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Technical and socio-economic analysis of supply chains for the production of biomethane

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Abstract

This study aims to assess the potential role of the biomethane supply chain in the Italian gas sector by analyzing its production capacity, environmental impact, and socio-economic implications. A comprehensive evaluation is conducted to estimate the availability of different feedstocks and the relative biomethane theoretical potential, followed by an assessment of the impact of biomethane deployment on greenhouse gas emissions, which correspond to social costs, through the construction of three scenarios.

The Ministerial Decree on Biomethane (15 September 2022), approved by the Italian government, promotes advanced biomethane production, supported by 1.73 billion euros from the PNRR. The goal is to reach 2.3 $bm^3/year$ *by 2026, aligning with Italy's PNIEC strategy. The 2023 PNIEC revision targets 5.7* $bm^3/year$ *by 2030, aiding the phase-out of Russian gas, transport decarbonization, and waste valorization.*

In this context, the maximum availability of different feedstocks for the biomethane production in Italy is estimated with reference to the year 2022, regardless their current final uses. The lack of a unified system results in the use of various data sources, such as ISTAT, ENEA, ISPRA, BDN, and CLAL, which later allow for the assessment of theoretical biomethane potential based on biochemical methane potential coefficients, estimating a value of 5.65 $bm^3/year$.

An evaluation of the actual biomethane production is conducted (0.250 $bm^3/year$*) and biogas produced at the national level (4.36* $bm^3/year$*) allows to estimate the extractable biomethane potential from biogas plants via upgrading technologies (2.61* $bm^3/year$*). Italy, having one of Europe's largest biogas sectors, expects significant biogas-to-biomethane conversions under the Biomethane Decree. The remaining untapped potential, equal to 2.79* $bm^3/year$*, could be leveraged through new plants construction.*

The study also quantifies biomethane-related greenhouse gas emissions, associating emission coefficients with different feedstocks and estimating the performance of different conversion pathways. A well-to-tank analysis accounts for all greenhouse gas emissions from feedstock supply to biomethane distribution, enabling a comparison with fossil natural gas.

Three scenarios for biomethane development until 2040 are presented:

1. *Business As Usual Scenario (2022 production levels)*
2. *Biomethane Decree Scenario (achievement of the decree's objectives)*
3. *Theoretical Potential Scenario (aligned with the 5,7* bm^3 *PNIEC target)*

Each scenario considers Italy's gas demand forecasts and the resulting biomethane-related emissions. Special focus is given to social costs of avoided emissions, using the Social Cost of Carbon (SCC) to quantify climate change mitigation benefits. Comparing the results obtained through the implementation of these three scenarios, the percentage of emissions reduction in cumulative terms varies between 3,03% and 6,26% if the reference BAU scenario is contrasted with respectively the BD and TP scenarios, referring to 2040. With regard to social costs, the difference in monetary terms between the case where the overall gas demand is met solely with natural gas and the three scenarios, leads to a range of cumulative benefits to 2040 which varies between $2,940M of the reference BAU scenario and $91,688M of the TP scenario, with the BD scenario at $44,381M (a discount rate of 3% is applied).

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LIST OF ABBREVIATIONS

EBA - European Biogas Association

PNRR - Piano Nazionale di Ripresa e Resilienza

PNIEC - Piano Nazionale Integrato per l'Energia e il Clima

SNAM - Società Nazionale Metanodotti

SCC - Social Cost of Carbon

OFMSW - Organic Fraction of Municipal Solid Waste

ISTAT - Istituto Nazionale di Statistica

ENEA - Ente per le Nuove tecnologie, l’Energia e l’Ambiente

ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale

BDN - Banca Dati Nazionale dell’Anagrafe Zootecnica

ENAMA - Ente Nazionale per la Meccanizzazione Agricola

SC – Separate Collection

PDO – Protected Designation of Origin

PGI – Protected Geographical Indication

DM – Dry Matter

VM – Volatile Matter

BMP - Biochemical Methane Potential

JRC - Joint Research Centre

RED - Renewable Energy Directive

IEA – International Energy Agency

PNRR - Piano Nazionale di Ripresa e Resilienza

CNG – Compressed Natural Gas

LNG - Liquified Natural Gas

FiT - Feed-in Tariff

TSO - Trasmission System Operator

WTT – Well to Tank

GHG – Greenhouse gases

GWP – Global Warming Potential

LHV - Lower Heating Value

CBA - Cost Benefit Analysis

RSE - Ricerca sul Sistema Energetico

OECD - Organization for Economic Co-operation and Development

US IWG - United States Interagency Working Group

Introduction

Biomethane is a renewable gas obtained from the purification of biogas, produced by the anaerobic digestion of biomass of organic origin, such as agricultural waste, livestock waste and urban organic waste. Thanks to its composition, similar to that of fossil methane, biomethane can be fed into the natural gas network or used as a fuel for transport, thus contributing to the reduction of greenhouse gas emissions and the transition to a more sustainable energy system.

According to the EBA (European Biogas Association) Statistical Report 2022, biomethane production in Europe grew by almost 20% in 2022 compared to the previous year, reaching 4.2 billion cubic meters. This increase highlights the growing role of biomethane in the European energy mix and its ability to contribute to energy security by reducing dependence on natural gas imports. In particular, Italy is home to one of the fastest biomethane markets in Europe, with a growth from 1 plant in 2018 to 47 operational plants by the end of 2022, leading to a biomethane production equal to about 250 million cubic meters. [1]

The Ministerial Decree on Biomethane of 15 September 2022, approved by the Italian government, encourages the production and introduction into the network of advanced biomethane, through a system of incentives to support the biomethane supply chain. In this sense, the PNRR (National Recovery and Resilience Plan) has allocated 1.73 billion euros to support the development of biomethane, with the aim of reaching at least 2.3 billion cubic meters of annual national production by 2026, thanks to the application of this legislation. [2]

The decree is part of an integrated strategy of sustainability, energy security and economic development, carefully described in the PNIEC (National Integrated Plan for Energy and Climate), which defines the Italian objectives and policies for the energy transition in the period 2021-2030. In particular, in the 2023 revision of the PNIEC, biomethane is seen as a key source for:

- Increasing national biomethane production up to 5.7 billion cubic meters by 2030.
- Contributing to the phase-out of Russian gas, reducing Italy's energy vulnerability.
- Supporting the transition in transport, especially in hard-to-abate sectors such as heavy and maritime transport.
- Valuing agricultural by-products and organic waste, improving the sustainability of the agro-industrial sector.

The aim is to define a national strategy, capable of meeting the requirements imposed by the European Union for each Member State in environmental matter, as outlined in Regulation (EU) 2021/1119, also known as the European Climate Law, which sets by law the objective of climate neutrality by 2050 and introduces an intermediate target of reducing emissions by 55% by 2030 compared to 1990 levels (Fit for 55 package). Moreover, the REPowerEU 2022 plan outlined measures to accelerate the energy transition and reduce Russia’s dependence on fossil fuels, primarily by strongly promoting the production of alternative fuels such as biomethane, green hydrogen and renewables. [3]

Referring to this context, the purpose of this study is to define the maximum availability of different feedstocks in order to evaluate the theoretical potential of advanced biomethane in Italy, with reference to the 2022. The lack of a national tracking system for these raw materials, more suited to the production of biomethane and which comply with the requirements established by the Biomethane Decree, leads to the usage of different data sources. Moreover, a focus on the current final uses of each feedstock is provided, just to highlight the fact that it would not be possible to use this maximum availability only for energy purposes, since there are already other markets for some of these raw materials. The estimate of the theoretical potential of advanced biomethane was carried out by considering the percentage of dry and volatile matter, as well as the biochemical methane potential coefficients derived from different literature studies, which have conducted experimental tests in order to obtain these average values for each feedstock. In this way, it was possible to turn this maximum availability into the advanced biomethane producible by means of the anaerobic digestion process, without considering the final uses that already characterized a share of these raw materials in Italy. The geographical allocation which characterizes the territorial estimate, in terms of quantity and producibility of advanced biomethane, will allow more accurate evaluation in terms of logistic and integration of energy networks. [4]

In addition, an analysis of the current biomethane and biogas production at national level was conducted, in order to determine the extractable potential of biomethane, which is possible thanks to the biogas purification process with the installation of appropriate technologies, such as upgrading units. Since Italy is one of the countries with the highest number of biogas production plants in Europe, a significant share of the incentivized plants that comply with the requirements of the Biomethane Decree, is expected to undergo a reconversion from biogas to biomethane production. Considering the theoretical potential, the extractable potential, and the biomethane already produced, it was possible to assess the remaining untapped potential for energy use, which could be harnessed through the construction of new plants, with reference to 2022.

After estimating the theoretical potential of advanced biomethane, a focus on the emissions related to the production of this alternative fuel was carried out. Starting from literature studies conducted in institutional and academic contexts, it was possible to associate an emission coefficient based on the typology of feedstock employed to produce a specific share of the theoretical potential. This approach ensures that all greenhouse gas emissions (GHG) generated throughout the entire supply chain of the selected raw material, as well as during the biomethane production process up to the point of fuel distribution, are accounted for. In this way, it is possible to evaluate the overall environmental impact and the potential benefit compared to fossil natural gas, which represents the counterpart that biomethane would replace. Of fundamental importance is the technology used for the production of biomethane itself, as it allows for a significant reduction in emissions associated with this process, making biomethane environmentally competitive with other fuels.

At the end of this study, three different scenarios were built in order to describe the evolution of the biomethane supply chain in Italy, until 2040. The Business As Usual Scenario, which is the reference one, was obtained by considering just the production of biomethane with reference to 2022. The Biomethane

Decree and Theoretical Potential Scenarios, instead, take into account respectively the effects of the Biomethane Decree and the possibility to exploit the overall theoretical potential, in accordance with the objective of 5.7 billion cubic meters, set by the PNIEC. At the basis of each individual scenario, the overall Italian gas demand derived from the perspectives developed by SNAM (the Italian TSO for gas), together with the expected biomethane production and the associated emissions. Particular attention has been given to evaluating the social costs associated with the emissions avoided by using biomethane instead of natural gas. For this purpose, an in-depth analysis carried out by RSE of the vast literature available on the social cost of carbon (SCC) was considered, in order to identify the best recommended values. The SCC represents the value, in monetary terms, of the global damage from climate change attributable to the emission of an additional ton of carbon dioxide (CO_2) into the atmosphere. The measurement of the SCC is fundamental to measure the costs of investments for the reduction of GHG with the benefits in terms of avoided climate damage. [5]

2. Maximum feedstock availability for advanced biomethane production in Italy

The selection of feedstocks for biomethane production, used to calculate the maximum availability, is determined by the current regulations. It should be noted that the estimate carried out does not take into account the current final uses of the selected raw materials, but the total quantity produced in Italy.

The Biomethane Decree of 2022 contains provisions for the incentive of biomethane fed into the natural gas network, in compliance with the sustainability requirements set out in Directive 2018/2001/EU of 11 December 2018. More precisely, biomethane eligible for incentives under this decree must:

- be produced by agricultural plants or organic waste plants

- comply with the quality characteristics set out in the Decree of 3 June 2022 containing the technical regulation on the chemical-physical characteristics and the presence of other components in combustible gas

- comply with the sustainability and GHG emission reduction requirements set out in Article 4, paragraph 1, letter c) and g), of the Ministerial Decree 2022, which ensures:

- The compliance with the sustainability and GHG emission reduction criteria (Article 4, paragraph 1, letter c), numbers 1) and 2):
  1) for biomethane intended for use in the transport sector: exclusive use of "advanced" raw materials and reduction of GHG emissions of at least 65%
  2) for biomethane intended for other uses: reduction of GHG emissions of at least 80%

- The compliance with the use of at least 40% by weight of livestock effluents in the overall feed recipe in the case of agricultural plants located in areas vulnerable to nitrates with a nitrogen load of livestock origin exceeding 120 m^3/ha (Article 4, paragraph 1, letter g).

The aim of these new directives is to increasingly encourage the usage of "advanced" feedstocks that derive mainly from waste, residues and by-products in order to reduce GHG emissions and limit competition with food crops [2].

In this context, different raw materials were analyzed according to their abundance, necessity to be disposed of or high potential of conversion into biomethane: agro-industrial waste, Organic Fraction of Municipal Solid Waste (OFMSW), urban wastewater sludge, zootechnical waste and whey. (Figure 1)

The estimate in terms of annual quantities of these feedstocks for a given territory is characterized by a variable uncertainty, mainly related to the weather and productivity (for example agricultural crops). Furthermore, the absence of a single entity which is responsible for keeping track of the different waste produced at national level leads to disaggregated, not harmonized and in many cases not directly deducible data. For this reason, multiple data sources specific to each sector of interest were consulted (ISTAT, ENEA, ISPRA, BDN, CLAL), in order to estimate the maximum availability of the raw materials considered, regardless of their current final uses.

The data collected refer to the year 2022 as they are the most updated data for every type of feedstock. Specific calculation methodologies were developed in order to aggregate and process in the most efficient way such data, well described in the following paragraphs. [4]

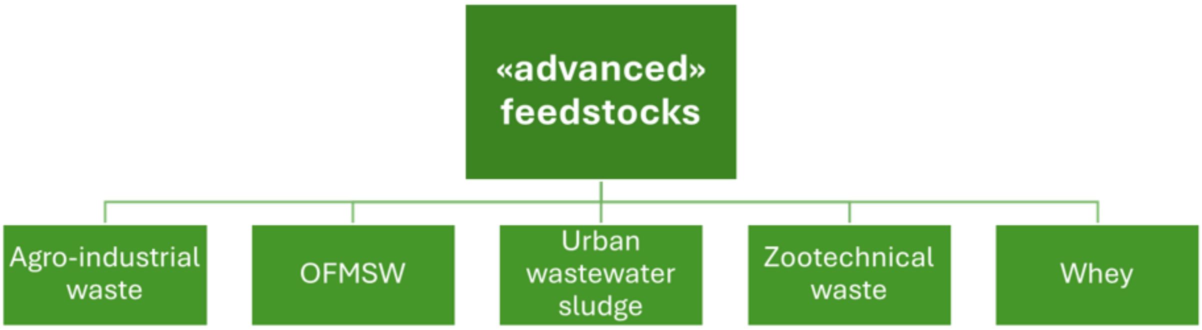


Figure 1 - "Advanced" feedstocks selected for the biomethane production

2.1 Agro-industrial waste

Since 2009, as part of activities funded by a program agreement with the Ministry of Economic Development, ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development) has developed the Biomass Atlas Portal. The aim is to census the national biomass potential and implement an interactive WebGIS platform to be used as a decision support for the choice and optimal location of biomass exploitation plants. The data presented express the theoretical potential of different agro-industrial residues which derive from ENEA elaborations on ISTAT, ISPRA, National Forest Inventory and other sector entities.

By means of this platform, the quantities expressed in tons of dry matter per year ($t_{d.m.}/year$) at regional level are evaluated just for that agro-industrial waste which can be used to produce advanced biomethane: straw, residues from pruning, residues from olive oil industry, residues from wine industry, residues from dried fruit processing, residues from rice processing, residues from citrus juice industry and residues from tomato processing. To this end, these feedstocks are usually exploited in co-digestion in order to optimize the anaerobic process, although some of these residues require particular pre-treatments to make them suitable for this purpose. [4]

2.1.1 Straw

Straw is the product obtained from the dried stalks of cereal plants such as wheat, barley, oats, rye or rice, which remain after the seeds have been harvested.

Italy occupies a prominent position in the European agricultural sector, thanks to its geographical and climatic diversity, which allows the cultivation of a wide range of high-quality products.

In terms of crops, Italy is one of the main producers of cereals in the European Union, in particular durum wheat, used for pasta. For this reason, straw represents one of the most abundant feedstocks analyzed at national level.

Regions	Straw [t_d.m./year]
Piemonte	2,088,878
Aosta	107
Liguria	871
Lombardia	2,065,365
Trentino Alto-Adige (BZ)	678
Trentino Alto-Adige (TN)	1,749
Veneto	1,610,595
Friuli-Venezia Giulia	394,026
Emilia-Romagna	1,457,820
Marche	437,342
Toscana	549,645
Umbria	267,103
Lazio	330,786
Campania	293,226
Abruzzo	208,989
Molise	107,995
Puglia	968,289
Basilica	361,459
Calabria	157,050
Sicilia	618,052
Sardegna	246,799
Total	**12,166,824**

Table 1 - Straw production in Italy, Biomass Atlas Portal, year 2022

However, it is necessary to consider that straw is already employed for different final uses as reported in a study of ENAMA (National Agency for Agricultural Mechanization) included in the Biomass Project, with the collaboration of the Ministry of Agricultural and Forestry Policies.

Crop	Final use	Usage percentage
Soft or hard wheat	Litter for animal shelter	40-50%
	Animal feed	5-10%
	Paper industry and various	5-10%
	Burned on the field	30-50%
Barley	Litter for animal shelter	40-50%
	Burned on the field	50-60%
Oats	Animal feed	40-60%
	Burned on the field	40-60%
Rice	Litter for animal shelter	20-30%
	Burned on the field	70-80%

Table 2 - Final uses of straw, ENAMA

At the same time, a variable but considerable share of the straw produced in Italy is disposed of by burning it in open fields, based on the crop from which it was produced. Therefore, anaerobic digestion could be a good opportunity to convert this share of straw into biomethane, in order to assign an adding value in economic and environmental terms to this agricultural waste. [6]

2.1.2 Residues from pruning

Pruning residues include agricultural waste resulting from the maintenance of tree crops such as: apple, pear, apricot, cherry, peach, nectarine, plum, hazelnuts, almonds, pistachios, figs, orange, mandarin, clementine, lemon, table grapes, wine grapes, table olives and oil olives. This type of biomass contains lignocellulosic components, which can be recovered for energy production. [6]

Regions	**Pruning [t_d.m./year]**
Piemonte	94,054
Aosta	1,847
Liguria	37,778
Lombardia	42,321
Trentino Alto-Adige (BZ)	32,437
Trentino Alto-Adige (TN)	31,078
Veneto	434,591
Friuli-Venezia Giulia	72,667
Emilia-Romagna	214,064
Marche	65,396
Toscana	155,085
Umbria	54,756
Lazio	141,111
Campania	228,821
Abruzzo	191,629
Molise	33,390
Puglia	582,541
Basilica	43,633
Calabria	664,136
Sicilia	571,403
Sardegna	112,583
Total	**3,805,321**

Table 3 - Production of residues from pruning in Italy, Biomass Atlas Portal, year 2022

Residues from pruning are only minimally recovered for firewood, while they are mostly chopped and buried on site or in some cases removed from cultivation and burned in order to prevent sources of pathogen inoculation. For this type of biomass, optimized harvesting and transport practices are required to make the usage for energy purposes possible. [7]

2.1.3 Residues from olive oil industry

Olive pomace is considered the primary waste of the olive oil industry because it represents a significant and easily recoverable fraction of the oil extraction process. It is an abundant by-product composed mainly of solid residues of pulp, pits and peels which contain a significant amount of organic matter, rich in lignocellulose and residual oils, making olive pomace suitable for energy production.

Regions	Pomace [t_d.m./year]
Piemonte	27
Aosta	1
Liguria	5,835
Lombardia	1,518
Trentino Alto-Adige (BZ)	-
Trentino Alto-Adige (TN)	744
Veneto	2,521
Friuli-Venezia Giulia	218
Emilia-Romagna	1,462
Marche	4,669
Toscana	19,847
Umbria	7,236
Lazio	35,612
Campania	33,039
Abruzzo	19,288
Molise	13,304
Puglia	118,392
Basilica	6,660
Calabria	104,712
Sicilia	103,020
Sardegna	9,569
Total	**487,674**

Table 4 - Oil pomace production in Italy, Biomass Atlas Portal, year 2022

Oil pomace is almost completely used, directly as fuel in many same oil mills where it is produced. In other cases, it is possible to separate the pit in order to obtain pellets or destinate it for direct combustion, while the peels can be employed for the production of biogas. Oil pomace represents also a good quality soil improver on agricultural land. [4]

2.1.4 Residues from wine industry

Grape marc, which consists of skins, seeds, and stems of grapes, represents a large amount of the residue from wine production. For this reason, it is an abundant and constant byproduct, rich in organic compounds such as cellulose, hemicellulose, lignin and fat which make grape marc suitable for energy production.

Regions	Marc [t_d.m./year]
Piemonte	33,867
Aosta	223
Liguria	1,089
Lombardia	18,869
Trentino Alto-Adige (BZ)	5,390
Trentino Alto-Adige (TN)	13,231
Veneto	105,929
Friuli-Venezia Giulia	14,499
Emilia-Romagna	152,823
Marche	13,778
Toscana	20,994
Umbria	6,024
Lazio	14,145
Campania	69,696
Abruzzo	27,779
Molise	20,718
Puglia	159,725
Basilica	1,640
Calabria	2,982
Sicilia	105,149
Sardegna	16,238
Total	**804,788**

Table 5 - Wine marc production in Italy, Biomass Atlas Portal, year 2022

Grape marc is already employed in distilleries for the production of grappa and for the extraction of grape seed oil, useful in the food, cosmetic and industrial sectors. [4]

2.1.5 Residues from dried fruit processing

Shells are that part of the waste resulting from the processing of dried fruit, in particular hazelnuts, almonds and pistachios, rich in lignocellulosic components which can be recovered for energy production. [6]

Regions	Shells [t_d.m./year]
Piemonte	13,882
Aosta	1
Liguria	8
Lombardia	37
Trentino Alto-Adige (BZ)	-
Trentino Alto-Adige (TN)	1
Veneto	428
Friuli-Venezia Giulia	28
Emilia-Romagna	146
Marche	78
Toscana	834
Umbria	241
Lazio	14,728
Campania	11,405
Abruzzo	86
Molise	449
Puglia	10,785
Basilica	315
Calabria	950
Sicilia	42,247
Sardegna	684
Total	**97,333**

Table 6 - Shells production in Italy, Biomass Atlas Portal, year 2022

Unlike other agro-industrial residues, which are collected on the agricultural field and therefore the origin of the residue flow can be geographically traced back to the province of production, for fruit shells the physical availability of the residue must be traced back to the place of consumption, which can be the final consumer of dried fruit as is, or the processing industry. [7]

Regarding the final uses, a good part of these residues is already used, both as a source of thermal energy in the companies themselves, and in some electricity generation plants. [6]

2.1.6 Residues from rice processing

Waste from rice processing, such as the husk, chaff, middling, green grain and broken grains, derive from the selection and cleaning processes of the grain.

In particular, the husk is made up of dry and thin, light and fragile vegetable fibers, rich in cellulose, hemicellulose and lignin, but poor in nutrients, which is why it is not used directly for human nutrition but can be used for energy purposes. [6]

Regions	Husk [t_d.m./year]
Piemonte	144,003
Aosta	-
Liguria	-
Lombardia	89,644
Trentino Alto-Adige (BZ)	3
Trentino Alto-Adige (TN)	-
Veneto	3,076
Friuli-Venezia Giulia	21
Emilia-Romagna	4,924
Marche	-
Toscana	413
Umbria	-
Lazio	-
Campania	-
Abruzzo	1
Molise	-
Puglia	2
Basilica	-
Calabria	210
Sicilia	29
Sardegna	4,539
Total	**246,865**

Table 7 - Production of residues from rice processing in Italy, Biomass Atlas Portal, year 2022

Among the various by-products, only the husk is used for energy production through direct combustion, while the others are used in various sectors: human nutrition, animal feed, pharmaceuticals and cosmetics, paint and glue industries. [6]

2.1.7 Residues from citrus juice industry

Citrus pulp is a by-product composed of peels, residual pulp, seeds and membranes, resulting from the industrial processing of citrus fruits. It is a moist mass, characterized by high quantities of fibers, residual sugars, essential oils, organic acids and a low percentage of proteins that make it suitable for energy production. In some agricultural areas, pulp can represent a high percentage of the initial weight of processed citrus, making its management and reuse a priority. [6]

Regions	Citrus pulp [t_d.m./year]
Piemonte	-
Aosta	-
Liguria	20
Lombardia	-
Trentino Alto-Adige (BZ)	-
Trentino Alto-Adige (TN)	-
Veneto	-
Friuli-Venezia Giulia	-
Emilia-Romagna	-
Marche	-
Toscana	13
Umbria	-
Lazio	437
Campania	3,801
Abruzzo	9
Molise	11
Puglia	31,823
Basilica	12,352
Calabria	119,014
Sicilia	151,803
Sardegna	2,116
Total	**321,399**

Table 8 - Citrus pulp production in Italy, Biomass Atlas Portal, year 2022

In this estimate, an overestimation of the real availability is carried out since all the citrus production is considered how it is completely turned into juice, even if a share of citrus fruits harvested is dedicated for the consumption of fresh fruit. [7]

Citrus pulp is already the subject of interest for the development of innovative industrial processes aimed at producing chemical intermediates for bioplastics, biofuels through the fermentation of sugars and more recently also fabrics. [4]

2.1.8 Residues from tomato processing

The waste resulting from the tomato transformation process consists of pulp (rotten fruit), peel and seeds, equal to 2-3% of the processed raw material and characterized by a prevalent composition of fibers, as well as proteins and fats. [6]

Regions	Tomato peel [t_d.m./year]
Piemonte	1,224
Aosta	-
Liguria	-
Lombardia	5,053
Trentino Alto-Adige (BZ)	-
Trentino Alto-Adige (TN)	1
Veneto	1,081
Friuli-Venezia Giulia	-
Emilia-Romagna	17,371
Marche	3
Toscana	1,358
Umbria	75
Lazio	1,240
Campania	2,110
Abruzzo	527
Molise	571
Puglia	13,206
Basilica	1,045
Calabria	989
Sicilia	681
Sardegna	227
Total	**46,762**

Table 9 - Production of residues from tomato processing in Italy, Biomass Atlas Portal, year 2022

These residues are often treated as waste or used as low-value feed with a high fiber content. However, “fermentable” tomato peels are the subject of interest for several studies regarding the development of new industrial processes aimed at producing chemical intermediates to be synthesized, such as bioplastics. [4]

2.2 Organic Fraction of Municipal Solid Waste (OFMSW)

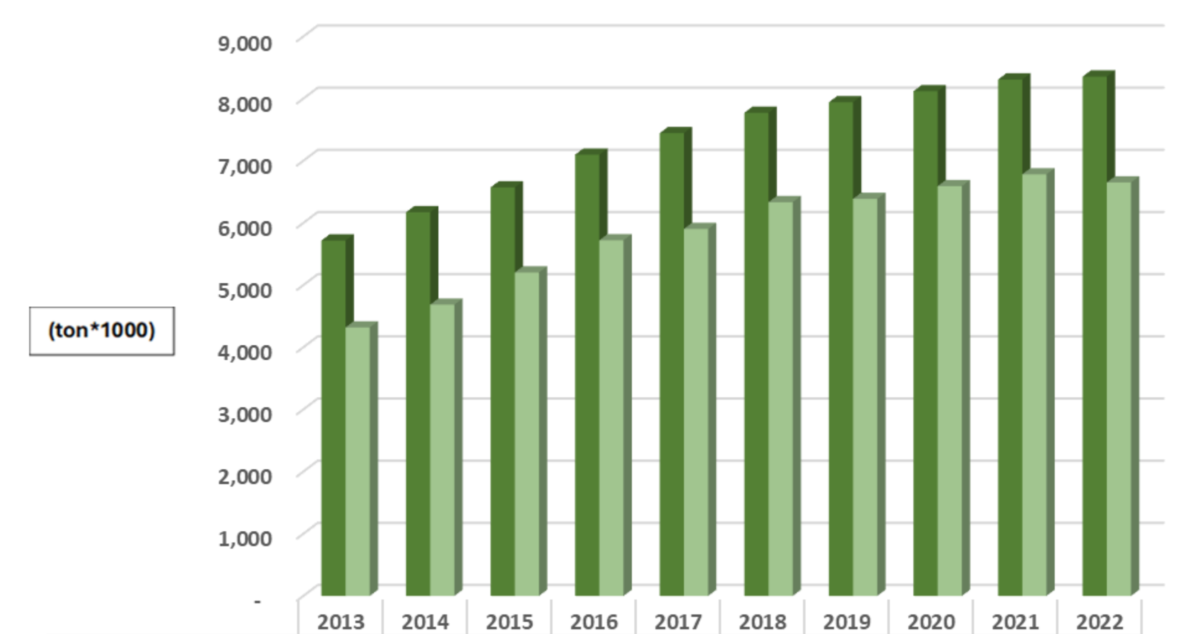
Every year the report "Rapporto Rifiuti Urbani" is prepared by ISPRA (Higher Institute for Environmental Protection and Research), thanks to a complex activity of data collection, analysis and processing with the contribution of the regional and provincial Agencies for Environmental Protection. From this source, it has been possible to determine the quantities of the OFMSW, expressed in tons per year ($t/year$) at regional level. [8]

Regions	**OFMSW [t/year]**
Piemonte	446,008
Valle d'Aosta	12,010
Liguria	149,735
Lombardia	1,146,548
Trentino-Alto Adige	136,678
Veneto	729,430
Friuli-Venezia Giulia	154,554
Emilia-Romagna	796,862
Marche	223,930
Toscana	525,315
Umbria	118,581
Lazio	579,436
Campania	634,343
Abruzzo	154,054
Molise	25,778
Puglia	432,476
Basilicata	49,990
Calabria	176,410
Sicilia	515,641
Sardegna	233,907
Total	**7,241,686**

Table 10 - OFMSW production in Italy, ISPRA, year 2022

Organic waste represents an abundant flow which must be accurately recovered and recycled according to the national objectives, well described by the legislation in force of matter. For this reason, more and more efforts are carried out to improve the efficiency of separate waste collection (SC), so that the quantities disposed of in landfills are reduced as much as possible. This requires adequate distribution of waste treatment plants throughout the territory. [8]

In Figure 2, the trend in the quantities of waste managed referring to the period 2013 - 2022, with particular attention to the organic faction recovered by means of separate collection (wet + green) is reported. In particular, it is possible to see a progressive growth of the overall quantities treated (+ 46.1% between 2013 and 2022), as well as the organic fraction alone which accounts for 54% in the same temporary range. [8]



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Total input	5,717	6,172	6,572	7,099	7,445	7,772	7,942	8,119	8,307	8,355
Organic waste from SC	4,319	4,685	5,203	5,721	5,903	6,334	6,387	6,592	6,782	6,651

Figure 2 - Quantities of waste subjected to biological treatment, ISPRA, years 2013 – 2022

The organic fraction recovered from separate collection with reference to 2022 (Figure 3) can be classified mainly in three categories:

- "Biodegradable waste from kitchens and canteens" (EER code 200108), which accounts for 5 million tons, equal to 74.8% of the total.
- "Biodegradable waste" from gardens and parks (EER code 200201), with over 1.6 million tons, represents 24.6%
- "Market waste" (EER code 200302), with over 38 thousand tons, constitutes the residual share of 0.6%. [8]

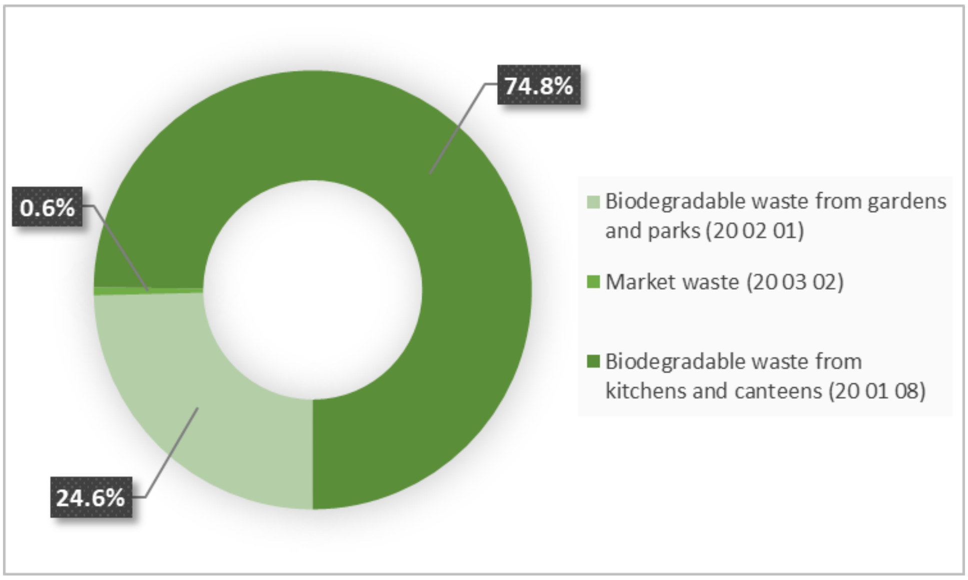


Figure 3 - Product composition of the organic fraction from separate collection, ISPRA, year 2022

Figure 4 shows the percentage distribution of the different types of biological treatment of organic waste adopted at national level in the year 2022. With a quantity of approximately 3.4 million tons, most of the recovered organic fraction is managed in treatment plants which exploit anaerobic and aerobic processes. In percentage terms, this amount accounts for 50.8%, showing an increase of 3.2 percentage points (compared to 2021) while a quantity of about 3 million tons, providing a contribution equal to 44.4%, is destined to composting plants. The remaining 4.8% share, equal to just over 315 thousand tons, is finally managed in anaerobic digestion plants. [8]

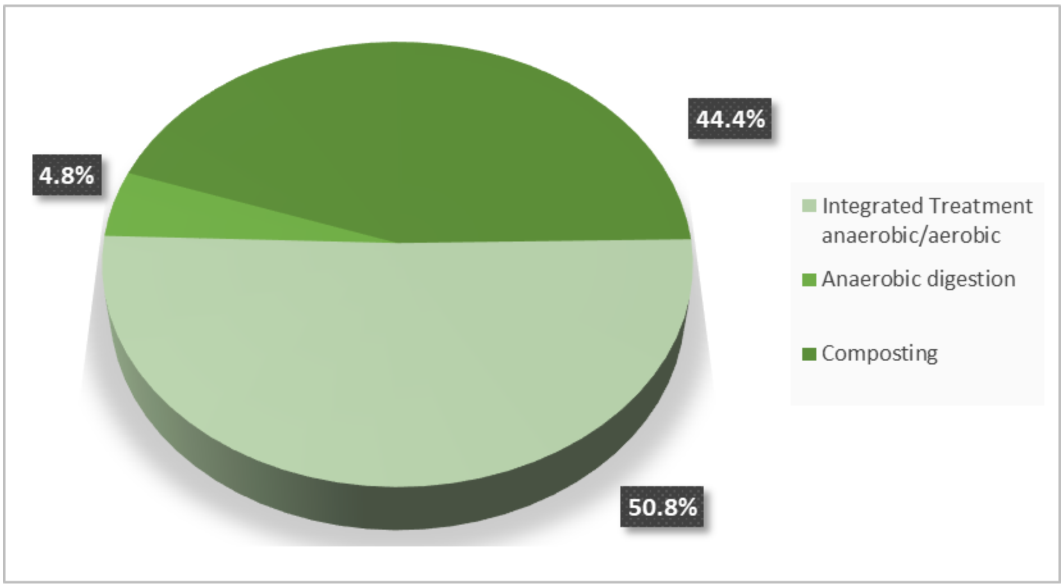


Figure 4 - Biological treatment of the organic fraction from separate waste collection, ISPRA, year 2022

In Figure 5, the typology of treatment system adopted at regional level is described, confirming the leading role of Lombardia with approximately 1.6 million tons, equal to 23.6% of the national total. In this region, 78 plants are operational, of which 63 are dedicated to composting, 7 to integrated anaerobic/aerobic treatment and 8 to anaerobic digestion only, for a total treatment capacity of approximately 2.9 million tons.

Veneto follows, with approximately 1.1 million tons, equal to 15.8% of the total and a plant capacity of 59 units (50 composting plants, 5 integrated anaerobic/aerobic treatment plants and 4 anaerobic digestion plants), for a total capacity of approximately 1.6 million tons.

Emilia-Romagna, with 24 operating plants (11 composting plants, 10 integrated anaerobic/aerobic treatment plants, 3 anaerobic digestion plants) and a total capacity of approximately 1.5 million tons, contributes to the treatment of organic waste with over 678 thousand tons, equal to 10.2% of the total.

These data analysis highlights the predominant role of the northern part of Italy, regarding the amount of organic waste from separate collection treated and in terms of number of plants. [8]

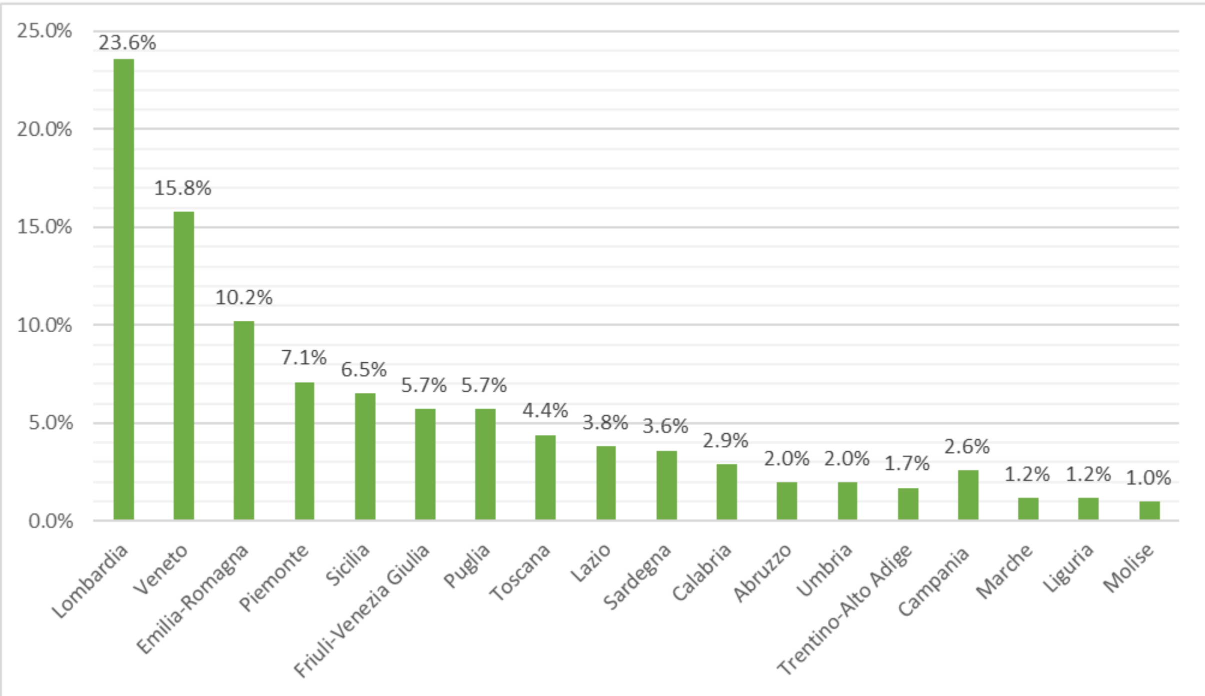


Figure 5 - Biological treatment of the organic fraction from separate waste collection by region, ISPRA, year 2022

2.3 Urban wastewater sludge

Sludge is the residue resulting from the purification processes of domestic, urban or industrial wastewater. Specifically, urban sludge is classified as a non-dangerous special waste, according to the EWL (European Waste List) with code 190805 which concerns waste produced by wastewater treatment plants, by water purification and by the treatment of water for industrial use.

Consequently, the quantities of urban wastewater sludge, expressed in tons per year ($t/year$) at regional level, are determined by means of the annual report “Rapporto Rifiuti Speciali”, elaborated by ISPRA. The national production of special waste was quantified starting from the information contained in the databases of the Single Environmental Declaration Model (MUD) relating to the annual declarations made pursuant to the sector legislation. [9]

Regions	Urban wastewater sludge [t/year]
Piemonte	346,224
Valle d'Aosta	8,982
Lombardia	541,636
Trentino-Alto Adige	147,042
Veneto	404,796
Friuli-Venezia Giulia	85,967
Liguria	51,011
Emilia-Romagna	365,174
Toscana	251,598
Umbria	43,813
Marche	80,518
Lazio	233,737
Abruzzo	73,479
Molise	5,077
Campania	173,230
Basilicata	3,748
Puglia	235,186
Calabria	30,248
Sicilia	49,738
Sardegna	66,239
Total	**3,197,443**

Table 11 – Urban wastewater sludge production in Italy, ISPRA, year 2022

Referring to the year 2022, most of the produced sludge from the treatment of urban wastewater was managed, covering a quantity of about 3 million tons. 54.2% of the total managed was sent for disposal operations, 43.4% was destined for recovery operations while the remaining 2.4% was stored at the end of the year waiting to be allocated to a treatment operation (Figure 6). In addition to the share exported abroad equal to 47 tons as explained below, the difference of approximately 150.443 tons with the total quantity of wastewater sludge produced in Italy, does not present specific information regarding its final destination. [9]

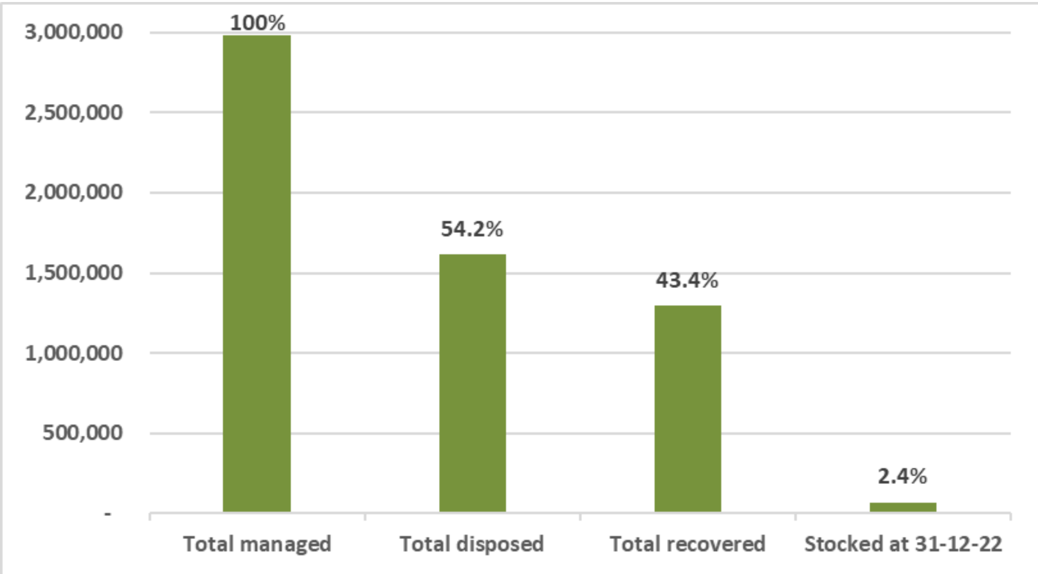


Figure 6 – Summary of forms of management of sewage sludge from urban wastewater, ISPRA, year 2022

Analyzing in more detail the destination of wastewater sludge (Figure 7), every type of treatment is indicated by a letter followed by a number. Among the disposal operations, "Biological treatment" (D8) is the most relevant, with just over 1 million tons, equal to 39.0% of the total managed and 72.0% of the total sent for disposal operations. It is followed by "Physical-chemical treatment" (D9) with respectively 7.7% of the total managed and 14.3% of the total disposed of and incineration (D10) with 4.9% of the total managed and 9.0% of the total sent for disposal. The data includes the quantities of special waste treated in incineration plants with energy recovery dedicated, mainly, to the treatment of urban waste. Landfill disposal (D1) represents 2.1% of the total managed and 3.9% of the total sent for disposal.

With reference to recovery, the prevalent operation is the "Recycling/recovery other organic substances" (R3) with more than 939 thousand tons; this operation involved 31.5% of the total managed and 72.6% of the total recovered. It is followed by "Exchange of waste to subject it to one of the operations from R1-R11" (R12) with 7.9% of the total managed and 18.2% of the total waste recovered, "Energy recovery" (R1) with 0.7% of the total managed and 1.6% of the total recovered while "Treatment in a terrestrial environment for the benefit of agriculture or ecology" (R10) represents the 2.9% of the total managed and 6.6% of the total sent to recovery operations.

To conclude, the 2.4 % of the total managed is destined to "Reserve" (R13), "Preliminary storage" (D15) and storage at producers, with reference to 31/12/2022. [9]

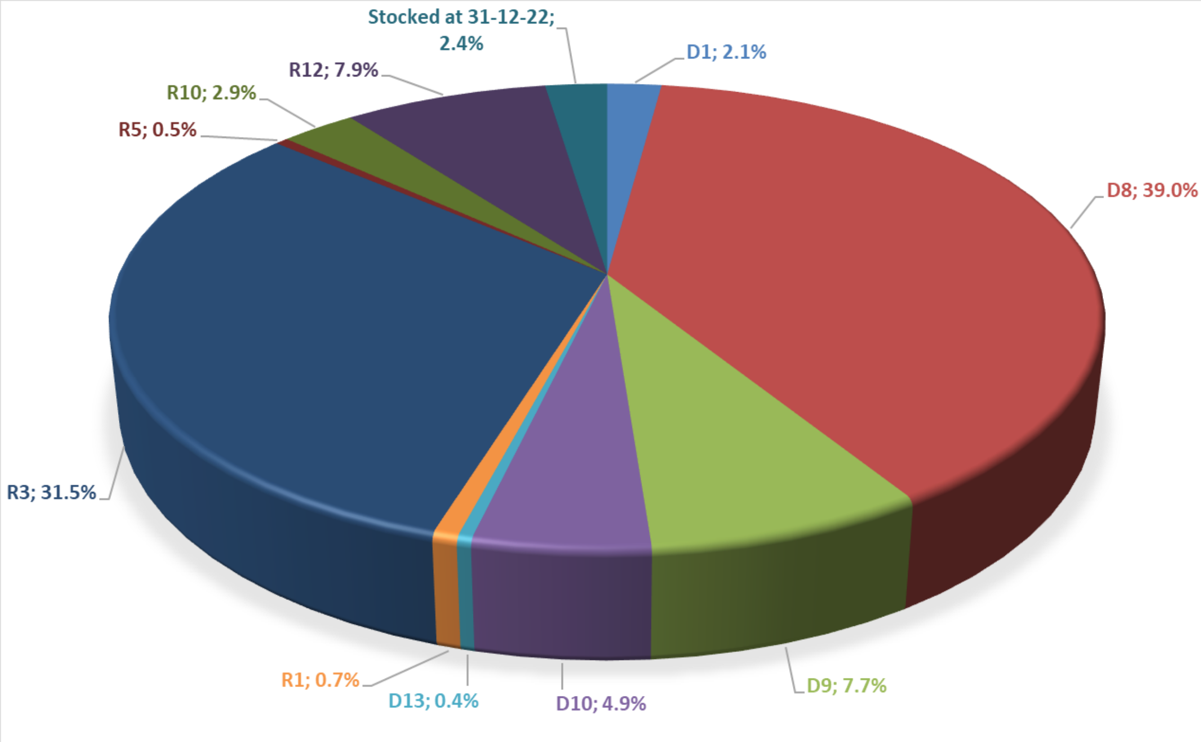


Figure 7 – Percentage distribution of urban wastewater treatment sludge management, ISPRA, year 2022

Table 12 highlights the total quantities disposed of and recovered at regional level, also in relation to 2021. The largest quantities managed are found in Lombardia, Emilia-Romagna and Veneto. Lombardia, with 28.8% of the total, is the region which managed most of the wastewater sludge produced in Italy. Recovery operations prevail, among which the most used are the “Recycling/recovery of organic substances” (R3), with 405 thousand tons, 47.2% of the total managed in the region, and the “Exchange of waste to subject them to one of the operations from R1 to R11” (R12) which, with almost 184 thousand tons, represents 21.4% of the total managed in the region.

In Emilia-Romagna, the sludge managed is equal to 14.7% of the national total; the most used management form is “Biological treatment” (D8) which, with over 245 thousand tons, represents 56.2% of the total managed in the region, followed by “Recycling/recovery of organic substances” (R3), with over 125 thousand tons.

In Veneto, the sludge managed is equal to 10.6% of the national total; the D8 disposal operation “Biological treatment” prevails with more than 144 thousand tons, 45,7% of the total managed in the Region, followed by “Recycling/recovery of organic substances” (R3) with just over 95 thousand tons. The sludge is sent for “incineration” (D10) in seven regions; the largest quantities are found always in Lombardia (over 102 thousand tons), followed by Toscana with over 15 thousand tons, Piemonte with almost 13 thousand tons and Emilia-Romagna with over 11 thousand tons.

Lower quantities are recorded in Veneto, Sicilia and Calabria with 1,888, 370 and 22 tons, respectively. In three regions "energy recovery" (R1) is practiced: in Lombardia, with more than 15 thousand tons, in Piemonte, with 167 tons and in Trentino-Alto Adige, with over 4 thousand tons. [9]

Regions	Total disposed [t] 2022	Total recovered [t] 2022	Total managed [t] 2022	Total managed [t] 2021
Piemonte	188,684	50,987	243,685	226,273
Valle d'Aosta	4,560	0	4,560	4,379
Lombardia	239,872	604,426	858,325	902,336
Trentino-Alto Adige	57,635	20,686	78,388	75,419
Veneto	166,761	125,519	315,962	312,490
Friuli-Venezia Giulia	45,677	14,243	59,955	47,078
Liguria	17,841	0	17,901	16,735
Emilia-Romagna	286,394	126,475	436,492	339,664
NORD	**1,007,424**	**942,336**	**2,015,268**	**1,924,375**
Toscana	169,887	42,264	212,691	238,314
Umbria	21,196	11,936	33,208	39,330
Marche	57,491	11,704	69,246	78,428
Lazio	151,515	28,453	180,019	176,479
CENTER	**400,089**	**94,357**	**495,164**	**532,551**
Abruzzo	21,833	7,192	30,385	33,291
Molise	10,858	950	11,876	8,807
Campania	3,896	49,647	55,491	11,695
Puglia	145,371	15,800	161,279	174,469
Basilicata	0	375	414	0
Calabria	725	13,624	14,940	8,942
Sicilia	9,523	121,124	130,973	138,072
Sardegna	14,873	49,238	64,433	76,428
SUD	**207,079**	**257,950**	**469,791**	**451,705**
TOTAL	**1,614,592**	**1,294,643**	**2,980,223**	**2,908,629**

Table 12 – Management of sludge produced by urban wastewater treatment by region, ISPRA, years 2021-2022

Figure 8 shows that approximately 47 thousand tons of sludge were exported abroad in the year 2022. Lazio mainly contributed, sending more than 23 thousand tons, equal to 50.3% of the total exported, followed by Veneto, Lombardia, Toscana and Piemonte with almost 9 thousand tons (19.3%), almost 6 thousand tons (12.6%), 5 thousand tons (10.8%) and almost 3.000 tons (6.2%) respectively.

Smaller quantities were exported by Calabria and Campania. There was a decrease in the quantities of sludge exported of more than 2,000 tons (-4.2%), going from 48,612 tons to 46,570 tons, compared to 2021. [9]

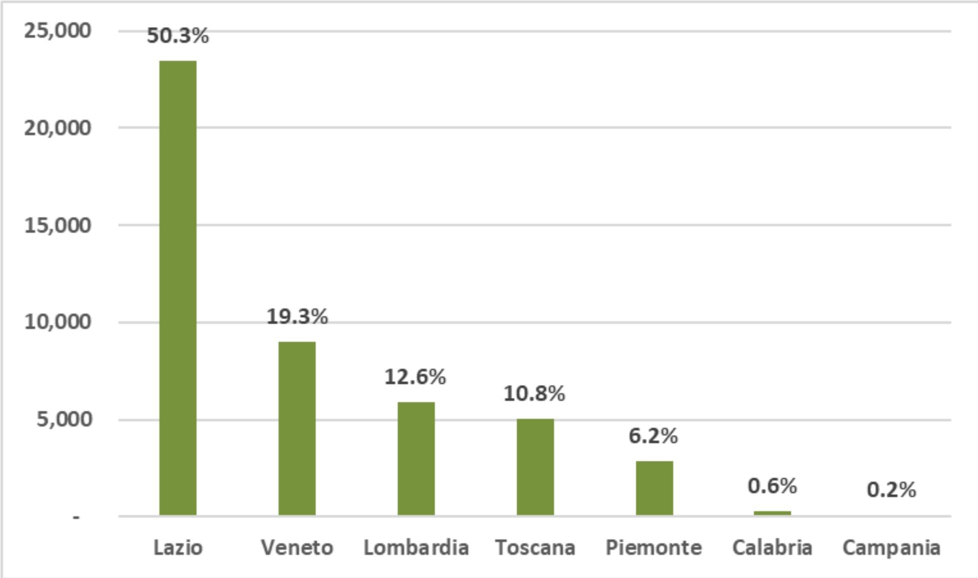


Figure 8 – Quantities of urban wastewater sewage sludge exported by region, tons, ISPRA, year 2022

2.4 Zootechnical waste

Livestock farming represents a key sector for the Italian agricultural and agri-food economy, contributing significantly to the production of meat, milk and other products of animal origin. Italy is famous for raising dairy and beef cattle, thanks to the high-quality milk produced which is required for iconic products such as Parmigiano Reggiano and Grana Padano, as well as the typical breeds to produce high-quality meat. Italy dominates the European market for buffalo milk, which is used almost exclusively to produce Mozzarella di Bufala Campana PDO. Pig farms play a central role for the production of PDO and PGI cured meats, such as Prosciutto di Parma and Culatello di Zibello. Sheep and goat farms are supported by a strong tradition in the central-southern regions where some typical cheeses are produced. To conclude, Italy is also a major producer of poultry and eggs, characterized by advanced production techniques and high food safety standards.

The theoretical estimate of zootechnical waste produced in Italy, expressed in tons per year ($t/year$) at regional level, was carried out by considering the overall amount of excrement resulting from the total number of heads of the most significant species, well described above.

For this purpose, the Banca Dati Nazionale dell'Anagrafe Zootecnica (BDN), which is an information system managed by the Ministry of Health, allows to determine the number of heads for every breed, divided according to age, sex and purpose of use. By means of the study « A spatial analysis of biogas potential from manure in Europe » developed by N. Scarlat, F. Fahl, J.-F. Dallemand, F. Monforti and V. Motola, it is possible to evaluate the manure produced thanks to specific conversion coefficients which represent the estimated manure potential expressed in tons per head ($t/head$), as shown in Table 13. [11]

Type of breeding	Manure [t/head]
Calves	2.9
Bovine	7.3
Male Bovine	9.1
Dairy Cows	19.3
Other Cows	9.1
Piglets	0.2
Other Pigs	1.6
Sows	4
Sheep	0.5
Goats	0.5
Broilers	0.04
Laying Hens	0.07
Other Poultry	0.11

Table 13 - Estimated manure potential from various livestock types and age groups

Regions	Poultry	Cattle	Buffaloes	Sheep & goats	Pigs
	Manure [t/year]				
Abruzzo	234,570	672,405	1,051	82,251	95,482
Basilicata	20,511	1,067,180	47,985	98,508	98,193
Calabria	37,056	1,202,562	17,898	147,253	4,643
Campania	179,485	1,604,131	3,456,057	109,333	79,357
Emilia romagna	1,529,885	5,991,612	3,267	30,874	107,854
Friuli venezia giulia	320,515	787,226	11,579	13,190	1,451,611
Lazio	202,113	2,066,631	971,269	296,592	366,756
Liguria	3,584	137,370	12	10,646	66,035
Lombardia	1,582,980	15,646,110	66,275	101,452	658
Marche	246,377	470,948	8,374	57,954	6,075,180
Molise	266,990	360,905	7,079	29,008	123,192
Piemonte	549,638	8,349,580	36,704	99,344	31,717
Puglia	240,607	1,753,161	143,509	113,442	1,734,187
Sardegna	61,083	3,210,956	119	1,568,833	36,570
Sicilia	338,493	3,677,311	26,450	376,616	373,687
Toscana	105,356	811,148	10,639	155,756	101,216
Trentino - alto adige (bz)	10,779	1,398,088	142	32,880	175,392
Trentino - alto adige (tn)	40,880	472,692	0	23,202	9,361
Umbria	171,993	603,715	8,677	46,273	255,972
Valle d'aosta	535	367,803	0	2,999	219
Veneto	2,637,864	6,142,961	23,821	47,435	874,694
Total	**8,781,296**	**56,794,495**	**4,840,908**	**3,443,835**	**12,061,978**

Table 14 - Manure production in Italy, author's calculation, year 2022

Manure is a precious resource in Italian agriculture, both for its nutritional properties and for its contribution to environmental sustainability, being used mainly as a natural fertilizer or substrate for biogas production. A consistent share of this potential resource must be disposed of because it is produced in large quantities and a good opportunity to satisfy this need could be the conversion of manure into biomethane. However, the lack of a national system that allows tracking the quantity of this raw material, combined with the variability of business management that occurs internally at each farm, makes it highly complex to accurately estimate the intended final uses for manure.

2.5 Whey

Whey is the liquid that separates from the curd during the cheese or ricotta production process. It is a natural component of milk, rich in nutrients, and is the main by-product of cheesemaking. Whey production in Italy is closely linked to the country's historic dairy tradition, which boasts a wide range of PDO and PGI cheeses, including Parmigiano Reggiano, Grana Padano, Mozzarella di Bufala Campana and Pecorino Romano. In particular, hard cheeses (such as Parmigiano Reggiano and Grana Padano) and fresh cheeses (such as mozzarella and ricotta) represent the main sources of production. In the European context, Italy competes only with Germany, France and the Netherlands in terms of volumes produced, opting for the traditional and artisanal use of whey, linked to its PDO cheeses and ricotta, rather than the industrial transformation of whey into innovative and high added value products.

The theoretical estimate of whey produced in Italy, expressed in tons per year ($t/year$), was carried out using the quantities of cheese carefully tracked by CLAL S.r.l which developed a leading platform for the analysis of the milk and dairy products market at Italian and global level. By means of specific conversion coefficients (Table 15), always elaborated by CLAL, it is possible to evaluate the equivalent milk necessary to produce every type of cheese and finally the obtainable whey (Table 16). [12]

Product	Cheese yield from 1 kg of whole milk	Liquid whey obtained [kg] from 1 kg of whole milk	Whey Powder obtained [kg] from 1 kg of Liquid Whey
Hard cheeses	0.08	0.85	0.063
Semi-hard cheeses	0.11	0.85	0.063
Soft cheeses	0.13	0.85	0.063
Fresh cheeses	0.15	0.85	0.063

Table 15 - Conversion coefficients, CLAL

Italy	Produced cheese [t]	Equivalent milk [t]	Obtainable whey [t]
Hard cheeses	470,000	5,831,266	**4,956,576**
Semi-hard cheeses	96,000	902,256	**766,917**
Soft cheeses	192,000	1,438,202	**1,222,472**
Fresh cheeses	572,000	3,888,511	**3,305,235**
Total	**1,330,000**	**12,060,235**	**10,251,199**

Table 16 - Cheese production and obtainable whey in Italy, CLAL, year 2022

The quantities of this by-product, expressed in tons per year ($t/year$), are determined at regional level by considering the distribution of production in previous years. [12]

Regions	Whey [t/year]
Marche	136,443
Abruzzo	27,293
Basilicata	24,013
Molise	170,605
Trentino Alto Adige	344,744
Puglia	382,011
Calabria	96,776
Campania	518,086
Lazio	149,037
Sardegna	605,404
Sicilia	115,898
Toscana	210,053
Piemonte	818,278
Emilia Romagna	1,725,574
Friuli Venezia Giulia	176,569
Valle d'Aosta	21,071
Veneto	1,059,313
Liguria	4,071
Lombardia	3,612,021
Umbria	53,937
Total	**10,251,199**

Table 17 - Whey production in Italy, author's calculation, year 2022

The abundancy of whey produced in Italy represents on the one hand a problem in terms of disposal of large volumes, on the other a resource considering the numerous derivatives that can be obtained in the field of commodities and derivatives aimed at market niches and which allow the creation of added value starting from a raw material characterized by high availability. More in detail, whey is mainly employed for animal feed, the pulverization (food or livestock usage) or the production of by-products such as ricotta, food lactose, liquid permeate, concentrated whey protein powder.

In Table 18 (and Figure 9), final uses of whey produced in Italy in the 2020 are reported according to the data collected by CLAL, in particular import and export as well as the internal use of this residue are showed. However, the tracked quantity of 5.91 million tons is just over half of the theoretical availability calculated for the same year (10.4 million tons). This discrepancy can be seen as the result of several factors, in particular whey destined for disposal of, for which there is no reference data, can represent a significant portion of this difference. This lack of data could be due to the fact that many companies operating in this sector are numerous and small, making a complete traceability strategy complex to determine this share of whey. Consequently, the possibility of collecting this latter for biomethane production requires specific and detailed studies to evaluate its economic feasibility. [12]

Final uses of whey - 2020 [t]		[%]
Whey used for ricotta	853,000	14.4
Whey used for cattle	2,282,000	38.6
Whey concentrate	1,440,000	24.3
Whey powder and chunks	872,000	14.7
IMPORT		
Whey powder (IMPORT)	114,000	1.9
of which:		
Sweet dairy Whey (12% protein) and WPC	72,000	
EXPORT		
Whey powder (EXPORT)	353,000	6.0
of which:		
Sweet dairy Whey (12% protein) and WPC	312,000	
Total	**5,914,000**	**100**

Table 18 - Final uses of whey in Italy, CLAL, year 2020

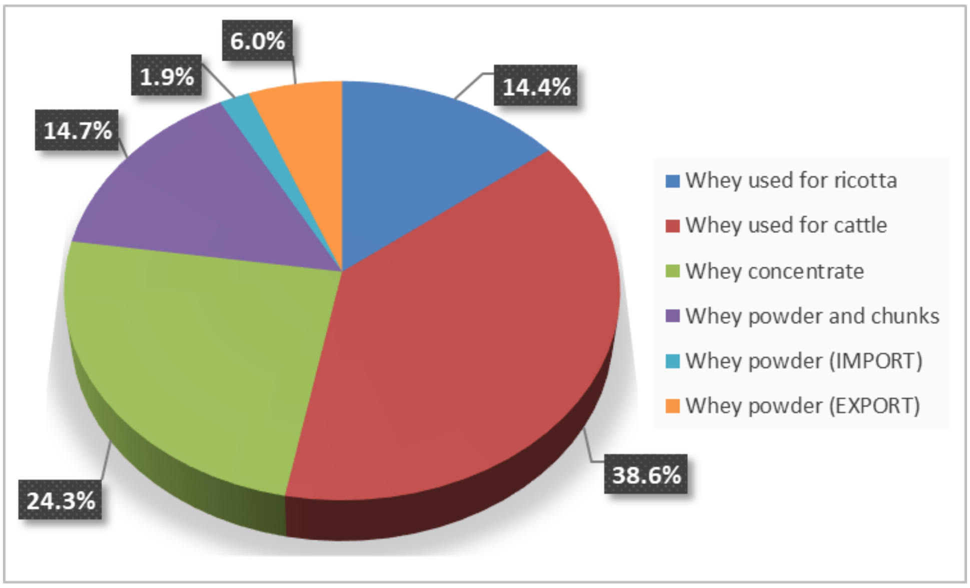


Figure 9 - Percentage distribution final uses of whey, CLAL, year 2020

3. Theoretical potential of advanced biomethane

Once the maximum availability of the incentivized feedstocks has been quantified, it is possible to estimate the advanced biomethane which can be produced. The methodology considered to achieve this goal initially consists of the determination of dry matter (DM), intended as the total fraction of matter, organic and inorganic, which is not evaporable. Subsequently, it is necessary to define the volatile matter (VM) which is, instead, the organic fraction of the dry matter that volatilizes or decomposes at high temperatures, thanks to the anaerobic digestion process. For every type of feedstock, these two parameters are obtained from different literature data where they were experimentally evaluated, by testing various samples at specific time and temperature conditions.

Biochemical Methane Potential (BMP) is a measure of the maximum amount of methane (CH_4) that can be produced by anaerobic degradation of a specific raw material under optimal conditions. It is a key parameter to evaluate the efficiency of a substrate in the anaerobic digestion process, used for the production of biogas and biomethane. Also in this case, the evaluation of such parameter is possible by means of experimental tests conducted in the laboratory. More in detail, feedstock is placed in an anaerobic reactor together with an inoculum, such as anaerobic sludge, under controlled conditions. The gas production is monitored over time, separating the CH_4 from the other components of the biogas (mainly CO_2) in order to obtain the total volume of CH_4 produced.

Considering that the BMP, derived from literature data, is expressed in cubic meters of CH_4 per ton of volatile matter ($m^3_{CH_4}/t_{VM}$), it was possible to estimate the theoretical potential of advanced biomethane deriving from the use of incentivized feedstocks whose maximum availability has been previously assessed. It is important to remember that the potential is theoretical in the sense that it does not take into account existing markets for some of the selected raw materials and their current end uses.

3.1 Agro-industrial waste

Table 19 shows the percentage of volatile matter and the BMP derived from different literature studies which refer to every type of agro-industrial residue, considered for the estimate of the maximum availability, developed in the in the previous chapters.

In the study "Evaluation of the biogas productivity potential of some Italian agro-industrial biomasses", batch trials were conducted to evaluate the biogas productivity potential of different biomasses, using 2-liter glass digesters kept in a thermostatic room at 40 °C for 40 days. Barley and rice straw gave a high specific methane yield of 229 and 195 $m^3_{CH_4}/t_{VM}$, from which the average value of 212 $m^3_{CH_4}/t_{VM}$ was derived. Similar results were also obtained from tomato peels and seeds that gave a specific yield of 218 $m^3_{CH_4}/t_{VM}$. At the end, grape marc produced the lowest quantities of specific methane, with a median value of 116 $m^3_{CH_4}/t_{VM}$. [13]

Vine and olive pruning, which are among the main ones produced in Italy, are evaluated in terms of biogas productivity potential in the study "Evaluation of Mediterranean Agricultural Residues as a Potential Feedstock for the Production of Biogas via Anaerobic Fermentation". Without considering particular pre-treatment processes, low specific methane yields equal to 53.8 and 56.8 $m^3_{CH_4}/t_{VM}$ are derived, obtaining an average value of 55 $m^3_{CH_4}/t_{VM}$. However, biomasses like pruning characterized by high percentage of lignocellulosic elements need specific pre-treatment processes to improve anerobic digestion. In fact, the specific methane yield can achieve high value up to 315.4 $m^3_{CH_4}/t_{VM}$ in the case of olive pruning if steam explosion is carried out. [14]

The anaerobic digestion was discussed in the study "Production of Biogas from Olive Pomace", as an alternative method for the treatment of olive pomace for energy purposes. Physico-chemical tests were conducted to identify the specific methane yield, showing a value of 95 $m^3_{CH_4}/t_{VM}$ for raw olive pomace which is 2.5 times smaller than the theoretical one. This effect can be attributed to the low accessibility of carbohydrates to methanogenic microorganisms which can be improved thanks to mechanical and chemical pretreatment. [15]

The study "Impact of Chemical and Physical Pretreatment on Methane Potential of Peanut Shells" focuses on the valorization of lignocellulosic waste such as peanut shells, through anaerobic digestion for energy purposes. The specific methane yield of raw peanut shells is equal to 48 $m^3_{CH_4}/t_{VM}$, low values compared to those obtained using ultrasound which allowed an increase in CH_4 production, reaching values of 78.6 $m^3_{CH_4}/t_{VM}$. The main effect of ultrasonic pretreatment was observed on carbohydrate solubilization, while the main operating cost of such pretreatment is the energy required to generate ultrasonic waves. [16]

According to the study "Citrus essential oils and their influence on the anaerobic digestion process: An overview", citrus waste represents more than half of the whole fruit when processed for juice extraction. Among the possible valorization strategies, anaerobic digestion for CH_4 generation is the most technically feasible and environmentally sustainable alternative. The specific methane yield in the mesophilic semi-continuous anaerobic digestion of citrus waste ranges between 210 and 290 $m^3_{CH_4}/t_{VM}$. Higher values of 300 – 600 $m^3_{CH_4}/t_{VM}$ have been reported at thermophilic conditions, however most of the digestors in Italy normally operate in mesophilic semi-continuous conditions, so an average value of 250 $m^3_{CH_4}/t_{VM}$ is considered. [17]

In the study "An Analysis of the Energy Potential of Anaerobic Digestion of Agricultural By-Products and Organic Waste", batch trials under mesophilic conditions were conducted to evaluate the specific methane yield of several agricultural by-products. In particular, the rise husk is characterized by the highest specific methane yield, equal to 381 $m^3_{CH_4}/t_{VM}$, between the residues analyzed, in addition to presenting a certain precocity in terms of CH_4 production, probably due to the very small size of the rice husk. [18]

Since the Portal Biomass Atlas takes into account the moisture content during the harvesting process, the maximum potential availability of agro-industrial residues is directly expressed as tons of dry matter. To conclude, the theoretical national potential of advanced biomethane producible was determined at regional level, as shown in Table 20.

FEEDSTOCK	VM (% DM)	BMP (m3_CH4/t_VM)
Straw	93.1	212
Pruning	90.5	55
Pomace	97.0	95
Marc	90.7	116
Shells	93.6	48
Husk	87.7	381
Citrus pulp	95.0	250
Tomato peel	97.8	218

Table 19 - Percentage of VM and BMP for agro-industrial waste

Regions	Straw	Pruning	Pomace	Marc	Shells	Husk	Citrus pulp	Tomato peel
	Biomethane potential [x 10^3 m3/year]							
Piemonte	412,286	4,707	2	3,563	625	48,117	-	261
Aosta	21	92	0	23	0	-	-	-
Liguria	172	1,891	527	115	0	-	5	-
Lombardia	407,645	2,118	137	1,985	2	29,953	-	1,077
Trentino Alto-Adige (BZ)	134	1,623	-	567	-	1	-	-
Trentino Alto-Adige (TN)	345	1,555	67	1,392	0	-	-	0
Veneto	317,886	21,750	228	11,145	19	1,028	-	230
Friuli-Venezia Giulia	77,770	3,637	20	1,525	1	7	-	-
Emilia-Romagna	287,733	10,713	132	16,079	7	1,645	-	3,704
Marche	86,319	3,273	421	1,450	4	-	-	1
Toscana	108,485	7,761	1,791	2,209	38	138	3	290
Umbria	52,719	2,740	653	634	11	-	-	16
Lazio	65,288	7,062	3,214	1,488	663	-	104	264
Campania	57,875	11,452	2,982	7,333	513	-	903	450
Abruzzo	41,249	9,590	1,741	2,923	4	0	2	112
Molise	21,315	1,671	1,201	2,180	20	-	3	122
Puglia	191,113	29,154	10,685	16,805	486	1	7,558	2,816
Basilica	71,342	2,184	601	173	14	-	2,934	223
Calabria	30,997	33,238	9,450	314	43	70	28,266	211
Sicilia	121,986	28,597	9,298	11,063	1,902	10	36,053	145
Sardegna	48,711	5,634	864	1,708	31	1,517	503	48
Total	**2,401,390**	**190,443**	**44,013**	**84,673**	**4,382**	**82,487**	**76,332**	**9,970**

Table 20 - Theoretical potential of advanced biomethane from agro-industrial waste in Italy, author's calculation, year 2022

3.2 Organic Fraction of Municipal Solid Waste (OFMSW)

The percentage of dry matter considered for OFMSW turns out to be equal to 23.7% of the fresh waste, of which 91.6% is composed of volatile solids, while the BMP is equal to 438 $m^3_{CH_4}/t_{VM}$. These data derive from the Science for Policy Report, elaborated by the Joint Research Centre (JRC) which is the European Commission's science and knowledge service, in the context of the Renewable Energy Directive (RED-recast). [19]

In Table 21, the theoretical national potential of advanced biomethane that can be produced was determined at regional level.

Regions	Biomethane potential OFMSW [x 10^3 m3/year]
Piemonte	42,409
Valle d'Aosta	1,142
Liguria	14,238
Lombardia	109,021
Trentino-Alto Adige	12,996
Veneto	69,359
Friuli-Venezia Giulia	14,696
Emilia-Romagna	75,771
Marche	21,293
Toscana	49,950
Umbria	11,275
Lazio	55,096
Campania	60,317
Abruzzo	14,648
Molise	2,451
Puglia	41,123
Basilicata	4,753
Calabria	16,774
Sicilia	49,030
Sardegna	22,241
Total	**688,585**

Table 21 - Theoretical potential of advanced biomethane producible from OFMSW in Italy, author's calculation, year 2022

3.3 Urban wastewater sludge

The percentage of dry matter considered for the sludge, derived from the urban wastewater treatment, turns out to be equal to 5% of the fresh waste, of which 70% is composed of volatile solids, while the BMP is equal to 308.8 $m^3_{CH_4}/t_{VM}$. These data come from a study developed by IEA Bioenergy with the aim of providing an overview of the anaerobic digestion process in wastewater treatment plants, together with the standard energy performance, nutrient recycling and different process options and their impacts. [20]

In Table 22, the theoretical national potential of advanced biomethane that can be produced was determined at regional level.

Regions	Biomethane potential Urban wastewater sludge [x 10^3 m3/year]
Piemonte	3,742
Valle d'Aosta	97
Liguria	551
Lombardia	5,854
Trentino-Alto Adige	1,589
Veneto	4,375
Friuli-Venezia Giulia	929
Emilia-Romagna	3,947
Marche	870
Toscana	2,719
Umbria	474
Lazio	2,526
Campania	1,872
Abruzzo	794
Molise	55
Puglia	2,542
Basilicata	41
Calabria	327
Sicilia	538
Sardegna	716
Total	**34,558**

Table 22 - Theoretical potential of advanced biomethane from wastewater sludge in Italy, author's calculation, year 2022

3.4 Zootechnical waste

The theoretical potential of advanced biomethane from zootechnical waste was calculated considering the overall amount of manure for each type of relevant species and specific productivity coefficients, which allow to express the quantity of advanced biomethane obtainable from the different types of animal waste (Table 23).

These data derive from the study «A spatial analysis of biogas potential from manure in Europe», which aims to provide an assessment of the spatial distribution of the biogas potential of agricultural manure from livestock and poultry in Europe. As this study highlights, the manure produced by every type of species is characterized by specific properties in terms of dry and volatile matter as well as BMP, according to the diet and metabolism of each animal. [11]

Table 24 shows the theoretical national potential of advanced biomethane that can be produced, determined at the regional level.

FEEDSTOCK	DM (%)	VM (% DM)	BMP (m3 CH4/VM)
Cattle	8.5	80	200
Dairy Cattle	8.5	80	230
Pigs	6.0	80	300
Sheep/Goats	30.0	80	200
Poultry	20.0	80	320

Table 23 - Percentage of DM, VM and BMP for zootechnical waste

Regions	Poultry	Cattle	Buffaloes	Sheep & goats	Pigs
	Biomethane [x 10^3 m3/year]				
Piemonte	28,141	124,897	552	4,769	24,972
Valle d'aosta	27	5,615	0	144	3
Liguria	183	2,082	0	511	9
Lombardia	81,049	235,941	1,010	4,870	87,483
Trentino Alto-Adige (bz)	552	21,397	2	1,578	67
Trentino - alto adige (tn)	2,093	7,224	0	1,114	135
Veneto	135,059	88,999	359	2,277	12,596
Friuli- Venezia Giulia	16,410	11,980	177	633	5,281
Emilia-romagna	78,330	91,236	49	1,482	20,903
Marche	12,614	7,064	127	2,782	1,774
Toscana	5,394	12,131	162	7,476	2,526
Umbria	8,806	9,022	130	2,221	3,686
Lazio	10,348	31,275	14,861	14,236	951
Campania	9,190	24,109	52,927	5,248	1,553
Abruzzo	12,010	10,112	15	3,948	1,375
Molise	13,670	5,439	109	1,392	457
Puglia	12,319	26,532	2,184	5,445	527
Basilicata	1,050	16,223	729	4,728	1,414
Calabria	1,897	18,133	274	7,068	1,143
Sicilia	17,331	55,574	398	18,078	1,458
Sardegna	3,127	48,595	2	75,304	5,381
Total	**449,602**	**853,582**	**74,066**	**165,304**	**173,692**

Table 24 - Theoretical potential of advanced biomethane from zootechnical waste in Italy, author's calculation, year 2022

3.5 Whey

The theoretical potential of advanced biomethane from whey was calculated by referring to the study «Evaluation of the biogas productivity potential of some Italian agro-industrial biomasses» where the percentage of dry matter turns out to be equal to 6.86% of the fresh residue, of which 91.1% is composed of volatile solids, while the BMP is equal to 501 $m^3_{CH_4}/t_{VM}$, the highest specific methane yield among the analyzed residues. [13]

Table 25 shows the theoretical national potential of advanced biomethane that can be produced, determined at the regional level.

Regions	Biomethane potential whey [x 10^3 m3/year]
Piemonte	25,620
Valle d'Aosta	660
Liguria	127
Lombardia	113,092
Trentino Alto-Adige	10,794
Veneto	33,167
Friuli-Venezia Giulia	5,528
Emilia-Romagna	54,027
Marche	4,272
Toscana	6,577
Umbria	1,689
Lazio	4,666
Campania	16,221
Abruzzo	855
Molise	5,342
Puglia	11,961
Basilicata	752
Calabria	3,030
Sicilia	3,629
Sardegna	18,955
Total	**320,963**

Table 25 - Theoretical potential of advanced biomethane from whey in Italy, author's calculation, year 2022

4. Biomethane production, potential and correlations in Italy

Once the theoretical potential of advanced biomethane has been evaluated, a further analysis of the actual biomethane and biogas production at national level is carried out, with reference to 2022. The potential determined is theoretical as it does not take into account possible alternative use of the substrates, such as direct use or production chains of by-products, as well as other biofuels (such as biogas). Considering the possibility to obtain biomethane through specific treatments of the biogas, it can be useful to also estimate the extractable potential of this alternative fuel. In this way, the assessment of the share of the theoretical potential already used in the biogas supply chain is carried out, which can be redirected for the biomethane supply chain.

Moreover, the results calculated in this study are compared with other literature references, developed by different European and national institutions, in order to confirm the validity and consistence of the maximum availability estimated for the selected feedstocks and the corresponding theoretical potential. This verification is fundamental when the evaluations carried out are based on different hypotheses and limitations, as in the case of this study.

4.1 Actual production of advanced biomethane

By the end of 2022, Italy accounted for 47 biomethane plants with a production of about 250 million of cubic meters, as reported in the article "Le alternative al metano che arriva con i gasdotti dall'estero. Nota 2 - Gli impianti di produzione del biometano in Italia" written by Carlo Giavarinia and Ferruccio Trifirò, making Italy one of the fastest growing biomethane markets in Europe. Such a marked development of the biomethane supply chain was encouraged by the entry into force of the Italian Ministerial Decree on Biomethane of 2018, with the aim of achieving a production target of 1.1 billion cubic meters of biomethane per year until 31 December 2022. Subsequently, these efforts have been carried forward by the Biomethane Decree of 15 September 2022 which provides a total financing of 1.7 billion euros, to continue to incentivize the production of biomethane in Italy. These funds come from the PNRR in order to produce unless 2.3 billion cubic meters of biomethane per year, by 2026. [1],[21]

Analyzing the situation at the end of 2022, Lombardia has the highest number of biomethane plants, equal to 17, followed by Emilia-Romagna characterized by the presence of 10 plants. Therefore, it is possible to see how the concentration of this type of infrastructure is mainly located in the north of the country, also considering the 5 plants in Piemonte and the 4 plants in Veneto. As reported in Table 26, biomethane plants are divided according to the typology of feedstock used for anaerobic digestion, showing how most of them are fed by OFSMW (about 67%).

Feedstock	Number of plants	Biomethane [m3/year]	Percentage [%]
OFMSW	24	167,550,000	67.0
Agro-zootechnical waste	9	33,408,000	13.4
Industrial waste	3	16,550,000	6.6
Agricultural waste	2	12,650,000	5.1
Landfill gas	2	3,656,000	1.5
Sewage sludge	2	1,015,000	0.4
Zootechnical waste	2	680,000	0.3
Mixed	3	19,400,000	7.8
Total	**47**	**250,149,000**	-

Table 26 - Biomethane plants according to the type of feedstock, operating in Italy at the end of 2022

Table 27 shows every single operative biomethane plant at the end of 2022, describing the year in which the plant entered into operation, the location, the type of feedstock used and the annual biomethane production. In particular, the highlighted plants are able to produce Liquified Natural Gas (LNG), cooled to very low temperatures (-162 °C) in order to reduce its volume and facilitate its transportation. [21]

Year	Location	Feedstock	Biomethane [m3/year]
2016	Ozegna (TO)	landfill gas	1,000,000
2017	Soliera (MO)	mixed	n.a.
2017	Montello (BG)	OFMSW	32,000,000
2018	Rende (CS)	OFMSW	4,500,000
2018	Foligno (PG)	OFMSW and pruning	4,000,000
2018	Finale Emilia (MO)	OFMSW and pruning	3,000,000
2018	Santagata Bolognese (BO)	zootechnical waste	7,500,000
2019	Faenza (RA)	agricultural waste (straw)	12,000,000
2019	Corbetta (MI)	Agro-zootechnical waste	3,850,000
2019	Este (PD)	industrial waste	17,000,000
2019	Maniago (PN)	landfill gas	25,000,000
2019	Olgiate Olona (VA)	OFMSW	5,000,000
2019	Lugo di Campagna Lupia (VE)	OFMSW	12,000,000
2019	Roncocesi (RE)	residues agro-industrial	250,000
2019	Bresso - Niguarda (MI)	sewage sludge	765,000
2019	Sarmato (PC)	sewage sludge	5,000,000
2020	Verolanuova (BS)	Agro-zootechnical waste	2,700,000
2020	Acea Pinerolese (TO)	agro-zootechnical waste	7,600,000
2020	Bottrighe (RO)	industrial waste (milk)	3,800,000
2020	Villanova del Sillaro (LO)	OFMSW	1,700,000

2020	Novi Ligure (AL)	OFMSW	156,000
2020	Candiolo (TO)	OFMSW	n.a.
2020	Codigoro (FE)	OFMSW	3,000,000
2020	Guglionesi (CB)	OFMSW	2,550,000
2020	Assoro (EN)	OFMSW	4,400,000
2020	Monte Scarpino (GE)	OFMSW and pruning	3,500,000
2020	Anzio (RM)	OFMSW and pruning	3,500,000
2021	Verolanuova (BS)	agro-zootechnical waste	2,550,000
2021	Cingia dei Botti (CR)	agro-zootechnical waste	2,808,000
2021	Santhià (VC)	agro-zootechnical waste	5,000,000
2021	Albairate (MI)	OFMSW	7,000,000
2021	Venosa (PZ)	OFMSW	4,250,000
2021	Caltanisetta	OFMSW	3,600,000
2021	Cadino (TN)	OFMSW and pruning	2,000,000
2021	Carbonara del Ticino (PV)	OFMSW and pruning	4,250,000
2021	Cairo Montenotte (SV)	zootechnical waste	6,000,000
2022	Cella Dati (CR)	agricultural waste	4,250,000
2022	Marcallo con Casone (MI)	agro-zootechnical waste	4,000,000
2022	Rivarolo del Re (CR)	agro-zootechnical waste	4,890,000
2022	Modugno (BA)	industrial waste	1,900,000
2022	Legnano (MI)	OFMSW	4,000,000
2022	Barbarano Mossano (VI)	OFMSW	8,500,000
2022	Bosco Gerolo (PC)	OFMSW	680,000
2022	Spilamberto (MO)	OFMSW	3,700,000
2022	Gavassa (RE)	OFMSW	9,000,000
2022	Ostra (AN)	OFMSW and agricultural waste	3,000,000
2022	Mosciano Sant'Angelo (TE)	OFMSW and agricultural waste	3,000,000
		Total	**250,149,000**

Table 27 - Biomethane plants operating in Italy at the end of 2022

4.2 Extraction potential from biogas

The Italian biogas supply chain started to develop in the early nineties, with the introduction of the first official subsidy, a green certificate system, in 1999. However, an important increment in terms of number of plants took place after the introduction of the "all inclusive" Feed-in Tariff (FiT) for small renewable energy plants (the tariffa omnicomprensiva) in 2008, which led to a substantial growth until 2012. After the beginning of 2013, the subsidies decreased due to the implementation of a less profitable biogas support strategy even if they were extended from 15 to 20 years. Nevertheless, both the number of biogas plants in Italy and the country's biogas production steadily increased between 2013 and 2021. [1]

Thanks to the data collection on the main quantities of the national electricity sector, carried out by Terna S.p.a which is the italian Trasmittion System Operator (TSO), it has been possible to provide a comprehensive overview of the biogas sector at national level, with reference to 2022. The biogas produced in Italy is mainly employed as fuel in internal combustion engines, installed on site, for the production of electricity or for the cogeneration, i.e. for the simultaneous production of electrical energy and heat.

With 2,175 biogas plants connected to the electrical grid, characterized by a total gross power of 1,46 GW and a produced gross energy of 7,844 GWh, Italy occupies a prominent position in the biogas sector in Europe, together with Germany and France. Table 28 shows biogas plants, classified according to the feedstock used.

Typology	Number of plants	Gross Power [kW]	Percentage [%]	Produced gross energy [GWh]	Percentage [%]
Electricity production only	**676**	**490,698**	-	**2,403**	-
from waste	192	230,917	47.1	611	25.4
from sludge	14	4,641	0.9	16	0.7
from zootechnical waste	201	62,942	12.8	376	15.6
from agricultural and forestry activities	291	192,199	39.2	1,400	58.2
Combined production of electricity and heat	**1,499**	**968,907**	-	**5,441**	-
from waste	188	141,178	14.6	378	6.9
from sludge	72	45,512	4.7	100	1.8
from zootechnical waste	518	191,276	19.7	901	16.6
from agricultural and forestry activities	840	590,941	61.0	4,063	74.7
Total	**2,175**	**1,459,605**	-	**7,844**	-

Table 28 - Biogas plants connected to the electrical grid in Italy, TERNA, year 2022

The amount of biogas produced in Italy can be estimated, considering the produced gross energy which represents the electrical energy generated by the systems, without taking into account internal losses or the energy self-consumed for the operation of the system itself and a conversion coefficient, derived from the study “La filiera del biogas per la produzione di energia elettrica in italia” of ENEA. Considering a produced gross energy of 7,844 GWh and a conversion coefficient equal to 1.8 kWh of electrical energy produced by one cubic meter of biogas, it is possible to obtain 4.36 billion cubic meters of biogas. [22]

In order to increase the biomethane production at national level, in addition to building new plants, it is also possible to convert existing biogas plants, representing a solution capable of reducing both construction times and costs. This procedure consists of an infrastructure retrofit with the addition of an upgrading unit, able to purify the raw biogas (containing approximately 50-60% CH_4 and the remainder consisting mainly of CO_2 and other gases) by removing carbon dioxide, water, sulfur compounds and other impurities. A range of technologies are available for the upgrading of biogas to biomethane: membrane separation, water or chemical scrubbing, pressure swing adsorption, physical scrubbing and cryogenic separation. The preferred technique for biogas upgrading in Italy, but also in the rest of Europe, is the membrane separation which allows to obtain biomethane with a purity of more than 96%. The reason behind this technical choice concerns the high efficiency achievable with low energy consumption, in addition to lower maintenance costs and the possibility of modulating the system, adapting to plants of different sizes even during the phase of increasing production capacity. Biogas upgrading presents a valuable opportunity, particularly as a transient solution to enhance biomethane production capacity. In fact, the Biomethane Decree offers incentives primarily for reconverted plants, which are mainly fueled by agro-industrial waste. [1],[2]

Based on the previously estimated biogas production in Italy and assuming that approximately 60% of each cubic meter of biogas consists of CH_4, the total amount of biomethane that can be extracted through an upgrading process is approximately 2.61 billion cubic meters.

4.3 Relation between theoretical potential, extraction potential and actual biomethane production

The estimates at national level of the theoretical potential of advanced biomethane that can be produced from incentivized raw materials are reported in Table 29. It should be reiterated that the theoretical potential (expressed in cubic meters per year, $m^3/year$) expresses the maximum quantity of advanced biomethane that can be potentially produced in a given territory, deducible from analyses that do not include any environmental, economic, social assessment, possible alternative, competing or competitive uses of the raw materials, technological limitations, etc. [4]

Feedstock	**Biomethane [x 10^3 m3/year]**
Straw	2,401,390
Pruning	190,443
Pomace	44,013
Marc	84,673
Shells	4,382
Husk	82,487
Citrus pulp	76,332
Tomato peel	9,970
OFMSW	688,585
Wastewater sludge	34,558
Bovine	853,582
Buffaloes	74,066
Pigs	173,692
Sheep/Goats	165,304
Poultry	449,602
Obtainable whey	320,963
Total	**5,654,044**

Table 29 - Advanced biomethane theoretical potential for different raw materials in Italy, author's calculation, year 2022

Figure 10 highlights the possible contribution of each feedstock to biomethane production, in percentage terms. Straw was considered separately from the rest of the agro-industrial waste due to its predominant role. In fact, straw together with zootechnical waste represent respectively 43% and 30% of the theoretical biomethane potential. However, the estimate of the theoretical potential also includes the share of raw materials already used in other supply chains, such as biogas (e.g. livestock waste, sludge from the purification of urban and industrial wastewater and OFMSW) which is currently mainly used for the production of thermal and/or electrical energy. Other feedstocks, such as cereal straw, are currently used in agriculture, livestock farming, etc. and only a limited share can be used for energy purposes, as accurately explained in the chapters dedicated to the determination of the maximum availability. Furthermore, the use of lignocellulosic raw materials for the production of biogas/biomethane, such as pruning residues, peels and shells of dried fruit, requires the usage of pre-treatment technologies aimed at facilitating the digestion process, as well as the possibility of operating in co-digestion, increasing the production yield if carried out appropriately. [4]

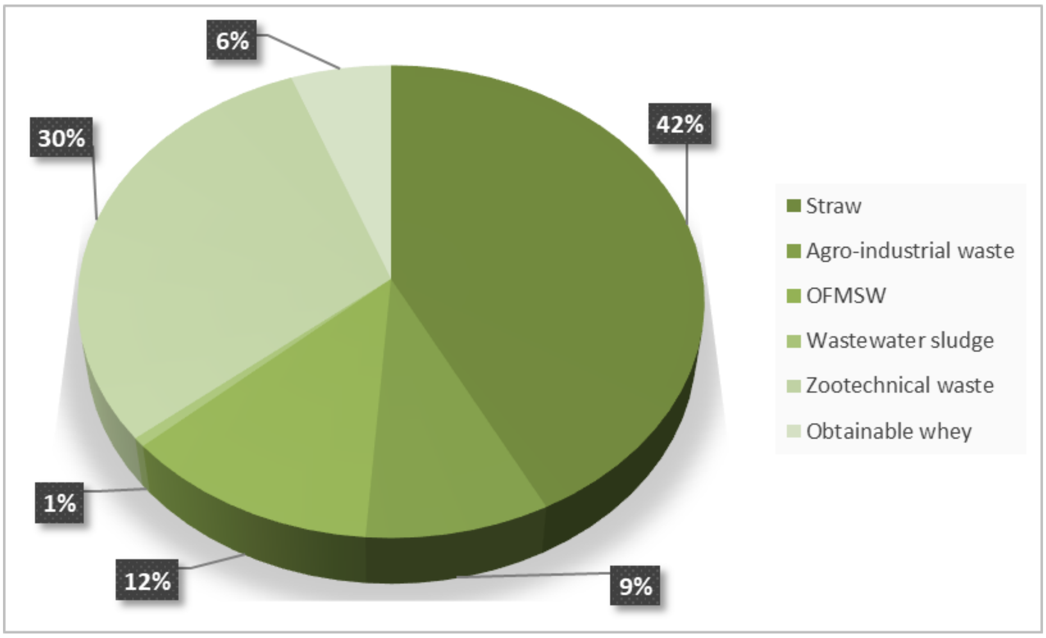


Figure 10 - Percentage distribution of the different raw materials considered for the calculation of the theoretical potential of advanced biomethane in Italy, year 2022

Considering the actual production of biomethane and the potential extractable from biogas, it is possible to evaluate the residual potential which is not yet employed for the production of biogas or biomethane in Italy (Table 30). Figure 11 shows how just 5% of the theoretical potential is actually exploited while the 46% is represented by the biomethane obtainable thanks to the purification process of the biogas already produced. The remaining 49% is represented by the residual potential, demonstrating how in the Italian context there is still ample room for growth for this sector.

Typology	Biomethane [x 10^3 m3/year]
Theoretical potential	5,654,044
Exctractable from biogas	2,614,700
Actual production	250,149
Residual potential	**2,789,195**

Table 30 – Residual potential of biomethane in Italy, author's calculation, year 2022

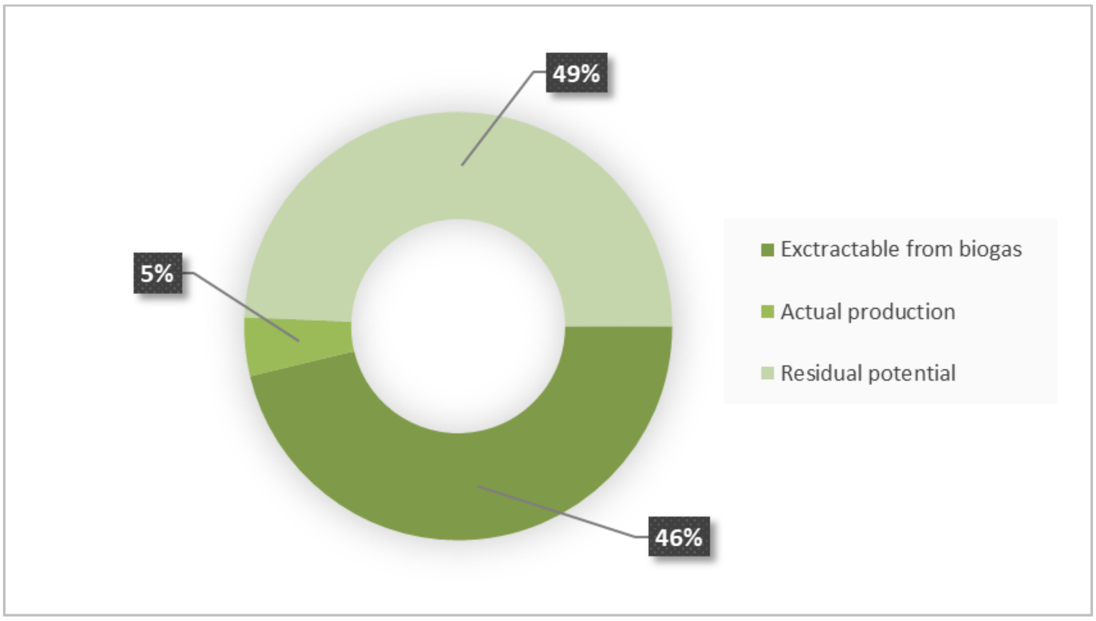


Figure 11 – Percentage of actual production, extractable and residual potential of biomethane in Italy, year 2022

4.4 Comparison of the results with other studies

Estimates of theoretical potential of advanced biomethane and maximum availability of incentivized raw materials are comparable with the estimates calculated in the study "Potenziale teorico di biometano avanzato in Italia", developed by ENEA in 2021. Also in this case, the objective is to evaluate the theoretical potential of advanced biomethane that can be produced from the anaerobic digestion of different feedstocks in Italy, referring to the year 2016. Furthermore, the hypothesis underlying the study turns out to be the same: the potential determined at regional level is theoretical as it does not take into account a possible alternative use of the feedstocks considered. In Table 31, the results obtained from this work and the ones carried out by ENEA are compared. [4]

Feedstock	Availability [t]	Availability [t]	Biomethane [x 10^3 m3/year]	Biomethane [x 10^3 m3/year]
Year	**2016**	**2022**	**2016**	**2022**
Straw	15,627,170	12,166,824	3,374,526	2,401,390
Pruning	-	3,805,321	-	190,443
Pomace	450,096	487,674	40,194	44,013
Marc	789,098	804,788	83,023	84,673
Shells	-	97,333	-	4,382
Husk	-	246,865	-	82,487
Citrus pulp	307,204	321,399	130,195	76,332
Tomato peel	50,408	46,762	10,747	9,970
OFMSW	6,516,800	7,241,686	619,403	688,585
Urban wastewater sludge	3,183,919	3,197,443	34,406	34,558
Industrial wastewater sludge	806,333	-	8,756	-
Zootechnical waste	91,791,700	85,922,512	1,601,384	1,716,247
Obtainable whey	9,552,896	10,251,199	296,140	320,963
Total	**129,075,624**	**124,589,806**	**6,198,774**	**5,654,044**

Table 31 – Comparison of the results with the study developed by ENEA

As regards the maximum availability of incentivized raw materials, the quantities reported are comparable to each other. Although both studies employ the same methodology, differences in assumptions and literature references may lead to some variations in the results obtained, such as for the zootechnical waste. Other factors are to be found in the change of trend, upstream of the production of these feedstocks, as in the case of OFMSW where the adoption of a more consumer-oriented lifestyle by the population has led to an increase in this waste in recent years. Furthermore, considering agro-industrial waste and in particular straw, production yield is strictly related to climatic conditions, characterized by high variability from one year to another. Also for the theoretical potential of the advanced biomethane, the results appear to be in line with each other. Obviously, the differences found are the direct cause of the variations between the maximum availability of feedstocks considered, calculated upstream. However, in this case as well, some literature references may differ to incorporate more updated and reliable data compared to the study conducted by ENEA, as seen in the cases of straw, pomace, and citrus pulp. In general, this study takes into account additional biomasses that, with due care in terms of pre-treatment processes, can become a resource to be used for the production of biomethane such as pruning residues, shells and husk. [4]

The PNIEC plans to produce 5.7 billion cubic meters of advanced biomethane per year by 2030, without specifying in detail the types of feedstocks from which this production is expected to be obtained. This ambitious value is given by the result of a balance between technical potential, support policies and expected demand in the national energy system. [3] This target is in line with the estimate defined by Gas for Climate which is an initiative promoted by a consortium of companies and operators in the European energy sector, including gas TSOs and biogas/biomethane producers, with the aim of promoting the role of renewable gases in the EU energy transition. The outlook for Italy foresees a potential of 5.8 billion cubic meters of biomethane (5.5 from anaerobic digestion and 0.3 from gasification) by 2030, of which 3.19 are attributable to the anaerobic digestion of sequential crops, not considered in this study. [23]

5. Environmental impact of the Italian biomethane supply chain

Referring to the carbon cycle, the combustion of biomethane is considered carbon neutral since the amount of CO_2 emitted into the atmosphere is the same which is captured by the biomass over their growth, before to be harvested and destined to the anaerobic digestion. However, extending the limits of the system from the combustion phase alone to the entire biomethane supply chain, there are different indirect emissions which are related to the production, transport and distribution of the biomethane.

The well-to-tank analysis (WTT) allows to evaluate the GHG emissions associated with the production and distribution of a fuel to the point of use, before the combustion phase. In the case of biomethane, emissions may be attributable to the feedstock sourcing, where the production, harvesting and transport of the raw materials take place. Subsequently, biomethane is produced, in this case by means of anaerobic digestion, which may be associated with emissions due to the power supply of auxiliary components of the plant and small leakages from the digester. Also during the purification and compression process may be generated some emissions related to energy consumption, needed to remove contaminants from biomethane and to obtain Bio-CNG or Bio-LNG. Finally, if the biomethane is transported by truck or ship, there are fossil fuel emissions, otherwise if it is fed into the gas grid, there are minimal losses due to some small leakages along both transport and distribution infrastructures.

By means of different literature studies conducted in institutional and academic contexts, it was possible to collect the emission coefficients, expressed in grams of equivalent CO_2 per megajoule of biomethane ($g_{CO_2}e/MJ$), associated with every single feedstock considered for the production of biomethane.

5.1 Emission coefficients associated with the type of feedstock

Considering the feedstock on the basis of the maximum availability and the corresponding theoretical potential calculated in the previous chapters, two different emission coefficients were selected for each raw material. In this way, it is possible to demonstrate how the methodology employed for the WTT analysis is strictly dependent on the hypotheses, technologies, energy sources and transportation methods taken into account.

Table 32 (and Figure 12) shows the emission factors, divided according to the database they come from and the type of feedstock they refer to. The calculation methodology is carried out by considering a reference scenario which describes the actual final use of each raw material, different from the energy purpose. The same conversion chain, represented by anaerobic digestion, followed by the upgrading and compression process, is the basis for the evaluation of emission factors. As the method of transportation, which occurs by road, and the final state of the biomethane, which is compressed, remain the same. The discrepancies which characterize the two coefficients for each feedstock are largely due to the use of more or less emission-efficient technologies adopted during the production chain.

Database_ID	Feedstock	emi_WTT [(g _CO2)e/MJ]
RICARDO_default	Agricultural residues	72.2
RICARDO_substitution	Agricultural residues	110.5
2016_Tonini	Straw	20
2019_Buchspies	Straw	6.58
REDII_default	Biowaste	71
REDII_typical	Biowaste	10
JECv5	Sewage sludge	22.2
2016_Tonini	Sewage sludge	9.55
REDII_default	Manure	22
REDII_typical	Manure	-103
2016_Tonini	Whey	614.3
2016_Tonini	Whey	219.6
JECv5	Natural gas	15.1

Table 32 – Emission coefficients according to the source database and the reference feedstock

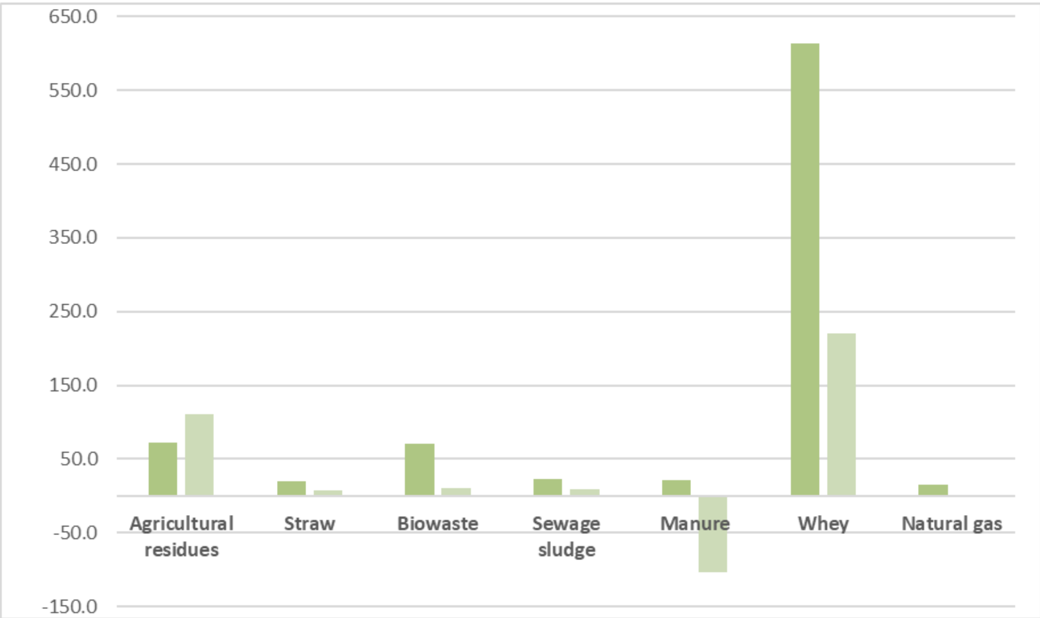


Figure 12 – Discrepancies between emission coefficients according to the reference feedstock

A particular figure of merit is represented by the straw and manure coefficients which result to be negative in one of the two options selected for each feedstock. In the Annex VI of the RED II directive (2018/2001/UE), methodologies for calculating GHG emissions for biofuels, bioliquids and biomass fuels are described in detail, as well as providing standard values for specific supply chains. The reference scenario for biomethane produced from manure is the one in which the manure is left to decompose naturally, releasing CH_4 into the atmosphere which has a global warming potential (GWP) approximately 28 times higher than CO_2. The negative emission coefficient of -103 $g_{CO_2}e/MJ$ is the result of the adoption of a closed digestate system and an off-gas combustion plant with respect to the emission coefficient of 22 $g_{CO_2}e/MJ$ calculated by considering the opposite configuration with an open digestate system and a no off-gas combustion. When digestate is stored in a closed system, post-digestion CH_4 emissions are avoided, which would otherwise be released into the atmosphere if the digestate were left in the open. In the calculation of emissions according to Annex VI, this reduction is accounted for as "avoided emissions", lowering the total value of net emissions. Since the reference scenario would have generated CH_4, capturing it and preventing its dispersion is recognized with an emission credit that can exceed the total emissions of the process, bringing the value to negative. Furthermore, if the off-gases (residual gases) produced in the post-treatment phase are burned, the CH_4 is converted into CO_2. Since biogenic CO_2 is not counted as greenhouse gas emissions, the combustion further reduces the emissions footprint of the system. [24]

As demonstrated in the study "GHG emission factors for bioelectricity, biomethane, and bioethanol quantified for 24 biomass substrates with consequential life-cycle assessment whey is characterized by particularly high emission coefficients" developed by Davide Tonini, Lorie Hamelin, Merlin Alvarado-Morales, Thomas and Fruergaard Astrup, whey is characterized by particularly high emission coefficients if it is assessed individually for biomethane production. In order to obtain a reduction in terms of net global emissions, possible mixtures with another feedstock, such as manure, can be exploited. The emission factor of 219.6 $g_{CO_2}e/MJ$ is calculated by considering the gasification of solid fraction and its combustion in combined heat and power units (CHP), in contrast to the value of 614.3 $g_{CO_2}e/MJ$ where the biomethane is just produced thanks to the upgrading of the biogas. However, these emission coefficients are significantly higher compared to the reference scenario, in which whey is used for animal feed. [25]

With regards to agricultural residues (including straw), biowaste and sewage sludge, the difference between the two emission coefficients selected for everyone is due to the application of a more emission-efficient technology. In the case of agricultural residues and biowaste, a closed digestate system and an off-gas combustion configuration is adopted, while for the sewage sludge direct combustion of solid fraction in CHP is taken into account. [24], [25], [26]

The JECv5 study, conducted by a collaboration between JRC, Concawe and Eurocar has the aim of assessing the GHG emissions and energy efficiency of different fuels and propulsion technologies in the transport sector. In particular, emissions related to the extraction, refining, compression and finally the transport of imported European natural gas are evaluated. The emission factor of 15.1 $g_{CO_2}e/MJ$ considers the imported natural gas, transported to Europe by pipeline (4,300 km to EU border, 700 km inside EU or Middle East 4,000 km), subsequently distributed through gas high pressure trunk lines and low-pressure grid, with compression to CNG at retail point. [27]

5.2 Assessment of emissions linked to the theoretical potential

Once the emission coefficients have been defined for each type of feedstock, it is possible to estimate the amount of CO_2 released into the atmosphere as a result of the biomethane production, based on the theoretical potential calculated in the previous chapters. The two emission factors selected for each raw material allow the construction of two different emission scenarios. Additionally, another scenario was developed by assuming that the biomethane produced corresponds to the emissions caused by an equivalent amount of fossil natural gas. While the combustion of biomethane is considered carbon neutral, different is for natural gas to which an additional share of emissions is associated. The stoichiometric condition, which refers to the situation where the amount of oxygen supplied for combustion is exactly that needed for the complete conversion of carbon into CO_2, represents the reference for the evaluation of the emissions caused by this process.

A lower heating value (LHV) of 36.1 MJ/m^3 and an absolute density of 0.77 kg/m^3 are assessed, in order to respect the eligibility ranges about the chemical-physical properties of natural gas injected into the Italian grid, imposed by the Ministerial Decree of 18 May 2018. In this condition, stoichiometric combustion is characterized by an emission coefficient of 57.5 $g_{CO_2}e/MJ$, almost four times higher compared to the WTT emission factor. [28]

Table 33 (and Figure 13) shows the total emissions, expressed in tons of equivalent CO_2 per year ($t_{CO_2}e/year$), associated with each feedstock by the utilization of the two different emission coefficients selected previously, as well as the total emissions produced if the amount of biomethane would be substituted by natural gas.

Feedstock	Biomethane [m3]	Obsolete technology scenario emissions [(t_CO2)e/year]	Advanced technology scenario emissions [(t_CO2)e/year]	Natural gas scenario emissions [(t_CO2)e/year]
Straw	2,401,390,387	1,733,804	570,421	1,311,184
Agricultural residues	492,299,857	1,964,031	1,283,909	268,801
Biowaste	688,585,107	1,764,912	248,579	375,975
Sewage sludge	34,557,964	27,755	11,913	18,869
Manure	1,716,247,403	1,363,044	- 6,381,523	937,089
Whey	320,962,856	7,118,020	2,544,784	175,249
WTT_emi	-	13,971,566	- 1,721,916	3,087,167
Stoich_comb_emi	-	-	-	11,736,381
Total	**5,654,043,573**	**13,971,566**	**- 1,721,916**	**14,823,548**

Table 33 – Total emissions referred to the theoretical potential, author's calculation, year 2022

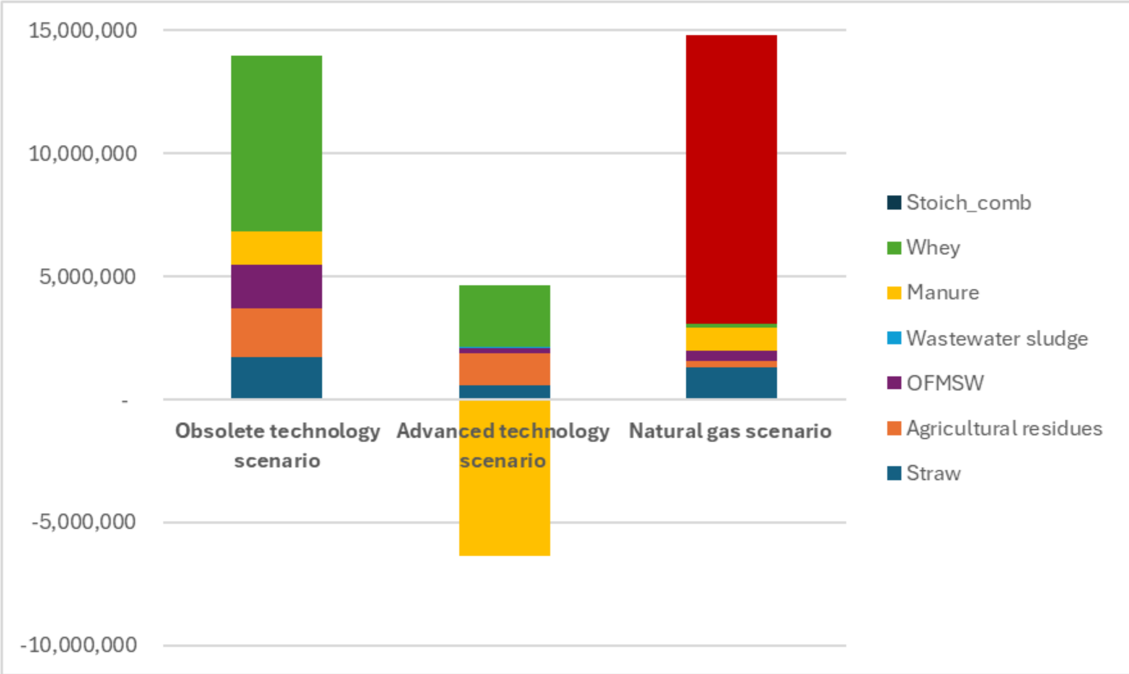


Figure 13 - Emissions contribution of each feedstock in the different scenarios, author's calculation, year 2022

As it is possible to notice, the natural gas scenario is characterized by the highest total emissions, where the share related to the combustion process is equal to about 79.2% of the overall amount. While the obsolete technology scenario is comparable to that of natural gas, the advanced technology scenario even shows negative values, implying not only the possibility of avoiding the emission of CO_2 but also the subtraction of this latter from the atmosphere. This comparison is only intended to demonstrate the fundamental role of the technology employed to produce the biomethane, which can lead to completely different environmental impacts. Compared to other countries in the world, Europe has a significant advantage in the maturity of biogas and biomethane production systems, mainly based on the anaerobic digestion process. There is also a strong collaboration between industries, governments and research centers, which has led to innovative solutions such as the advanced purification of biogas to produce high-quality biomethane, ready for injection into gas networks. In particular, Italy is characterized by the presence of highly efficient plants, thanks to the vast experience gained over many years and to the continuous research carried out in this sector. Therefore, the advanced technology scenario could represent the Italian biomethane production if the entire theoretical potential was exploited, since most of the national plants adopt high-efficiency solutions (such as closed digestate systems and off-gas combustion configurations).

6. Socio-economic analysis of the Italian biomethane supply chain

The evaluation of the economic and social impact, associated with GHG emissions from the biomethane supply chain, requires an estimate of the monetary value to be assigned to each ton of CO_2 that is emitted into the atmosphere or whose emission could be avoided. The concept of Social Cost of Carbon (SCC) is therefore introduced, in order to assess the global climate change damage attributable to the emission of one additional ton of CO_2 into the atmosphere, expressed in monetary terms.

The phenomenon of climate change is the result of the negative cumulative effect, associated with the GHG emissions over the time, which lead to a continued increase in average global temperature. The consequence is represented by multiple impacts on the planet's productive, economic and social systems which have had and will continue to have significant negative social and economic repercussions. Since CO_2 is characterized by an extremely long residence time into the atmosphere, each ton emitted carries an increasingly significant weight, further exacerbating the phenomenon. Therefore, the total cost of the impact of climate change can be "referred" to each ton emitted, in order to quantify its negative contribution.

CO_2 emissions represent an optimum example of "negative economic externality," meaning they impose a cost that affects not only the responsible for the emissions but also a broader population, without any direct economic compensation for those affected by the consequences. In this context, the release of one ton of CO_2 by an individual turns out to be a negative effect (an economic cost) borne by all of humanity, as climate change is a global phenomenon despite emissions occurring locally. This is referred to as a "social cost" since it is experienced collectively by society.

The SCC can also be understood in reverse terms: as the monetary value of the "damage avoided" (and thus the economic benefit) when the emission of one ton of CO_2 is prevented. These two interpretations, the social cost for emissions generated and the social benefit for emissions avoided, are equivalent. The SCC serves as a key benchmark for assessing the economic viability of initiatives aimed at reducing CO_2 emissions by comparing the social benefit of emission reductions with the associated economic costs.

For any project aimed solely at cutting CO_2 emissions to be economically justified, its implementation cost must be lower than or at most equal to the avoided social cost of the unproduced emissions. This highlights the crucial role of accurately defining the SCC in decision-making processes concerning projects that include CO_2 reduction among their expected outcomes. [29]

Compared to other European countries, Italy strongly believes in expanding biomethane production, considering this latter a strategic option for energy transition and decarbonization, despite other alternative fuels. In confirmation of this, several incentive measures have already been implemented, such as the Biomethane Decree of 2022, to promote its production and integration into the national energy system. Even within the PNIEC, biomethane plays a crucial role in meeting gas demand to achieve the targets set for 2030, as well explained in the previous chapters.

In this context, three different scenarios have been built with the aim of estimating the CO_2 emissions and the relative social costs, referring to the evolution of the biomethane supply chain in Italy, in accordance with the objectives expected:

- Business-As-Usual Scenario: The reference scenario where the biomethane production is attributable only to existing plants in the year 2022, which will be decommissioned.
- Biomethane Decree Scenario: The biomethane production is supported through incentives, outlined in the Biomethane Decree of 2022.
- Theoretical Potential Scenario: The biomethane production reaches its estimated theoretical potential, aligning with the PNIEC objectives, within a time horizon up to 2040.

These scenarios are designed to incorporate the conditions outlined in the reference scenario while also estimating the expected effects of biomethane targets characterized by a different time horizon, considered until the year 2040. At the base of each scenario, the trend of the national gas demand is assumed while the emissions associated with the biomethane production are calculated with the same emission coefficients used in the advanced technology scenario, shown in the previous chapters. The social costs due to the GHG emissions (or the economic benefit related to the avoided emissions) are determined by using a SCC which is expressed by means of three different discount rates, respectively 2%, 3.5% and 5%.

6.1 Selection of the Social Cost of Carbon (SCC)

The definition of a suitable value for SCC must be able to describe the damage caused by climate change, due to the emission of an added ton of CO_2 produced in the present until a specific moment in the future. Therefore, it is necessary to express the economic impact associated with such damage or, in other terms, to quantify the economic value to current society of avoiding future impacts of climate change.

In order to satisfy these requests, the assignment of a representative value for SCC can be relatively complex due to several reasons:

- The global nature of the climate change phenomenon makes the definition of its effects extremely difficult, the greater the granularity and precision required, which are also affected largely by the time horizon considered. As "precise" as the value calculated for SCC may be, it will always be characterized by a more or less significant uncertainty. However, the science of climate change has produced a volume of research that is decidedly sufficient to obtain reliable estimates.
- Climate change is a phenomenon with concrete effects already today, but which progressively worsen as time passes, As well as its negative economic consequences: as a result, each ton of CO_2 emitted causes greater damage than the previous one. The social cost associated with each ton emitted is higher compared to the social cost referred to the previous ton: the SCC is thus not a constant value but increases with each ton emitted, growing over time.
- The monetization of the effects of climate change is an operation that is not without critical issues from an ethical point of view. At geographical level, the effects of climate change are typically worse in the poorest and developing countries, which have fewer economic means for the necessary mitigation and protection works. At temporal level (perhaps even more importantly), the assignment of an economic value also to the damage that will be suffered by future generations, runs the risk of considering them "less serious" than they actually will be because they will not be suffered by those who must quantify them today.

Regarding this last point, one of the most complex operations is the selection of a “discount rate” to the economic value of the damage associated with climate change in future years. In addition to being already problematic in many other sectors, the discounting operation is often debated reason in the context of climate change. Several economists criticize the application of discount rates for very long periods in the future, such as those on which climate change has an effect (e.g. up to 2100), since it could be a relevant source of uncertainty. Moreover, the tendency to consider the present more important than the future leads to the devaluation of the consequences related to climate change that will occur at a later time than the current one. This is due to the awareness that more time is available to deal with tomorrow's problems than with today's, but by doing so the future is just put at risk, which in reality is the present of future generations.

For these reasons, the choice of the discount rate to apply to the SCC is central to research and debates on the topic. Many values for the SCC have been proposed in the literature, even very different from each other depending on the hypotheses adopted, the social and geographical context and the time horizons considered, the simulated climate scenarios and the discount rate values to be taken as a reference. [29]

Many States, which in their legal system apply cost-benefit analysis (CBA) in the preventive evaluation of incentive policies or specific public investments, have developed guidelines for the estimation of the SCC, thus recognizing its practical economic importance for the purpose of achieving the objectives of reducing greenhouse gas emissions. The Italian Government has equipped itself with a methodological manual that addresses this issue with reference to transport infrastructures (Guidelines of the Ministry of Infrastructure and Transport for the evaluation of investments in public works, 2017). Regarding the evaluation of external costs related to climate-altering emissions, the national Guidelines propose the central value of 90 $€_{2010}/t_{CO_2}$, a constant value independent by the year of emission, in turn derived from the second edition of the community manual on the external costs of transport, published in 2014. However, the literature references on which the national Guidelines are based now date back a decade ago, requiring an update.

In the latest edition of the Community Handbook (2019), developed by the European Commission as a reference for Member States, the "recommended" external cost for the evaluation of CO_2 has been updated, introducing two values differentiated based on the emission period (100 $€_{2016}/t_{CO_2}$ for emissions up to 2030, 269 $€_{2016}/t_{CO_2}$for emissions in the period 2031-2060). Both in the latest edition of the Community Handbook and in the previous one, the recommended values for the external costs of CO_2 were obtained through a review of the literature on the "*global costs of reducing CO_2 emissions*", an approach that was preferred to the "*climate change damage assessment (SCC)*" one. The reasons for this choice of the Community Handbook are essentially three:

- The damage assessment approach would generate results with a high range of variability, a sign of high uncertainty in the assessment.
- This approach would encounter difficulties in assessing damage to ecosystems and catastrophic damage (not only for economic aspects but also for biophysical ones), a limit that risks determining strong underestimations.
- Given that the 2015 Paris Agreement established a global temperature containment target (1.5 – 2.0 °C), the global emission reduction costs method can benefit from a benchmark that is precise and ambitious enough to replace the climate change damage assessment (SCC).

According to the report "Social cost of carbon: rassegna della letteratura", developed by RSE (Energy System Research), this orientation is unfounded for several reasons. From a theoretical point of view, it is simply contradictory that a manual for the evaluation of external costs (intended for cost-benefit analysis) proposes for the calculation of the benefits of climate mitigation, values based on the same approach with which the costs of emission reduction technologies are calculated. By definition, the SCC aims at measuring the economic benefits of emissions reduction through the modeling of climate damage, while the reduction cost is a metric that does not take into account the risks of climate change in any way.

The aim of this study is to deepen the scientific literature on SCC, referring especially to the reviews and main studies published in the last decade, in order to identify the best estimates of SCC, possibly with a long-term time horizon. Among the non-institutional reviews examined, the contribution of Howard and Sterner stands out. Unlike other academic reviews, which are more interested in analyzing the variability of all available estimates than in proposing the "best estimates" in the light of the most advanced literature, they have tackled the problem of selection: after providing a broad overview of the studies and methods used in estimating the damages of climate change, Howard and Sterner have selected a smaller set of empirical studies on the damage function with respect to temperature, from which they have obtained the best estimates, avoiding non-original duplicates and multiple estimates. Howard and Sterner arrive at two different estimates of the SCC: the first is based exclusively on non-catastrophic climate damages (a concept that includes damages associated with the growth of temperature and the rise of sea levels, including the possible increase in the frequency of extreme weather events); the second also includes catastrophic events (particularly critical phenomena for the climate, the so-called "tipping points", which require more advanced modeling at a continental scale, such as permafrost thawing). To conclude, the Howard and Sterner estimate including catastrophic events emerged as the most convincing candidate, among those emerging from the literature reviews considered, to propose a better estimate of the SCC sufficiently complete, robust and updated to the literature of the last decade.

Following the indications of the OECD (Organization for Economic Co-operation and Development) and the US IWG (United States Interagency Working Group) on the need to offer differentiated SCC estimates for the social discount rate, it was considered appropriate to rework the results of Howard and Sterner to offer a sensitivity analysis of the SCC with respect to a range of discount rate options (in addition to the 4.2% implicitly assumed, 2.5%, 3% and 5% were also considered, as in the sensitivity analysis of IWG).

Table 34 reports the best estimates of the SCC for emissions in the period 2020-2040 for total climate change damages (non-catastrophic and catastrophic), obtained by reworking the results of Howard and Sterner as reported above. [5]

Discount rate	2020	2025	2030	2035	2040
2,5%	411	515	619	722	826
3,0%	256	321	386	451	515
5,0%	66	83	100	117	133

Table 34 - SCC calculated for different discount rates in the period 2020-2040, RSE rework, year 2022

Figure 13 shows the variation of the SCC year by year, obtained thanks to the cubic interpolation (more accurate than linear and quadratic interpolation) of the values reworked by GSE for the different discount rates, in the period 2020-2040. This evolution is the result of the very nature of the SCC, since the accumulation of CO_2 emissions cause a worsening of climate impacts (e.g. extreme events, damage to infrastructure, reduction in agricultural productivity), increasing the social cost associated with each ton of CO_2 released. Moreover, the discount rate applied represents a sort of "devaluation" degree referred to the future damage, leading to a more or less pronounced increase in the SCC value over the time. [5]

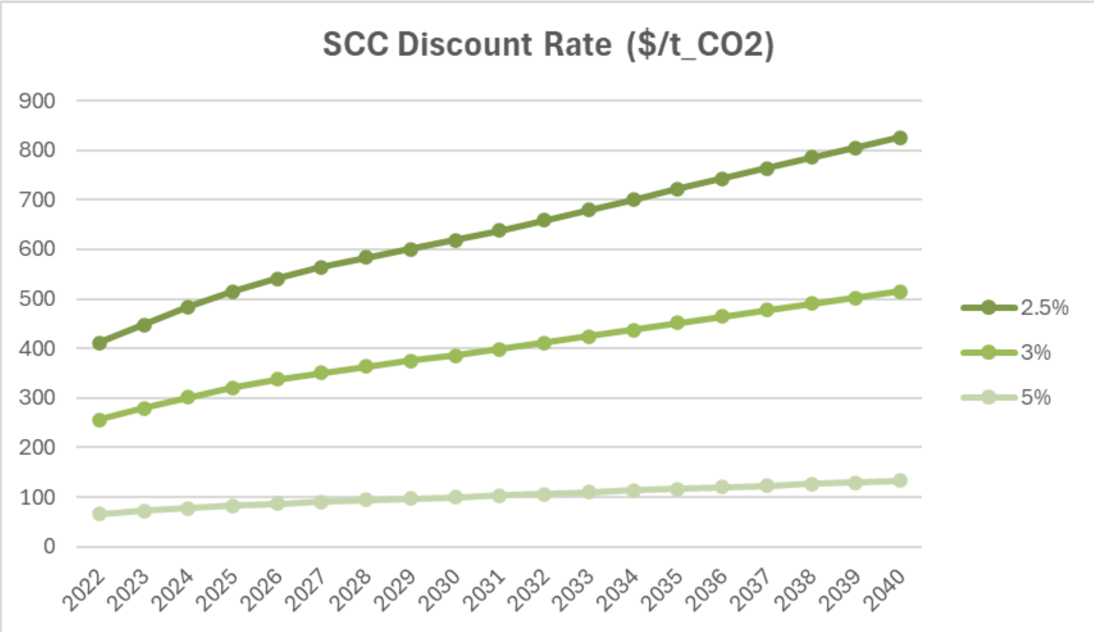


Figure 13 - Variation of the SCC year by year for different discount rates in the period 2020-2040, RSE rework, year 2022

For the purposes of applying the SCC values in the various analyses in order to evaluate the social costs/benefits, here appropriately differentiated in relation to the social discount rate, the central value of 3% is considered as a reference by the US IWG and is also the one recommended up to now in Italy by the current Guidelines for the Evaluation of Public Investments. [5]

6.2 Scenario building: approaches and methods

In order to evaluate the environmental and social effects, related to the evolution of the biomethane supply chain in Italy, it is necessary to take into account the future trend of the overall national gas demand. By means of the study "Analisi degli Scenari 2024" developed by SNAM, the evolution of gas demand was estimated, according to the energy and environmental policy objectives at both national and European level for the horizon years 2030, 2035 and 2040. [30]

Figure 14 shows the variation of the annual gas demand, obtained thanks to the cubic interpolation of the values provided by the SNAM analysis, in the period 2020-2040. In particular, a constant reduction in the amount of gas is expected year after year, as a consequence of both the increase in energy efficiency and the greater electrification of consumptions, due to the energy transition and decarbonization process, as well as the decline in population.

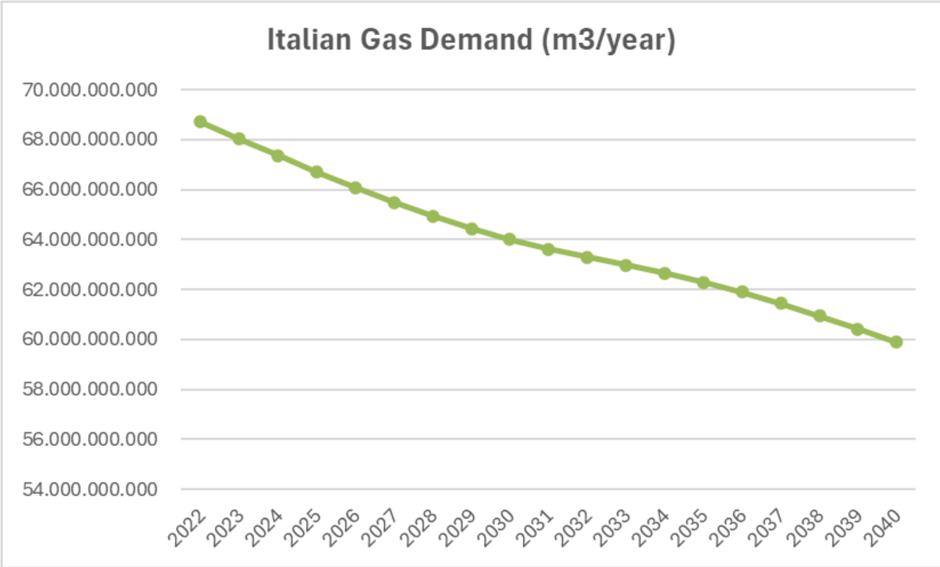


Figure 14 - Variation of the Italian gas demand year by year in the period 2020-2040, SNAM, year 2024

Each scenario is characterized by a specific trend of the biomethane produced, which allows to calculate the corresponding annual volume of natural gas, required to satisfy the national gas demand. By means of the emission coefficients accurately selected in the previous chapters, it is possible to estimate the amount of equivalent CO_2 produced by the mix of natural gas and biomethane foreseen by each scenario. In particular, the emission factors employed in the advanced technology scenario are used to evaluate the environmental impact due to the CO_2 emissions, since the technology related to the biomethane supply chain can be defined highly efficient in Italy. To conclude, the social costs associated with the emissions are determined thanks to the selected SCC which is expressed, according to the different discount rates.

The Business As Usual Scenario (BAU) shows a projection of the future evolution of the biomethane supply chain, without considering significant changes in policies aimed at incentivizing this sector, as done for example with the implementation of Biomethane Decree 2022. In this context, biomethane production is linked just to the plants already operational, with reference to the year 2022, while those built in subsequent years due to past policies have not been considered, making this baseline scenario even more conservative. Assuming a useful life of the plants of 15 years, the production of biomethane will begin to decrease for the decommissioning in 2032 until it stops in 2038, so that the national gas demand coincides with that of natural gas. Figure 15 shows the biomethane production evolution, as described above.

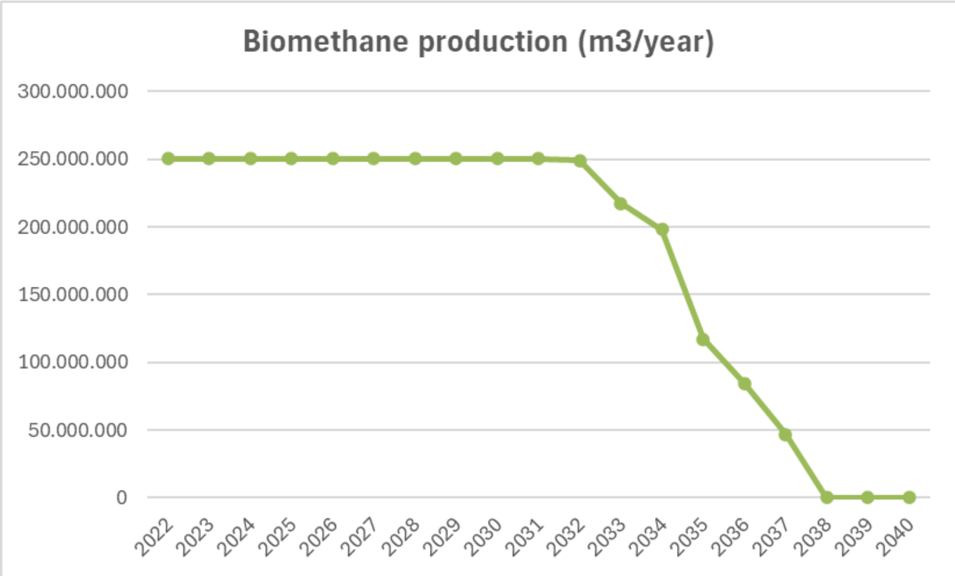


Figure 15 - Biomethane production for the BAU scenario, author's calculation

Focusing on the emissions associated with the biomethane produced in this scenario, it is possible to carry out a correct estimate, since the type of feedstock employed to feed every single plant is provided by owners. As most of the plants operate in co-digestion with various substrates, the relative emission coefficients consist in a weighted average, where the utilization of every raw material is perfectly aligned with their availability, according to the balanced market hypothesis (reference to the composition of the theoretical potential). Figure 16 illustrates the emissions caused by biomethane production, showing a general decline due to the decommissioning of plants from 2032. However, the trend also features two peaks, respectively in 2034 and 2037, resulting from the closure of plants that process manure, able to remove the CO_2 from the atmosphere.

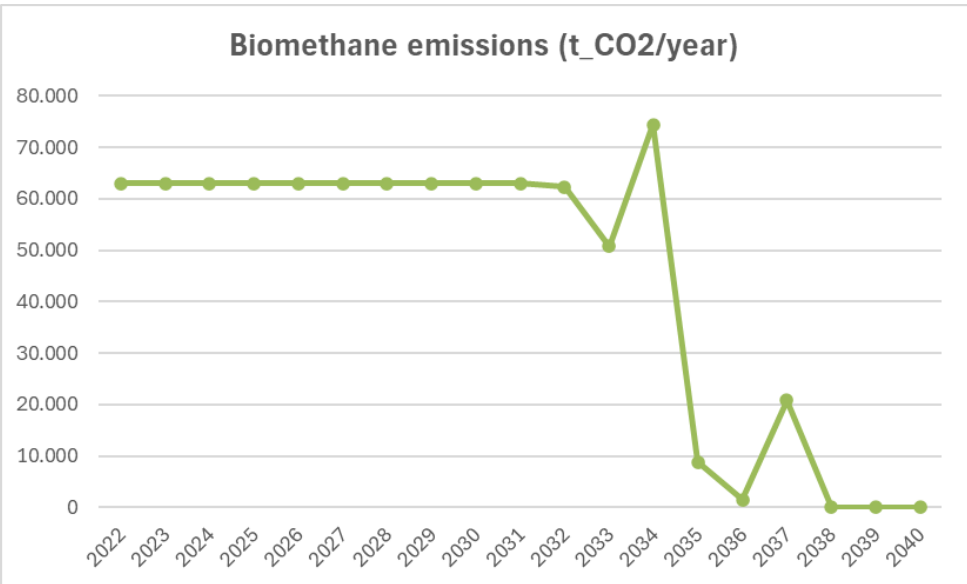


Figure 16 - Emissions related to biomethane for the BAU scenario, author's calculation

To emphasize the impact of the biomethane supply chain on the national gas sector in terms of social costs, the economic benefit of avoided emissions is calculated as the difference between a scenario where total gas demand is met exclusively with fossil natural gas and the BAU scenario. The conversion of the emissions in monetary terms requires the utilization of the SCC, expressed through the three different discount rates, accurately selected in the previous chapters. As demonstrated in Figure 17, this social benefit reaches its maximum value in 2032, the year before the decommissioning of the first plants begins, for then follows a constantly decreasing trend until the entire gas demand coincides with that of natural gas, cancelling the social benefit.

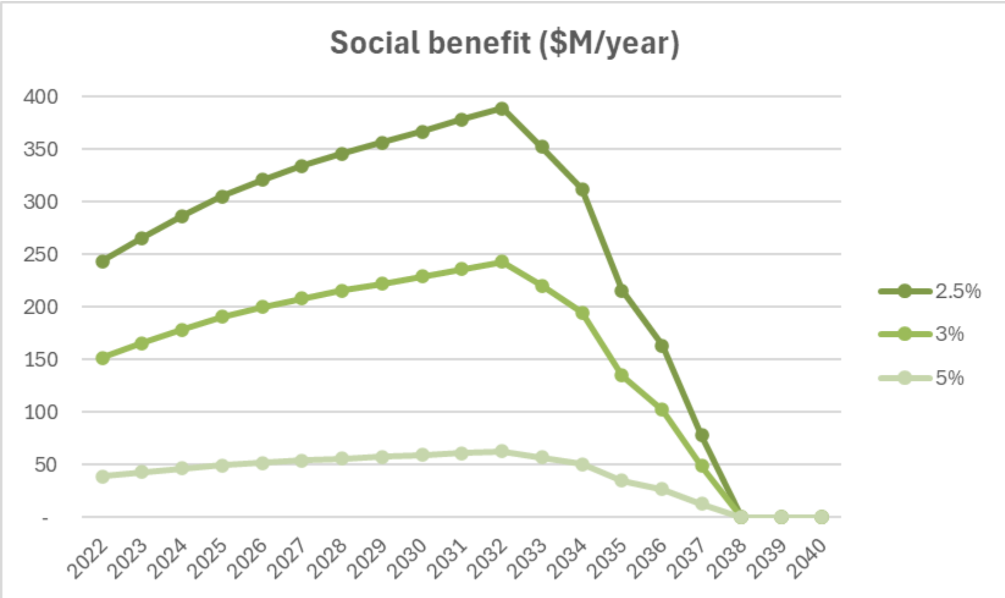


Figure 17 - SCC difference between only natural gas and BAU scenario, author's calculation

The Biomethane Decree scenario (BD) has the aim of investigating the effects of the incentivizing strategy provided by this policy, on the national biomethane supply chain. At the time of analysis, the agricultural or organic waste plants that meet the pre-established requirements to benefit from the allocated funds were reported in four calls for tenders, published by GSE. Between the various information provided for each single plant, the most important are represented by the typology of plant, according to the feedstock used, the date of signature and the plant production capacity, expressed in standard cubic meter per hour (Sm^3/h). In this way, it is possible to quantify the biomethane production in addition to the already existing one, which is reported in the BAU scenario.

Due to a participation by biomethane producers below expectations, further calls for tenders will be issued in the following years, in order to exhaust the funds provided by this provision. To estimate the biomethane production associated with the future accession of new plants, the participation rate of the year 2023 is adopted to achieve the production limit of 2.3 $bm^3/year$, as foreseen by the Biomethane Decree. In particular, some plants which had applied for 2023, applied again for the following year, in order to take advantage of the new incentive rates, adjusted according to inflation. Therefore, the participation rate selected does not consider these plants, accounting for 121 plants of which 20 operate with organic waste while the remaining 101 operate with agricultural residues. Figure 18 shows the biomethane production, where maximum capacity is reached in 2029 (three years later than the Decree target) and then begins to decrease starting from 2032, always in correspondence with the decommissioning of the first plants, as in the BAU scenario.

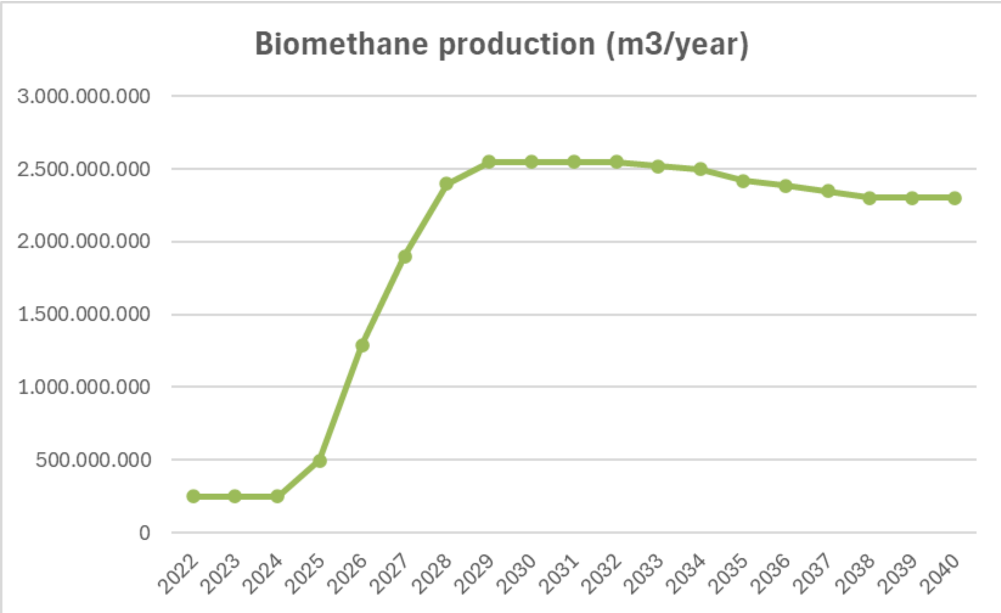


Figure 18 – Biomethane production for the BD scenario, author's calculation

Compared to the BAU scenario, the agricultural plants which will be built according to the Biomethane Decree lack in a detailed description of the feedstock employed. Therefore, the evaluation of emissions caused by the biomethane produced is carried out by using a weighted average of the emission coefficients corresponding to the raw materials indicated for these plants. More specifically, agro-industrial residues, including straw and whey, as well as manure are taken into account, based on their respective contributions to the theoretical potential, in percentage terms. Figure 19 illustrates the emissions related to the biomethane production, which are characterized by negative values due to the removal of CO_2 linked to the anaerobic digestion of manure which is largely available between agricultural waste. After reaching the maximum negative value in 2029, there are variations due to the decommissioning of the first plants which start in 2032.

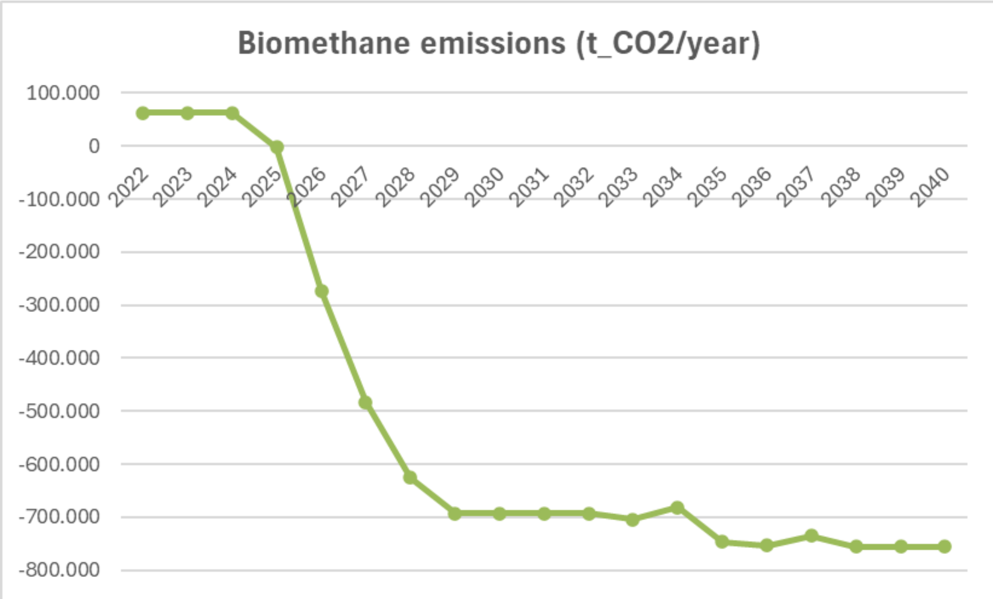


Figure 19 - Emissions related to biomethane for the BD scenario, author's calculation

As in the BAU scenario, the social costs associated with the biomethane supply chain are expressed by means of the SCC with the three different discount rates, as an economic benefit of avoided emissions. As demonstrated in Figure 20, this social benefit presents a steep increase until 2029, when the production limit established by the Biomethane Decree is reached, followed by a relatively constant increase due to the intrinsic evolution of SCC and the reduction of the overall gas demand over the years. However, small bends occur in this section of the curve due to the decommissioning of the first plants.

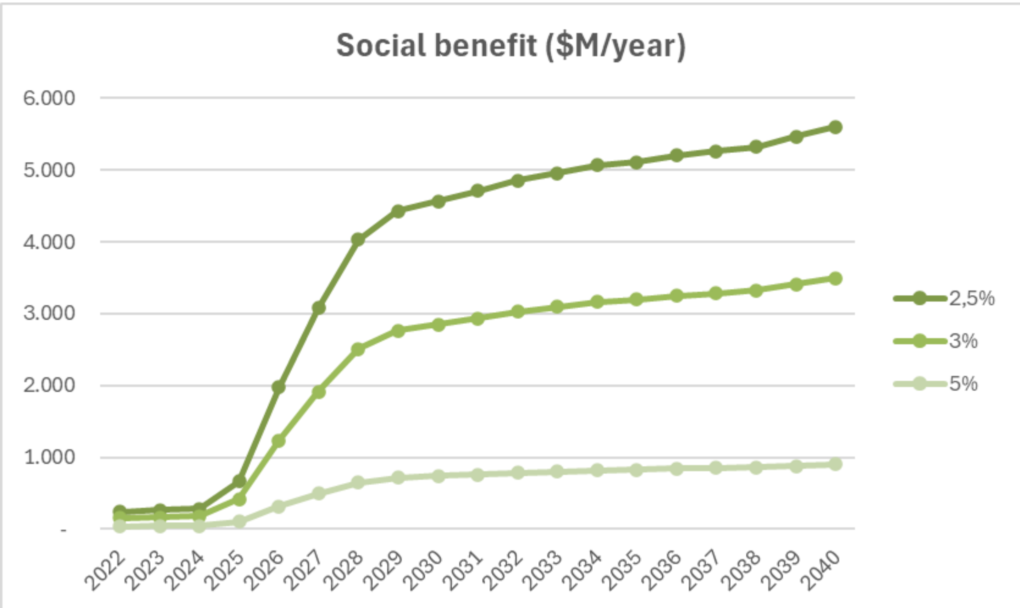


Figure 20 - SCC difference between only natural gas and BD scenario, author's calculation

The Theoretical Potential scenario (TP) represents an extreme case, where all the estimated theoretical potential is exploited by the biomethane supply chain. As well as considering the biomethane already produced in 2022 and the one confirmed by the implementation of the Biomethane Decree, the participation rate of 2023 is adopted again to achieve the production limit of about 5.65 $bm^3/year$, equal to the theoretical potential and in line with the PNIEC objective (5.7 $bm^3/year$). Figure 21 shows the biomethane production which follows a relatively linear trend, driven by the commissioning of plants incentivized by the Biomethane Decree in 2025, until production capacity reaches the saturation in 2035 (five years later than the PNIEC target). An evolution of this type is the result of the constant participation rate assumed, while the effect related to the decommissioning of the first plants is cancelled, supposing that they are substituted by new plants, in order to maintain the maximum production capacity.

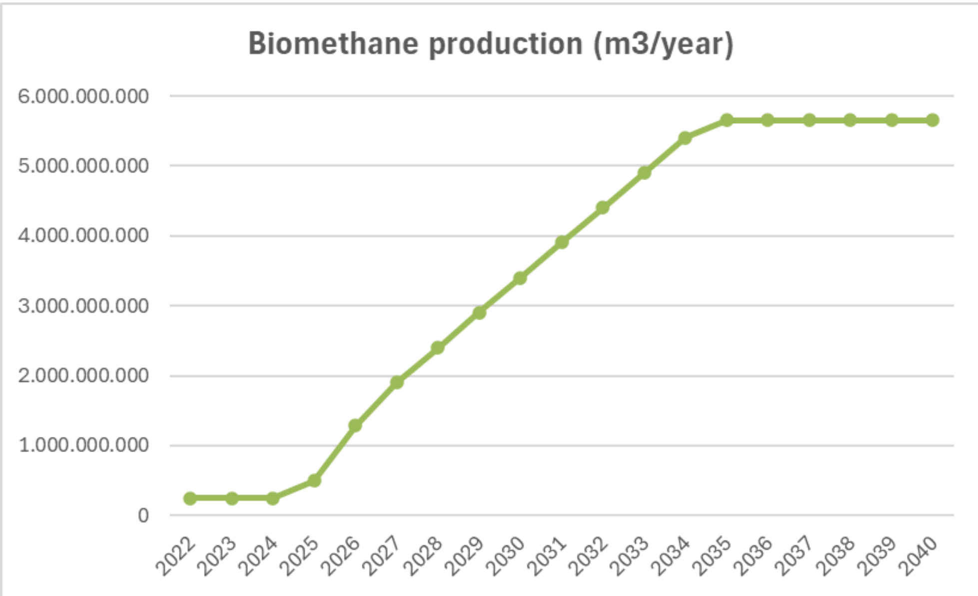


Figure 21 - Biomethane production for the TP scenario, author's calculation

In this scenario, it is supposed that new plants required to reach the saturation of production capacity will utilize all feedstocks considered for energy purposes. Therefore, the evaluation of emissions caused by the biomethane production requires a weighted average of the emission coefficients, corresponding to the raw materials that contribute to the theoretical potential in varying proportions. Furthermore, plants destined for decommissioning are replaced with new generation ones, like the plants just mentioned. Figure 22 illustrates the emissions associated with the biomethane production, characterized by negative values which present a reduction between 2025 and 2029 for the entry into operation of the plants foreseen by the Biomethane Decree. Then a further decrease, in accordance with a linear trend, is followed for the adoption of a constant participation rate until 2035, where the biomethane production achieves its saturation limit.

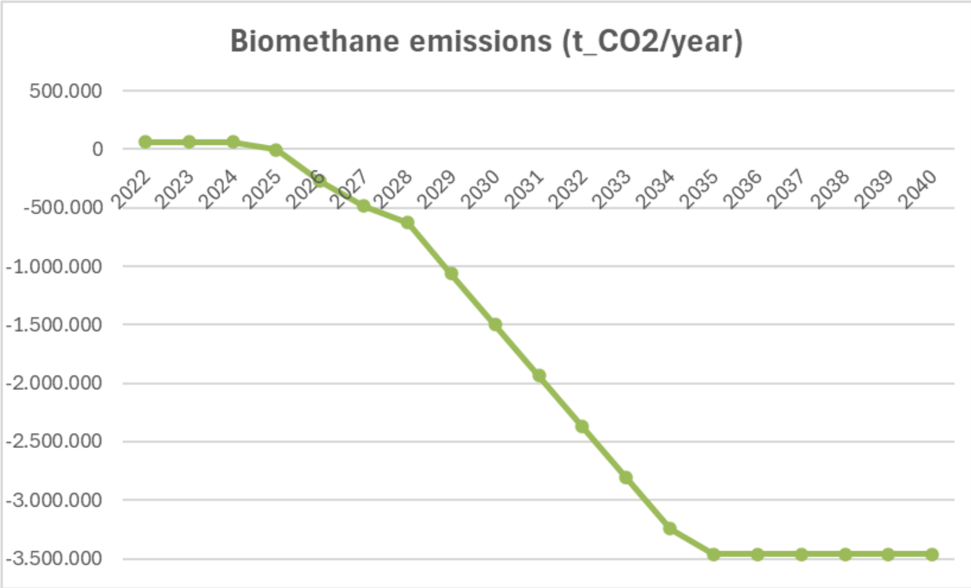


Figure 22 - Emissions related to biomethane for the TP scenario, author's calculation

As in the other two scenarios, the economic benefit of avoided emissions is defined with the adoption of the same procedure. As demonstrated in Figure 23, this social benefit follows an almost linear trend, between 2025 and 2035 due to the superimposition of two effects: the constant participation rate assumed and the intrinsic evolution of SCC over the years. Subsequently, another linear trend with a different slope emerges solely due to the progression of SCC, as production capacity reaches the saturation from 2035 onwards.

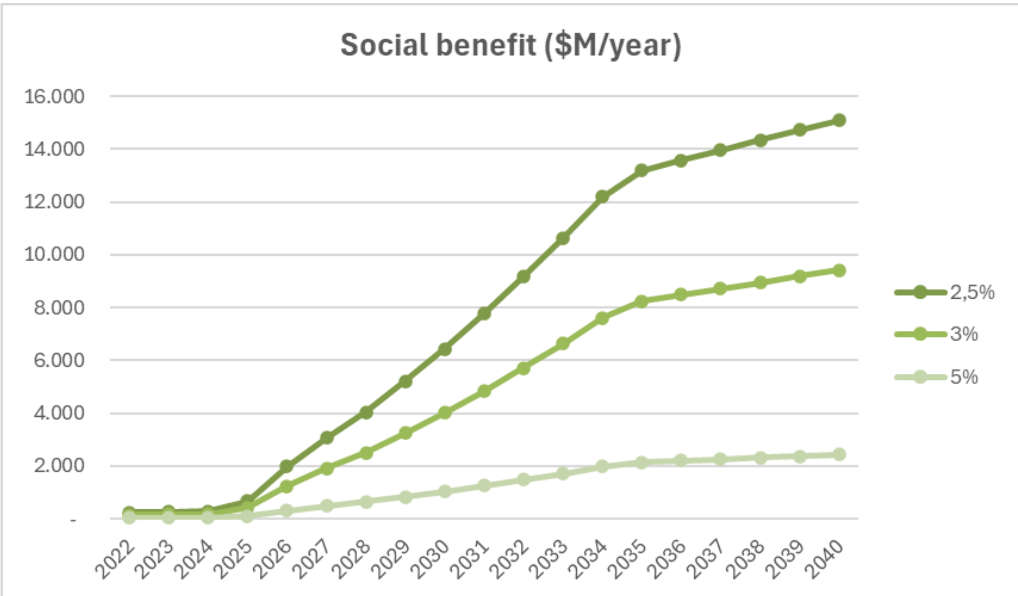


Figure 23 - SCC difference between only natural gas and TP scenario, author's calculation

6.3 Comparison of the three scenarios

From the biomethane production point of view, the three scenarios show different trends, which are mainly distinguished by the orders of magnitude and time horizons associated with the production objectives assumed. Figure 24 summarizes these aspects, through the comparison of the biomethane production evolutions, referred to each scenario.

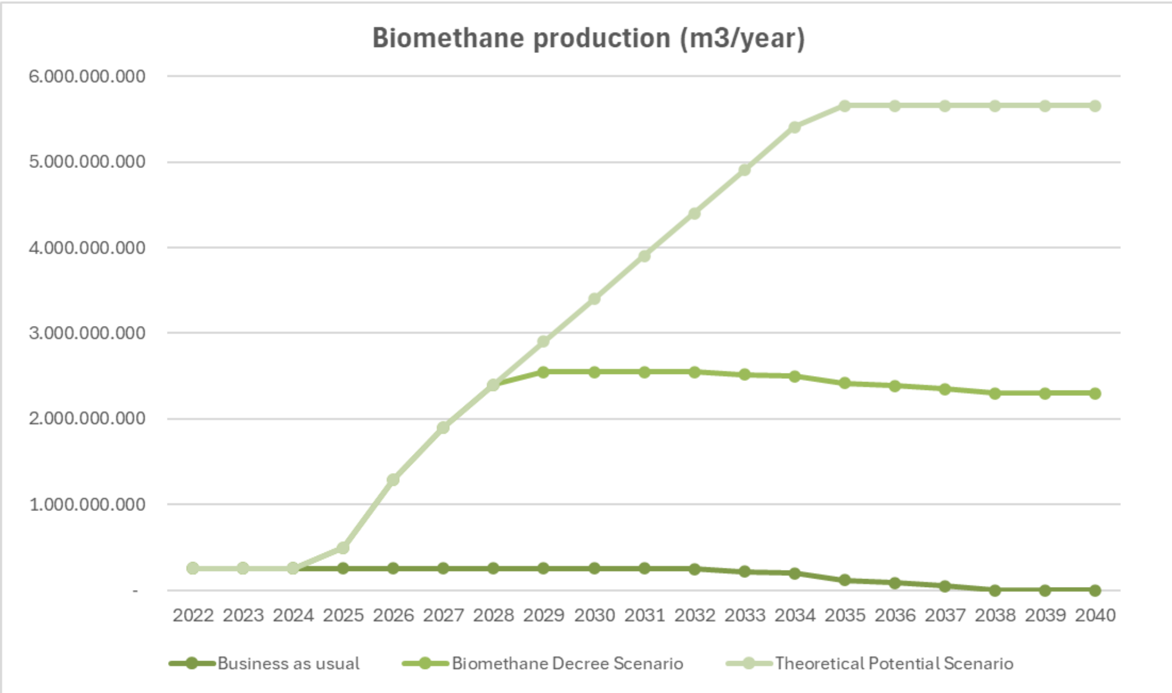


Figure 24 - Comparison of the biomethane production associated with each scenario, author's calculation

With regards to the emissions related to the evolution of the biomethane supply chain in the different scenarios, the comparison of annual emissions cannot be effective, since the CO_2 released in the atmosphere is characterized by an extremely long permanence time (decades-millennia of years), before to be naturally degraded. CO_2 is the most critical greenhouse gas for long-term climate change, precisely because it contributes to the greenhouse effect for an important period compared to other gases. The expression of these emissions in cumulative terms allows to evaluate the total impact rather than just annual values, as well as whether the overall accumulation over time is decreasing. In fact, even if emissions are decreasing year after year, the total could continue to grow if they are not eliminated.

Figure 25 illustrates the cumulative curves of the emissions associated with the biomethane produced in the various scenarios. Referring to the year 2040, an overall amount of CO_2 equal to 0.849 Mt_{CO2} is estimated for the BAU scenario, in contrast to the -9.85 Mt_{CO2} and -34.9 Mt_{CO2} of the BD and PT scenarios, respectively. In the first case, the value obtained is the result of the progressive decommissioning of the plants which lead to the utilization of fossil natural gas to completely satisfy the overall gas demand. In the other two cases, the negative values are due to the CO_2 removal effect resulting from anaerobic digestion of some feedstocks.

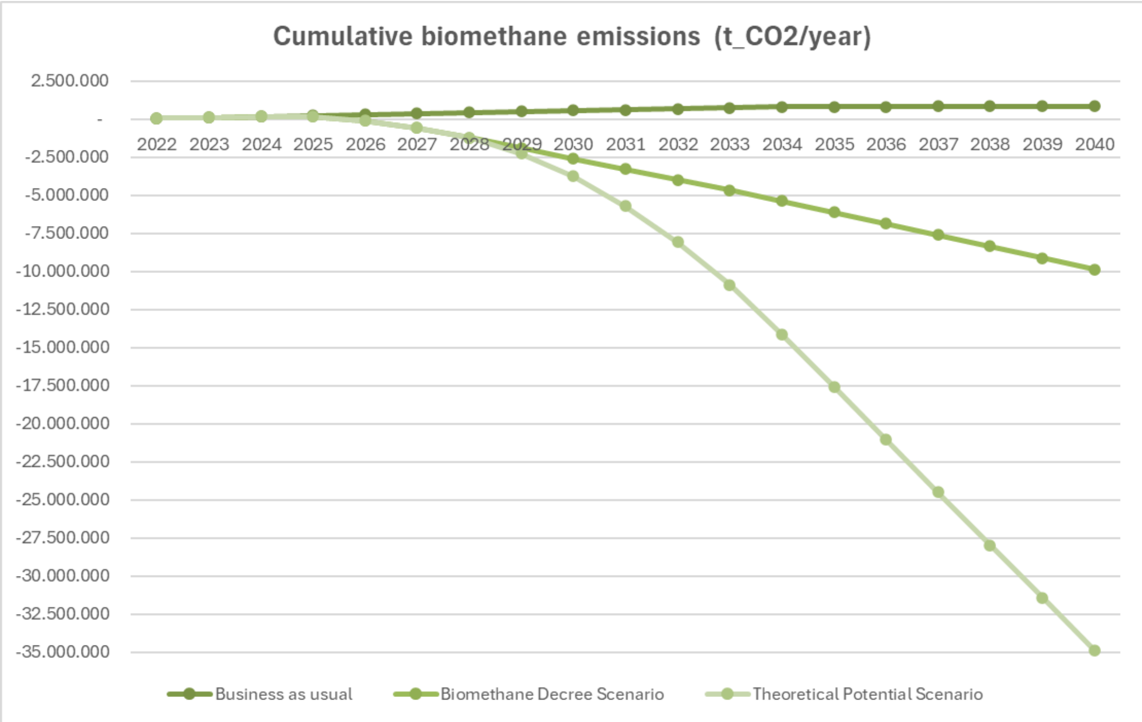


Figure 25 - Comparison of the cumulative curves referred to biomethane emissions, author's calculation

Extending the analysis on the total emissions caused by the national gas sector, the biomethane supply chain assessed by the different scenarios leads to important consequences, as reported in Figure 26. With respect to the BAU scenario, where total emissions account for 3,178 Mt_{CO2}, BD and PT scenarios allows to obtain respectively 3,081 Mt_{CO2} and 2,979 Mt_{CO2} which correspond to an emissions reduction of 3.03% and 6.26% compared to the first reference scenario. The difference in terms of percentage between the BD and PT scenarios is equal to 3.33%, thus representing a middle way, always with reference to the year 2040.

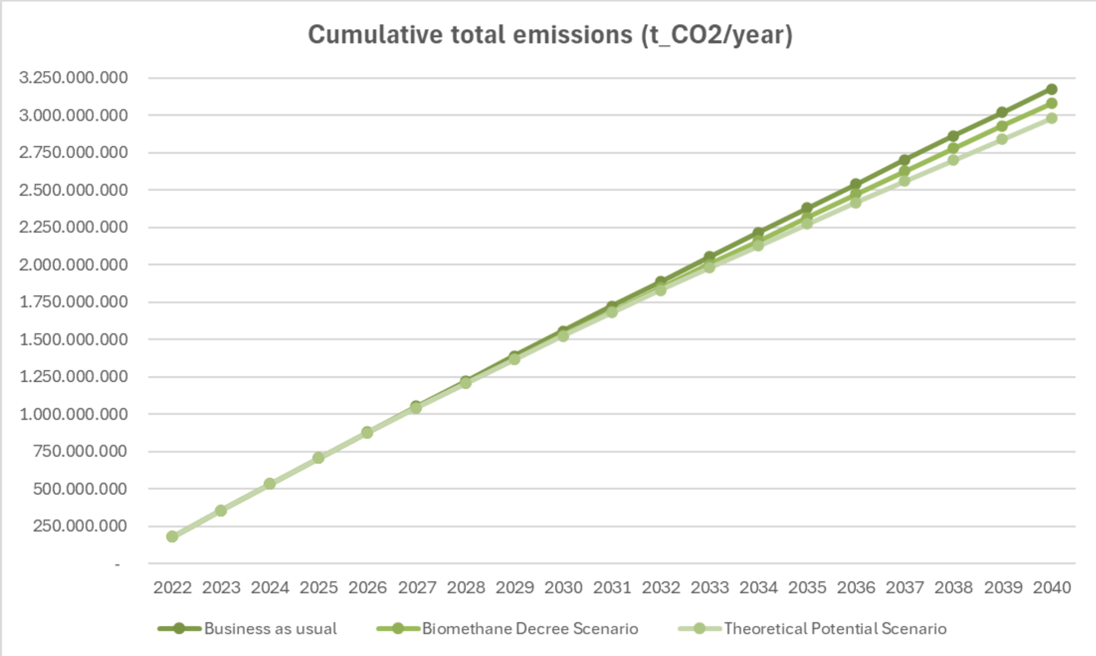


Figure 26 - Comparison of the cumulative curves referred to total emissions, author's calculation

As carried out for the CO_2 emissions, also the social benefit associated with the emissions avoided thanks to biomethane replacement with the fossil natural gas, can be expressed in cumulative terms. Figure 27 shows the cumulative curves relative to the social benefit obtained in the three different scenarios, assuming the discount rates selected in the previous chapters of 2.5%, 3% and 5%. Comparing the results to the year 2040, the BAU scenario is characterized by a cumulative social benefit of $2,940M in contrast with the values of $44,381M and $91,688M of the BD and PT scenarios. The discount rate of 3% has been applied to obtain these monetary results, which represents the reference according to US IWG and in particular by the current Guidelines for the Evaluation of Public Investments in Italy.

Since new benefits from emissions reductions are added each year (and these benefits themselves increase over time), the cumulative value follows a curve that appears exponential, especially at low discount rates. More generally, the behavior of the social benefit is a direct consequence of the characteristics of the SCC and how the discount rate affects future benefits. The same considerations can be made for the analysis carried out with the other discount rates of 2.5% and 5%, as illustrated in the following figure. Obviously, the application of a lower discount rate leads to higher present value, favoring long-term investments, in contrast to a higher one.

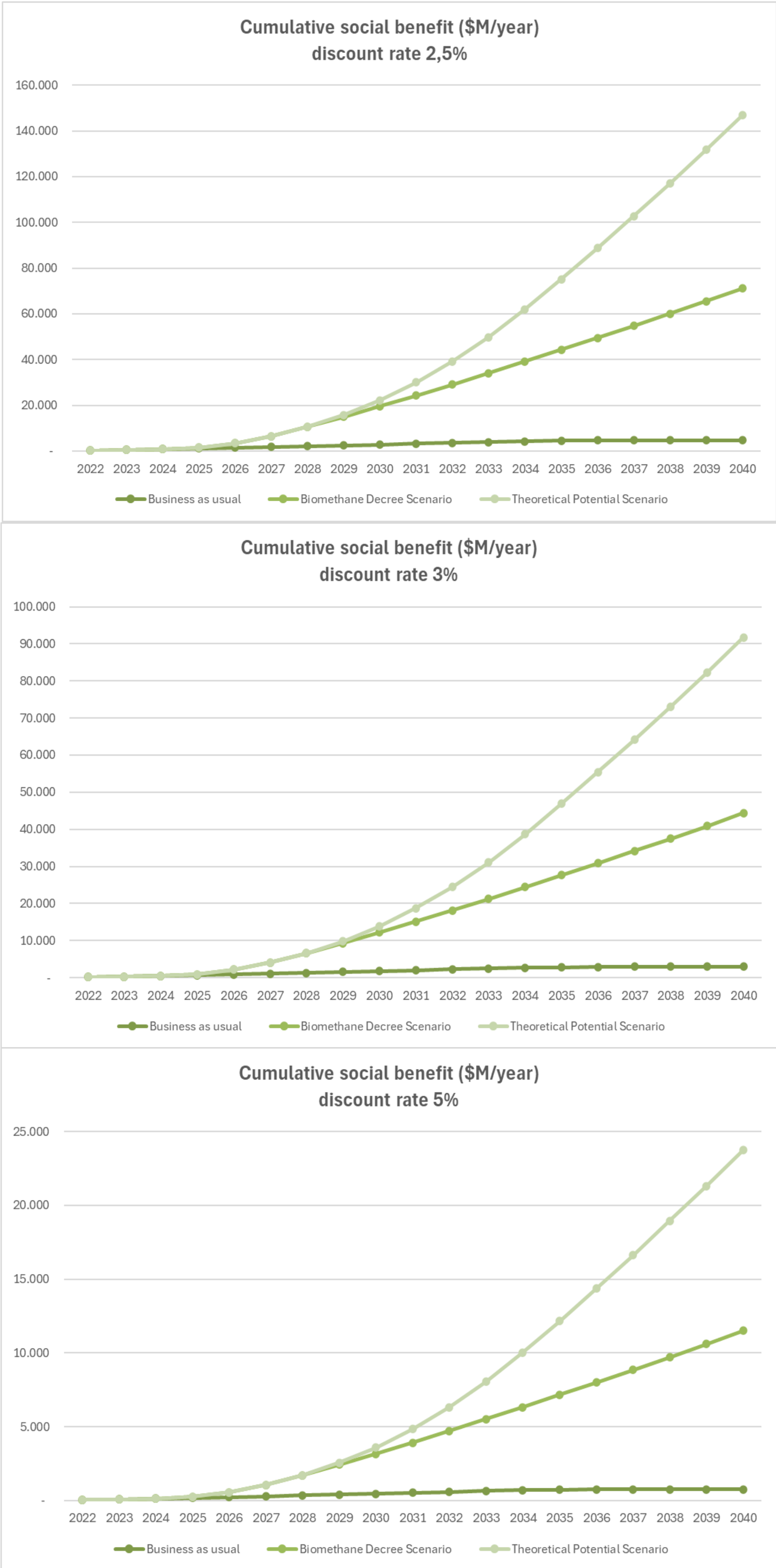


Figure 27 - Cumulative curves referred to the social benefit for different discount rates, author's calculation

7.0 Discussion and Conclusion

This study consists of two fundamental parts with distinct yet closely interconnected objectives: estimating the theoretical potential of biomethane at the national level and assessing the socio-economic impact of the biomethane supply chain in Italy. Initially the maximum availability of some raw materials, considered more suitable for the production of biomethane, was evaluated by means of different data sources, with reference to the year 2022. More in detail, a focus was carried out on the "advanced" feedstock intended as processing waste, without analyzing the dedicated crops production for energy purposes.

Subsequently, the annual quantities of these raw materials, defined at regional level, were turned into the theoretical potential of biomethane which would be produced if the maximum availability was destined to the biomethane production, regardless of the current final uses. Table 26 (and Figure 29) summarizes the biomethane producible in each region, according to the type of feedstock employed and it is possible to notice the crucial role of straw, which accounts for 2,401 million cubic meters of biomethane (equal to 42% of the total). Also zootechnical waste represents an important resource, accounting for 1,716 million cubic meters (30% of the total), while OFMSW with its 689 million cubic meters (12% of the total), is one the most employed feedstock for biomethane production, so as to reduce the quantities destined for landfill.

Considering the biomethane already produced in 2022, equal to 250 million cubic meters (5% of the total) and the biomethane which can be extracted by the Italian biogas supply chain (one of the most developed in Europe), it was possible to define the potential not yet exploited. In particular, with an extraction potential of 2,614 million cubic meters (46% of the total), the residual potential is equivalent to 2,789 million cubic meters, which represents 49% of the overall theoretical one.

Therefore, the biomethane sector enjoys large margins for growth in the Italian context, especially if the existing biogas infrastructure is exploited, which is very extensive across the territory. The conversion of the already existing biogas plants represents an optimum transient solution in terms of economic feasibility, as it requires lower initial investment costs rather than the construction of a completely new plant. Having large quantities of waste, mainly from the highly developed agricultural sector, the production of biomethane in Italy would allow obtaining a valuable energy resource and safely disposing of these residues at the same time. This is in line with the policies implemented against climate change and energy independence, imposed by Europe for all Member States and foreseen also by the national objectives for the energy sector.

To evaluate the GHG emissions associated with the biomethane supply chain, different emission coefficients for each feedstock were selected. The Well-To-Tank analysis at the basis of the calculation of these parameters allows to take into account the overall emissions, from the feedstock used until the single cubic meter of biomethane produced, in grams of CO_2 equivalent per megajoule. The discrepancies of emission coefficients referred to the same feedstock are due to mainly the technology used for the biomethane production, even leading to an effect of removing CO_2 from the atmosphere. Calculating the emissions related to the potential, two diametrically opposed results can be obtained, respectively 12,8 million tons of CO_2 and -5,23 million tons of CO_2, if the best and worst emission factors are used in the two cases. The first result is comparable with the value of 14,8 million tons of CO_2 which represents the emissions associated with the fossil natural gas imported, including the combustion phase. Therefore, it is possible to understand the crucial role of the technology applied for biomethane production, which can erode the environmental benefits of this alternative fuel. Fortunately, Italy together with other European States has been committed for many years to the development and research of innovative solutions in the biogas and biomethane sector, allowing to already have cutting-edge technologies and so very low emission levels.

The possibility of quantifying the emissions associated with biomethane production is at the base on the assessment referred to the socio-economic impact of the biomethane supply chain. For this purpose, a suitable SCC was accurately chosen in order to attribute a monetary value to the global damage due to climate change, related to the emission of an additional ton of CO_2 into the atmosphere.

Three different scenarios were built, with the aim of analyzing the possible evolution of the biomethane sector in Italy, until the year 2040. While the BAU scenario considers a progressive abandonment of this technology, BD and PT scenarios assume the achievement of the Biomethane Decree and theoretical potential targets, respectively. From the cumulative emissions point of view, compared to the BAU scenario, where total emissions reach 3,178 Mt_{CO2}, the BD and PT scenarios achieve reductions of 3.03% and 6.26%, respectively. The emission difference between BD and PT scenarios is 3.33%, positioning BD as an intermediate solution, all referring to the year 2040.

The social benefit due to the avoided emissions is calculated as the difference between a scenario where total gas demand is met exclusively with fossil natural gas and the scenario considered. The conversion of the emissions in monetary terms requires the utilization of SCC, expressed through three different discount rates, respectively 2.5% 3% and 5%. Given the long permanence of CO2 in the atmosphere, the social benefit can also be expressed in cumulative terms, growing over time. By 2040, the BAU scenario shows a social benefit of $2,940M, compared to $44,381M for the BD scenario and $91,688M for the PT scenario. A 3% discount rate, in line with different institutional organizations, was applied to these results, even if the same considerations can be carried out for the other discount rates.

The results clearly show that emission reduction policies, such as those in the BD and PT scenarios, can lead to significant social benefits. Compared to the BAU scenario, the benefits from emission reduction are considerable, with the increase in social benefits for the BD and PT scenarios significantly exceeding that of the first reference one. The benefits of reducing emissions avoid economic, health and environmental damage, which often exceed the initial costs of the infrastructure. With a positive return in the form of greater social well-being, these investments contribute not only to environmental sustainability, but also to improving the quality of life, through a reduction in pollution-related diseases and the creation of economic opportunities. Therefore, the assessment of social benefits is essential, especially for planning and evaluating public policies. Energy transition policies should include not only an analysis of direct costs, but also of long-term indirect benefits, thus ensuring that investments are evaluated in a comprehensive and collective well-being-oriented manner.

REGIONS	BIOMETHANE THEORETICAL POTENTIAL [x 10^3 m3/year] Straw	Pruning	Pomace	Marc	Shells	Husk	Citrus pulp	Tomato peel	OFMSW	Urban wastewater sludge	Zootechnical waste	Whey	Total
Piemonte	412,286	4,707	2	3,563	625	48,117	-	261	42,409	3,742	183,331	25,620	**724,664**
Valle d'Aosta	21	92	0	23	0	-	-	-	1,142	97	5,790	660	**7,826**
Liguria	172	1,891	527	115	0	-	5	-	14,238	551	2,786	127	**20,411**
Lombardia	407,645	2,118	137	1,985	2	29,953	-	1,077	109,021	5,854	410,352	113,092	**1,081,236**
Trentino Alto-Adige	479	3,179	67	1,959	0	1	-	0	12,996	1,589	34,162	10,794	**65,227**
Veneto	317,886	21,750	228	11,145	19	1,028	-	230	69,359	4,375	239,289	33,167	**698,476**
Friuli-Venezia Giulia	77,770	3,637	20	1,525	1	7	-	-	14,696	929	34,482	5,528	**138,595**
Emilia-Romagna	287,733	10,713	132	16,079	7	1,645	-	3,704	75,771	3,947	192,000	54,027	**645,757**
Marche	86,319	3,273	421	1,450	4	-	-	1	21,293	870	24,361	4,272	**142,263**
Toscana	108,485	7,761	1,791	2,209	38	138	3	290	49,950	2,719	27,690	6,577	**207,650**
Umbria	52,719	2,740	653	634	11	-	-	16	11,275	474	23,865	1,689	**94,076**
Lazio	65,288	7,062	3,214	1,488	663	-	104	264	55,096	2,526	71,672	4,666	**212,045**
Campania	57,875	11,452	2,982	7,333	513	-	903	450	60,317	1,872	93,027	16,221	**252,944**
Abruzzo	41,249	9,590	1,741	2,923	4	0	2	112	14,648	794	27,460	855	**99,379**
Molise	21,315	1,671	1,201	2,180	20	-	3	122	2,451	55	21,067	5,342	**55,426**
Puglia	191,113	29,154	10,685	16,805	486	1	7,558	2,816	41,123	2,542	47,008	11,961	**361,250**
Basilicata	71,342	2,184	601	173	14	-	2,934	223	4,753	41	24,144	752	**107,160**
Calabria	30,997	33,238	9,450	314	43	70	28,266	211	16,774	327	28,515	3,030	**151,235**
Sicilia	121,986	28,597	9,298	11,063	1,902	10	36,053	145	49,030	538	92,838	3,629	**355,088**
Sardegna	48,711	5,634	864	1,708	31	1,517	503	48	22,241	716	132,409	18,955	**233,338**
Total	**2,401,390**	**190,443**	**44,013**	**84,673**	**4,382**	**82,487**	**76,332**	**9,970**	**688,585**	**34,558**	**1,716,247**	**320,963**	**5,654,044**

Table 35 - Theoretical potential of the advanced biomethane for different feedstocks with regional details, author's calculation

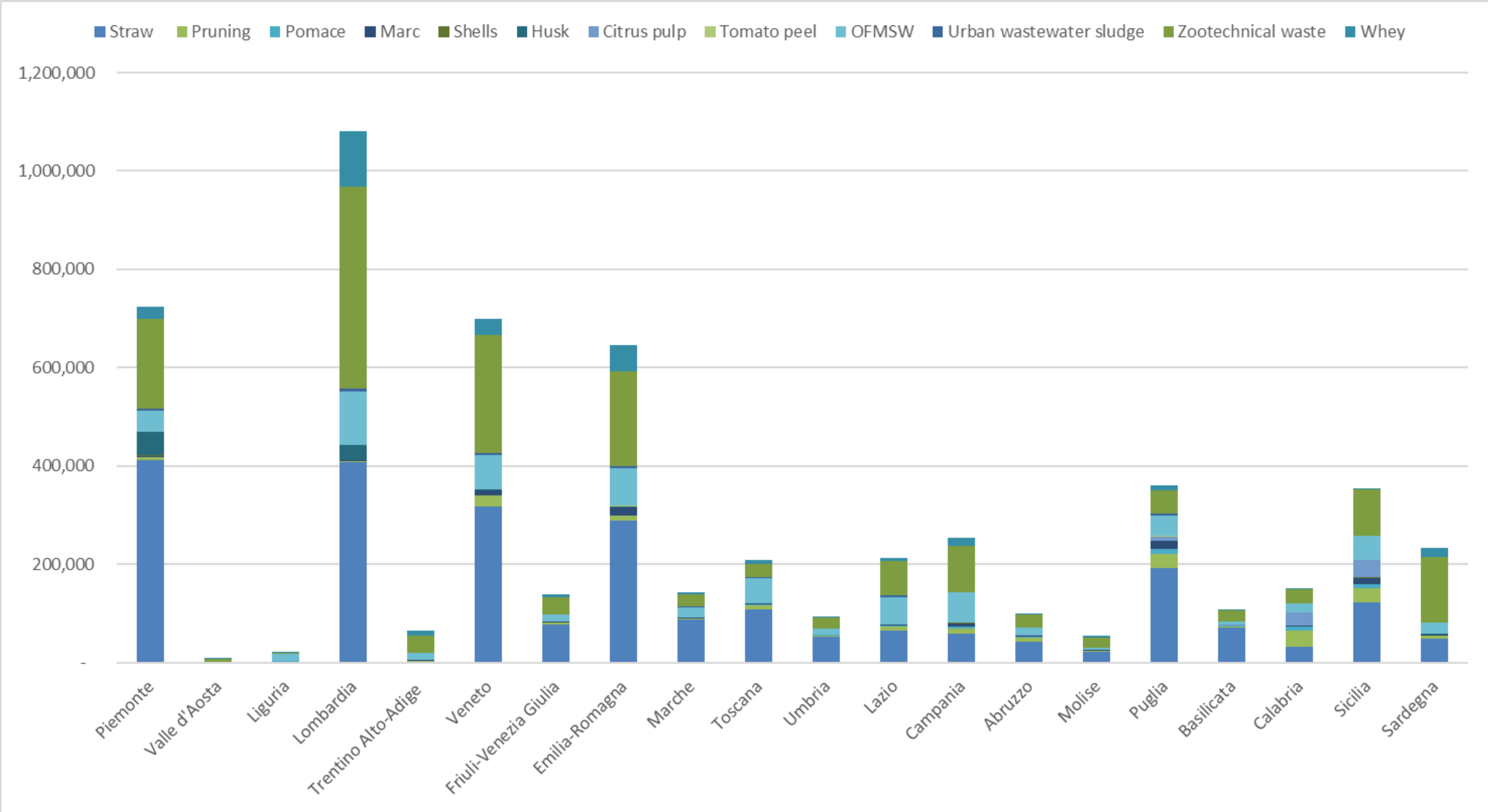


Figure 29 - Contribution of each feedstock to the theoretical potential of the advanced biomethane with regional details, author's calculation

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