This sector is currently dominated by the use of fossil fuels in Europe [11].

The biomethane sector is mainly developed in Europe with a dominant position being played by Germany which has opted to use biomethane in combined heat and power plants; however, recent changes occurred in subsidies provided by public policies,

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Nomenclature

BIO-CNG	Biomethane
C_{NGV}	Consumption of a NGV
CE	Circular Economy
CNG	Compressed Natural Gas
DCF	Discounted Cash Flow
DBCR	Discounted Cost-Benefit Ratio
DDNC	Discounted Do Nothing Cost
DDNC-1	Discounted Do Nothing Cost for 1 year
DENA	Deutsche Energie-Agentur
DNE	Discounted Net Externality
DPBT	Discounted Payback Time
ETS	European Trading Scheme
EU	European Union
EUA	European Emission Allowances
fc	Fuel consumption
Federmetano	National Federation of Methane Distributors and Transporters
GHG	Greenhouse Gas
GU	Official Journal
I	Cash In-flows
I_0	Initial Investment
IEA	International Energy Agency
Inf	Rate of Inflation
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
l_{us}	Losses in the upgrading system
LNG	Liquefied Natural Gas
MSW	Municipal Solid Waste
n	Lifetime of the project
n_{km}	Number of kilometres
n_{NGV}	Number of NGVs
NGV	Natural Gas Vehicle
NPV	Net Present Value
NPV/P	The ratio of NPV to plant size
NPV/S	The ratio of NPV to the amount of substrate
O	Cash Out-flows
ofmsw	Organic fraction of municipal solid waste
p_{CD}	Price of Carbon Dioxide
PBT	Payback Time
PI	Profitability Index
PSA	Pressure Swing Adsorption
Q_{biogas}	Quantity of biogas
$Q_{biomethane}$	Quantity of biomethane
$Q_{substrate}$	Quantity of substrate
r	Opportunity cost of capital
r_{bm}	Recovery rate of biomethane
RES-T	The share of Renewables in the Transport sector
RGHG	Reduction of Greenhouse Gas
$S_{biomethane}$	Plant size biomethane
t	Time period
uRGHG	Unitary value of Reduction of Greenhouse Gas
$\%CH_4$	Percentage of methane

which will influence future biomethane usage patterns [12]. Sweden uses biomethane as a vehicle fuel, in which the municipalities use environmentally-friendly buses, cars and trucks. They also use it to power public transport and separate collection vehicles [13]. Additionally, private actors can benefit from tax exemptions and transport fuel certificates [14]. However, an effective green transition in the transport sector can be realized if the implementation of biomethane production is accompanied by other actions such as construction and usage of methane gas service stations and an increase of the number of Natural Gas Vehicles (NGVs) [15].

The biomethane potential for several European cities was estimated and a large share of this potential can be used as vehicle fuel, and therefore, can help the European Union (EU) to achieve its Paris Agreement, commitments within the transport sector [16]. In particular, the theoretical biomethane potential of the organic fraction of municipal solid waste (ofmsw) can provide sufficient biomethane to result in substantial reductions of fossil-carbon based GHG emissions [17] and the same is true for usage of by-products (e.g. animal manures, agricultural wastes, and other wastes from the agro-industry) in the production of biomethane and the related fermentate-based fertilizers [18]. To make more effective progress toward achieving CE, it is essential to also address the economic aspects [19]. In this perspective, some authors focused on exploring the techno-economic feasibility of coupling biomethanation with digestate gasification for the wastewater industry [20]. Production costs of biomethane are not competitive with fossil methane [21]. Consequently, its economic sustainability is strictly linked to the adoption of subsidies [22]. Finally, the roles of cities as sites of sustainability transitions has not been sufficiently explored in the literature [23] except for few cases. Recently, a distributed system of biorefineries was utilized to evaluate the economic feasibility of producing renewable biomethane for gas pipeline injection in an effort to decarbonize New York's natural gas grid and lower environmental impacts [24].

The novelty of this work arises from the following reasoning: i) the adoption of subsidies is strategic to develop the biogas-biomethane market [25], ii) decision-makers need detailed information about the waste management to help to transform cities into more circular economies [3], iii) biomethane is a sustainable resource and its use in the transport sector should be increased [16], iv) biomethane is defined as a clean fuel [26] and v) economic analyses are typically aimed at supporting investors' decisions [27]. Bearing this in mind, the authors of this paper propose a new framework to evaluate the application of a CE model to a city level. Starting by the recovery of both ofmsw and by-products, the biomethane produced is used as vehicle fuel to satisfy local demand. The environmental analysis was performed by employing existing values proposed in literature, while the economic assessment was defined using an array of potential economic indicators to provide valuable information for various groups of stakeholders – i.e. consumers, producers and policy-makers. Special attention was given to estimate the "do nothing cost", an indicator extremely important for policy makers. A baseline scenario was assessed against alternative scenarios to assess whether the biomethane and the co-produced digestate can contribute to the needed double green-transition, by integrating waste management, renewable energy production and enhancement of agricultural soils. The model was applied to a single case study of the municipality of Rome, in a subsidized market. However, the proposed framework can be adapted and replicated in alternative geographical environments.

2. Materials and methods

A resource can be classified as value-added when some conditions are verified: its use as an alternative to fossil resource can help to reduce the levels of GHG emissions providing that it also fulfils the same technical requirements. In fact, biomethane (also called green gas) has properties potentially equivalent to the methane [28], and represents a valid option to valorise bio-wastes while producing energy [29]. At the same time, the proposed action plan will only be viable when economic viability and positive environmental impact are consistently achieved.

The map of scenarios used in this work was depicted in Fig. 1. The economic viability is based on Discounted Cash Flow (DCF) methodology analysing two different business models (section 2.1). The environmental impact model is based on literature data, which allows quantifying the Reduction of GHG (RGHG) emissions using biomethane as a green fuel substitute for natural gas analysing three different scenarios (section 2.2). Economic and environmental scenarios were independently conducted. The typology of the business models and relative choices of sizes realized did not influence the environmental performance because it was assessed considering the same quantity of energy produced in all economic scenarios.

The models and relative results were applied to a specific case study (section 2.3).

2.1. *The economic model for the assessment of biomethane plants*

The DCF analysis can be used to help determining a project's potential profitability based upon the concepts of money time value [30]. Several researchers have investigated the economic performance of biomethane plants. Some considered biomethane production costs, that varied from 0.54 €/m^3 to 0.73 €/m^3 [31] and from 0.5 $US/m^3 to 1.5 $US/m^3 [10].

The International Energy Agency (IEA) published long-term projections of the wholesale gas prices in Europe [32]. It estimated a steady increase 17 €/MWh in 2017 to 30 €/MWh in 2040. Instead, the production cost of biomethane is equal to 90 €/MWh for 2017. Other authors have proposed values of biomethane lower than IEA's estimate: 50–70 €/MWh [31] and 60–70 €/MWh [21]. However, externalized costs are not properly internalized into cost structures. In this context, the suggested minimum subsidy was 0.13 €/m^3 for biomethane production systems [33] with a fossil-carbon footprint impact, ranging from 123 to 171 €/tCO_2 avoided [15].

The calculated profitability was based upon the presence of subsidies. The Net Present Value (NPV) was equal to −585 k$US if subsidies were not provided, otherwise it was 5667 k$US [34]. The NPV varied from 0.49 M€ to 132.7 M€ based upon the mix of recovered waste [35].

In this paper, the authors used the following indicators (see Table A1): i) NPV; ii) Profitability Index (PI); iii) The ratio of NPV to plant size (NPV/P); iv) The ratio of NPV to the amount of substrate (NPV/S); v) Discounted Payback Time (DPBT); vi) Internal Rate of Return (IRR); vii) Discounted Do Nothing Cost for 1 year (DDNC-1); and viii) Discounted Cost-Benefit Ratio (DBCR) that includes the Discounted Net Externality (DNE).

The mathematical model used was:

$$\mathrm{NPV} = \sum_{t=0}^{n} (\mathrm{I_t} - \mathrm{O_t}) \Big/ (1+\mathrm{r})^{t} \tag{1}$$

$$\mathrm{PI} = \mathrm{NPV}/\mathrm{I_0} \tag{2}$$

$$\mathrm{NPV} \,/\, \mathrm{P} = \mathrm{NPV}/\mathrm{S_{Biomethane}} \tag{3}$$

$$\mathrm{NPV} \,/\, \mathrm{S} = \mathrm{NPV}/\mathrm{Q_{Substrate}} \tag{4}$$

$$\sum_{t=0}^{\mathrm{DPBT}} (\mathrm{I_t} - \mathrm{O_t}) \Big/ (1+\mathrm{r})^{t} = 0 \tag{5}$$

$$\sum_{t=0}^{n} (\mathrm{I_t} - \mathrm{O_t}) \Big/ (1+\mathrm{IRR})^{t} = 0 \tag{6}$$

$$\mathrm{DDNC} - 1 = \sum_{t=0}^{n} \mathrm{I_t} - \mathrm{O_t}\Big) \Big/ 1+\mathrm{r}\Big)(1+\mathrm{r})^{t} - \sum_{t=1}^{n+1} \mathrm{I_t} - \mathrm{O_t}\Big) \Big/ (1+\mathrm{r})^{t} \tag{7}$$

$$\mathrm{DBCR} = \sum_{t=0}^{n} \mathrm{I_t} + \mathrm{DNE_t}\Big) \Big/ 1+\mathrm{r}\Big)(1+\mathrm{r})^{t}\Big) \Big/ \sum_{t=0}^{n} \mathrm{O_t}\Big) \Big/ (1+\mathrm{r})^{t}\Big) \tag{8}$$

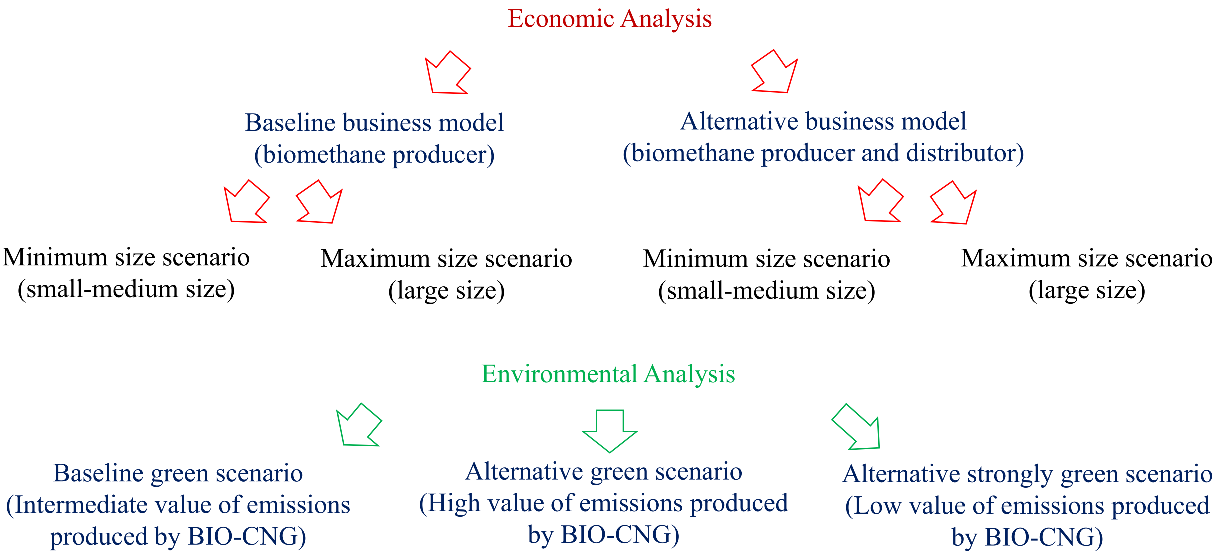

Fig. 1. A new framework: the map of scenarios used in this research.

$$I = I_{\text{subsidies}} + I_{\text{selling biomethane}} + I_{\text{selling food-grade } CO_2} + I_{\text{selling digestate}} + I_{\text{treatment ofmsw (net)}} \tag{9}$$

$$O = O_{\text{investment}} + O_{\text{interest rate}} + O_{\text{labour}} + O_{\text{substrate}} + O_{\text{transport}} + O_{\text{maintenance\&overhead}} + O_{\text{depreciation funds}} + O_{\text{energy}} + O_{\text{insurance}} + O_{\text{zeolite}} + O_{\text{digestate}} + O_{\text{compression}} + O_{\text{distribution}} + O_{\text{filling station}} + O_{\text{taxes}} \tag{10}$$

$$O_{t+1} = O_t{*}(1 + \text{inf}) \tag{11}$$

In March 2018, the Italian Government adopted a policy Decree (GU (Official Journal) no. 65 of 19-03-2018) to stimulate the development of biomethane [36]; however, after one year, the results were not encouraging since only a few plants are now recovering the organic waste. The Decree defined a value of incentive equal to 0.305 €/m^3 (single-counting)[1] for the first ten years and a premium was provided for some substrates (i.e. the ofmsw and by-products).

In the proposed business model, the incentive value was set equal to 0.61 €/m^3 (double-counting). The above-cited substrates were investigated for two biomethane plant sizes. The first was calculated iteratively to define the minimum size, in which NPV was positive. The second size proposal was based upon the maximum value analysed by the [37].

The complete list of input data is presented in Table A2-Figure A1 [9,21,34,36,38,39]. About six months are needed to build and to activate a biomethane plant. The DCF analysis is characterized by two key-variables: i) lifetime of a project and ii) discount rate, also called opportunity cost of capital. The time horizon of the project (n) was linked to its lifetime which was assumed to be 20 years [30]. The opportunity cost of capital (r) measured the projected returns from an alternative project, which has the same risk level, and was assumed to be equal to 5% [19,27,40,41]. However, other values have also been reported in the literature (e.g. 4% [22] and 6% [42]). Upgrading technology used in our study is Pressure Swing Adsorption (PSA) according to the model proposed by Ref. [43]. Furthermore, the Italian decree provides a premium for the realization of new filling stations (under the condition that the methane distributor is a biomethane producer). Consequently, the value of the incentive was calculated to be equal to 0.73 €/m^3.

The authors of this research investigated two business models: i) the Baseline Business Model, in which the investor is the biomethane producer and ii) the Alternative Business Model, in which there is a joint implementation between the biomethane producer and the methane distributor.

Additionally, both baseline and alternative business models were assessed for the: i) minimum size scenario, in which the realization of small/medium sizes was analysed and ii) maximum size scenario, in which the construction of large sizes was analysed.

2.2. The environmental model for the assessment of biomethane plants

The GHG emissions of vehicle systems were recorded for the entire process of energy flow, from energy sourcing to a vehicle being driven (Well to Wheel). The environmental values reported in Fig. 2, document that the transition from fossil fuels to renewable energy sources can provide significant reductions of GHG emissions. They were compared between BIO-CNG (Biomethane) and Compressed Natural Gas (CNG) in this work.

This assumption is based on several works, in which authors proposed environmental analysis and the reduction of GHG emissions was quantified as follows: 23 gCO_2eq/MJ [44], 40 gCO_2eq/MJ [45], 53 gCO_2eq/MJ [46] and 62 gCO_2eq/MJ [47].

The GHG emissions of vehicles were estimated at 164 and 156 gCO_2eq/km for petrol and diesel, respectively. The use of CNG has a lower impact than both diesel and petrol, with a level of GHG emissions of 124 gCO_2eq/km. The GHG emissions of BIO-CNG use depends on the feedstock type according to the analysis conducted by the International Renewable Energy Agency (IRENA) [10]. In particular, the maximum value is associated with production from maize (66 gCO_2eq/km); the emissions were primarily released during cultivation and harvesting.

The value of RGHG was equal to 58 gCO_2eq/km, and it was calculated as the difference between value of BIO-CNG obtained by maize and the corresponding value associated to CNG. There was a higher reduction potential when organic wastes and residues instead of energy crops were used. The IRENA defined RGHG as being equal to 91 gCO_2eq/km (the difference between 124 and 33) and 76 gCO_2eq/km (the difference between 124 and 48) based upon usage of liquid manure and organic wastes as substrates in comparison with using natural gas, respectively.

Another study authored by the Deutsche Energie-Agentur (DENA) company [48] calculated GHG emissions linked to biomethane production as equal to 5 gCO_2eq/km. The value of RGHG was equal to 119 gCO_2eq/km (difference between 124 and 5) using BIO-CNG as an alternative to CNG. These results revealed that biomethane offers significant reduction of GHG emissions, but its quantification is not simple because several factors can influence the yields.

The authors of this paper did not present new environmental analyses, but based their calculations upon literature data to define the value of RGHG. In particular, it is used a conservative perspective considering the values estimated by IRENA (that are greater than those estimated by DENA). Regarding BIO-CNG, 33 and 48 gCO_2eq/km were considered because the use of energy crops was not hypothesized in this study, while concerning CNG, the value of 124 gCO_2eq/km was used.

Therefore, three scenarios were analysed: i) the *baseline green scenario*, was considered as the average value between 33 gCO_2eq/km and 48 gCO_2eq/km and the Unitary value of Reduction of GHG emissions (uRGHG) for the NGV was assumed to be equal to 83.5 gCO_2eq/km (obtained as the difference between 124 and 40.5); ii) the *alternative green scenario*, in which the high value of BIO-CNG was used, the value of uRGHG for a NGV was equal to 76 gCO_2eq/km (deriving by the difference between 124 and 48); and iii) the *alternative strongly green scenario*, which was based upon the low value of GHG emissions linked to the BIO-CNG, considered the value of uRGHG for a NGV to be equal to 91 gCO_2eq/km (deriving by the difference between 124 and 33).

The purchase of a NGV was recommended by car salesmen when the consumer has an annual mileage of 20,000 km (n_{km}), or above. Consequently, it is possible to estimate the Consumption of a NGV (C_{NGV}) in function of the specific fuel consumption (fc) fixed equal to 15 km/m^3. The definition of the overall RGHG must be considered for all biomethane production and consequently, the number of NGVs (n_{NGV}) fuelled by this plant were based upon the assumptions depicted in the following equations:

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[1] The Decree assign an economic value to the Certificates of Emission of Biofuel in Consumption (CICs). A single CIC is issued for 10 Gcal (single counting) of biomethane produced. Considering that 1 m^3 CH_4 is equal to 8121 kcal, one CIC corresponds to approximately 1231 m^3 CH^4. The Decree defines a value of 375 € for each CIC.

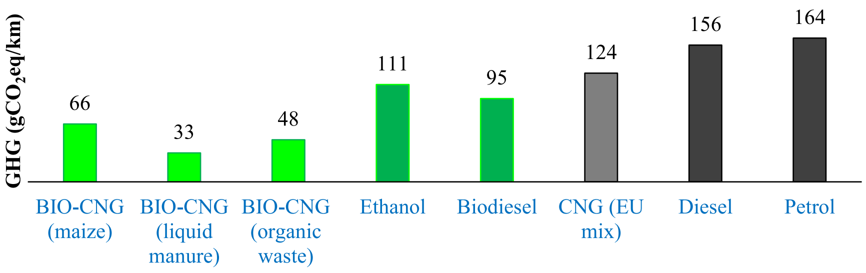

Fig. 2a. Comparative GHG emissions from biofuels [10]. Biomethane is able to reduce significantly the level of emissions than fossil fuels.

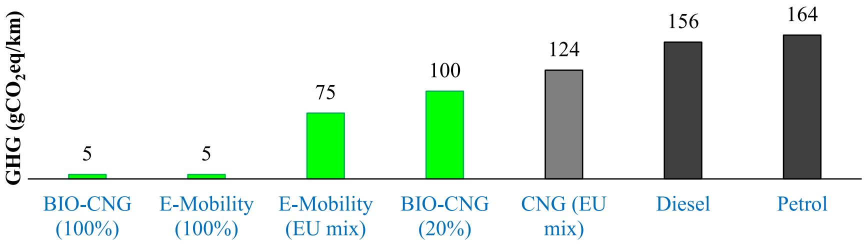

Fig. 2b. Comparative GHG emissions from biofuels [48]. Both biomethane and electric cars are able to reduce very significantly the level of emissions than fossil fuels.

$$RGHG_{NGV} = uRGHG_{NGV} * n_{km} \tag{12}$$

$$Q_{biomethane} = Q_{biogas} * (CH_4) * (1 - l_{us}) * r_{bm} \tag{13}$$

$$C_{NGV} = n_{km} / fc \tag{14}$$

$$n_{NGV} = Q_{biomethane} / C_{NGV} \tag{15}$$

$$RGHG = RGHG_{NGV} * n_{NGV} \tag{16}$$

$$DNE = \sum_{t=0}^{n} \left(RGHG * p_{CD,t} \right) \Big/ (1+r)^t \tag{17}$$

The price of Carbon Dioxide (p_{CD}) was based upon European Emission Allowances (EUA). Figure A2 shows the trend between June 2018–March 2019 [49]; it was assumed p_{CD} equal to 20 €/tCO_2eq (average value). Emissions reductions in the transport, agriculture and heat sectors are known as non-European Trading Scheme (ETS) sectors. Biomethane is multifunctional and can contribute to emissions reductions in non-ETS or ETS sectors depending on end use [50]. For this reason, EUA represents a good tool to monitor the current price of CO_2eq.

2.3. The case study – the Municipality of Rome

The utilization of natural gas for mobility purposes significantly differs across countries. For instance, Italy has 1186 stations and Germany has 885 stations, which are approximately 64% of all the European stations. Methane using vehicles are concentrated mainly in Italy, with approximately 74% of all European methane using vehicles [51]. The average number of vehicles per station is 60 in Netherlands, 106 in Germany and 314 in Sweden – and increases to 558 in Bulgaria and 844 in Italy (the EU28 average was 400 - Table A3).

Italy has a great potential to expand its green transition in its transport sector because it currently has a vehicle fleet composed almost exclusively of petrol and diesel which include 91% of the vehicles of 38.5 million. Figure A3 presents the situation over the period 2015–2017, showing that CNG vehicles had a 2% share [52].

The Italian Municipal Solid Waste (MSW) generation amounted to 29,588 thousand tonnes and separated collection rate was equal to 55.5% in 2017 [53]. Although an increase of 2.9% of separated collection was documented during the period 2016–2017, the goal of recycling MSW at the rate of 65% was clearly not achieved. Within the MSW collected, the organic waste was assumed to be the dominant fraction that was about 40% of the waste. This represents a huge opportunity for biomethane production.

Rome produces about 5.7% of the Italian MSW, followed by Milan (2.3%) and Naples (1.7%). Waste management in Rome is not effective and underperforms national achievements. In particular, waste management is weak with only 44% of the waste collected as separated materials in 2017. As showed in Fig. 3 (orange curve), the last 3 years trend of available data, depicts only a slight increase in waste collection, which is far below the target of 65%. The weakness of waste management is even more evident looking at the amount of unsorted waste which is well above 20% of waste production. In addition, waste production per capita in Rome was 587 kg/capita, compared with the Italian average of 490 kg/capita, [54].

Regional energy plan elaborated by the [55] quantified the following values for biogas potential: i) the manure residues and slaughterhouse waste have the potential for production of 23,065 thousand m^3 biogas/year and ii) the ofmsw and green wastes for 53,816 thousand m^3 biogas/year. This estimated value was reduced to 45,227 thousand m^3 biogas/year, considering the waste allocated to composting processes. This estimate considered achievement of 65% separate waste collection.

Assuming a percentage of methane equal to 60% for the ofmsw, the biomethane potential was estimated to be 27,136 thousand m^3/year. Instead, a percentage of 55% was used for by-products and the biomethane potential was estimated to be 12,686 thousand m^3/year.

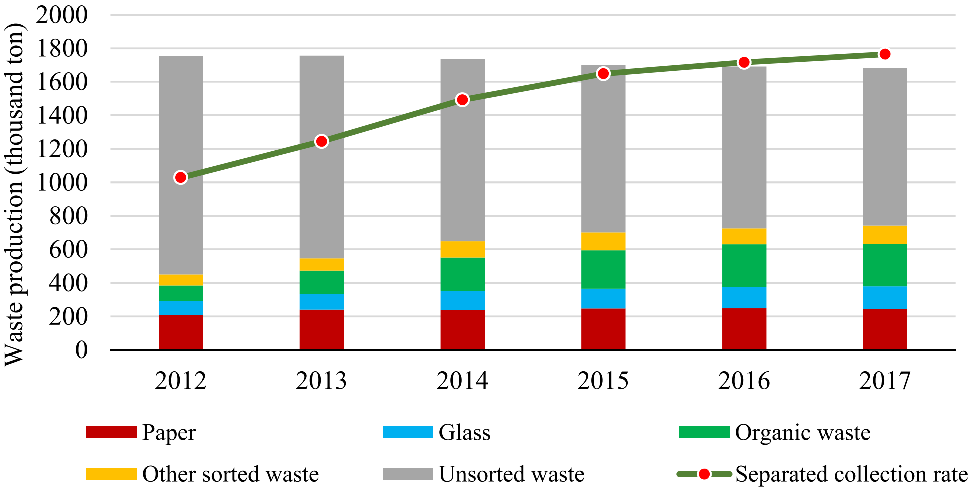

Fig. 3. Waste production and the separated waste collection rate in Rome [54].

Finally, biomethane plants are typically proposed in terms of m^3/h and assuming a number of operating hours of 8000 h/year, the following values were obtained: 3390 m^3/h for ofmsw and 1586 m^3/h for by-products.

The National Federation of Methane Distributors and Transporters (Federmetano) estimated that in the territory of Rome, there are 19,939 cars, 3887 trucks, 493 buses, 279 special vehicles, 41 trailers and 31 motorcycles fuelled by methane. The number of distributors is 40 [56]. The ratio between NGV vehicles and NGV stations was equal to 617 (greater than European average of 217).

3. Results and discussion

The outcomes of this investigation are presented and discussed in the following section. Specifically, a profitability analysis is conducted in sub-section 3.1, while the opportunity to implement a CE model for the Municipality of Rome is presented and discussed in sub-sections 3.2 and 3.3, respectively.

3.1. Profitability analyses

The authors used an iterative process to calculate the minimum size in which the economic feasibility can be potentially achieved. It was found to be equal to 350 m^3/h and 200 m^3/h for by-products and the ofmsw, respectively.

The maximum size analysed was 500 m^3/h. These values were evaluated according to the literature [21]. Fig. 4 shows a complete overview of the economic performances in the baseline business model. Tables A4-A7 outlined the specific business plans.

The NPV was equal to 131 thousand € and 421 thousand € for by-products and the ofmsw, respectively. The alternative case studies showed a significant increase of profit by potentially achieving the following values: 1656 thousand € and 8016 thousand €.

To achieve these performance levels, subsidies will have to play a key-role according to two observations. Firstly, the subsidies were greater for by-products (50%) than for ofmsw (39.5%). These findings were linked to the presence of another item in the mix of revenues for the ofmsw (see the net income by the treatment of municipal solid waste). Secondly, the analyses documented that the projects would be unprofitable in the absence of public support [34,50].

The selling of both digestate and food-grade CO_2 (through outsourcing) improves not only the environmental performance of these plants, but it also has economic advantages [57]. The selling price of digestate was fixed equal to 50 €/t, because after its recovery can be sold as compost to adjacent territories. Digestate can be used as a bio-fertilizer under some technical roles [58] and some countries have implemented certification schemers for producers to favour the sale of digestate [59]. The net revenue of CO_2 was assumed equal to 10 €/t and when it is recovered at a high level of purity, can be used in the food industry [27]. The distribution of discounted cash inflows are presented in Figure A4.

The NPV was the main indicator used in the economic analyses because it provides a more complete picture of the potential of the proposed project, based upon quantifying the economic value of money [60]. Its limit is represented by estimates of the cash flows. Other indicators confirmed that a 500 m^3/h ofmsw plant has a dominant position in comparison with other sized plants.

The PI is a dimensionless indicator, which is useful when there is a constraint in the budget. Profits vary from 2 € cent to 83 € cents for 1 € of capital invested. The NPV/P makes it possible to estimate the impact of economies of scale. Its increase was 2938 €/(m^3/h) for by-products and 13,925 €/(m^3/h) for the ofmsw. These values were not influenced by the scheme of subsidies (there were no corrective coefficients for small sizes). The advantage of NPV/P is that it can measure homogeneous data.

Also, the NPV/S provided a clear projection: the value for an ofmsw plant of 200 m^3/h was similar than the value for a by-product's plant of 500 m^3/h. The same corrective coefficient was applied to both substrates although their environmental impacts were different. In addition, each substrate was calculated to have a specific biomethane yield, which was equal to 75 m^3/biomethane and 50 m^3/biomethane for ofmsw and by-products, respectively. In this way, 500 m^3/h plants could operate at full capacity with 53,333 tons of organic waste or 80,000 tons of by-products/year. The strength of this indicator was based upon its capacity to measure the economic performance based upon variable feedstocks availabilities.

The DPBT was set to be equal to 1 year for the minimum sizes, while it was lower than 1 year for both types of 500 m^3/h plants. The operation costs (mainly maintenance and overhead of biogas production) represent about 80% of discounted cash outflows and consequently, the percentage of investment costs was less significant. In addition, the work assumed the use of third-party funding and a period of debt equal to fifteen years. In this way, the payment will be spread over multiple years rather than be concentrated in early years. Certainly, other configurations of debt payback are possible but nonetheless the value of DPBT will remain low, which

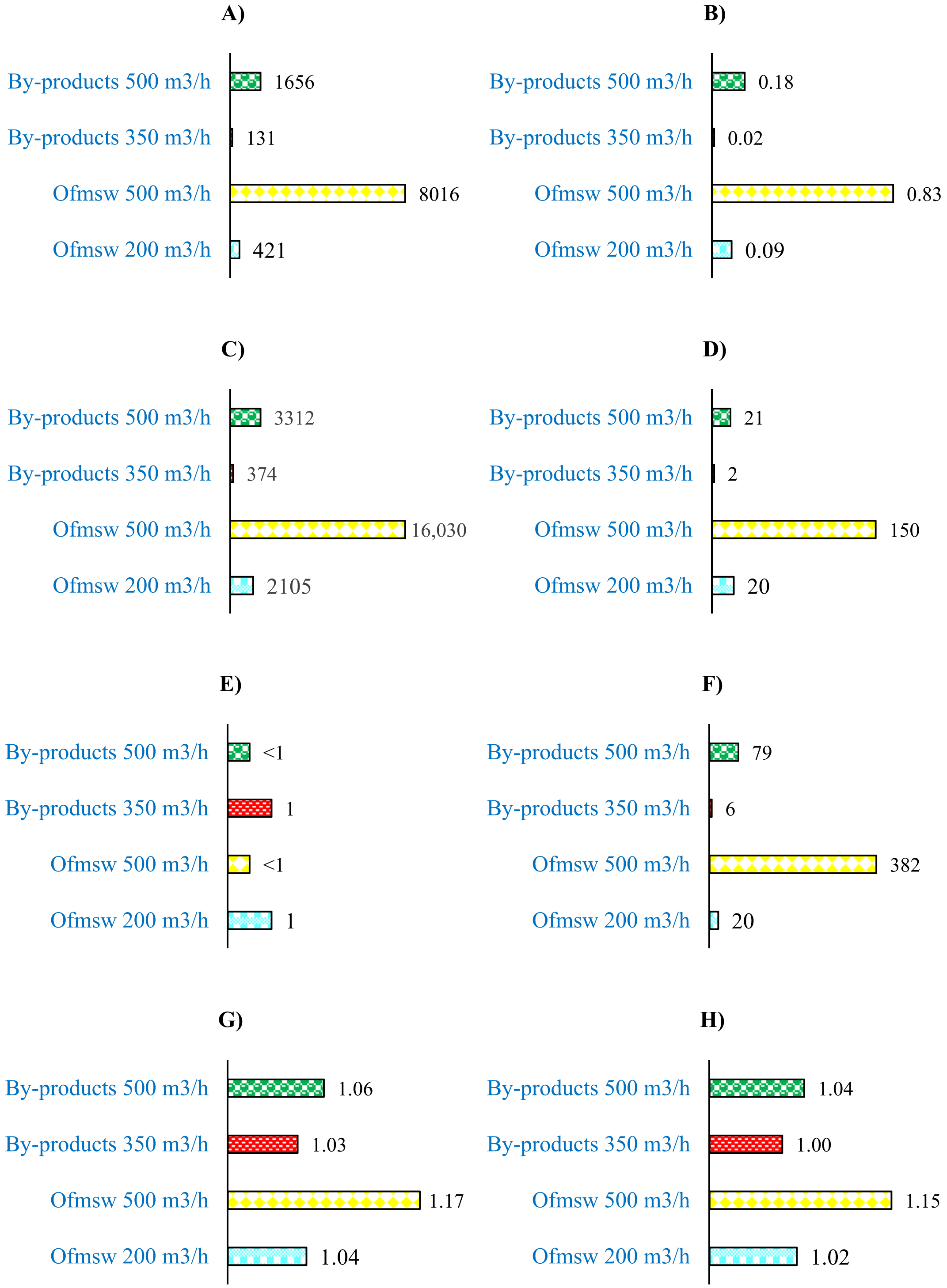

Fig. 4. Profitability analysis of biomethane plants – Baseline business model.
Legend: A) Net Present Value (thousand €); B) Profitability Index (€/€); C) Net Present Value/Size (€/m^3/h)); D) Net Present Value/Substrate (€/ton); E) Discounted Payback Time (years); F) Discounted Do Nothing Cost 1 year (thousand €); G) Discounted Cost-Benefit Ratio (€/€) and H) Discounted Cost-Benefit Ratio without Discounted Net Externality (€/€).

is a characteristic of projects with a low value of investment share [61]. It is straightforward to calculate the DPBT and substitutes the payback time (PBT), as it considers the value of money.

However, the DPBT has a great limit: it fails to consider the profitability of the entire project, because it considers cash flows from the initiation of the project until the payback period and fails to analyse the cash flows after the payback period.

The NPV evaluates the entire lifetime of the project. In three out of the four case-studies examined in this research (the 500 m^3/h ofmsw plant was the exception) there were negative values of the discounted cash flows after the end of the subsidization-period. Several changes of sign among cash in-flows determined the presence of multiple IRR, therefore it was not possible to calculate this indicator. The DDNC can be used to measure the socio-economic

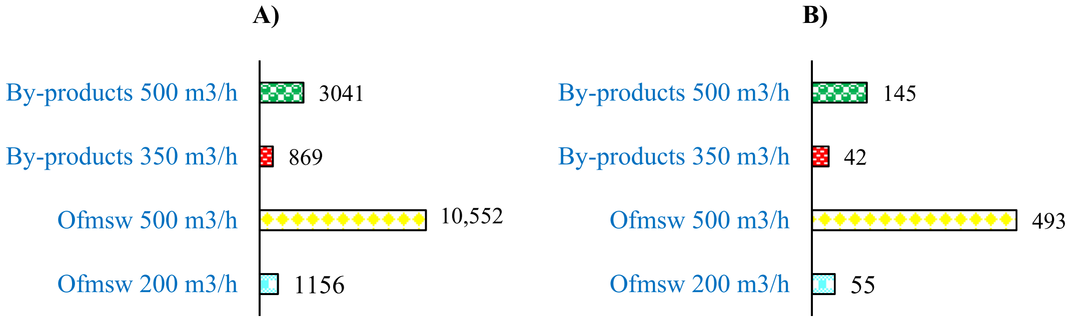

Fig. 5. Profitability analyses of biomethane plants – Alternative business models.
Legend: A) Net Present Value (thousand €) and B) Discounted Do Nothing Cost 1 year (thousand €).

impacts of an investment (revenues not realized assume a negative sign and can be interpreted as costs). It captures the delay determined by low public acceptance. In addition, it measures the possible delay linked to uncertainties associated with the introduction of incentives. The DDNC-1 varies from 6 thousand € to 382 thousand €.

Finally, the DBCR is an indicator often used by policy-makers, because it captures the value of externalities. The BIO-CNG is an alternative to CNG that can reduce the fossil-carbon-based levels of GHG emissions and provides environmental advantages that can be translated into economic terms. The DBCR is a dimensionless indicator and the value of discounted benefits is about 17% greater than relative costs in 500 m^3/h ofmsw plant. It ranged from 1.03 to 1.06 in other case studies. The DBCR, in the absence of DNE, is coherent to NPV. The weight of DNE was equal to 2–3% among discounted benefits.

An interesting alternative business model was represented by the opportunity of a joint implementation between biomethane producer and methane distributor [50]. In fact, the number of methane filling stations in Italy is at the highest level in the European context, but its distribution in the Italian territory is patchy. Some consumers chose not to use this fuel because they do not have a methane filling station close to them. For this reason, the Italian Government has supported the implementation of new activities, as part of its policy strategy (GU no.65 of 19-03-2018) [36].

Fig. 5 shows economic results of this alternative scenario. Specifically, the attention was concentrated on two indicators: i) the NPV, which calculated the exact value of profits to be derived by implementation of the project and ii) the DDNC, which measured the economic costs associated with the delay in implementation of green plants.

Results of analyses of the alternative business models showed an increase of about 2108–2770 € for m^3/h regarding by-products, while this change was more significant for the ofmsw (about 3675–5072 € for m^3/h).

The application of a new corrective coefficient increased the value of subsidies. They were always the first items among discounted cash in-flows, but the increase of profits was determined mainly by the selling price of the biomethane. In fact, final consumers' price of natural gas was equal to 0.529 €/m^3 (that is greater than 0.25 €/m^3 used in the baseline scenario). Its percentage weight changed from 25% to 40% for by-products and from 20% to 33% for the ofmsw – Figure A5.

Finally, the development of new methane filling stations and biomethane plants after one year presents a reduction of NPV that was greater than the baseline business model, ranging from 42 thousand € to 493 thousand €.

Sensitivity and scenario analysis are useful to prove robustness of results. Previous works had identified the following critical variables: subsidies, selling price of biomethane, net income linked to ofmsw treatment, digestate recovery [27], investment costs of biogas production, transport costs of substrates and percentage of maintenance and overhead costs in biogas production [19]. In addition, as defined in section 2.1, opportunity cost of capital is a key-variable in all analysis in which DCF is used as methodology.[2] Bearing this in mind, we conducted an extensive sensitivity analysis, considering all critical variables. This assessment showed how our results are not appreciably affected by variations in the opportunity cost of capital (see Table A8). As for the other critical variables, we proposed alternative scenarios that confirm results proposed in literature (Tables A9-A10). On the one hand, the key role played by subsidies on cash inflows was confirmed; and on the other hand, it emerged how this role is associated to the maintenance and overhead costs in biogas production among cash outflows. Additionally, plant size influences significantly the profitability with a high risk of not reaching economic profitability being associated to the smaller sizes.

3.2. The opportunity of implementation of a circular economy model for the Municipality of Rome

The waste mismanagement in Italy concerns several parts of Italy [62,63] and a recent crisis has involved the city of Rome [64].

A possible way forward for improving municipal management of wastes could be via implementation of the adoption of a CE model to take the maximum advantage from waste with the goal of zero landfilling, and re-introducing waste into productive processes. Indeed, waste recovery and its transformation into clean energy can contribute positively to countering fossil-carbon based fuel's contributions to worsening of climate changes [65].

In this way, the realization of biomethane plants could be an example of making progress toward an Italian CE. At the same time, a double-green transition could be achieved by: i) increasing the share of Renewables in the Transport sector (RES-T); and ii) by improving waste management practices. In fact, citizens have an interest to increase the separated waste collection rate to reduce the unsorted waste and to transform organic waste into a green resource [6]. The benefits to agricultural productivity via the usage of the fermentate also need to be underscored, as much as the aesthetic and economically positive impacts on the tourism sector due to an efficient, clean and proper management of MSWs [66].

The number of biomethane plants necessary to manage the

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[2] We allowed for variations of the opportunity cost of capital in the range 1–10%; the baseline value was assumed equal to 5%. Concerning the other critical variables, one pessimistic scenario and one optimistic scenario were analysed according to values proposed in the literature [19,27].

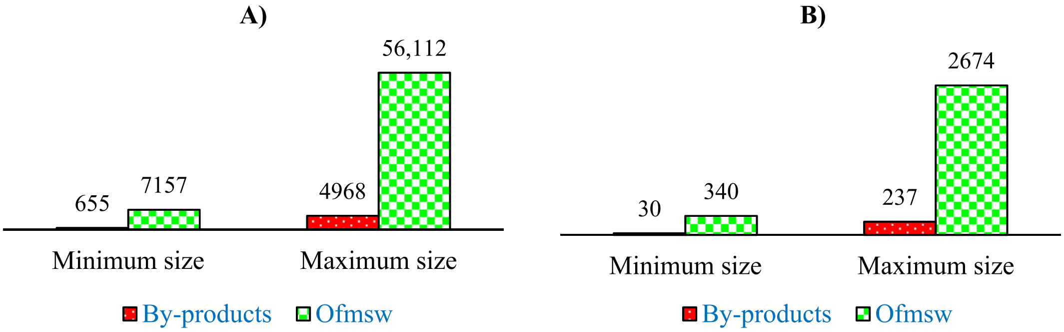

Fig. 6. Overall economic results – The Baseline Business Model.
Legend: A) Overall Net Present Value (thousand €) and B) Discounted Do Nothing Cost 1 year (thousand €).

MSWs of the municipality of Rome in terms of substrate available was calculated in two economic scenarios: i) the first "Minimum size", envisioned having seventeen 200 m^3/h ofmsw plants and five 350 m^3/h by-products plants and ii) the second "Maximum size", envisioned the need for seven 500 m^3/h ofmsw plants and three 500 m^3/h by-products plants.

The choice between the "Minimum size" and "Maximum size" was not based solely upon an economic motivation. Indeed, the recovery of waste produced within the same neighbourhood represents a good practice of waste management [67]. However, several elements need to be considered when defining the 'right plant size'.

Transport costs were considered in this model, and their impacts were greater when centralized plants were implemented. In addition, environmental costs were associated with transportation of wastes and by-products to and from the transformation plants. Consequently, the optimal plant sizes will depend upon economic and environmental costs. The social acceptance of the plants must be monitored understanding the motivations of possible opposition of citizens living in close proximity to the future biomethane production facilities. The positive reception of the people must be nurtured by education, involvement and empowerment [68].

Overall economic results linked to the economic scenarios were proposed in Fig. 6 and Fig. 7 for baseline and alternative business models, respectively.

The findings of this research shows how the development in the municipality of Rome of biomethane can provide a total NPV that varies from 7.8 million € to 61.1 million € (baseline business model).

Hence, postponing the implementation of sustainable waste management practices represents a delay in benefitting from the economic opportunities. However, it also represents an environmental threat associated, with continued reliance upon fossil-carbon-based energy sources, some of which can be provided as bio-based energy and can thereby, reduce Rome's overall fossil-carbon footprint.

$RGHG_{NGV}$ of a NGV that use BIO-CNG than CNG is equal to a reduction of: i) 1670 $kgCO_2eq$/year in the "*baseline green scenario*"; ii) 1520 $kgCO_2eq$/year in the "*alternative green scenario*"; and iii) 1820 $kgCO_2eq$/year in the "*alternative strongly green scenario*".

Considering feedstock availability in the Municipality of Rome, a potential production of biomethane was estimated to be equal to 37.6 million m^3 (26,306 thousand m^3 from the ofmsw and 11,281 thousand m^3 from by-products).

Assuming that the consumption of a NGV is equal to 1333 m^3 (see section 3.2), the total number of NGVs (fuelled by CNG or Liquefied Natural Gas (LNG)) is equal to 28,200. Hence, the current entire demand of this territory can be satisfied. Such a switch to biomethane would yield a reduction of GHG emissions by 47 thousand ton CO_2eq/year in the *baseline green scenario*. This value varies from 43 to 51 thousand-ton CO_2eq/year in the *alternative scenarios* – Fig. 8.

3.3. Discussion

The projected results are specific for the Municipality of Rome, in which the recycling rate of 44% was far below the target for MSW of 65%. This could represent an obstacle for the market uptake of biomethane in terms of local feedstock availability. Therefore, much work must be done to inform, engage and empower the involvement of Rome's citizens in the effective development of an optimal MSW management system, which requires the implementation of appropriate separate collection for all types of wastes.

Recycling results crucially depend upon householders' participation [69] and the related awareness about the recycling practices and overall resulting benefits [70]. This, in turn, could reduce the amount of landfill taxes paid by citizens and would improve the quality of recycled materials to increase the yield of biomethane [71]. In this perspective, information campaigns concerning waste management practices play a vital role [72].

The approach and methodologies employed by the authors of this paper, can be replicated in other cities providing support for local and global communities for achieving CEs and based dramatic reductions in emissions of GHG from fossil-carbon sources while supporting the double-green transition.

Societal sustainability requires involvement and support from people of all levels of society to replace negative outcomes from unsustainable societal models with integrative CE systems at rural and cities around the world [73]. However, for these transitions to become realities a strong synergy must be created. For instance, although incentives are provided by the central government, the authorizations for the realization of the biomethane plants are controlled at the local level (regional or municipal).

Biomethane can be defined as a value-added resource and the Swedish context is a best-practice to follow [13,14,58]. The adoption of this double-green revolution in the transport sector for the Municipality of Rome will also provide advantages to the agricultural sector by improving soil quality, reducing needs for fertilizer. This will inprove food security in the region, as well. Other profits will be linked to: private and/or public activities involved in the waste management system (profits derived by the recovery of the ofmsw); the creation of new green jobs and the reduction of potential penalties (transport fuel retailers have the obligation to sell advanced biofuels).

This type of initiative must be supported via a multi-year approach of tax relief and incentives along the whole waste management chain to encourage the transition phases by driving new investments and by establishing greater market certainty for

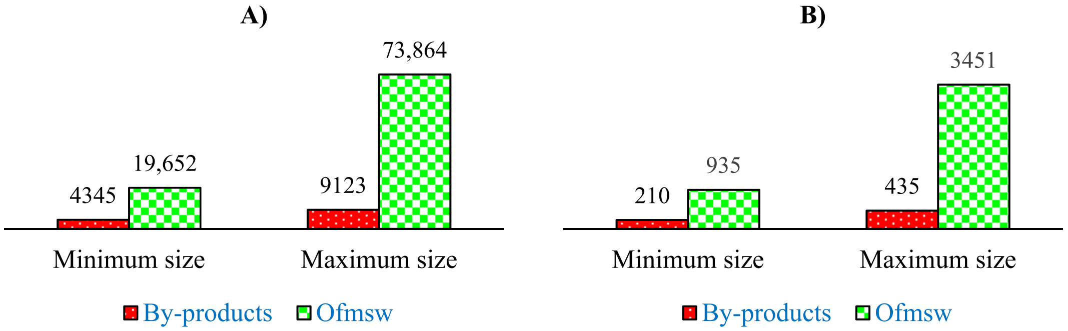

Fig. 7. Overall economic results – The Alternative Business Model.
Legend: A) Overall Net Present Value (thousand €) and B) Discounted Do Nothing Cost 1 year (thousand €).

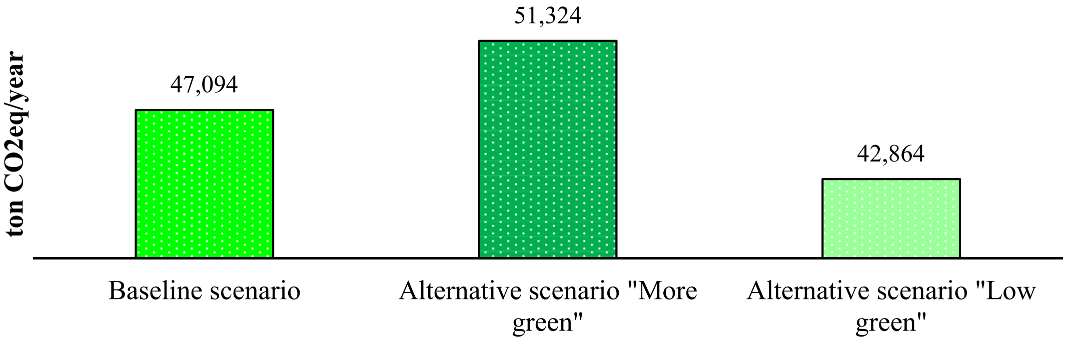

Fig. 8. Overall environmental results.

involved stakeholders [74]. Biomethane is an energy carrier, which can help the Municipality of Rome to achieve the targets set by the Renewable Energy Directive (2009/28/EC, REDI) as well as to the achieve targets for 2030 agreed upon in the compromise recently achieved on the recast of the directive (REDII) [16]. At a regional scale, the same principle can be applied to different Italian Regions to sensitize 'reluctant' politicians to agree to the urgent need to create a fertile ground for biomethane system development from the production to consumption phase.

There is the need to replace old vehicles (in particular if fuelled by petrol and diesel) with new electric and BIO-CNG vehicles and by building and operating a fueling infrastructure mainly for heavy, methane-using vehicles, for transport of cargo and for public transport, which will drive the utilization of biomethane in the total transport industry [75]. This can be advantageous to the automotive manufacturers and to the recyclers because old vehicles contain many valuable materials and components. Particularly, Italy, being one of the largest vehicle markets in the European Union is a relevant example for a market where the uptake of BIO-CNG vehicles has lagged far behind expectations. In this vein, the design of effective public policies and investor strategies designed to create markets for alternative fuel vehicles are urgently required [76].

In this context, the key factors potentially affecting the development of biomethane for the transport sector in a CE perspective entails the delivery of infrastructure, tax exemptions and incentives, changes in consumer knowledge, attitudes and behaviours, as well as a systematic coordination among stakeholders in different markets [23,77].

Overall, the transition towards a model of CE capable of valorising currently wastes materials is a particularly complex task, given that the matching between demand and supply is based upon education, attitudes, markets (e.g. innovation, preferences, duties, etc.) and policy dynamics (e.g. incentives, subsides, tax relief, etc.) [78,79]. New models of energy production usually require research and technological transfer among various value-chain actors which, are often hampered by economic and institutional issues (i.e. high transaction costs; imperfect appropriability of R&D outcomes) [80,81]. Also, kindergarten through life-long education about the climate change-related urgencies to accelerate the transition to equitable, liveable, sustainable, post-fossil carbon societies, is urgently needed.

This study is able to provide some policy suggestions that can be applied to favour the development of biomethane plants, as part of the Next Generation EU recovery plan. In particular, two actions are identified and suggested. The application of a corrective coefficient applied to the small plants in function of size. This can be applied for substrates compatible to the double counting (e.g. by-products) with the exception of the ofmsw. This policy measure would significantly reduce the economic risks associated to the realization of 350 m^3/h by-products plants – the same being true for plants with a smaller size. In addition, a bonus could be provided for digestate obtained by the biogas-biomethane chain – a measure that could be meaningfully applied also to 200 m^3/h ofmsw plants. Building on the model presented here, a full economic assessment of the profitability of these measures could be done in a future work.

4. Conclusions

The authors of this paper analysed the roles of biomethane in a CE transition that is based upon integration of renewable energy management and waste management at the urban level. The results of the analyses were found to be influenced by the incentive scheme for the production of biomethane together with the revenues linked to the management of organic wastes. The construction and operation of larger plants (500 m^3/h) was projected to be associated with significant economic improvements when compared with constructing and using smaller biomethane production plants. The results showed how the delay of the implementation of biomethane plants would cause significant economic losses, ranging from 370 thousand € to 2.9 million € (baseline scenario).

The feedstock availability in the Municipality of Rome can assure production of biomethane equal to 37.6 million m^3 (26,306 thousand m^3 from the ofmsw and 11,281 thousand m^3 from by-products), which is sufficient to fuel about 28,200 NGVs with an overall reduction of GHG emissions equal to 47 thousand tons of CO_2eq/year. As a result, the whole fuel demand for transportation in this territory can be entirely satisfied.

The definition of a double-green model of waste management and renewable energy management can pave the way to the increase of implementation of a wide variety of sustainable processes based on resource circularity as part of a broader CE, to capture the enormous potential of using currently wasted resources as sources for biomethane and agricultural fertilizers. In this perspective, biomethane plants can transform huge quantities of waste into clean energy which will help to reduce the fossil-carbon footprint of the transport sector.

Finally, the implementation of new biomethane plants is a green choice but it must be integrated with other policies such as the realization of new fuelling stations and the increase usage of NGVs. Therefore, national and local policies should be integrated to accelerate the green transition of transport sectors.

As a final remark, it is important to note that the analyses conducted for this paper were not complete since they were primarily built on two pillars of sustainability, namely economic and environmental. However, our findings may open the path for future investigations that, along with deepening economic and environmental aspects, also consider the social aspects. Specifically, future lines of research should: (i) consider different stakeholders' perspectives to catalyse the social acceptance of green plants; (ii) investigate self-sufficient conditions for renewable energy supply in urban areas; (iii) provide a better understanding of the choices between "Minimum size" and "Maximum size" (e.g. the proximity issue); and assign a major economic penalty for fossil-carbon-based carbon dioxide emissions (e.g. the "Polluters Pay Principle).

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.renene.2020.10.072.

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