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Incentive policies in biomethane production toward circular economy

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A R T I C L E I N F O

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A B S T R A C T

The transportation sector is marked by high emissions, and new sustainable solutions are required to solve this problem. Biomethane, also known as green gas, has the potential to regenerate certain wastes, promoting resource circularity. This study aimed at evaluating the profitability of small- and medium-sized plants using the organic fraction of municipal solid waste (OFMSW) and by-products, considering a new incentive decree within the mature biogas-biomethane market of Italy. Net present value (NPV) was used as a key indicator, and sensitivity, scenario, and risk analyses were proposed. The results showed that a high subsidy for by-products contributed to the profitability of by-products plants across multiple contexts. Conversely, stringent incentive values for the OFMSW led to diminished profitability for plants treating this substrate. Consequently, profitability was verified for 100 m^3/h plants with by-products and 300 m^3/h plants with the OFMSW. The break-even point analysis showed that the tariff value determining project profitability, contingent on size and substrate, ranged from 0.61 to 0.95 €/m^3 for the OFMSW and 0.76–1.01 €/m^3 for by-products. The results provide valuable policy and managerial insights, emphasizing the support needed for biomethane – a renewable and circular resource – to achieve the twin goals of energy independence and a low-carbon economy. Consequently, biomethane has the potential to contribute to the achievement of Sustainable Development Goals 7 and 12.

Credit Author Statement

All authors equally contributed to the writing of the paper and its revision.

1. Introduction

The world is facing an energy crisis, making an exploration of alternative energy solutions necessary to ensure energy livelihood. For centuries, human energy needs have relied heavily on fossil fuels, contributing to the problem of climate change. As a result, all countries are now mobilized to seek solutions and ensure that global standards for reduced greenhouse gas emissions, sustainability, and economic growth are met [1,2]. Biomethane, representing a renewable fuel, has emerged in recent years as a sustainable alternative with the potential to decarbonize various sectors, including but not limited to those defined as "hard to abate" [3]. In more detail, biomethane has the ability to reduce global emissions and contribute to the management of increasingly large amounts of organic waste. The valorization of organic waste, in turn, is aligned with policies concerned with energy, waste, and the circular economy [4,5]. Thus, use of biomethane may address key challenges in modern society.

Waste reduction guidance issued by global organizations emphasizes the need for better management of recyclable waste and a trend toward zero landfilling. Bioenergy recovery through anaerobic digestion (AD) stands out as an attractive waste management approach in modern industrial facilities, due to its environmental suitability and clean energy output from biogas [6,7]. In this context, biomethane has the potential to support a circular bioeconomy model, promoting resource longevity, waste minimization, and economic value creation through innovative business models, thereby addressing the pressing problems of resource depletion and climate change [8]. Shifting from a take-make-waste model to a circular bioeconomy will require coordinated efforts by stakeholders throughout the supply chain, taking into account technical, cultural, and political variation across regional bioeconomy [9]. This

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Nomenclature

Abbreviations

AD	anaerobic digestion
BEP	Break-even point
CO_2	carbon dioxide
NPV	net present value
OFMSW	organic fraction of the municipal solid waste
RO	research objective
SDG	Sustainable Development Goal

Symbols

1°s	biogas production
2°s	upgrading
3°s	compression and distribution
AIT_u	unitary all-inclusive tariff
$C_{df}^{1°s}$	depreciation fund (1°s)
$C_{df,t}^{2°s}$	depreciation fund (2°s)
$C_{e,t}^{1°s}$	electricity cost (1°s)
$C_{e,t}^{2°s}$	electricity cost (2°s)
$c_e^{u,1°s}$	unitary electricity consumption (1°s)
$c_e^{u,2°s}$	unitary electricity consumption (2°s)
$C_{i,t}^{1°s}$	insurance cost (1°s)
$C_{i,t}^{2°s}$	insurance cost (2°s)
C_{inv}^{com}	investment cost (compression)
C_{inv}^{dig}	investment cost (digestate)
C_{inv}^{dis}	investment cost (distribution)
C_l	labor cost
$C_l^{u,a}$	unitary labor cost
C_{lcs}	loan capital share cost
C_{lis}	loan interest share cost
$C_{lcs,t}^{dig}$	loan capital share cost (digestate)
$C_{lis,t}^{dig}$	loan interest share cost (digestate)
$C_{inv}^{u,1°s}$	unitary investment cost (1°s)
$C_{inv}^{1°s,*}$	initial investment cost (1°s)
$C_{inv}^{1°s}$	investment cost minus capital grant (1°s)
$C_{inv}^{u,2°s}$	unitary investment cost (2°s)
$C_{inv}^{2°s,*}$	initial investment cost (2°s)
$C_{inv}^{2°s}$	investment cost minus capital grant (2°s)
$C_{inv}^{3°s,*}$	initial investment cost (3°s)
$C_{inv}^{3°s}$	investment cost minus capital grant (3°s)
$C_{mo}^{1°s}$	maintenance & overhead cost (1°s)
$C_{mo}^{2°s}$	maintenance & overhead cost (2°s)
C_o^{com}	operative cost (compression)
C_o^{dig}	operative cost (digestate)
C_o^{dis}	operative cost (distribution)
C_s	substrate cost
C_s^u	unitary substrate cost
C_t^{OFMSW}	cost of the OFMSW
C_{tax}	taxes cost
C_{ts}	transport cost of substrates
C_{ts}^u	unitary transport cost of substrate
C_{gv}	generic variable cost
$C_{z,t}^{2°s}$	zeolite cost (2°s)
cf_{CO_2}	conversion factor (CO_2)
CF	cash flow
DCF	discounted cash flow
Com	compression
Dig	digestate
I_t	cash inflows
inf	rate of inflation
l_{bs}	losses in the biogas system
l_{us}	losses in the upgrading system
n	lifetime of investment
n_{debt}	period of loan
n_{oh}	number of operating hours
n_{op}	number of operators
n_r	period of realization
n_s	period of subsidies (biomethane)
O_t	cash outflows
p_b^u	unitary potential of biomethane
$p_{biomethane}$ (p_{sng})	biomethane (natural gas) sale price
$p_{capital\ grant}$	percentage of capital grant
$p_{CO_2}^u$	unitary price of CO_2
$p_{compost}^u$	unitary price of compost
p_{df}	percentage of depreciation fund
p_e	unitary price of electricity
p_i	percentage of insurance cost
$p_{mo}^{1°s}$	percentage of maintenance & overhead cost (1°s)
$p_{mo}^{2°s}$	percentage of maintenance & overhead cost (2°s)
p_{tax}	percentage of taxes
p_z^u	unitary price of zeolite
r	opportunity cost
r_{bm}	recovery rate (biomethane)
r_{CO_2}	recovery rate (CO_2)
$R_{compost}$	revenues from compost
r_d	interest rate on loan
$R_t^{CO_2}$	revenues from selling CO_2
R_t^{OFMSW}	revenues from treatment of the OFMSW
$R_{gross,t}^{OFMSW}$	gross revenues from the OFMSW
$R_t^{selling}$	revenues from selling biomethane
$R_t^{subsidies}$	revenues from subsidies
Q_{biogas}	quantity of biogas
Q_{biogas}^{nom}	nominal quantity of biogas
$Q_{biomethane}$	quantity of biomethane
Q_{CO_2}	quantity of CO_2
$Q_{compost}$	quantity of compost
$Q_{biomethane}^{nom}$	nominal quantity of biomethane
Q_{OFMSW}	quantity of the OFMSW
Q_S	quantity of substrate
Q_z	quantity of zeolite
S_{biogas}	plant size (biogas)
$S_{biomethane}$	plant size (biomethane)
t	time of the cash flow
$\%CH_4$	percentage of methane
$\%CO_2$	percentage of carbon dioxide

sustainable model is particularly important for the agricultural sector, where large volumes of agricultural waste may be used to generate energy and fertilizer, thereby reducing environmental pollution while adding value for farmers and stakeholders from other industries [10].

Beyond air pollution reduction, biomethane also offers other environmental benefits, such as improved soil health and sustainable agricultural practices. Additionally, it is linked to social and economic benefits, including job creation, reduced health care costs, and improved community quality of life [11,12]. In particular, biomethane may create new economic opportunities in rural areas, as biomethane production involves the conversion of organic waste materials into a marketable product, which can increase employment and income for the agricultural sector and local workers. In addition, use of biomethane may ensure energy security and independence, thereby reducing energy demand from foreign sources [13]. AD plants, sustainable production, and biomass sources are promising pathways for pursuing global sustainability and, more specifically, many Sustainable Development Goals (SDGs), including: poverty reduction (SDG 1), hunger eradication (SDG 2), shared health and well-being (SDG 3), reliable and affordable energy production across rural and urban communities (SDG 7), economic growth (SDG 8), industry value added by small enterprises (SDG 9), and responsible production and consumption (SDG 12) [14].

As discussed, biomethane may contribute to establishing the more circular practices associated with the bioeconomy. However, its successful implementation requires collaboration across sectors, ranging from waste management to energy production, policymaking, regulation, infrastructure, and education. Policies such as premium tariffs focus on the renewable portfolio, and appropriate regulation may incentivize the development of biomethane-dependent technologies and infrastructure, thereby creating an environment conducive to the circular economy and sustainable development practices. For this energy carrier to become a mainstream solution, certain barriers – including the higher production cost compared to fossil fuels, insufficient infrastructure for effective green gas distribution, and resistance to electric-equivalent solutions (in, e.g., the transportation sector) – must be overcome. While energy policies are increasingly favoring electrification, they are showing relatively less attention to the use of waste organic matter, and thus failing to uphold certain principles of sustainability [15]. Therefore, use of green gas may be conducive to an energy transition [16,17]. In support of this, the RepowerEU strategy envisages a substantial increase in biomethane production by 2030 [18].

Several studies place attention on the Italian market, which is considered a benchmark for the biogas-biomethane chain [19,20]. Use of the organic fraction of municipal solid waste (OFMSW) and by-products highlights biomethane's potential for fostering a sustainable transition to a green and circular economy in Italy [21,22], particularly within the transportation sector [23]. Thus, the role of biomethane as an energy resource for sustainable production is evident [24]. Previous profitability analyses have highlighted a significant dependency on incentive structures [13,25] and there is an increasing focus on small and medium-sized plants to support decentralized energy systems [24,26].

Some analysis show that the biogas-biomethane market in the European sector is strongly influenced by policy mix [27], and this aims to assess how a new incentive decree can support the sector within a mature market. In fact, there is untapped potential [23], and it is crucial to assess the relationship that exists between the profitability of biomethane plants and the relevant market and policy conditions [24].

Economic analyses are useful for assessing policy impacts, and they may provide valuable insights to diverse stakeholders, and particularly investors. Accordingly, this study established the following research objectives (ROs), aimed at evaluating the economic profitability of small- and medium-sized plants (i.e., 100, 200, 300 m^3/h) using two distinct substrates (OFMSW, by-products), considering an incentive scheme applied in Italy.

- RO1 - assessing the economic profitability of plants processing OFMSW; and
- RO2 - evaluating the economic profitability of plants treating by-products.

In this way, it is possible to transfer these results to other geographical contexts and this study aims at deriving policy implications to promote a circular and sustainable model.

2. Literature review

Biogas, representing a mixture of carbon dioxide (CO_2), methane, and other gases, transforms into an almost pure source of methane (i.e., biomethane) through biogas upgrading or the gasification of solid biomass, followed by methanation [28]. The biogas-biomethane chain offers several advantages [29,30]. The European Biogas Association Statistical Report showed that, in comparison to the previous year, biomethane production in Europe increased by nearly 20 % in 2022 [31]. With biogas and biomethane combined, Europe produced 21 billion cubic meters of biogas in 2022, or 6 % of the natural gas consumed by the EU. The production of biomethane alone increased from 3.5 billion cubic meters in 2021 to 4.2 billion cubic meters in 2022. The balanced distribution pattern of biomethane's end-uses, which shows how versatile it is as a renewable energy source, showed that in 2022, 22 % of it was used for buildings, 14 % for industry, 19 % for transportation, and 15 % for power generation.

This section summarizes relevant works pertaining to substrates (Section 2.1), circularity (Section 2.2), subsidies (Section 2.3), and economic analyses (Section 2.4).

2.1. Biomethane and substrates

Biomethane production enables the exploitation of different types of biomass [18], including agricultural by-products [32] and the OFSMW [12]. Both of these materials have been extensively analyzed due to their alignment with sustainability requirements [33,34]. The International Renewable Energy Agency [35] measures the biomethane emissions of various feedstock types, including liquid manure (33 gCO_2eq/km), organic waste (48 gCO_2eq/km), maize (66 gCO_2eq/km), and methane (124 gCO_2eq/km), underlining significantly higher numbers for the latter. Other studies have confirmed the environmental benefits of this resource, quantifying biomethane emissions of 23 gCO2eq/MJ [36], 40 gCO2eq/MJ [37], 53 gCO2eq/MJ [38], and 62 gCO2eq/MJ [39].

The predominant sources of biomass vary between countries [40], and their availability directly impacts the competitiveness and social acceptability of plants [41]. Several studies have demonstrated the energy advantage of agricultural waste [42], while other works have focused on the higher yield of biomethane, proposing innovative approaches to optimizing the production process [43]. Some analysis have evaluated the biomethane production life cycle, revealing similarities between the total emissions generated by biomethane production and those generated through the processing of the two other biomass sources [44]. One of these sources, the OFMSW, has generated considerable attention in the most recent period, both within the scientific community and at the political-legislative level, due to its substantial potential for industrial applications [17]. Despite the attractive economic and renewable qualities of the OFMSW, its improper management can generate adverse consequences for the environment and public health [45].

2.2. Biomethane and circularity

Environmental systems are under pressure due to high resource consumption and waste generation [46]. Over the last decade, the creation of a bioeconomy and the use of alternative biofuels have become primary goals for diverse stakeholders [33,47] and the circular economy approach proposes waste as added value [3]. However, the success of circular bioeconomy models is closely linked to technological development, as well as local availability, economic feasibility, and effective connection between actors in the value chain [48]. In particular, the engagement of local actors is crucial. In a circular economy model involving multiple actors, the strengths lie in the long-term net revenues derived from a secure supply and demand network, in which agents work in synergy to support the economy of the entire value chain, from upstream to downstream [49]. The use of biological resources in the circular bioeconomy holds significant potential but requires control and regulation to ensure effective waste management [41]. Some analysis identify biomethane as a good example of a circular bioeconomy [8].

2.3. Biomethane and subsidies

The economic potential of biomethane is closely tied to subsidies [50]. As technology develops and investment costs rise, subsidies become increasingly crucial for ensuring profit and preventing a slowdown in stakeholder investment in this energy carrier [13]. Various forms of subsidies, such as feed-in tariffs [5], feed-in premiums [24], capital contributions [51], biomethane certificates [52], Certificates of Emission of Biofuel in Consumption [53], and auctions [54], are designed to incentivize companies to improve the industrial supply chain and resource utilization capabilities, thereby reducing emissions [55]. Policy schemes must consider energy communities' limitations in building large-scale plants, due to the scarcity of local resources [56]. Additionally, improvements in policy and market mechanisms are necessary to transition biomethane plants from waste treatment systems to new resource utilization systems [49]. Such measures would significantly contribute to eliminating the relatively indifferent attitude toward biomethane plants [43]. Additionally, awareness campaigns and investment in education and skill development could prove key to influencing societal functioning and ensuring energy success [49]. The green transition requires renewables to be competitive, so as to generate attractive returns for investors [57]. Incentive schemes are thus likely to be crucial for their development [58]. In line with this, this study aimed at evaluating economic performance related to an incentive attached to biomethane fed into the grid. In this vein, it is useful to now direct attention to the price of natural gas [59,60] and emission allowance prices [61,62].

2.4. Biomethane and economics

The cost of biomethane is primarily dependent on the cost of biogas. Certain analyses have indicated that the cost of AD is four times that of upgrading [63]. The cost of biogas varies depending on the substrate used, ranging from 0.32 to 0.56 US$/$m^3$ [64,65]. Another relevant variable is plant size, with costs ranging from 0.22 to 0.88 US$/m3 for plants greater than 500 m^3/h, and from 1 to 1.55 US$/$m^3$ for plants of approximately 100 m^3/h [35].

Given the dynamic system that distinguishes these plants [66], some studies underscore the need to evaluate economic profitability under various policy scenarios [13,66]. As highlighted in Section 2.3, subsidies play a key role in assessing plant profitability because, in their absence, a loss condition occurs [67,68]. The cash flow method and the use of net present value (NPV) as an indicator are widely verified in the studies. Previous analyses have considered several case studies, calculating different ranges of NPV: 8685–10,518 k€, depending on the percentage of biogas that is produced and subsequently upgraded to biomethane [69]; 3–14 M€, contingent on the value of an incentive in an integrated system with photovoltaic panels and solar thermal collectors [70]; 19.6–29.5 k€, in accordance with digestate waste heat recovery [71]; (−7.87)–9.26 M$, depending on alternative scenarios of mono-digestion or co-digestion of residues [6]; 23–40 M$, considering changes in multiple variables in an integrated system [72]; (−125)–949 k$, contingent on several technical parameters [73]; (−3.7)–17.2 M€ in a baseline policy scenario; and (−5.2)–7.6 M€ in an alternative scenario, depending on plant size [24]. Other recent studies show how NPV varies according to critical parameters: from −13.2 to 35.8 M€ for energy certificates [19], from −3.0 to 2.6 million USD for selling price [74] and from 1.4 to 33.4 M$ for technological aspects [75].

3. Methodology

This section outlines the variables that were considered in the economic assessment of a new incentive decree. Section 3.1 presents the policy framework in Italy, while Section 3.2 describes the economic methodology used. The technical and economic input data are described in Section 3.3.

3.1. Policy framework

Italy's new incentive decree (Ministerial Decree September 15, 2022) aims at achieving an additional biomethane production of at least 2.3 billion m^3 by June 30, 2026. The decree primarily encourages biomethane integration into the natural gas grid through two measures: (i) a capital grant, providing a maximum of 40 % coverage for expenses incurred; and (ii) an energy account incentive, offering an incentive tariff applied to net biomethane production for a period of 15 years. The incentives are applicable to newly built agricultural or waste-based biomethane production plants and the conversion of existing agricultural plants to biomethane production plants. The Guarantee of Origin serves as an electronic certification confirming the renewable origin of the energy sources. The All-Inclusive Tariff, a key incentive mechanism, consists of a single tariff corresponding to the payable amount, including the economic value derived from the sale of natural gas and the value of the Guarantee of Origin.

The reference tariff is set at 62 €/MWh for any size of organic waste or agricultural plant. For capacities up to and including 100 m^3/h, it is 115 €/MWh; otherwise, it stands at 110 €/MWh. The offered tariff is the reference tariff, adjusted based on the percentage reduction during participation in the procedure, and the tariff payable may incorporate further reductions.

3.2. Economic model

The discounted cash flow method offers the advantage of considering the time value of money and aggregating different cash flows by an appropriate opportunity cost of capital. NPV indicates the wealth generated by the project [24,52,76].

The biogas-biomethane chain typically undergoes three phases: (i) biogas production, (ii) upgrading, and (iii) compression and distribution. On the revenue side, there are subsidies and the sale of biomethane, digestate, and food-grade CO_2. In addition, if the OFMSW is treated, net revenues are also obtained from its management. On the cost side, factors include depreciation for mechanical and electrical elements, electricity consumption, insurance, investment, labor, maintenance and overheads, purchase of zeolite, substrate, and transport. Several assumptions are necessary, from a technical point of view (i) the final gas specifications (e.g., composition and pressure): are tailored to the end use, and (ii) the size of the biogas plant is chosen to maximize the grade of saturation in the upgrading phase. The employed model aligns with that proposed in the existing study [24]:

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

$$NPV \Big/ Size = \left(\sum_{t=0}^{n} (I_t - O_t) / (1+r)^t \right) \Big/ S_{biomethane} \quad (2)$$

$$I_t = R_t^{subsidies} + R_t^{selling} + R_t^{CO_2} + R_t^{compost} + R_t^{OFMSW} \; \forall t = 1 \ldots n \quad (3)$$

$$R_t^{subsidies} = Q_{biomethane} * AIT_u \; \forall t = n_r \ldots n_s \quad (4)$$

$$R_t^{selling} = Q_{biomethane} * p_{biomethane} \; \forall t = n_s + 1 \ldots n \quad (5)$$

$$R_t^{CO_2} = Q_{CO_2} * p_{CO_2}^u \; \forall t = n_r \ldots n \quad (6)$$

$$R_t^{compost} = Q_{compost} * p_{compost}^u \; \forall t = n_r \ldots n \quad (7)$$

$$R_t^{OFMSW} = Q_{OFMSW} * \left(R_{gross,t}^{OFMSW} - C_t^{OFMSW}\right) \ \forall t = n_r \ldots n \tag{8}$$

$$0_t = C_{lcs,t}^{1^\circ s} + C_{lis,t}^{1^\circ s} + C_{lcs,t}^{2^\circ s} + C_{lis,t}^{2^\circ s} + C_{lcs,t}^{3^\circ s} + C_{lis,t}^{3^\circ s} + C_{lcs,t}^{dig} + C_{lis,t}^{dig} + C_{l,t} + C_{s,t} + C_{ts,t} + C_{mo,t}^{1^\circ s} + C_{df,t}^{1^\circ s} + C_{e,t}^{1^\circ s} + C_{i,t}^{1^\circ s} + C_{mo,t}^{2^\circ s} + C_{df,t}^{2^\circ s} + C_{e,t}^{2^\circ s} + C_{i,t}^{2^\circ s} + C_{z,t}^{2^\circ s} + C_{o,t}^{dig} + C_{o,t}^{com} + C_{o,t}^{dis} + C_{tax,t} \ \forall t = 0 \ldots n \tag{9}$$

$$C_{inv}^{1^\circ s,*} = C_{inv}^{u,1^\circ s} * S_{biogas} \tag{10}$$

$$C_{inv}^{1^\circ s} = C_{inv}^{1^\circ s,*} * p_{capital\ grant} \tag{11}$$

$$C_{lcs,t}^{1^\circ s} = C_{inv}^{1^\circ s} \Big/ n_{debt} \ \forall t = 0 \ldots n_{debt} - 1 \tag{12}$$

$$C_{lis,t}^{1^\circ s} = \left(C_{inv}^{1^\circ s} - C_{lcs,t}^{1^\circ s}\right) * r_d \ \forall t = 0 \ldots n_{debt} - 1 \tag{13}$$

$$C_{inv}^{2^\circ s,*} = C_{inv}^{u,2^\circ s} * S_{biomethane} \tag{14}$$

$$C_{inv}^{2^\circ s} = C_{inv}^{2^\circ s,*} * p_{capital\ grant} \tag{15}$$

$$C_{lcs,t}^{2^\circ s} = C_{inv}^{2^\circ s} \Big/ n_{debt} \ \forall t = 0 \ldots n_{debt} - 1 \tag{16}$$

$$C_{lis,t}^{2^\circ s} = \left(C_{inv}^{2^\circ s} - C_{lcs,t}^{2^\circ s}\right) * r_d \ \forall t = 0 \ldots n_{debt} - 1 \tag{17}$$

$$C_{inv}^{3^\circ s,*} = C_{inv}^{com} + C_{inv}^{dis} \tag{18}$$

$$C_{inv}^{3^\circ s} = C_{inv}^{3^\circ s,*} * p_{capital\ grant} \tag{19}$$

$$C_{lcs,t}^{3^\circ s} = C_{inv}^{3^\circ s} \Big/ n_{debt} \ \forall t = 0 \ldots n_{debt} - 1 \tag{20}$$

$$C_{lis,t}^{3^\circ s} = \left(C_{inv}^{3^\circ s} - C_{lcs,t}^{3^\circ s}\right) * r_d \ \forall t = 0 \ldots n_{debt} - 1 \tag{21}$$

$$C_{lcs,t}^{dig} = C_{inv}^{dig} \Big/ n_{debt} \ \forall t = 0 \ldots n_{debt} - 1 \tag{22}$$

$$C_{lis,t}^{dig} = \left(C_{inv}^{dig} - C_{lcs,t}^{dig}\right) * r_d \ \forall t = 0 \ldots n_{debt} - 1 \tag{23}$$

$$C_{l,t} = C_l^{u,a} * n_{op} \ \forall t = n_r \ldots n \tag{24}$$

$$C_{s,t} = C_s^u * Q_S \ \forall t = n_r \ldots n \tag{25}$$

$$C_{ts,t} = C_{ts}^u * Q_S \ \forall t = n_r \ldots n \tag{26}$$

$$C_{mo,t}^{1^\circ s} = p_{mo}^{1^\circ s} * C_{inv}^{1^\circ s} \ \forall t = n_r \ldots n \tag{27}$$

$$C_{df,t}^{1^\circ s} = p_{df} * C_{lcs,t}^{1^\circ s} \ \forall t = n_r \ldots n \tag{28}$$

$$C_{e,t}^{1^\circ s} = c_e^{u,1^\circ s} * Q_{biogas} * p_e \ \forall t = n_r \ldots n \tag{29}$$

$$C_{i,t}^{1^\circ s} = p_i * C_{inv}^{1^\circ s} \ \forall t = n_r \ldots n \tag{30}$$

$$C_{mo,t}^{2^\circ s} = p_{mo}^{2^\circ s} * C_{inv}^{2^\circ s} \ \forall t = n_r \ldots n \tag{31}$$

$$C_{df,t}^{2^\circ s} = p_{df} * C_{lcs,t}^{2^\circ s} \ \forall t = n_r \ldots n \tag{32}$$

$$C_{e,t}^{2^\circ s} = c_e^{u,2^\circ s} * Q_{biogas} * p_e \ \forall t = n_r \ldots n \tag{33}$$

$$C_{i,t}^{2^\circ s} = p_i * C_{inv}^{2^\circ s} \ \forall t = n_r \ldots n \tag{34}$$

$$C_{z,t}^{2^\circ s} = p_z^u * Q_z \ \forall t = n_r \ldots n \tag{35}$$

$$C_{o,t}^{com} = C_o^{com} \ \forall t = n_r \ldots n \tag{36}$$

$$C_{o,t}^{dis} = C_o^{dis} \ \forall t = n_r \ldots n \tag{37}$$

$$C_{tax,t} = CF_t * p_{tax} \ \forall t = n_r \ldots n \tag{38}$$

$$C_{gv,t+1} = C_{gv,t} * (1 + inf) \ \forall t = n_r \ldots n \tag{39}$$

$$Q_S = (n_{oh} * S_{biomethane}) \Big/ p_b^u \tag{40}$$

$$Q_{biogas}^{nom} = S_{biogas} * n_{oh} * \%CH_4 \tag{41}$$

$$Q_{biogas} = Q_{biogas}^{nom} * (1 - l_{bs}) \tag{42}$$

$$Q_{biomethane}^{nom} = S_{biomethane} * n_{oh} \tag{43}$$

$$Q_{biomethane} = Q_{biogas} * (\%CH_4) * (1 - l_{us}) * r_{bm} \tag{44}$$

$$Q_{CO_2} = S_{biogas} * n_{oh} * (\%CO_2) * cf_{CO_2} * r_{CO_2} \tag{45}$$

Equations (1) and (2) refer to performance indicators, i.e., NPV and NPV parameterized with respect to plant size. Equation (3) describes the set of cash inflows that consists of five components of revenue: subsidies (eq. (4)), biomethane sales (eq. (5)), CO_2 sales (eq. (6)), compost sales (eq. (7)) and additional revenue from OFMSW treatment (eq. (8)). Equation (9) collects all cash outflows related to the three phases of biogas-biomethane chain. It is necessary to distinguish investment costs from operating costs. Regarding the former, equations (10)–(13) refer to the first phase of biogas production; equations (14)–(17) refer to the second phase of production the upgrading and finally equations (18)–(21) refer to the third phase, namely compression and distribution. The calculation of the investment required for digestate production should also be highlighted (eq. (22) and (23)). Regarding the second there are several items present and a further distinction can be made. Some are specific to certain phases such as labor (eq. (24)), substrate (eq. (25)), and substrate transport (eq. (26)) and others that characterize multiple phases, such as maintenance and overhead (eqs. (27) and (31)), depreciation found (eqs. (28) and (32)), electricity (eqs. (29) and (33)), and insurance (eqs. (30) and (34)). The output enhancement process examined in this study also includes ziolite, proposed in Equation (35). Finally, the third stage of the process must also be considered and thus include the calculation of the operating cost of compression (eq. (36)) and that of distribution (eq. (37)). From the cash flow, obtained as the difference between revenues and costs, it is possible to calculate the taxes associated with this project (eq. (38)). Very relevant is Equation (39) which makes it possible to point out that all operating costs considered in this work are subject to an inflation rate over their entire useful life. The same approach was not used for the revenue components, and it is therefore inferred that a conservative assumption from an economic point of view has been made. The approach of having separate inflation rate and opportunity cost of capital is done in accordance with previous studies [77,78] and the same is done for the conservative hypothesis [24]. Finally, equations (40)–(45) report useful technical data for the economic model in order to calculate the quantities of substrate, biogas, biomethane and CO_2.

Table 1 presents the input values, of which most were identified in accordance with the research. In addition, the data were validated by experts in the field. Specifically, two European academics and two European industrial managers, each possessing decades of experience in the biogas-biomethane sector, were consulted.

The following comparison parameters were used to evaluate the biomethane potential from residues. For the OFMSW, a value of 90 m^3 biomethane/t was considered, in accordance with the research [24]. Regarding by-products, contributions from citrus pulp, olive pomace, whey, pomace and grape dregs, cattle manure, pig slurry, and cereal straw were considered. A value of 65 m^3biomethane/t was assumed, reflecting a mix of substrates with different biomethane potentials (e.g., cereal straw: 138 m^3biomethane/t; pomace and grape dregs: 54 m^3biomethane/t; cattle manure: 30 m^3biomethane/t) [91].

The subsidy was considered in line with the details outlined in Section 3.1. In addition, scenarios in which this incentive was reduced to 53 €/MWh for the OFMSW and 90–95 €/MWh for by-products were explored. Since the incentive decree expresses values in €/MWh while the economic analysis was conducted in €/m^3, the conversion factor proposed in Table 1 (0.0105 MWh/m^3) was applied. The following scenarios were considered.

- high tariffs (0.651 €/m^3 associated with the OFMSW for all sizes, 1.207 €/m^3 associated with by-products for a 100 m^3/h plant, 1.155 €/m^3 associated with by-products for 200 and 300 m^3/h plants); and
- low tariffs (0.556 €/m^3 associated with the OFMSW for all sizes, 0.998 €/m^3 associated with by-products for a 100 m^3/h plant, 0.945 €/m^3 associated with by-products for 200 and 300 m^3/h plants).

Finally, different revenues associated with OFMSW treatment were assessed.

- high OFMSW (15 €/t); and
- low OFMSW (10 €/t).

For this assessment, gross revenues from OFMSW treatment were considered, with values equal to 65 or 70 €/t. OFMSW cost was set to 55 €/t.

4. Results

This section elaborates on the results obtained for each scenario, following the research methodologies previously described. Sections 4.1–4.2 address RO1, while Sections 4.3-4.4 pertain to RO2, providing evaluations under the baseline scenario and several alternative scenarios.

4.1. Baseline scenario – OFMSW

The baseline scenario concerning the OFMSW encompassed twelve case studies, considering the three sizes of small- and medium-sized plants (i.e., 100, 200, 300 m^3/h) and the two potential values for the main revenue items: (i) incentive value and (ii) net revenue from the OFMSW (Fig. 1).

The results showed that profitability was not verified in most scenarios, with one exception for the largest size (300 m^3/h) under the high configuration for both variables, yielding an NPV of 699 k€. In the scenarios for which profitability was not verified, the negative NPVs were substantial and not close to zero. Among these scenarios, the 200 m^3/h size achieved the best performance, with an NPV of −250 k€. The research supports these findings, demonstrating a significant decrease in profitability given a reduced incentive [24]. The results also align with estimation analyses for the incentive decree, as, when the incentive was set to 0.40 €/m^3, NPV was never positive. As for the scenario with the 0.90 €/m^3 incentive, only the 100 m^3/h size demonstrated non-profitability, coinciding with the scenario featuring a Certificates of Emission of Biofuel in Consumption of 0.61 €/m^3 and a selling price of 0.50 €/m^3.

In the comparison of cases under the baseline scenario, profitability 2330 €/(m^3/h) was achieved by the 300 m^3/h size with a high tariff and high OFMSW. Across the cases, NPV varied according to the three key parameters: from 5823 to 7800 €/(m^3/h) comparing the high and low tariff scenarios; from 568 to 1259 €/(m^3/h) comparing the high and low OFMSW scenarios; and from 14,130 to 15,045 €/(m^3/h) comparing the 200 m^3/h and 100 m^3/h sizes, and from 3580 to 4848 €/(m^3/h) comparing the 300 m^3/h and 200 m^3/h sizes.

The calculation of the levelized cost of energy for biomethane

Table 1
Input data.

Variable	Value	Reference
Conversion factor (CO_2)	1.84 kg/m^3	[79]
Conversione factor (MWh/m^3)	0.0105 MWh/m^3	[24] [c]
Cost of the OFMSW	55 €/t [a]	[12] [c]
Interest rate on loan	3 %	[80]
Investment cost (anaerobic digestion)	4050–4950 €/kW [a] 3950–4850 €/kW [b]	[24] [c]
Investment cost (compression)	55,000–65,000 €	[81] [c]
Investment cost (digestate)	300,000–900,000 €	[82] [c]
Investment cost (distribution)	230,000–250,000 €	[83] [c]
Investment cost (upgrading)	4000 - 5700 €/(m^3/h)	[24] [c]
Lifetime of investment	20 y	[84]
Loan duration	10 y	[80]
Losses in the biogas system	6 %	[83]
Losses in the upgrading system	1.5 %	[83]
Number of operating hours	8000 h	[80]
Number of operators	3–5	[85] [c]
Operation cost (compression)	40,000–50,000 €/y	[81] [c]
Operation cost (distribution)	10,000–20,000 €/y	[81] [c]
Operation cost (digestate)	80,000–230,000 €/y	[82] [c]
Opportunity cost	5 %	[24]
Percentage of capital grant	40 %	Section 3.1
Percentage of carbon dioxide	47 %	[86]
Percentage of depreciation fund	10 %	[87]
Percentage of insurance cost	2 % [a] 1–2% [b]	[c]
Percentage of maintenance & overhead cost (anaerobic digestion)	20 % [a] 18 % [b]	[84] [c]
Percentage of maintenance & overhead cost (upgrading)	10 %	[84] [c]
Percentage of methane	60 %	[88]
Percentage of tax value	27.5 %	[84]
Period of realization	0.5 y	[24] [c]
Period of subsidies	15 y	Section 3.1
Plant size (biogas)	300–900 kW	[c]
Plant size (biomethane)	100–300 m^3/h	[c]
Price of biomethane (after subsidies)	0.65 €/m^3	[c]
Quantity of compost	2222–6667 [a] 3077–10,000 [b]	[79] [c]
Quantity of CO_2	2074-6221 t	[24] [c]
Quantity of substrate	8889–26,667 t [a] 12,308–40,000 t [b]	[24] [c]
Quantity of zeolite	22 - 47 t/y	[24] [c]
Rate of inflation	3 %	[24] [c]
Recovery rate (biomethane)	97 %	[84] [c]
Recovery rate (CO_2)	97 %	[85]
Gross revenues from treatment of the OFMSW	65 - 70 €/t [a]	[24] [c]
Unitary electric consumption (anaerobic digestion)	0.13 kWh/m^3	[89]
Unitary electric consumption (upgrading)	0.29 kWh/m^3	[90]
Unitary labor cost	25,000 €/y	[24] [c]
Unitary potential of biomethane	90 m^3 biomethane/t [a] 65 m^3 biomethane/t [b]	[24,91]
Unitary price of CO_2	12 €/t	[79] [c]
Unitary price of compost	50 €/t	[82] [c]
Unitary price of electricity	0.25 €/kWh	[c]
Unitary price of zeolite	800 €/t	[24] [c]
Unitary subsidy (biomethane)	53-62 €/MWh [a] 90-115 €/MWh [b]	Section 3.1 [c]
Unitary substrate cost	0 €/t [a] 3 €/t [b]	[85] [c]
Unitary transport cost of substrate	0.5–1.5 €/t [a] 1–2 €/t [b]	[85] [c]

[a] OFMSW.
[b] By-products.
[c] Survey.

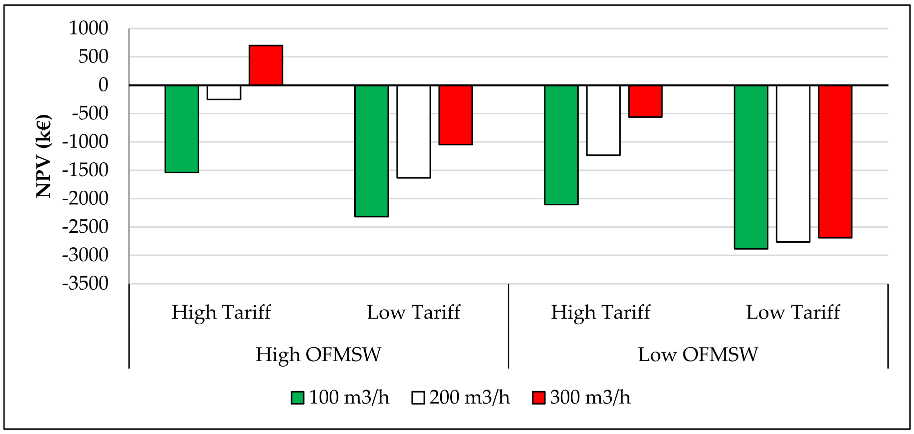

Fig. 1. Profitability analysis – baseline scenario OFMSW (organic fraction of municipal solid waste).

production – a key metric that is often compared with the unsubsidized biomethane sale price – revealed interesting insights. The results proposed levelized costs of 0.67 €/m^3, 0.72 €/m^3, and 0.84 €/m^3 for plant sizes of 300 m^3/h, 200 m^3/h, and 100 m^3/h, respectively. While these values are slightly higher than those proposed in the research (0.61–0.78 €/m^3) [24], the presence of a 40 % capital contribution significantly reduced investment costs, resulting in adjusted values of 0.50 €/m^3, 0.53 €/m^3, and 0.62 €/m^3. On average, there was a reduction from 0.17 to 0.22 €/m^3.

The cash flow analysis revealed further important aspects. With regard to revenues, subsidies accounted for 50–58 % of the total value, followed by net revenue obtained from OFMSW treatment (12–19 %) (Fig. 2). The sale of biomethane carried a lower weight, given the incentive structure, wherein this factor contributed only during the last

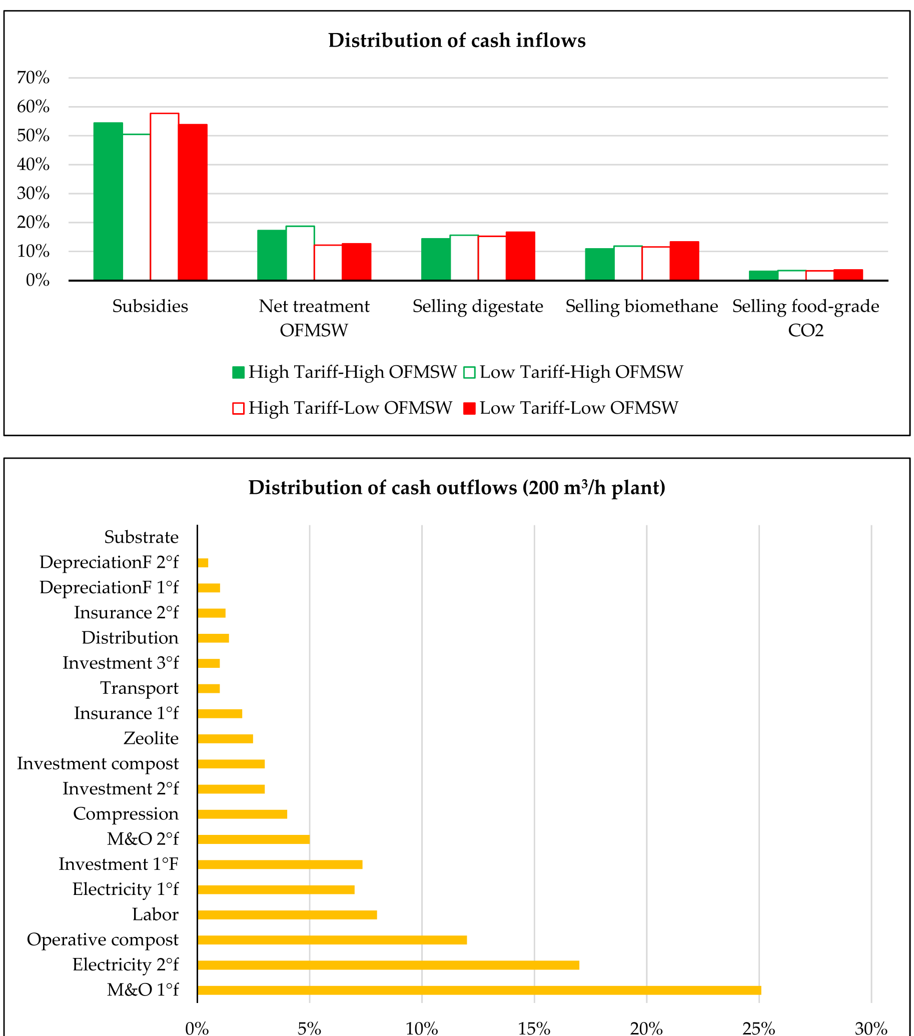

Fig. 2. Distribution of cash flows – Baseline scenario OFMSW.

5 years of the project. Thus, this value, which occurred only in the terminal phase of the project, had a reduced influence due to discounting. On the cost side, in the context of a capital contribution (Fig. 2), investment costs became less significant. In contrast, maintenance costs during biogas production emerged as a key factor, impacting 25 % of the total costs. Additionally, electricity costs during the first two phases, operating costs for compost, labor, and investment costs in the first phase collectively contributed to three-quarters of the total costs.

4.2. Alternative scenario – OFMSW

4.2.1. Sensitivity analysis

Economic analyses rely on certain estimates. Thus, to enhance the robustness of the results, critical variables (specified in accordance with previous studies [24,84]) were systematically varied to illustrate the impact on economic outcomes across a range of alternative scenarios. Initially, a sensitivity analysis was conducted, varying a single variable. Critical variables were identified from the previous distribution analysis. On the revenue side, biomethane sale price was adjusted in an optimistic/pessimistic scenario by a value of 0.05 €/m^3. Regarding the subsidy, only a reduction scenario of 0.05 €/m^3 was explored, because the high tariff scenario already considered the maximum value and, in the low tariff scenario, the optimistic scenario coincided with the pessimistic high tariff scenario. Finally, for net OFMSW revenue, a 5 €/ton increase was considered. A pessimistic high OFMSW scenario was not considered, since it coincided with the baseline low OFMSW scenario. For a similar reason, only the pessimistic low OFMSW scenario was configured. In total, forty-eight case studies were considered (Fig. 3).

The results confirmed the previous results, with a positive NPV observed in only four scenarios. In particular, consistent with the baseline scenario, these scenarios referred to the 300 m^3/h size in the high tariff and high OFMSW combination in the three scenarios analyzed. Profitability in these scenarios related to the change in biomethane sale price (689 k€ and 1118 k€) and the increase in OFMSW management (2022 k€). However, profitability was not verified when subsidies were reduced (−148 k€). While the latter scenario always pertained to a higher benefit from OFMSW treatment, it only occurred in the low tariff condition (550 k€). Thus, three important findings emerged from this analysis: (i) the profitability of such plants tends to manifest only in specific cases, (ii) reducing the incentive by even 0.05 €/m^3 in the high tariff scenario results in a non-positive NPV, and (iii) higher revenues from OFMSW can enhance profitability, even in the presence of a low tariff.

On the cost side, pessimistic scenarios were considered, involving three variables: a 5 % increase in maintenance costs in the first phase, a 0.05 €/kWh increase in electricity costs related to both phases, and a 200 €/kW increase in investment costs in the first phase, evaluated in accordance with the research. In total, thirty-six case studies were analyzed (Fig. 4).

The results were expected, due to the consideration of pessimistic scenarios. Among the scenarios examined, only one yielded a positive outcome (354 k€). This specific case arose when the AD investment cost (i.e., the variable with the least impact on the overall percentage distribution) increased by 200 €/kW. Finally, a further sensitivity analysis was conducted on the opportunity cost of capital, representing a key discounted cash flow parameter. In this instance, a pessimistic scenario was assumed, with a value of 7.5 %, inevitably leading to a reduction in NPV (Fig. 5). In total, twelve case studies were considered.

The NPV remained positive only in the 300 m^3/h high tariff and high OFMSW scenario, with a value of 611 k€. The outcome of these sensitivity analyses showed that profitability for these plants manifested in an extremely limited number of scenarios, contingent on the values assumed by the critical variables.

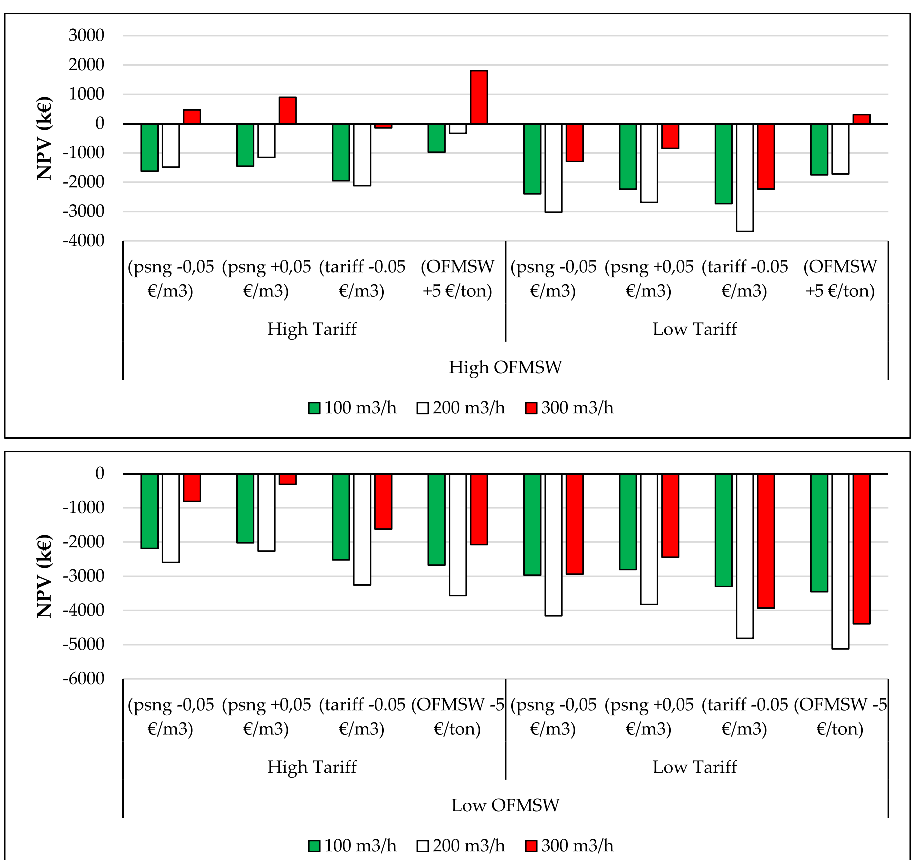

Fig. 3. Profitability analysis – sensitivity analysis (revenues) OFMSW (organic fraction of municipal solid waste). The following acronyms are used: psng (biomethane sale price) and tariff (unitary all-inclusive tariff).

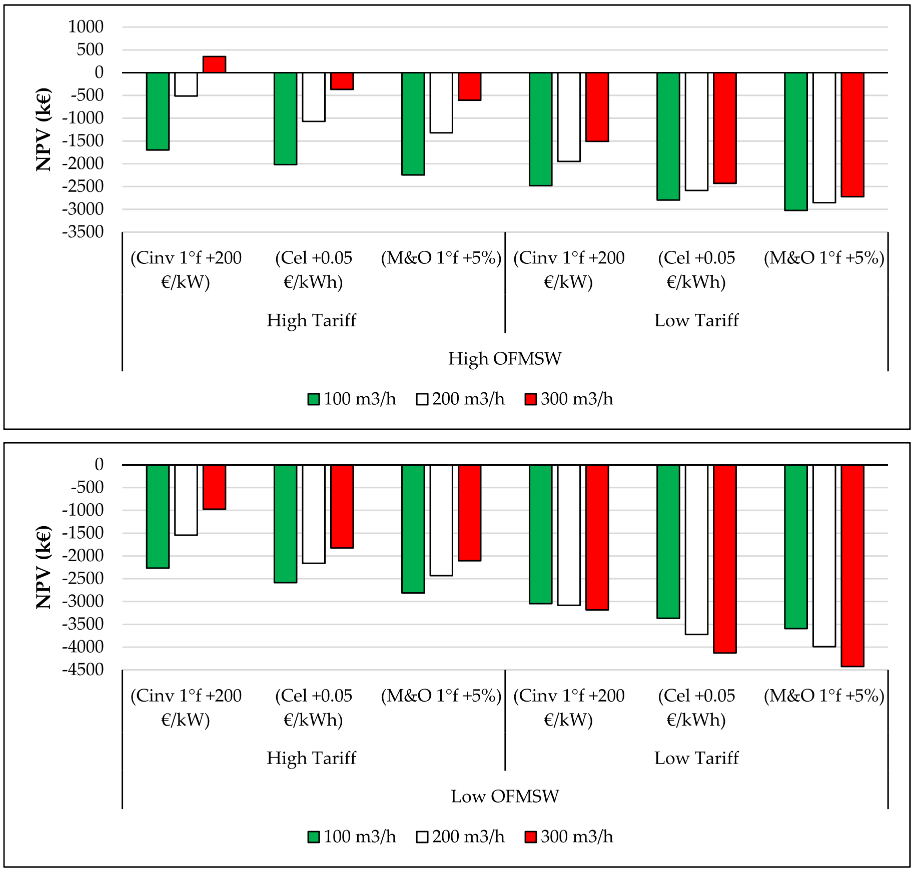

Fig. 4. Profitability analysis – sensitivity analysis (costs) OFMSW (organic fraction of municipal solid waste). The following acronyms are used: Cinv (unitary investment cost in the AD phase), Cel (electricity cost in both AD and upgrading phases), and M&O 1°f (percentage of maintenance & overhead cost in the AD phase).

4.2.2. Scenario analysis

The subsequent step in the analysis involved a simultaneous variation of variables. The factors outlined, with variations in the same range, were considered. Regarding revenues, an optimistic scenario was considered, entailing an increase of 5 €/ton of the OFMSW and 5 €/m^3 of the biomethane sale price. Conversely, a negative scenario involved a decrease of 5 €/ton of the OFMSW and 5 €/m^3 of the biomethane sale price, and an additional reduction of 5 €/m^3 for the subsidy. The subsidy variable could not be adjusted in the optimistic scenario, as its maximum value was already considered. In total, twenty-four cases were analyzed (Fig. 6).

The scenario analyses confirmed the previous findings for the single variable variations. The 300 m^3/h plant in the high OFMSW condition remained profitable in the two optimistic scenarios, regardless of the subsidy value (1960 k€ and 460 k€). In addition, two other scenarios presented profitability in the optimistic scenarios: (i) the 300 m^3/h plant with low OFMSW but a high tariff (896 k€) and (ii) the 200 m^3/h plant with a high tariff and high OFMSW (698 k€).

A similar approach was followed for the cost components. The optimistic scenario predicted a 5 % reduction in AD maintenance costs, a 0.05 €/kWh decrease in electricity costs, and a 200 €/kW cut in the AD investment cost. Speculatively, the pessimistic scenario predicted an increase in these variables, again generating twenty-four cases for analysis (Fig. 7).

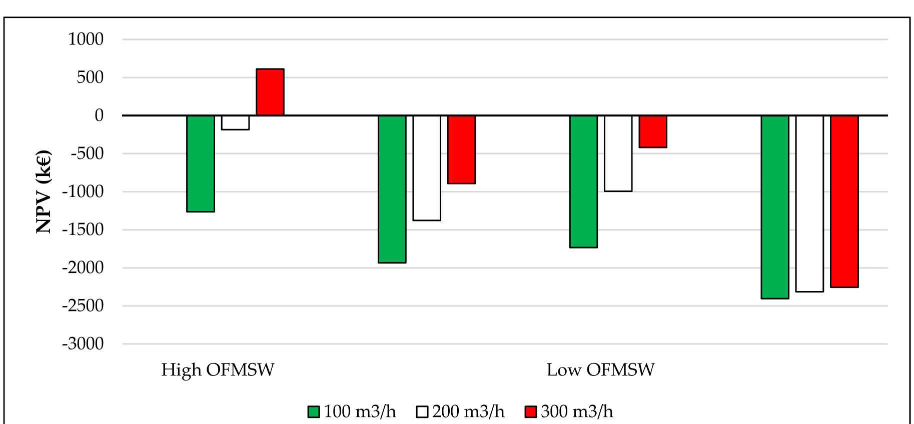

Fig. 5. Profitability analysis – sensitivity analysis (cost opportunity of capital) OFMSW (organic fraction of municipal solid waste).

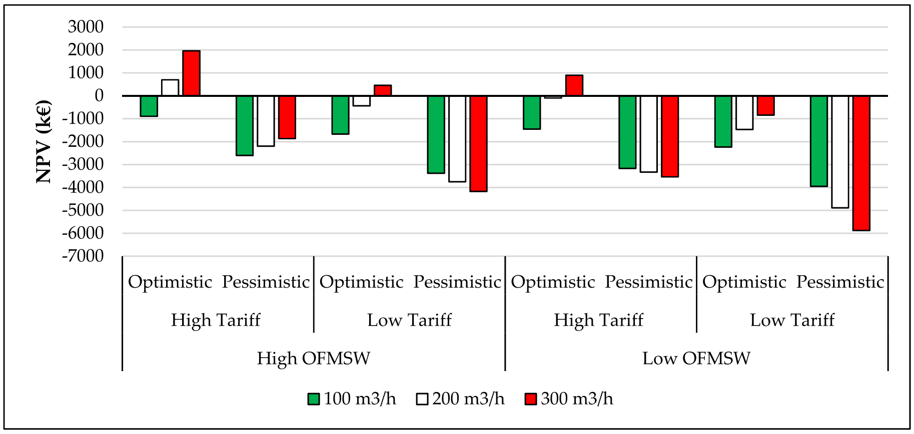

Fig. 6. Profitability analysis – scenario analysis (revenues) OFMSW (organic fraction of municipal solid waste).

The number of scenarios generating a positive NPV increased in this analysis, referring to the following optimistic scenarios.

- 300 m^3/h plants in the high OFMSW context with a high or low tariff (2961 k€ and 1512 k€, respectively);
- 200 m^3/h plants in the high OFMSW context with a high or low tariff (1411 k€ and 427 k€, respectively);
- 300 m^3/h plants in the low OFMSW context with a high or low tariff (1912 k€ and 422 k€, respectively); and
- a 200 m^3/h plant in the low OFMSW context with a high tariff (704 k€).

These analyses suggest that smaller cost reductions present very attractive market conditions. However, a direct comparison between cost and revenue variables could not be made, due to the differing variable ranges.

4.2.3. Risk analysis

The previous case studies did not assign a probability of occurrence to the events. Therefore, a risk analysis was conducted, whereby the different critical variables were modified and the probability of NPV in each case was calculated (Table 2). In these analyses, the value of the subsidy was not varied, since the high tariff scenario already provided the maximum value. The Monte Carlo method, which applies the cumulative distribution function associated with stochastic variables, was used to assess project risk, simulating one thousand iterations. The mean value was set equal to the baseline value, while the standard deviation was assumed to be equivalent to the range used in the alternative analyses.

The results of the analysis showed that the 300 m^3/h plant with a high tariff and high OFMSW had a 59 % chance of achieving a positive NPV. The summary data further pointed to the relevance of the subsidy value, showing that the probability of achieving a positive NPV decreased to 25 % in the low tariff context. Similarly, the analysis highlighted the equally strategic role associated with net revenues related to OFMSW treatment, as in the low OFMSW context, the probability of achieving a positive NPV reduced to 35 %. The only case that demonstrated a significant probability of achieving a positive NPV (at 45 %) was the 200 m^3/h scenario in the dual high combination. In some cases, the probability was 0 % (i.e., 100 m^3/h size with a low tariff). These findings align perfectly with previous predictions for an inadequate incentive system within a mature biogas-biomethane market such as that of Italy [24].

4.2.4. BEP analysis

The final stage in the analysis of RO1 involved a break-even point (BEP) analysis, aimed at supporting decision-makers by identifying the

Table 2
Monte Carlo simulation OFMSW (organic fraction of municipal solid waste) – percentage of positive NPV.

	High OFMSW		Low OFMSW	
	High Tariff	Low Tariff	High Tariff	Low Tariff
100 m^3/h	6 %	1 %	2 %	0 %
200 m^3/h	45 %	18 %	24 %	5 %
300 m^3/h	59 %	25 %	35 %	12 %

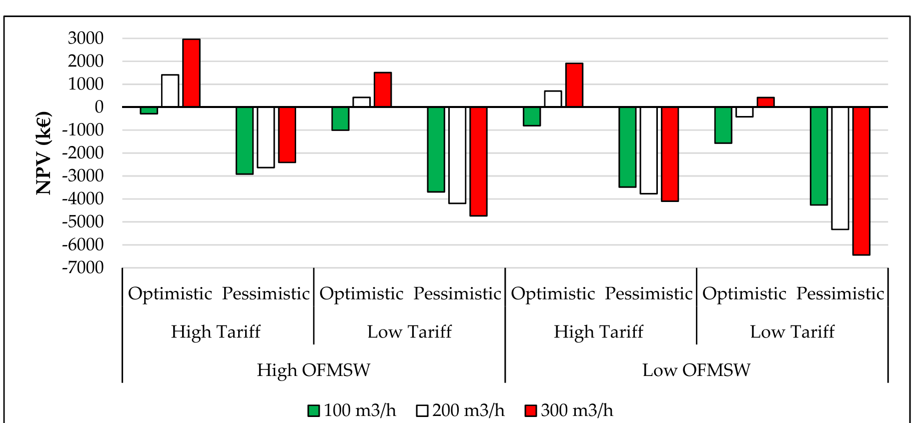

Fig. 7. Profitability analysis – scenario analysis (costs) OFMSW (organic fraction of municipal solid waste).

values of the critical variables that would reduce NPV zero [24]. On the OFMSW side, both subsidy value and the value related to OFMSW treatment were considered (Fig. 8).

4.3. Baseline scenario – by-products

The subsequent analysis aimed at assessing RO2. Initially, it examined by-products from substrates, in line with sustainability principles. The baseline scenario included six case studies derived from the three plant sizes and two potential tariff values (Fig. 9). The plant sizes and high/low tariff conditions were consistent with those proposed for the OFMSW. However, the incentive values differed according to the incentive decree proposed in Section 3.

The results highlighted that the new incentive decree led to significantly different outcomes for by-products. Despite by-products generally having lower biomethane potential than the OFMSW, as well as one fewer revenue item (i.e., net OFMSW treatment revenue), the NPV was positive in almost all cases in the baseline scenario. This can be attributed to the incentive value, which was higher than the cost of biomethane production. Specifically, the costs were 0.81 €/m^3, 0.71 €/m^3 and 0.67 €/m^3 for the 100 m^3/h, 200 m^3/h, and 300 m^3/h sizes, respectively. These values exceed those proposed in the research (0.57–0.60 €/m^3 [84]). As observed for the OFMSW, values were lowered by the policy measure of a 40 % reduction in investment costs across the three stages. After this measure was applied, the following costs were recorded: 0.61 €/m^3, 0.53 €/m^3, and 0.51 €/m^3, respectively. Thus, they enabled a cost reduction of 0.16–0.20 €/m^3.

The 100 m^3/h size in the high tariff scenario proved more profitable than the only plant with a positive NPV related to the OFMSW (Fig. 1), which achieved an NPV of 988 k€. In comparison, the highest NPV for by-products was recorded by the 300 m^3/h size with a high tariff, at 5936 k€. Of note, for by-products, plant size is highly dependent on the availability of substrates, since these raw materials are not as easily transportable as the OFMSW. Analyzing the economic results per unit size, NPV ranged from 9880 to 19,787 €/(m^3/h). The minimum value of this range was four times larger than the maximum value found for the OFMSW.

A further comparison was made based on incentive value and size. Regarding the first variable, the difference between the high and low tariff scenarios (i.e., an incentive varying by 0.21 €/m^3) resulted in a significant change in NPV in the range of 10,403–10,445 €/(m^3/h). Concerning the second variable, NPV increased between 6270 and 6585 €/(m^3/h), considering the difference between 100 and 200 m^3/h plant sizes; and between 3637 and 3678, considering the difference between 200 and 300 m^3/h plant sizes.

The cash flow decomposition revealed that, among the revenue components, subsidies dominated, ranging from 69 to 75 %. Biomethane sales components did not exceed 10 % (Fig. 10). Regarding costs, maintenance costs during biogas production excelled by approximately 21–22 %. These accounted for approximately 75 %, together with five other cost items, including electricity costs in the two phases, compost operations, labor, and investment costs in the first phase (Fig. 10).

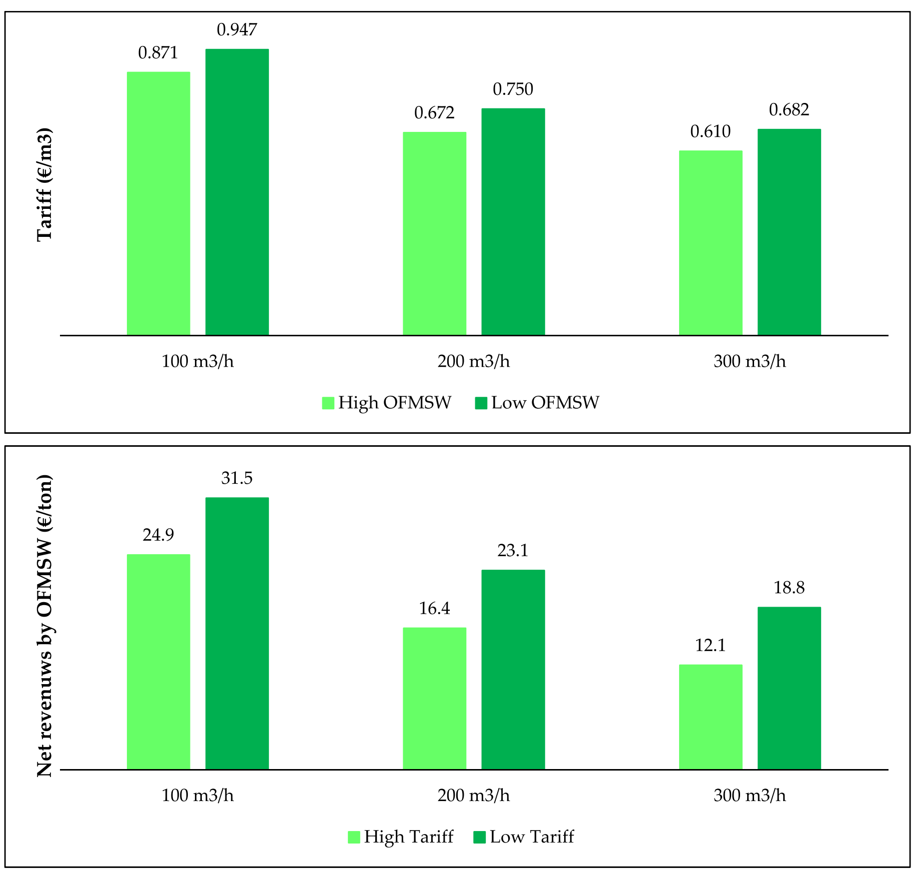

Fig. 8. BEP analysis – OFMSW (organic fraction of municipal solid waste). The following acronym is used: tariff (unitary all-inclusive tariff) The results showed that, for the 300 m^3/h size, the incentive value was 0.610 €/m^3 lower than that of the high tariff scenario, thus confirming profitability. The other two scenarios studied in this work (300 m^3/h low OFMSW, 200 m^3/h high OFMSW) required only 0.02–0.03 €/m^3, compared to 0.65 €/m^3. Therefore, the choice did not tend to favor the implementation of these plants. Regarding net OFMSW treatment revenue, there was a 12.1 €/ton value for the high tariff scenario in the 300 m^3/h size, which increased to 16.4 €/ton in the 200 m^3/h size. In the low tariff scenario, a value of 18.8 €/ton was recorded in the 300 m^3/h size. This variable may indicate the profitability of these plants for certain tariff levels, but with the costs falling on citizens.

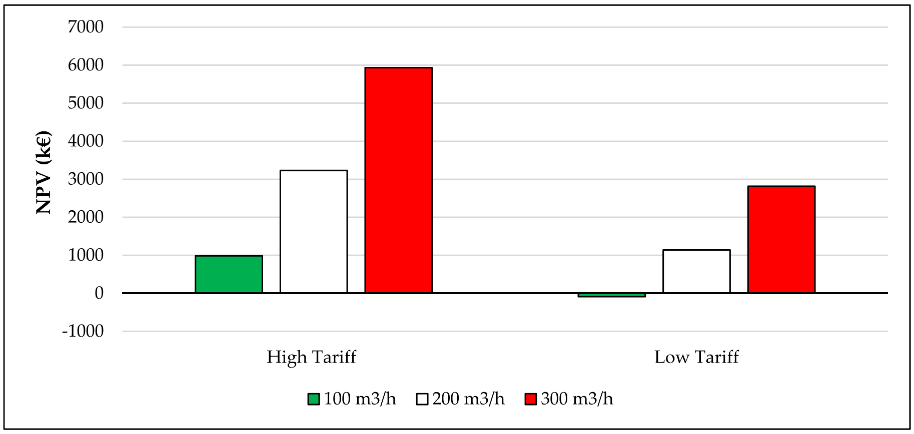

Fig. 9. Profitability analysis – Baseline scenario by-products.

4.4. *Alternative scenario – by-products*

4.4.1. *Sensitivity analysis*

The structure of the by-products aligned with that which was proposed for the OFMSW. Analyses supporting the baseline scenario were also conducted for these resources, with the objective of measuring how NPV varied as a function of critical variables. Regarding revenue, the biomethane sales price was adjusted by 0.05 €/m^3 to affect an optimistic and a pessimistic scenario. Since the proposed subsidy corresponded to its maximum value, only the pessimistic scenario was considered, with a variance of 0.10 €/m^3 (twice that proposed for the OFMSW, due to the significantly larger starting point). In total, eighteen cases were

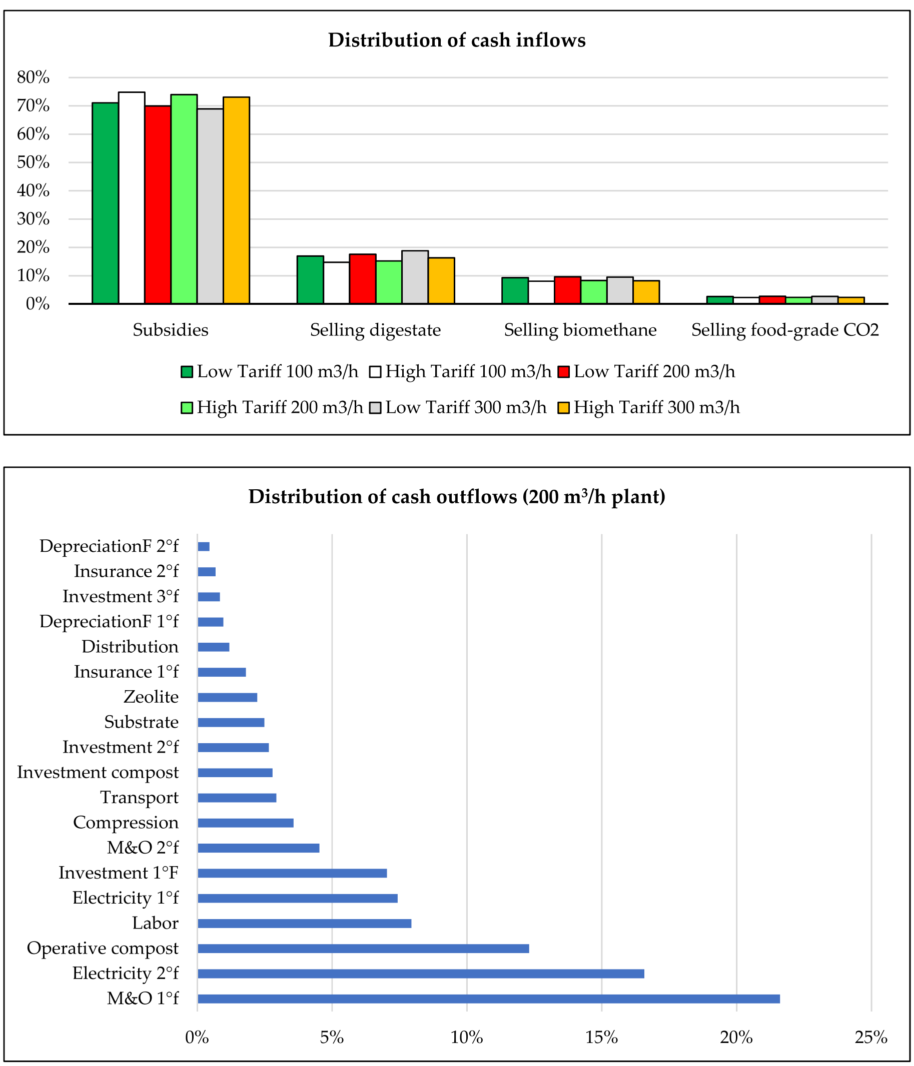

Fig. 10. Distribution of cash flows – Baseline scenario By-products.

considered (Fig. 11).

NPV, similar to the baseline scenario, proved unprofitable in the low tariff scenarios for the 100 m^3/h size. The impact of subsidies on the 200 m^3/h size was also notable, with the positive NPV reduced to 109 k€ given a 0.10 €/m^3 subsidy reduction.

Regarding costs, the variations were identical to those reported for the other substrate. Thus, the following three variables were considered in the pessimistic situation: a 5 % increase in maintenance costs in the first phase, a 0.05 €/kWh rise in electricity costs for both phases, and a 200 €/kW increase in investment costs in the first phase. In total, eighteen cases were considered (Fig. 12).

These additional sensitivity analyses confirmed the previous findings, with the 100 m^3/h size proving unprofitable in the low tariff scenarios. In this context, the 200 m^3/h size achieved its minimum positive value with increased maintenance costs in the biogas production phase (301 k€). Finally, the last key variable that was made to vary was the opportunity cost of capital, which was assumed equal to 7.5 %. In total, six cases were considered (Fig. 13), all of which demonstrated a positive NPV.

4.4.2. Scenario analysis

The alternative scenario analysis extended to a scenario analysis involving the variation of multiple variables simultaneously. In this analysis, the two variables in focus were biomethane sale price (5 €/m^3) and subsidy value (10 €/m^3). Of note, the pessimistic scenario concerned both policy reference scenarios, while the optimistic scenario only concerned the low tariff context. Therefore, a total of nine cases were analyzed (Fig. 14).

The results confirmed the previous findings, indicating a negative NPV for both the 100 m^3/h and the 200 m^3/h sizes in the low tariff context. The minimum positive NPV value was associated with the 100 m^3/h size in the pessimistic high tariff context (398 k€).

On the cost side, the three variables considered varied within the same range. The pessimistic scenario predicted a 5 % increase in AD maintenance costs, a 0.05 €/kWh rise in electricity costs, and a 200 €/kW increase in the AD investment cost. The optimistic scenario predicted their decrease, and the number of case studies increased to 12 (Fig. 15).

The results for costs mirrored the observations for revenues. In this case, the minimum positive NPV was 52 k€ in the pessimistic scenario of the 100 m^3/h size with a high tariff. Thus, a strong correspondence was evident between these alternative results and those of the baseline scenario, wherein the number of case studies analyzed was fewer than that analyzed for the OFMSW, due to the exclusion of the net OFMSW treatment revenue. Furthermore, subsidy value played a key role in determining plant profitability.

4.4.3. Risk analysis

In the previous analyses, many cases emerged in which by-products proved profitable. Subsequently, a probability of occurrence was assigned to each of these cases using a Monte Carlo analysis with one thousand iterations. In these analyses, the value of the subsidy was not made to vary, since the high tariff condition already reflected the maximum value (Table 3).

The results of this analysis solidified the findings for the baseline scenario. It emerged that the 300 m^3/h size with a high tariff was certainly profitable, but the two smaller sizes also had very high probabilities. In one case, the probability exceeded 95 %, while in the other it was close to 100 %. In the low tariff context, a predictable outcome occurred: probability decreased, but the significance of this change only applied to a few dimensions. In more detail, the probability shifted from approximately 44 % for the 100 m^3/h size to 97 % for the 300 m^3/h size.

4.4.4. BEP analysis

The analysis of RO2 concluded by identifying the value of the critical variable that rendered NPV zero (Fig. 16).

This BEP analysis compared the “minimum” subsidy values needed for profitability with the expected subsidy. From this, it emerged that the 300 m^3/h size value was approximately 0.18 €/m^3 lower than the low tariff, but this difference reduced to 0.11 €/m^3 for the 200 m^3/h size. As for the 100 m^3/h size, two markedly different situations emerged: the high tariff was profitable and had a margin of 0.19 €/m^3, while the low tariff had a value of 0.998 €/m^3, and was therefore lower than the BEP (1.015 €/m^3).

5. Policy implications

The transportation sector is actively progressing toward decarbonization, as is required to meet the requirements of the ambitious European Green Deal and address the challenges posed by climate change. This study did not compare different sustainable alternatives [92], as its sole focus was biomethane. Decarbonization of the transportation sector requires a mix of sustainable solutions. Included among these, biomethane is capable of reducing emissions by approximately 85 $gCO2_{eq}$/km (section 2.1). Thus, fueling a natural gas vehicle traveling 20,000 km entirely with biomethane could reduce emissions by approximately 1.7 tCO_2eq. This reinforces the importance of biomethane to environmental sustainability [35].

Biomethane, also referred to as “green gas,” exhibits strong potential for supporting the SDGs [14]. Furthermore, it aligns with the virtuous model of circularity by using sustainable substrates [8]. These include those evaluated in this research, such as the OFMSW and potential by-products (e.g., citrus pulps, olive pomace, whey, pomace and grape

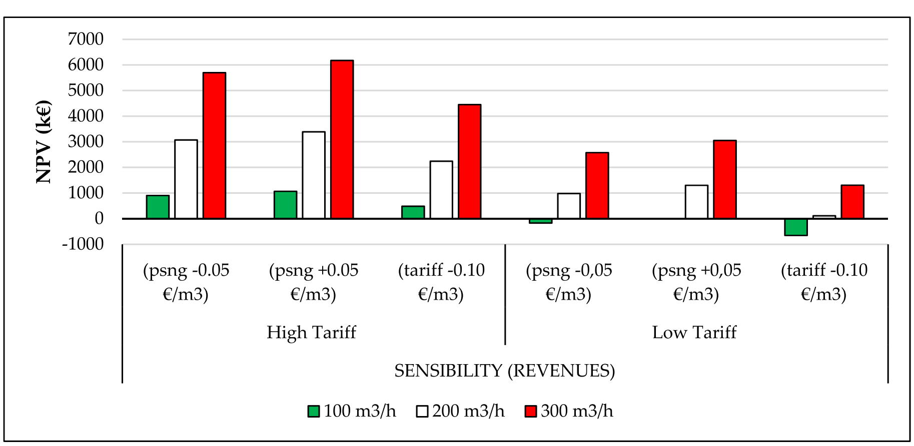

Fig. 11. Profitability analysis – sensitivity analysis (revenues) by-products. The following acronyms are used: psng (biomethane sale price) and tariff (unitary all-inclusive tariff).

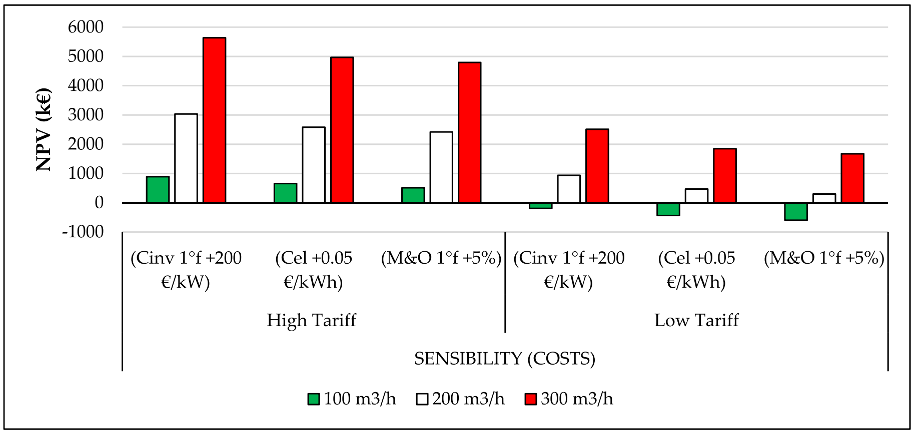

Fig. 12. Profitability analysis – sensitivity analysis (costs) by-products. The following acronyms are used: Cinv (unitary investment cost in the AD phase), Cel (electricity cost in both the AD and the upgrading phases) and M&O 1°f (percentage of maintenance & overhead cost in the AD phase).

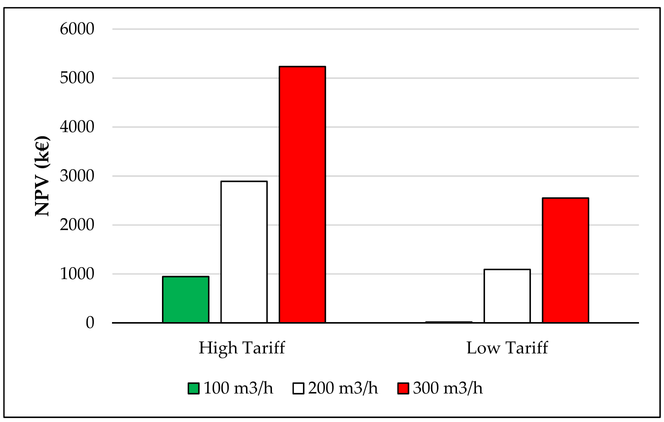

Fig. 13. Profitability analysis – sensitivity analysis (cost opportunity of capital) by-products.

dregs, cattle manure, pig slurry, cereal straw). The Italian National Agency for New Technologies, Energy and Sustainable Economic Development report highlights biomethane's substantial potential in Italy [91], and a similar result is proposed by another study [23]. Furthermore, a Guarantee of Origin can be applied to confirm the renewable origin of the energy sources used.

Strict control over the feedstock used in biomethane plants is essential [41], not only to meet sustainability requirements but also to protect public funds. Subsidy policies aim at reducing the costs associated with sustainable technologies, in order to increase the competitiveness of renewable sources over fossil sources. However, positive externalities related to social and environmental benefits must also be considered in the cost-benefit analysis of any renewable project [84].

Several studies have emphasized the strategic role played by subsidies in the economic analysis of biomethane plants [12,51,52,54,55], producing findings that are consistent with this study. However, the Italian case presents a distinct policy picture. Existing OFMSW plants, which previously benefited from an incentive scheme that did not differentiate between the OFMSW and by-products (and could therefore generate advantages related to OFMSW-related revenues), now face penalties under the Ministerial Decree September 15, 2022, making plants treating by-products more economically attractive. The data proposed in Section 4 indicate profitability for by-product treatment in the majority of cases, even for small-scale plants. Thus, expanding on a previous work [84] that considered a minimum profitability size of 350 m^3/h for by-products, this study verified profitability for even 100 m^3/h plants. The sustainable benefits of by-products have been highlighted [10,32], and the new incentive decree supports a circular economy model, aligning resource recovery with economic opportunities.

Going into the merits of the decree, the different incentive applied to 100 m^3/h plants compared to 200 and 300 m^3/h plants should not impact the choices made by decision-makers, since the value of this difference is insignificant (0.05 €/m^3). However, the choice of plant size depends strongly on the substrate considered. In this vein, future research should be directed toward social analyses to better understand stakeholder involvement in this process. Lack of cooperation or

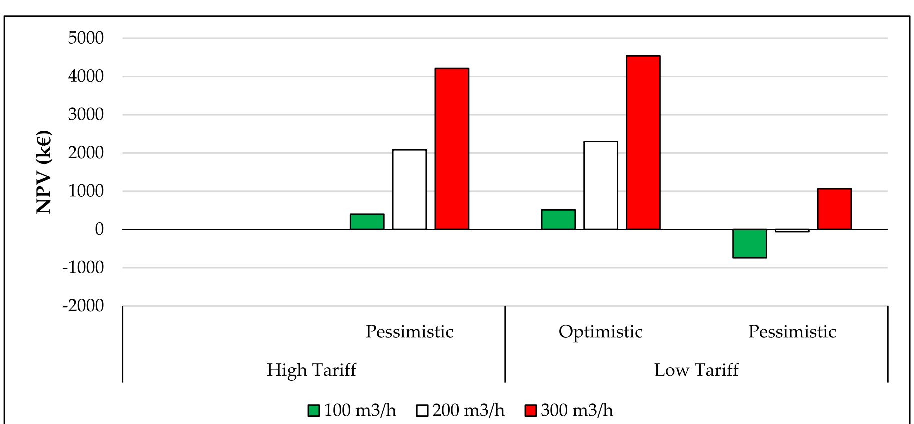

Fig. 14. Profitability analysis – scenario analysis (revenues) by-products.

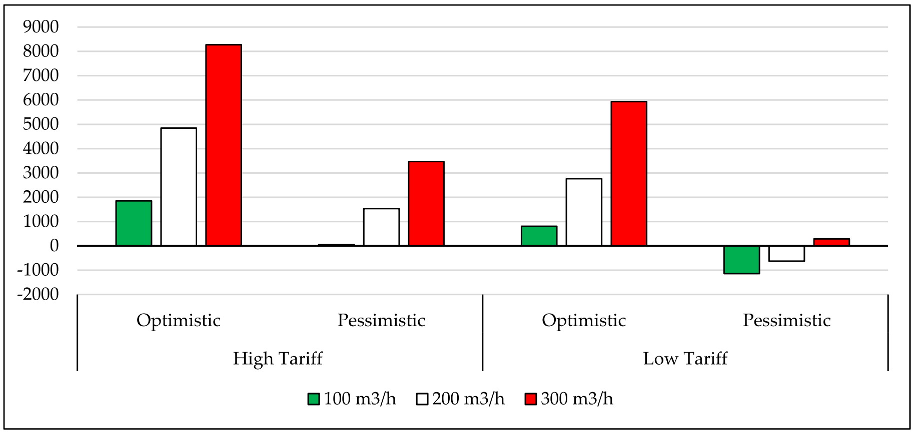

Fig. 15. Profitability analysis – scenario analysis (costs) by-products.

Table 3
Monte Carlo simulation by-products – percentage of positive NPV.

	High tariff	Low tariff
100 m^3/h	95.2 %	44.4 %
200 m^3/h	99.8 %	84.9 %
300 m^3/h	100 %	97.2 %

consortia may hinder the creation of a collection point for different substrates and the subsequent establishment of AD and upgrading plants. Thus, the concept of biomethane communities is part of the collaboration between different stakeholders and thus the pursuit of sustainable communities [93].

On the OFMSW side, no distinction between plant sizes is considered in the current policy, in order to encourage local sector development and minimize the transportation of this waste. Thus, smaller sizes are no longer cost-effective, and a shift from 200 m^3/h [84] to 300 m^3/h plant sizes has been observed. The motivation for this shift is likely the value of the incentive, which is set to the intermediate value between the baseline (0.40 €/m^3) and high tariff scenarios (0.90 €/m^3) [24]. A separate correction coefficient should be proposed for the 100 and 200 m^3/h plant sizes, in order to attract investment. Otherwise, a higher cost may be demanded from citizens, resulting in higher revenues from municipal solid waste management. In this regard, a social analysis should be conducted, aimed at not only increasing separated collection (at the moment, the availability and efficiency of separated collection varies across Italian regions), but also improving the quality of this service. This work shows that a sale price of 0.65 €/m^3 downstream of the subsidy would not break even on costs.

The virtuous model of circularity may also support solutions associated with other outputs, such as digestate [88] and CO_2 [94]. Industrial eco-systems and the appropriate use of public funds are essential for a sustainable transition in the transportation sector. Within this framework, biomethane can play a strategic role internationally [95,96]. Europe moves toward ambitious goals [18] and the price of the European Union Allowance will play a key role. The Next Generation EU finances biomethane plants, and the Mattei Plan serves as a connection point between Italy and Africa. The combination of natural gas (i.e., the least polluting among fossil sources) and biomethane would enable a more sustainable cooperation.

Beyond the subsidy period, the costs of selling biomethane at the values examined in the model (i.e., the final 5 years of the project lifetime) do not cover costs, thereby generating losses. Solutions to this problem are urgently needed to prevent production from becoming undesirable in these final project years. Likewise, it is important that the sustainability of these plants become less associated with subsidies over time, and that links to gas sales and emission allowance prices be evaluated. At the same time, the decree also applies to the conversion of existing biogas plants related to agricultural installations, warranting more in-depth sustainability analyses due to the flexibility afforded by electricity and heat production.

Finally, this work aligns with the existing research, emphasizing the relevance of economic models for assessing the profitability of plants [25,50,68] and framing efficient policy choices [24]. The results underscore that biomethane holds the potential to contribute to a model of energy independence [13], alongside other green and circular resources. Finally, while the construction of small- and medium-sized plants may not leverage economies of scale, they may nonetheless contribute to the

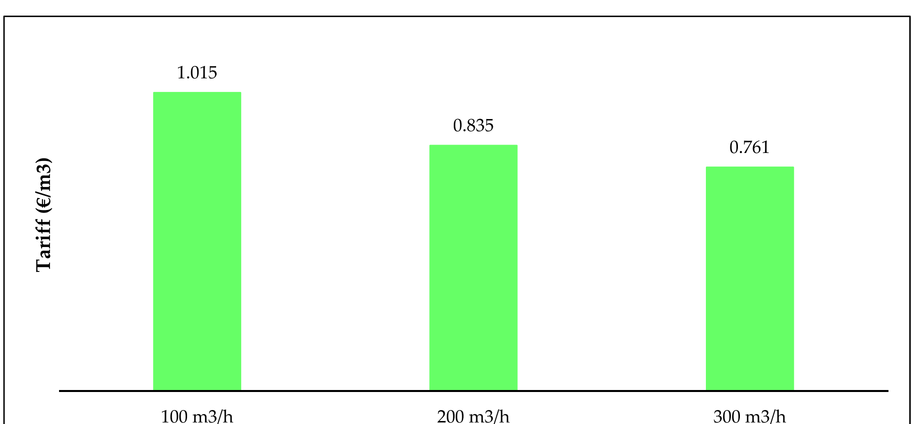

Fig. 16. BEP analysis – by-products. The following acronym is used: tariff (unitary all-inclusive tariff).

development of virtuous models utilizing local resources [56]. To this end, information campaigns may be crucial for raising awareness among citizens, and particularly youth, fostering stakeholder engagement and the creation of sustainable communities.

6. Conclusions and way forward

Biomethane offers a virtuous model of a circular bioeconomy, aligned with the SDGs. Its capacity to replace gas derived from fossil sources is essential for maintaining a trajectory toward energy decarbonization. In a virtuous supply chain, certain substrates (e.g., the OFMSW, by-products) can be valorized, generating renewable energy sources (i.e., green gas) and new products (e.g., digestate, food-grade CO_2), and offering significant benefits in the form of reduced pollutant emissions.

This study focused on economic analyses related to an incentive decree that, for 15 years, has provided a tariff with a maximum value of 0.651 €/m^3 for the OFMSW and 1.155–1.207 €/m^3 for by-products. Regarding the OFMSW, the baseline scenario proved profitable only for a 300 m^3/h plant size in a high tariff and high OFMSW context. The risk analysis indicated profitability in 59 % of the cases, which reduced to 45 % for 200 m^3/h plants under the same conditions. Transitioning from high to low OFMSW resulted in a 21–24 % reduction in the probability of achieving a positive NPV. This highlights the importance of not imposing costs on citizens, as sustainability aims at aligning the interests of all stakeholders towards a pragmatic approach.

The situation was notably different for by-products. In the baseline scenario, NPV was negative only for 100 m^3/h plants with a low tariff. The risk analysis demonstrated 44 % profitability, rising to 95–100 % in the high tariff scenario. Thus, the new decree offers significant economic opportunities for the construction of biomethane plants fueled by by-products.

To ensure replicability, BEP values were calculated. For the OFMSW, the following values were recorded: 0.61–0.68 €/m^3 for 300 m^3/h plants, 0.67–0.75 €/m^3 for 200 m^3/h plants, and 0.87–0.95 €/m^3 for 100 m^3/h plants, depending on the low versus high OFMSW context. For by-products, the values were: 1.01 €/m^3, 0.83 €/m^3, and 0.76 €/m^3 for the 100, 200, and 300 m^3/h plant sizes, respectively.

Biomethane supports a model advancing toward energy independence, mitigating the geopolitical risks faced by countries that are heavily dependent on the importation of gas. In particular, small- and medium-sized plants are crucial, as is the utilization of all substrates. Therefore, a positive contribution of by-products is anticipated for the future. It is also necessary to increase separated collection in all Italian regions and to use the OFMSW to produce green energy, by providing correction coefficients for 100 and 200 m^3/h plant sizes, making them more economically attractive without increasing costs to citizens. In this direction, social analyses may be useful to evaluate the perspectives of different stakeholders, fostering the realization of industrial ecosystems. The pragmatic model of sustainability advocates for solutions to be provided and for circular models to be placed at the core of economic activities.

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.

Data availability

Data will be made available on request.

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