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Life Cycle Assessment of Biomethane vs. Fossil Methane Production and Supply

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Abstract: Considering the current geopolitical situation that has hindered the gas supply gas from Russia, Europe's main supplier, it is necessary to find alternative routes to guarantee the Italian gas stocks in winter at a reasonable cost. Such energetic strategies should consider the environmental sustainability of the different available options, fitting the targets of the EU environmental policy. With the aim of supplying a quantitative tool to support the European green transition, this paper reports the entire life cycle assessment (LCA) of three different options for the production and supply of natural gas/methane in Italy: the production of biomethane from biogas (considering a real-scale plant in Italy), the use of liquefied natural gas (LNG) supplied by Qatar by vessel, and the use of compressed gas delivered from Algeria via pipeline. The application of the LCA standardized method allowed for the quantification of the environmental benefit provided by the first option, against all the considered impact categories, thanks to a combination of several advantages: (a) its low-impact anaerobic production, (b) its exploitation of a waste product from the food/agriculture industries, and (c) its production of valuable by-products, which can be considered environmental credits. The results proved the possible environmental gain resulting from an integrated energy supply system that would be able to enhance the economic fabric of specific areas.

Keywords: LCA; biogas; biomethane; LNG; natural gas; circular economy; environmental footprint

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1. Introduction

The decomposition of organic matter under anaerobic conditions leads to the production of a gaseous mixture comprised of CH_4 and CO_2 (and some impurities), which is widely known as biogas. Even though biogas and its potential were not appreciated in recent decades, it is currently considered one of the most promising alternatives in the international energy planning context [1]. European legislation regarding waste management was updated in previous years to prioritize advanced fuel production from waste and residue valorization [2]. The biological process of organic matter decomposition for biogas production is known as anaerobic digestion (AD), and it includes four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [3].

Several kinds of waste streams have been tested as conventional or innovative substrates in the context of the circular economy model, contributing mainly to sustainable development goals 7 (affordable and clean energy), 8 (decent work and economic growth), 9 (industry innovation and infrastructure), 11 (sustainable cities and communities), and 15 (life on land) [4,5]. Regarding the conventional substrates, the organic fraction of municipal solid waste (such as kitchen waste, garden waste [6], or fruit and vegetable waste [7]) is one of the most used substrate types, and it has been extensively evaluated, along with a variety of agricultural waste streams, such as manure [8], olive mill wastes [9], and corn silage or other lignocellulosic materials [10]. On the other hand, alternative and innovative substrates, such as used disposable nappies [11] or the prunings from several plants (e.g., *Hippophae rhamnoeides* [12] and *Opuntia ficus* [13]), have also been assessed in recent years to evaluate their methane yields. Theoretically, 1 g of the volatile solids (VS) of carbohydrates, proteins, and lipids can produce 370 NmL, 740 NmL, and 1014 NmL of CH_4, respectively, through AD. To both maximize the production yield and increase the digestibility of complex substrates, many pretreatment processes have also been tested and classified as physical, chemical, biological, or a combination thereof. Beginning with physical pretreatment, a surface area increase in the substrate is targeted to improve the contact between the substrate and microorganisms. These pretreatments can be divided into thermal, mechanical, microwave, ultrasonic, and pulsed electric field pretreatments. Chemical pretreatment methods use acidic or alkaline solutions, ionic liquids, ozonation, or the Fenton process, which can efficiently break down complex macromolecules into smaller ones. The biological pretreatments involve microorganisms (aerobic or anaerobic microorganisms, enzymes, or fungi). According to the literature, all of these methods exhibit both advantages and disadvantages when applied alone; nevertheless, the CH_4 yields can be favored through their simultaneous or sequential application [14]. The conditions mentioned above (including the substrates and pretreatment methods) have taken place at the lab-scale, with few applications in full-scale plants.

Regarding a full-scale unit and its techno-economic assessment, it is essential to mention that the feedstock substrate used can significantly affect the cost of CH_4 generation. More specifically, variable impurities concentrations (H_2S, silicon compounds, NH_3, H_2, O_2, halogenated compounds, volatile organic compounds, and hydrocarbons) should be removed, with the exception of the CO_2 [15]. The process above is known as "biogas upgrading," and it results in high-purity biomethane. The leading technologies, considered the most relevant on the market, are high-pressure water scrubbing, amine scrubbing, potassium carbonate scrubbing, pressure swing adsorption, and membrane separation [16].

More specifically, high-pressure water scrubbing is based on water's high CO_2 and H_2S solubility. A high-pressure column of 6–10 bar (usually with packed material) is used for the absorption, where a water flow washes the biogas. Subsequently, the absorption solution is regenerated by CO_2 stripping, where air is injected into a desorption column (1 bar), and then CO_2-rich gas is released [16,17]. Amine scrubbing technology utilizes an aqueous amine solution, which is contained in an absorption column (with packing material at 1–2 bar) due to its selectivity and absorption regarding CO_2. CH_4 loss is limited due to the amine scrubbing while a CO_2-rich solution is exited from the absorber. Regarding potassium carbonate scrubbing technology, its principle is the same as that of amine scrubbing; however, it has different operating parameters. The specific technique has some advantages due to the increased solvent availability, lower toxicity, and cost. On the other hand, pressure swing adsorption is a well-known technique that leans on the capacity of a molecular sieve for the retention of CO_2, thanks to the different size, compared to CH_4. Regarding the procedure, the biogas is compressed (4 to 10 bar) and led to the adsorption columns, which are packed with adsorbent materials, such as activated carbon, alumina, zeolites, silica gel, and resins. Focusing on the efficiency of the specific technique, a lower-purity CH_4 is observed, even if the N_2 and O_2 are partially removed. However, it is mandatory to process the H_2S in a pretreatment stage [16,18,19]. Finally, membrane separation technology relies on the polymeric membranes' selective abilities to retain CO_2 and part of O_2. In any case, a pretreatment step of H_2S removal is recommended for both protection of the equipment (as, for instance, membrane pores can be obstructed by H_2S, or their life can be decreased) and compliance with the quality standards, which occurs in cases of injection into the national gas grid [15,16,20,21]. In this regard, different technologies have been implemented in European plants. Approximately 31% of European plants use water scrubbing, while 30%, 21%, and 8% have implemented chemical scrubbing, pressure swing adsorption, and membranes separation, respectively [22].

Europe is currently the greatest producer of biogas, with an average annual production of 170 TWh of biogas and 35 TWh of biomethane, respectively [23]. Nowadays, approximately 75% of the biogas produced in the EU is used for heat and electricity generation, while 20% is converted to biomethane. According to the REPowerEU plan, at least 350 TWh of biomethane must be produced annually by 2030, pointing out not only the need for new biogas plants but also the greatest attention to biomethane conversion. REPowerEU has indicated near-term actions, such as national biomethane strategies fostering evaluation and barriers identification at a national level, as well as the integration of biomethane into an EU strategy for rural development and regional job creation [24]. Except for the elements mentioned above, such an EU plan will significantly enhance the achievement of climate and energy security goals and promote EU independence from Russian natural gas production [15,24].

Biomethane could represent an alternative to fossil natural gas, mainly for transport options, as well as for direct injection into the gas grid. In both cases, the biomethane must meet the quality standards of the respective country (countries such as France, Sweden, Italy, Switzerland, and Germany have defined their own standards) or the EU (EN 16723-part I for grid injection and part II for automotive use) [22]. In the EU, biomethane is produced mainly by Germany, Sweden, and Switzerland, where 288, 205, and 140 biomethane plants are located, respectively [25]. On the other hand, natural gas in the EU is extracted mainly by Russia and Norway, presenting a decreasing trend year by year, and production fell by 7.6% in 2021 compared to 2020 [15,26].

From an environmental point of view, many studies in the literature have focused on the life cycle assessment (LCA) of biogas production and upgrading it to biomethane. As concerns the case of biogas production from the organic fraction of municipal solid waste, the work of Ardolino et al. [27] showed that the production of biomethane for transport (cars, vehicles, etc.) is always cleaner than biomethane production for energy. At the same time, several impacts have been reduced (such as respiratory inorganics, global warming, or non-renewable energy) thanks to the use of biomethane instead of conventional fuels or natural gas. Furthermore, the same research team investigated the upgrading of biogas to biomethane, comparing the environmental and economic aspects of the most known techniques, as mentioned above. More specifically, they stated that all the examined options were fully sustainable. Furthermore, membrane separation proved to be the best option, even though the results strongly depended on conditions such as local economic incentives or the injection pressure in the gas grid [28]. Some authors have investigated biomethane's LCA via biogas and syngas [29], biomethane vs biohydrogen [30], biomethane as a diesel substitute [31], and LNG vs biomethane [32]. Others have conducted studies and detailed LCAs about biomethane with different plant configurations, substrate mixtures, and CO_2 capture technologies [33–43]. LCAs and environmental analyses have also been carried out for LNG that are, for instance, focused on different re-liquefaction systems [44] or different uses as marine fuel [45,46], bus fuel [47], or truck and heavy-duty vehicle fuel [48–50].

Other studies have described the production of LNG from alternative feedstocks such as coke [51] or compressed natural gas (CNG) from sugarcane bagasse [52]. Environmental analyses have also been conducted on CNG as a transportation fuel [53–55]. The results showed that CNG has several advantages over diesel and gasoline fuel, e.g., a substantial decrease in exhaust emissions when vehicles are fueled by bio-CNG.

The present paper deals with a comparison among the LCAs of three different options for delivering methane. The scenarios listed referred to Italy and involve the following:

- biomethane produced from a biogas plant, coupled with CO_2 capture
- liquefied natural gas (LNG) extracted in Qatar and delivered by gas tanker to a regasification plant
- compressed natural gas extracted in Algeria and delivered to Italy by a gas pipeline

LNG can also be imported from the United States, where shale gas is extracted by fracking. This is one of the highest polluting extraction techniques [56], and it has been demonstrated that it may induce earthquakes [57]. Moreover, well leakages and longdistance transportation indicate that exporting LNG from the United States is likely to increase global greenhouse gas emissions [58]. All these aspects make this the worst result of the scenario obvious, and therefore, this option was not considered in the present study.

The novelty of this article lies in its LCA comparison among three different production routes to supply natural gas. Similar studies have yet to be found in the literature. Hence, it is a proactive response to the required energy supply planning because of the recent Ukrainian crisis, and it is thus necessary to find and manage different alternative supply routes that consider only the economic and geopolitical aspects but also the environmental agenda and treaties whose commitments are binding.

In this context, the present study aimed to supply the real quantification (thanks to the normalized LCA method) of the possible environmental gains resulting from the increasing contribution of biogas production from waste. The relevance of the analysis is enhanced by the possibility of using real-scale information related to a facility that uses food/agriculture residues that is representative of the Italian industry. The results could represent an important tool not only for the scientific community but also for the stakeholders involved within the development of new energy strategies able to fit the sustainability principles in the EU.

2. Description of the Production Scenarios

2.1. Scenario A: Biomethane from Biogas

The overall plant is composed of two twin plants with the same capacities built in the Campania region of South Italy. The area is characterized by the production of several seasonal vegetables and fruits that are either frozen or packaged for direct selling. Tomatoes are also used to produce sauces, whereas fruit is transformed into juices. In the same area, there are several buffalo farms where milk is collected and used to make mozzarella cheese. Hence, there is a tremendous amount of vegetable waste and manure, offering good biogas potential. The capacity of one of the two plants, with its expected feedstock type, is reported in Table 1. The numbers listed in Table 1 are expressed as average values as the vegetable waste is seasonal, whereas the buffalo manure is delivered to the plant daily throughout the year.

Table 1. Feedstock and capacity of one biogas plant.

Organic Waste	Average Daily Capacity (tons/day)	Average Annual Capacity (tons/year)
Buffalo manure and straw	100.00	36,500
Buffalo liquid manure and washing water	120.00	43,800
Cornstalk	5.37	1960
Arundo donax	36.71	13,400
Tomato peels	5.78	2110
Pear pulp	5.30	1935
Legume scraps [1]	3.64	1329
Bean scraps	4.03	1471
Total	280.83	102,505

[1] Lentils, chickpeas, and fava beans

Hence, the total biomass feedstock is approximately 205,000 tons/year. The productivity levels of the different biomasses were determined experimentally in terms of BBP (biochemical biogas potential) and BMP (biochemical methane potential). Since these values were obtained at the laboratory scale, a 90% conversion rate of volatile solids (VS) into biogas was considered. The VS were the majority of the total solids (TS), approximately 92% wt. The productivity measures of a single plant, considering a continuous operation mode of 8400 h/y (350 days/y because of ordinary maintenance), were 7,104,653 Nm^3/y (846 Nm^3/h) and 4,062,740 Nm^3/y (484 Nm^3/h) for biogas and biomethane, respectively. Hence, the average concentration of CH_4 was 57.2%vol. The same biomethane amount, produced by the second plant, was conveyed through a 4530 m pipeline to the first plant and stored at 16 bar in a 400 m^3 horizontal tank. The biomethane was thus compressed at 70 bar and injected into the distribution network located 300 m from there. The layout of the biogas generation system is shown in Figure S1. Each biogas plant was composed of the following main pieces of equipment:

- trenches for the storage of solid biomasses
- one circular closed tank for the storage and mixing of pumpable wastes
- one circular open tank, which could be loaded by mechanical means, for the homogenization of the milled solid feedstocks
- primary bioreactors (2 × 4800 m^3, mesophilic conditions, heated by steel coils)
- secondary bioreactors (2 × 4800 m^3, mesophilic conditions, heated by steel coils)
- purification of the biogas with the removal of H_2S, NH_3, H_2O, siloxanes, and volatile organic compounds (VOCs), where a rough desulphurization was carried out in the primary and secondary bioreactors through the addition of $FeCl_3$ addition; nevertheless, a deep removal was required to protect the membranes that separated the CH_4 from the CO_2, and in particular, one alkaline scrubber, one chiller, and one fixed-bed column with activated carbon were installed upstream of the membrane module
- a combined heat and power (CHP, 330 kWe) engine for the electrical and thermal self-consumption of the plant
- a containerized biogas upgrading plant based on a three-stage hollow-fiber membrane technology (EVONIK© Sepuran or equivalent), working at 16 bar with a biogas capacity of 1000 Nm^3/h
- a biomethane storage tank
- a compression, measuring, odorization, and injection station
- a composting plant where the digestate was treated by a screw separator and the liquid was stored in a tank from which a certain percentage was recycled back to the primary bioreactors and the solid fraction was used to produce a fertilizer by the addition of wood scraps and pruning. The liquid digestate was thus continuously sprayed on the solid mass, avoiding its treatment for nitrogen removal. The digestate could not be scattered on the fields as it was since the area was vulnerable to nitrates, and the Italian environmental regulation allows a maximum amount of 170 kg of nitrogen per hectare per year.
- one 960 kW_p photovoltaic power station (240 kW_p × four trenches), installed on the roofs of the composting plant, which produced 1,248,000 kWh/y with an average amount of solar irradiation for the area
- a plant for the compression and liquefaction of the CO_2, which was compressed to 15 bar and cooled to −28 °C. This plant was installed free of charge by a company that paid back the cost of the electrical energy and purchased food-grade CO_2 at a low agreed-upon price (CO_2 is usually sold to the beverage industry).

The plant was completed with all the equipment and devices required for its continuous running, including the boiler, pumps, mixers, grinder, conveyor belts, etc. A complete list of the equipment and the heat and material (H&M) balances are reported in the Excel calculation sheet enclosed in the Supplementary Materials. The flow sheet for the biogas plant is reported in Figure S2 of the Supplementary Materials.

The CHP plant and the photovoltaic power station could supply all the electrical energy required by the equipment whereas the thermal energy was not sufficient, and for this reason, a 220 kW_{th} boiler was required.

Hence, the total production of the two plants could be summarized as follows:

- a total of 6.804 million Nm^3/year biomethane was injected into the national distribution network
- a total of 9247 tons/year of CO_2 were recovered (i.e., emissions were avoided)

- a total of 2,496,000 kWh/year of renewable electrical energy was produced by the photovoltaic panels
- nearly 16,000 tons/year of certified slow-release fertilizer was produced

2.2. Scenario B: LNG from Qatar

Qatar is the fifth largest natural gas producer in the world and hosts the third largest proven reserves [59]. Italy imports approximately 6.59 billion normal cubic meters (bncm) per year [60]. Qatargas is the company that extracts natural gas from a gas field located approximately 80 km east of Qatar's mainland and 208 wells supply 18.5 billion standard cubic feet per day (bscfd) of sour gas to 14 LNG trains and four sales gas trains onshore. The gas and the associated condensate are transferred to shore via subsea pipelines. The onshore operations are conducted in Ras Laffan Industrial City, located northeast of the Qatari peninsula [61] (see map in Figure S3 of Supplementary Materials).

Qatar's production of LNG can be summarized in four steps [62]:

- extraction and upstream operations
- liquefaction
- shipping
- regasification

2.3. Scenario C: CNG from Algeria

The Trans-Mediterranean (*Transmed*) pipeline, which begins in the Hassi R'Mel gas fields in the middle of Algeria, reaches Mazara Del Vallo, a coastal city in Sicily. The pipeline covers 550 km across the desert (until the Tunisian border), and thus, the other 370 km of pipeline run up to El Haouaria, a city on the Cape Bon peninsula. The pipeline continues offshore and crosses the 155 km Sicilian Channel, landfalling in Mazara Del Vallo. The pipeline ends in Minerbio, a gas hub close to Bologna [63] (see map in Figure S3 of Supplementary Materials).

Algeria's production of CNG can be summarized in two main steps:

- extraction and upstream operations
- compression (several stages along the pipeline)

3. Materials and Methods

LCA Methodology

The LCAs were performed in agreement with the ISO standards 14040 and 14044:2006 ("ISO 14044:2006 Environmental management-Life cycle assessment-Requirements and guidelines," 2006 and UNI EN ISO 14040:2006, Environmental management-life cycle assessment-principles and framework). The software used for data collection was LCA for Experts, and it was integrated with Professional Database version 2023.1. The method selected for the analyses, which included the classifications and characterizations, normalizations, and weighing steps, was Environmental Footprint (EF) 3.0, and it included all environmental categories and recommended models at midpoint, together with their indicators, units, and sources [64,65]. The method was recommended by the European Platform on Life Cycle Assessment as a common way of measuring the environmental performance of processes [66,67].

The functional unit selected for the present study was 1 Nm^3 of methane, which simplified the analysis scale for further possible comparisons. Figure 1 summarizes the system boundaries considered for the present study. Assumptions were performed for the analysis. As concerns scenario A, both the $FeCl_3$ and the activated carbons were excluded from the analysis since their amounts were lower than 1% of the input flows and they were considered not relevant for the whole result. The valuable products, resulting from scenario A (mainly the slow releasing fertilizer, the beverage-grade CO_2, and the electricity surplus), were enhanced by environmental credits with negative values to quantify the avoided impacts of the primary production [30–37]. The extraction process selected for scenarios

B and C was related to methane, and it included natural gas extraction and the further removal of water, hydrogen sulfide, and higher hydrocarbons. The energy for liquefaction was assumed to be produced by natural gas. The LNG tanker selected for the transport (suitable for deep sea) had a payload capacity of 125,000 m^3 and an average capacity utilization of 48%. Furthermore, the results were compared to those of the average process used for the production of 1 Nm^3 of natural gas supplied to Italy, which were selected from the LCA for Experts database. This process (represented in Figure 1 as scenario D) included the steps of production and transport and considered Italian suppliers in 2019 (the most relevant were Russia (44%), Algeria (13%), and LNG from Qatar (9%)).

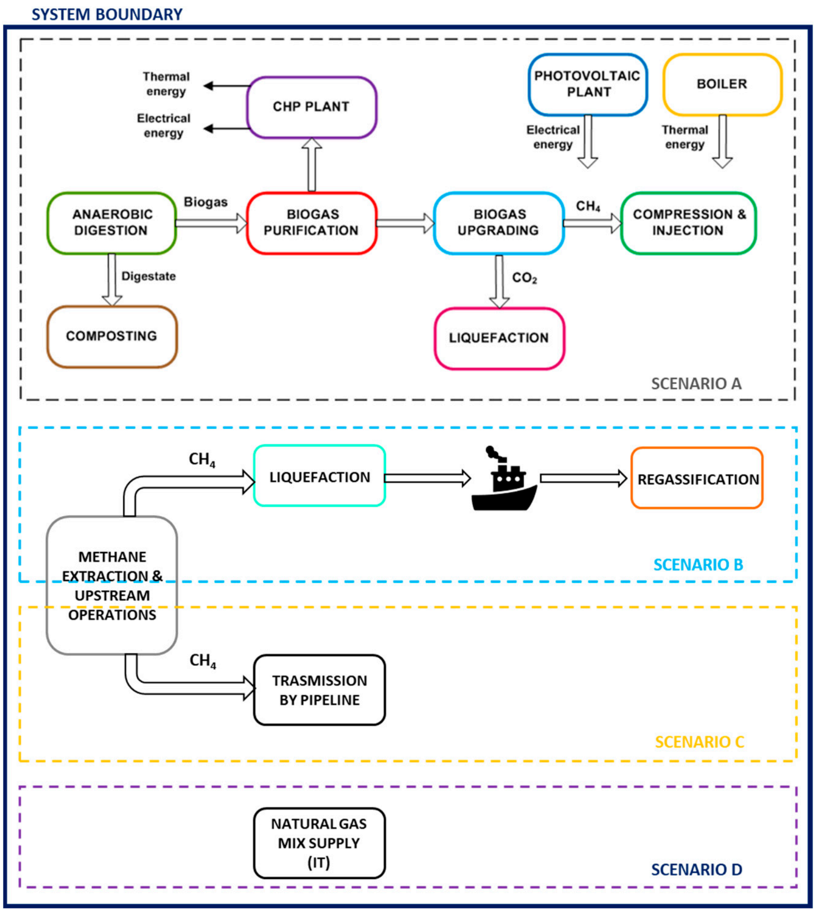

Figure 1. System boundaries considered for the LCAs.

Table 2 summarizes the mass and energy balances built for each scenario, including the primary data for scenario A and the secondary data (from the literature) for scenarios B and C. As reported in the table, the electricity resulting from the CHP and photovoltaic systems responded to the electric energy demand of the plant, with a 5% surplus considered as an environmental credit. On the other hand, the thermal energy produced on-site covered approximately 90% of the process. Both the liquefaction and regasification electricity consumption levels were estimated from information in the literature, and they were considered to have been produced from natural gas [68]. The data quality was evaluated in paragraph 4.3 to assess the possible effects of the choices. The distance selected in scenario B was 7139 km, which represented the route from Qatar to the Adriatic LNG terminal [69]. As concerns scenario C, the energy demand for the gas transportation via pipeline was estimated based on the model proposed in the professional database LCA for Experts, and it considered diameters of between 0.4 and 1m and an average utilization ratio of 28%, corresponding to 15 $kW \cdot ton^{-1} \cdot km^{-1}$. The Trans-Mediterranean pipeline was selected for scenario 3, with an entire distance of 2475 km [70].

Table 2. Mass and energy balances used for the LCAs related to the production of 1 Nm^3 of methane.

Energy/Mass Flow		Input	Output
	Scenario A		
Anaerobic digestion	Mixed biomass (kg)	30	
	$FeCl_3$ (kg)	1.2×10^{-3}	
	Electricity (kWh)	0.21	
	Thermal energy (kWh)	1.6	
	Diesel (L)	3.0×10^{-3}	
Composting	Pruning scraps, straw, leaves, and swarf (kg)	1.2	
	Electricity (kWh)	0.06	
	Slow-release fertilizer (kg)		2.3
CHP plant	Electrical energy (kWh)		0.81
	Thermal energy (kWh)		1.0
Biogas purification	Make-up water (L)	0.21	
	NaOH (kg)	0.03	
	Activated carbon (kg)	3.0×10^{-3}	
	Electricity (kWh)	8.2×10^{-3}	
	Wastewater (L)		0.21
Biogas upgrading (membranes)	Electricity (kWh)	0.51	
Compression and injection	Electricity (kWh)	0.22	
	Biomethane (Nm^3)		1.0
Liquefaction	Electricity (kWh)	0.12	
	Beverage-grade CO_2 (kg)		1.4
Photovoltaic plant	Electricity (kWh)		0.37
Boiler	Natural gas (m^3)	0.04	
	Thermal energy (kWh)		0.37
	Scenario B		
Extraction and upstream operation	Methane (Nm^3)		1.0
Liquefaction	Electricity (kWh)	0.83	
Shipping	Diesel for compression on board	1.0×10^{-4}	
Regassification	Electricity (from natural gas) (kWh)	0.48	
	Scenario C		
Extraction and upstream operation	Methane (Nm^3)		1.0
Pipeline	Electricity (kWh)	2.4×10^{-2}	

4. Results

4.1. The Life Cycle Impact Assessments

The classification and characterization steps allowed for the evaluation of scenario impacts in the categories recommended by the EF 3.0 method, including environmental effects (Figure 2a–g), resource depletions (Figure 2h–k), and human health effects (Figure 2l–p). The most important information resulting from the LCAs was the advantage of scenario A for most of the categories. Indeed, the biomethane production combined the lowest burden of the process with the further production of valuable by-products, such as fertilizer and the beverage-grade CO_2, quantified as environmental credits, thanks to the avoided primary production. The positive effect could be further enhanced by adding the credit for the avoided management of the waste, which was composed of vegetable and buffalo farm residues. This advantage was excluded from the present assessment to ensure conservative conditions. Indeed, the credit of the avoided waste disposal had high value, which could have made the study of scenario A difficult. In only considering the climate change category, there was a 0.7 kg CO_2 eq. saving for each kg of waste (if classified as hazardous waste, C-rich) and 0.9 kg CO_2 eq. for each kg (if classified as average municipal waste). Despite the waste classification, the environmental gain was relevant considering the amount of exploited waste for each m^3 (30 kg of waste biomass plus 1.2 kg of pruning scraps, straw, leaves, and swarf) and that this gain should have been added to the already relevant credit of the by-products (Figure 2b). The negative effect of scenario A in the categories of ozone depletion and resource use mineral and metals was explained by the selected process for the electricity production by photovoltaic panels, which included the whole technology lifecycle, from manufacturing to end-of-life (Figure 2g,i). In the second category, the highest impact was completely offset by the beverage CO_2 and fertilizer credits. Furthermore, the weight of these two environmental aspects on the whole EF of scenario A was assessed in the further LCA steps of normalization and weighting.

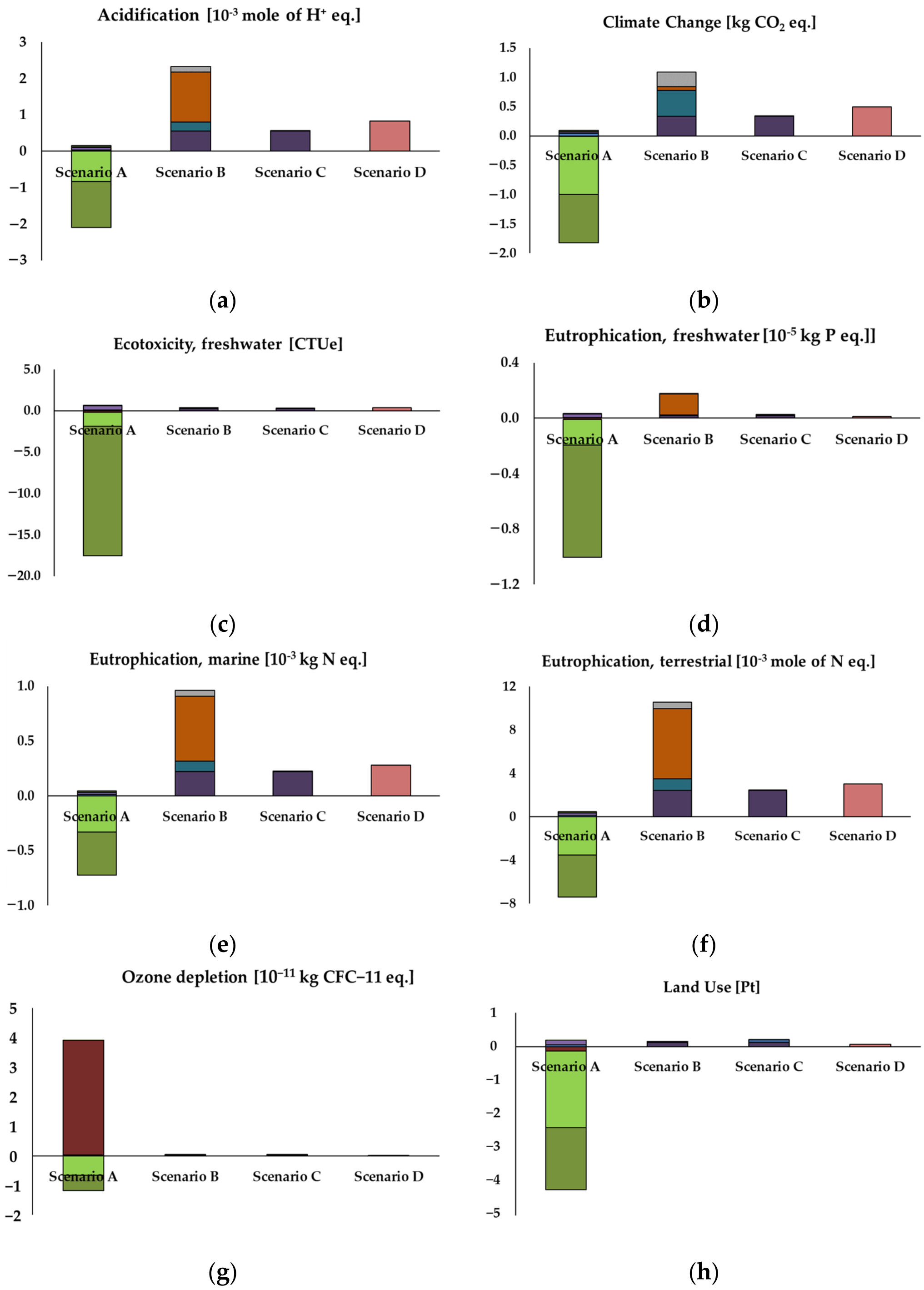

Figure 2. *Cont.*

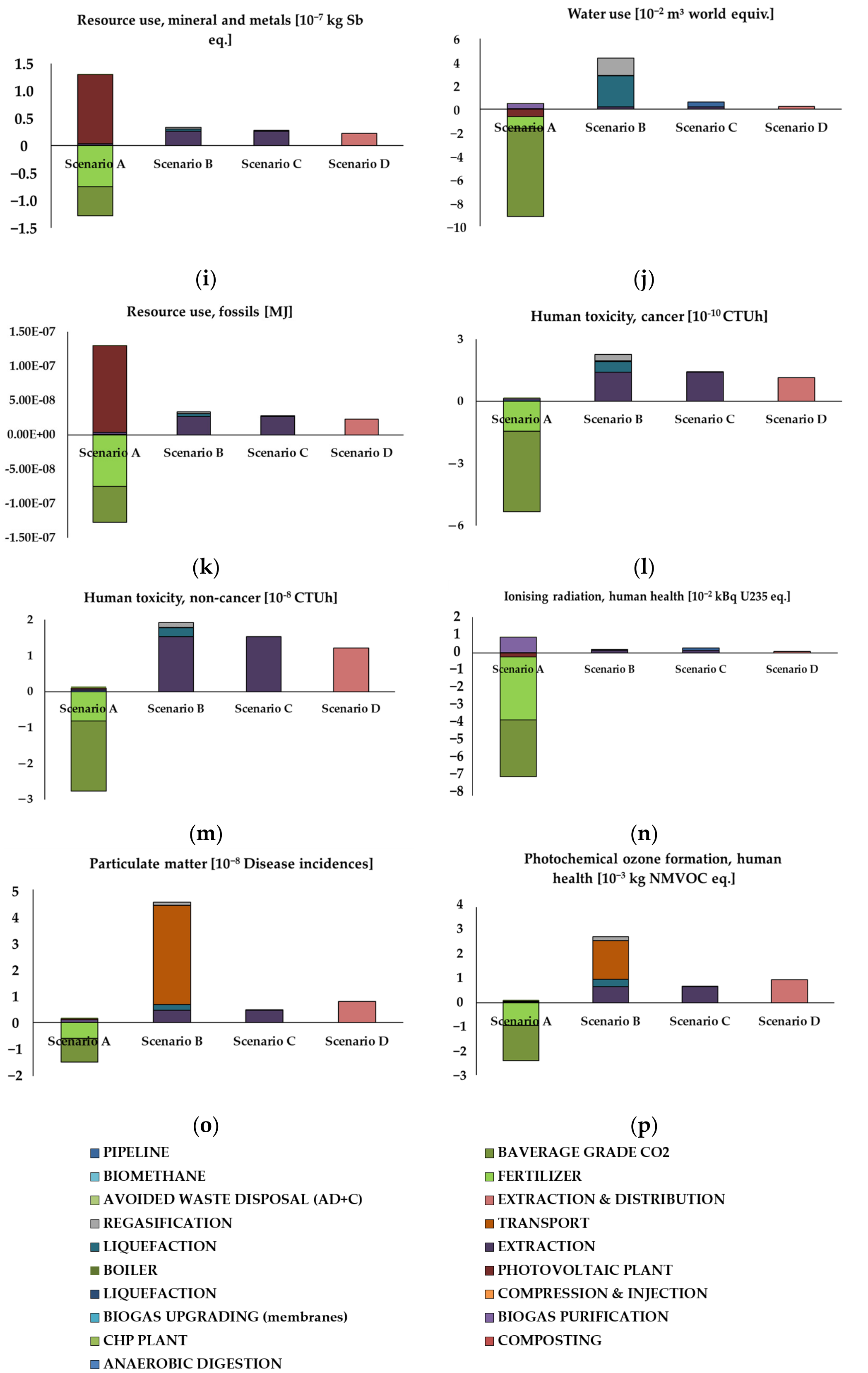

Figure 2. Results of the classification and characterization steps of the LCAs, with comparisons among the four scenarios related to 1 Nm^3 of methane. Letters (**a**–**p**) represent the considered categories.

The LNG from Qatar, considered in scenario B, turned out to be the worst option, and the most relevant issues changed on a category basis. The methane extraction and upstream operations of drying, desulfurization (resulting in hydrogen sulfide), and higher hydrocarbons separation, included in both scenarios B (before liquefaction) and C, caused the highest burdens in the categories of resource use, fossils, and human toxicity (both cancer and not cancer effects) (Figure 2k–m). The important difference between liquefied and compressed methane was due to the transport by LNG and the consequent combustion emissions. The negative effect of this aspect was mainly highlighted in the categories of acidification, eutrophication (marine and terrestrial), and photochemical ozone formation, where the transport represented the 60% of the whole impact of scenario B (Figure 2a,e,f,p). This percentage reached 80% in the category of particulate matter, which was quantified as disease incidences and eutrophication of freshwater (Figure 2d,o). The energy demands for both liquefaction and regasification contributed to the worsening of scenario B compared to the others. The comparable results for scenarios C (based on the information collected from the literature) and D (based on the LCA for Experts database) increased the reliability and robustness of the data.

4.2. The Estimation of the Environmental Footprints

For the estimation of the EF at the end of the normalization and weighting operations, which allowed an overall view of the results, we assigned a weight to each category analyzed during classification and characterization (following the EF 3.0 method). The results in Figure 3 confirmed the advantage of scenario A, with irrelevant effects for the categories of ozone depletion and resource use (mineral and metals), where the issue of biomethane production was identified at the end of classification and characterization (Figure 2g,i). The possibility of self-generated energy (both electrical and thermal) significantly reduced the impact of scenario A, decreasing the consumption of energy from the grid. The EF of the biomethane production process was almost equally divided among the thermal energy for the AD (27%), the sodium hydroxide used in the biogas purification (24%), and the natural gas consumption of the boiler (33%). On the other hand, the high energy demand for liquefaction and regasification, which added to the impact caused by the dedicated transport by tanker, caused an environmental load increase of approximately 40% compared to the methane supply by pipeline (scenario C).

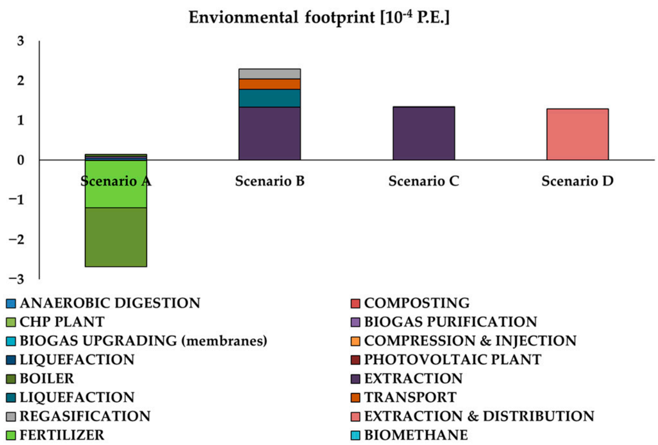

Figure 3. Results of the normalization and weighting steps of the LCAs, with comparisons among the four scenarios related to 1 Nm^3 of methane.

The normalized and weighted categories were grouped in three sets: environmental effects (including acidification, climate change, ecotoxicity, eutrophication freshwater, marine, terrestrial, and ozone depletion), human health effects (including human toxicity cancer, non-cancer, ionizing radiation, particulate matter, and photochemical ozone formation), and resource depletion (including land use, resource use (fossils), resource use (mineral and metals), and water use), which identified the most affected aspects. The analysis considered the three scenarios built within the study, identifying an equal distribution of impacts between the environmental effects and resource depletion in scenario A (Figure 4a). Climate change played a primary role in the environmental aspects, which was caused by the need for thermal energy (43% of the climate change impact), NaOH (26%), and natural gas for boiler operations (20%). Interesting observations were related to the benefit resulting from the by-product credits in the same two sets of categories, as shown in Figure 4b. As concerns scenarios B and C, it was evident that resource depletion represented the main issue (Figure 4c,d).

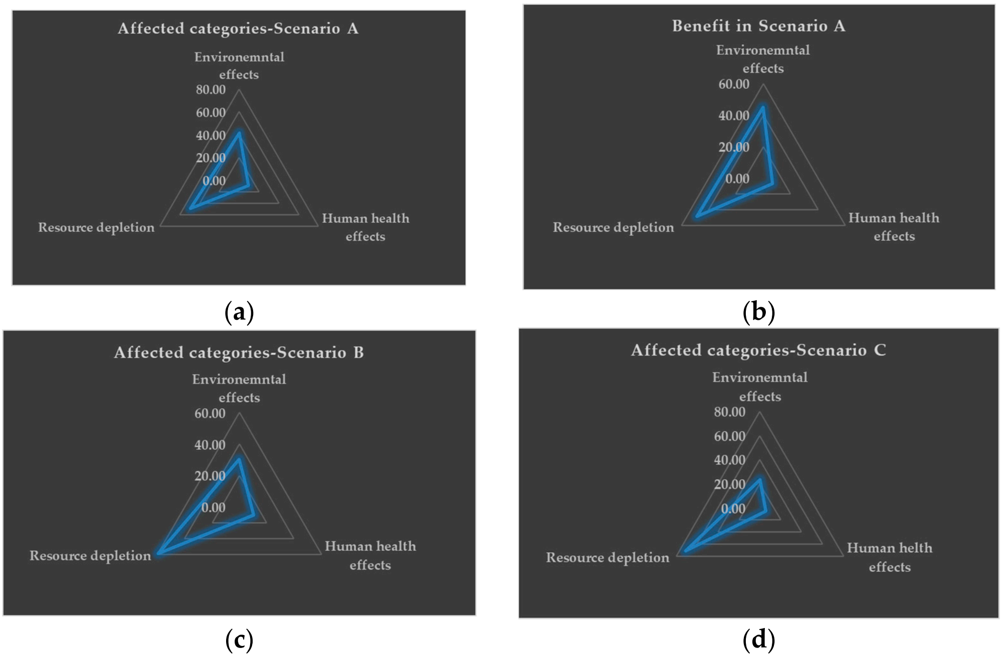

Figure 4. Most affected categories in scenarios A (**a**), B (**c**), and C (**d**). Figure 4 (**b**) shows the categories with the greatest benefits due to the environmental credits.

4.3. Evaluation of Data Quality

The data quality assessment was necessary to evaluate the credibility of the LCAs and the relevance of the described results. The mass and energy balances used for scenario A came from the primary information, which was supplied by the involved parties. For this reason, the reliability and robustness of the data were not controversial. On the other hand, some considerations regarding scenarios B and C were performed since they were built using information from the literature. With this aim, Table 3 reports the effects on climate change (performed by different methods) of several scientific papers, resulting in an average value of 1.1 $\pm$ 0.2. On the other hand, a confirmation of scenario C assumptions was supplied by the comparable impact of scenario D, which was selected from the LCA for expert database and related to an average Italian natural gas mix where the pipelines represented the main supply method (in natural gas quantity terms, Figure 2b). The comparison with the literature confirmed that data variability did not affect the results of the present paper, and there was a significant advantage for scenario A.

Table 3. Effect on climate change: a comparison between Scenario B and the literature results.

Impact on Climate Change (kg CO_2 eq/Nm^3 methane)	Reference
Scenario B (LNG)	
1.1	Present work
1.0	[71]
0.9	[68]
1.3	[62]

5. Discussion

The establishment of efficient, low impact strategies for energy supply represents a priority for the European economy. It is evident that fast and complete autonomy represents the ideal, but an integrated system could be implemented in the territory with positive effects for both the economy and the environment. Among the multiple energy resources to consider, the present study quantified the environmental benefit resulting from the exploitation of agriculture and food waste for biomethane production. The present paper encloses all the steps of biogas and biomethane production and supply, integrating the results already available in the literature, and it is often focused on specific aspects. In this regard, Table 4 summarizes relevant LCA studies that refer to biogas upgrading techniques [28,41] or that compare them with other fuels (both renewable [30] and not renewable [32,33]). On the other hand, additional studies have deepened LNG's sustainability [62,68,71], confirming liquefaction, regassification, and transport as the main issues [68]. In addition, the relevance of the achieved results is closely linked to the considered case study, which was related to a real Italian plant. Furthermore, the strong interest in the spread of these approaches for renewable energy production is confirmed by several funded projects, mainly in the Italian territory, where the agriculture/food industry represent a key sector and the possibility of by-product management and self-energy production represents a dual opportunity. In this regard, an excellent example is the Italian project GRASCIARI RIUNITI (within the European plan to support the regional development of FEASR-PSR MARCHE 2014–2020), which involves several farms in central Italy that have identified a relevant problem due to the management of organic residue from their agriculture activities [72]. The project stakeholders highlighted that modern agriculture has changed the ways the residues are considered—from a biomass resource in the past to a waste to dispose of in the present. In response, the project has evaluated the integration of energy recovery with innovative bio-product synthesis, starting with the organic residues [73].

Despite that the circular economy does not represent an innovation for the agriculture sector, it introduces several variables, such as the plant scales (micro vs. macro), and it often antagonizes of population, which is worried about possible emissions and bad odors. Nevertheless, the present paper proved that implementing the high-efficiency biomethane production processes that are equipped with emission abatement systems represents the most sustainable option compared to LNG or compressed methane, and there was a decrease in emissions. This advantage was further enhanced by both of the resulting valuable products (i.e., the fertilizer and beverage-grade CO_2) and the avoided waste disposal. The results represent an integration with the available research about the most common energy supply methods, and it is useful to quantify the environmental benefits resulting from the diffusion of high-efficiency and highly sustainable alternatives. Furthermore, they prove the relevance of a deepened study of the peculiarity of a territory in building an effective integrated economy that is able to respond to the necessities of the driving sectors of the geographic areas. The facility described can solve the problem of organic waste management, producing a green energy and functioning more sustainably than the most common supply routes, while implementing a very short supply chain. Biomethane plants can never supply the entire amount of natural gas a country requires for industrial purposes, heating, and transportation. Still, they can certainly reduce the dependence on oil supplied from areas abroad, especially in countries such as Italy with few fossil fuel reserves. Although the advantages of biomethane production are already known at the qualitative level, there is a necessity to make available the quantitative information to push public opinion towards the acceptance of energetic innovation to favor a sustainable green transition.

Table 4. Scientific literature regarding LCA analyses applied to biomethane/biogas.

LCA Objective	Main Observations	Ref
Comparisons among biogas upgrading technologies (water scrubbing, membrane separation, pressure swing adsorption, and chemical absorption with amine solvent)	• All the examined options as fully sustainable • The membrane separation shows the best performance • The technique performances are site-specific	[28]
Comparison between biomethane and biohydrogen produced from organic waste streams	• The biohydrogen use in the electricity generation system is more sustainable than its use in vehicles in agro-industrial areas • Opposite results were achieved for both urban and rural settings	[30]
Comparison among LNG, liquefied biomethane, and diesel in heavy transports, including their production, distribution, and use	• LNG can increase the impact on climate change by up to 10% compared to diesel • Liquefied biomethane can reduced the impacts by 45–70% (if produced from manure) and 50–75% (if produced from food waste) compared to diesel • The impact of biomethane can even be less than zero if digestate is used to replace the mineral fertilizer	[32]
LCA of biomethane production and comparison with traditional natural gas	• The process needs only 12% non-renewable energy • Biomethane allows a climate change impact reduction of 82% compared to natural gas	[33]
Comparison among biogas upgrading technologies (pressurized water scrubbing, chemical scrubbing, membrane separation, and pressure swing adsorption)	• Membrane separation is the most sustainable technology since it combines the highest biomethane production with the carbon mitigation for the digestate production • Pressure swing adsorption is the worst scenario for high off-gas emissions	[41]
Analysis of the effect of the increase in United States liquefied natural gas exports on global greenhouse gas (GHG) emissions	• Emissions for electricity generation using United States-exported LNG were 655 g CO_2-equiv/kWh • Shipping is not the main cause of LNG GHG emissions • The coal substitution by LNG could be translated into savings of 550 g CO_2-eq. per kWh of electricity and 20 g per MJ of heat • LNG decreases GHGs under upstream fugitive emissions rates up to 9% for electricity and 5% for heating	[62]
Lifecycle assessment of LNG imported from Qatar to the United Kingdom, considering variable factors (energy for liquefaction and vaporization, fuel for propulsion, shipping distance, tanker volume, and raw gas composition)	• The steps of liquefaction, transport, and vaporization cause more than 50% of the global warming potential of LNG • The analysis includes all the environmental indicators of the CML methodology	[68]
Comparison between conventional shipping fuels and LNG	• LNG can reduce lifecycle emissions up to 18% compared to conventional fuels • The integration with renewables-based power generation in liquefaction could allow further savings of 5–10%	[71]

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16124555/s1, Figure S1: Location of the two plants (blue line polygons), layout of the pipelines, and the final injection point in the methane distribution network (red circle); Figure S2: Flow sheet of one of the two biogas plants producing biomethane; Figure S3: Production and delivery points for the LNG vessel; Figure S3: Route of the Algerian–Italian gas pipeline through Sicily. Excel file titled "Biomethane plant calculation".

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Abbreviations

AD	Anaerobic digestion
BBP	Biochemical biogas potential
BMP	Biochemical methane potential
CHP	Combined heat and power
CNG	Compressed natural gas
EF	Environmental footprint
H&M	Heat and material
LCA	Lifecycle assessment
LNG	Liquefied natural gas
TS	Total solids
VOC	Volatile organic compounds
VS	Volatile solids

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