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The impact of regional factors and new bio-methane incentive schemes on the structure, profitability and CO_2 balance of biogas plants in Italy

P. Patrizio [a]*, D. Chinese [a],

[a] DIEGM, University of Udine, Via delle Scienze, 33100 Udine, Italy

Corresponding email address: patrizio.piera@spes.uniud.it

Abstract

The Italian Ministry for Economic Development recently started a new incentive program for biomethane grid injection and biomethane for transportation. This opens up new opportunities for more efficient utilization of agricultural biogas, which in the past was mainly used in Italy for power only solutions. Because of the wider range of feasible options, entrepreneurs and local authorities need support tools to identify optimal alternatives, from an economic and environmental viewpoint, respectively. Thus, a biomass supply chain optimization model, including current costs and new incentives for biogas exploitation, is introduced in this paper. The model is used to explore the impact of Italian energy policies on the profitability of alternative biogas utilization pathways in two regional cases studies, characterized by different penetration of CNG refueling stations. The effect of local factors on energy vectors share and on GHG emission reduction are investigated with factor analysis. It is found that CBM production represents the most profitable choice for entrepreneurs under current levels of bio-methane incentives, however because of the small Italian CBM market size it risks to be overly subsidized. Allocating funds to promote a further expansion of CNG would probably help CBM development and benefits more than increasing specific incentives.

Keywords: Biomethane supply chain, MILP, Tradable Certificates, economic optimization

1. Introduction

Europe has witnessed a substantial growth in power generation from biogas over the past few years: the gross electricity output from decentralized agricultural plants, centralized co-digestion plants and municipal methanization plants increased from approximately 17 TWh in 2006 to almost 36 TWh in 2011 [1].

Several countries in Europe also subsidized upgrading plants, which use suitable technologies [2] to remove carbon dioxide from biogas and yield bio-methane, having similar composition and heating value to natural gas and suitable for injection into the gas grid or for use as a vehicle fuel: some 200 plants exist in Europe, mainly located in Germany, Sweden, Austria, Switzerland and the Netherlands [2].

Italy could be a promising market for biomethane for vehicles, as it boasts a mature natural gas market for vehicle use [3,4], as well as for injection into the gas grid to meet heating demand. However, no upgrading facilities converting biogas into biomethane have been installed in the country so far because no specific regulation or support scheme was available. The long-awaited incentive program for biomethane grid injection and biomethane for transportation started only in December 2013, and only recently [5] procedures for firms to qualify as biomethane producers in order to attain incentives have been defined.

The economics of single biogas upgrading plants for transport applications under the prospected incentive scheme has been partially explored by [2]: under their assumptions, only large plants hold by producer-distributor firms would be profitable. However their analysis was not linked with the territorial distribution of feedstock and natural gas demand, which are likely to affect real technology and capacity choices by entrepreneurs and ultimately the economic and environmental outcome of introduced biogas support schemes. As the same authors observe in [2], the proper balance of public funds, so that the effective sustainability of various renewable sources is taken into account, is an unexplored theme in the literature, at least, but not only, as far as concerns Italy.

The aim of this paper is to contribute to fill this research gap by investigating the expected evolution of biogas utilization under new schemes and its environmental impact at systems level, i.e. by exploring regional case studies and examining all subsidized utilization pathways.

In the literature, regional case studies have been used to analyze biogas policy schemes in several works. In Sweden, [6] conducted a regional case study to assess the economic feasibility of several biomethane distribution methods under different levels of subsidies for the production of biogas, regardless of its utilization pathway. The effects of existing policy schemes in the Netherlands were analyzed by [7,8] who considered the natural gas grid option alone. Use of biomethane for vehicles was not specifically considered. For Poland, an extensive analysis of biomethane support schemes affecting the economic feasibility of different biogas plant configurations has been produced by [9], who also analyzed the presence of a climate policy instrument in the form of a carbon mitigation premium, concluding that by introducing such measure the profitability of commercial biogas projects is somewhat raised.

All aforementioned papers ([3], [6]-[9]) contribute to underline the policy and regulatory issues connected with the development of biogas technologies in selected regions. However, most of them focus on single stages or pathways of biogas conversion and none of them assesses the impact of supporting policy choices on the capital and operational performance of biogas supply chains as a whole, considering the competition between different utilization pathways and the effect of territorial factors such as biomass availability and natural gas distribution infrastructure in a spatially explicit way: this is the objective of the present research.

Because of the spatially varied locations of different biomass sources the assessment of biomass potential for biogas production and siting biogas plants in optimal locations includes the use and handling of a wide range of geographical data [10]. Geographical Information Systems (GIS) have been considered as an appropriate platform for spatial related issues and have been adopted in many biogas related studies for assessing the potential biomasses for biogas production [11,12] and for biogas plant location analysis.

To perform such assessment, Mixed Integer Linear Programming is the most widely used methodology in literature, especially for decisions on location, technology selection, capital and investment, production planning, and inventory management as confirmed by many studies dealing with biomass-to-energy and biofuel supply chain optimization [13–15].

A biogas supply chain optimization model for Northern Italy has been developed by [4] by expanding the existing solid biomass supply chain model BeWhere [16,17] and used it to analyze some environmental implications of biogas upgrading in Italy. However, computational limitations depending on structure and scope of that model prevented its application for detailed analysis of existing policies based on a combination of stepwise tariffs, and only carbon price was investigated.

Incentive schemes can be more easily incorporated in biomass supply chain models at regional level, as proposed by [18] for biogas based power in Italy.

In this paper, we build upon the model by [18] to incorporate incentive schemes for biogas upgrading both to biomethane as a vehicle fuel and for injection into the grid in regional supply chain models. The main features of the present model, as well as the biomethane policy schemes under investigation are discussed in section 2.

With the aim of evaluating the impact of new policies on biogas utilization pathways and relevant GHG emission reduction potentials, it is assumed that plants will be built if and only if (and where) they are profitable. The economic performance (particularly considering the amount of private investments mobilized by public incentives) and the environmental performance in terms of GHG emission balance are thus calculated at supply chain level.

To explore the overall impact of proposed policy schemes on biogas upgrading potentials and relevant environmental impact, two regional case studies are compared, differing by current market levels of natural gas for vehicles. Details of the case studies and scenario assumptions are discussed in section 2.

Results are presented in section 3, which also includes the sensitivity analysis performed via factor analysis [19], as explained in section 2. Factor analysis allows to highlight both single and combined effects of policy and territorial factors affecting the likely mix of profitable technologies, and corresponding environmental and economic impacts. Based on the discussion of results, conclusions on prospects for agricultural biogas plants under the new Italian incentive schemes are drawn in section 4.

2. Material and Methods

Current biomethane promotion schemes are briefly analyzed in section 2.1 and incorporated in a MILP model accounting for the most relevant steps of the biogas supply chain as described in section 2.2. The model considers different biogas utilization pathways such as production of electricity and biogas upgrading to biomethane for heating and for transport purposes. The goal is to find the optimal mix of conversion technologies, plant capacities and locations under current biogas promotion schemes. To this end, the methodology has been applied to the North Italian regions of Friuli Venezia Giulia (Figure 1) and Emilia Romagna (Figure 2), as detailed in section 2.3. Areas selected for comparison have similar biogas potentials but different market potentials for bio-methane for vehicles (compressed bio-methane, CBM in the following), as they currently have different compressed natural gas (CNG) demand levels and number of existing refueling infrastructures. A reference scenario is defined as baseline in section 2.3, where methodological details are also given on how sensitivity analysis is performed through factorial design to understand which uncertain parameters (particularly: market and incentive parameters) affect the economic optimum, that is to say the expected scenario under those economic circumstances.

2.1 Policy framework

The long-awaited incentive program for biomethane grid injection and biomethane for transportation started in December 2013, when the Italian Ministry for Economic Development introduces different incentive levels for biomethane producers depending on plant capacity and feedstock mix.

To support biomethane injection a stepped Feed in Tariff is introduced, based on three feedstock mix classes, with growing tariffs depending on the percentage of manure employed (i.e. below 50% in weight, above 50% in weight and 100% by product mix), and four size classes, with decreasing tariffs for larger plants as specified in table 1.

For CBM, a tradable certificate (called CIC, as in the Italian regulation, in the following) mechanism is introduced as for other biofuels, which is based on the quota obligation for fossil fuel traders in the transport sector. The certificate size is assumed to be equivalent to 1166 Nm^3, and, as summarized in Table 1, the number of certificates granted by the managing authority depends on the substrate mix with three classes based on exploited manure shares (below 70% in weight, above 70% in weight and 100% by-products). If biomethane producers become direct biomethane distributors (labelled "Own" in Table 1), rather than wholesalers to existing natural gas distributors (labelled "Third "in Table 1), they are eligible for 10 years to an increment of 50% of the certificate value.

Additional incentives, in the form of supplementary certificates are introduce to support the construction of new refueling station (FS in table 1).

Manure %	**Natural gas injection (INJ) equivalent tariff [€/Nm3]**				**Manure %**	**Number of tradable certificates (CICs) for compressed bio-methane (CBM)**			
	Size class upper limit (Sm3/h)					**New Fuelling Station**		**Existing Fuelling Station**	
	250	**500**	**1000**	**<1000**		**Third**	**Own**	**Third**	**Own**
< 50	59.9	28.5	28.5	28.5	< 70	1	1.5	0.7	1.05
≥ 50	59.9	59.8	57.0	54.2	≥ 70	1.7	2.55	1.19	1.8
100	75.6	75.6	71.3	67.0	100	2	3	1.4	2.1

Table 1. Current bio-methane support mechanism

2.2 Modeling actual biomethane promotion schemes

A biogas supply chain optimization model has been originally developed for power station siting and is described in detail elsewhere [18]. In this paper, the objective function is expanded to accommodate all alternative biogas utilization pathways *Bp* (i.e. electricity as explained in [18], biomethane for injection *INJ* or compressed bio-methane for vehicles *CBM*) .

The production of energy vectors is a function of biogas conversion efficiency $\eta_{s,tech}$, which is influenced by technology *tech* and size class of the plant *s*, the biogas lower calorific value K_bg (6.2 kWh/Nm^3) and the total biogas production $ProdBg_{j,s}$ (Nm^3/year) , depending on the total amount $Q_{j,t,s}$ (kWh) of feedstock of different types *t* adopted in the digestion process.

Moreover, each upgrading technology is characterized by a specific methane recovery factor φ representing the total CH_4 content (%) of biomethane after the purification process. Thus, the upgrading process is described by equation (1), which calculates biomethane flows $ProdEvUp_{s,j}$ derived by upgrading at each site *j*.

$$ProdEvUp_{s,j} = \sum_{tech}\left(\eta_{s,tech} * \varphi_{tech}\right) * \left(ProdBg_{j,s} * K\_bg\right) \tag{1}$$

The upgraded biomethane $ProdEvUp_{s,j}$ may be further injected into the grid or used as a vehicle fuel, as defined by equations (2), in which subscript *f* and *g* account for the feedstock mix class, depending on the percentage of manure utilized in the digestion process as indicated by the tariff schemes for compressed bio-methane for vehicles *CBM* or for grid injection *INJ*.

$$\sum_s ProdEvUp_{s,j} = \sum_s\left[\sum_f ProdEvCBM_{j,s,f} + \sum_g ProdEvINJ_{j,s,g}\right] \tag{2}$$

For each size class, annual incomes from upgrading are thus obtained as product of energy vector quantities produced in size class *s* and feedstock mix class *f* or *g*, respectively, by corresponding feed-in-tariffs (or equivalent tradable certificates). As mentioned in section 2.1, by introducing additional grants the current biogas promotion scheme supports the construction of new CBM refueling stations, which may either be located in proximity of the upgrading plant, or be served by remote biomethane production plants. To account for both options, equation (3) imposes that the amount of CBM produced in the *j-th* municipality may be associated to the corresponding CBM demand and thus consumed locally, or allocated to another municipality.

$$\sum_s\sum_f ProdEvCBM_{j,s,f} = DemCBM_j + \sum_{k\neq j} DemCBM_k * binFS_{j,k} \tag{3}$$

Where the binary variable $binFS_{j,k}$ equals 1 if an upgrading plant is built in the *j-th* municipality to serve the refueling station located in *k*. Equation (4) imposes that each CBM production plant serves at maximum one refueling station. Another simplifying assumption, considering social acceptance constraints and typical sizes of plants and of municipalities, is that injection into the gas grid for heating purposes is compatible with all other utilization pathways, while fuel production and power generation are incompatible at municipal level: equation (5) thus imposes that a maximum of one CBM or power plant can be installed in each municipality.

$$\sum_{k \neq j} binFS_{j,k} \leq 1 \tag{4}$$

$$binCBM_j + binMCI_j + \sum_{k \neq j} binFS_{j,k} \leq 1 \tag{5}$$

To be allocated to remote stations, CBM has to be transported, which has economic and environmental implications. As to transport, both the possibility to inject the biomethane into a local gas grid and to adopt a truck-based distribution have been considered in this study. The connection through the local gas grid at a fixed cost was deemed a reasonable solution for refueling stations located in the same municipality as CBM plants, since low pressure gas distribution networks exist in every municipality in the areas of concern. Furthermore, existing natural gas refueling stations are often located near high pressure gas transport pipes, which results in lower operational costs and energy consumption. On the other hand, to connect upgrading plants to remote refueling stations located in different municipalities in a flexible way, the distribution of CBM between different municipalities in the area of concern has been assigned to specific trucks, such as a demountable platforms, in which compressed gas cylinders are loaded and then distributed. For small volumes (less than 10 MNm^3/year) and small distances (up to 50 km), which characterized the territories of concern as further explained in section 2.3, this process may be less expensive than distribution through pipes [20].

2.3 Case studies description and scenario analysis

2.3.1 System boundaries

Within the systems boundaries considered in this analysis, biogas can be either used directly in a co-generative reciprocating engine for power production or upgraded into biomethane and then injected into the natural gas grid or used as vehicle fuel.

Besides these technologies, the actual biogas promotion scheme also incentivizes the production of heat deriving from high efficiency cogeneration units, having an overall efficiency equal or greater than 75 % [21]. In the case of biogas plants, such threshold value requires that the heat recovered from the internal combustion engine is almost equal to the electric power produced. Individual cases in which the produced heat is completely absorbed by private or public units (to meet high heat requirements of e.g. greenhouses or a chick farms) might exist in the territory of concern, however data on the location of these particular cases are not currently available. Alternatively the heat produced might be distributed via district heating systems, which are very rare in the Italian territory. For these reasons, and since the issue of developing new district heating infrastructure is out of the scope of this study, the cogeneration option have been excluded as potential biogas conversion technology.

Several technologies are available for biogas upgrading to biomethane to meet standards for use in vehicles or injection in municipal grids. According to literature ([1], [22]), the technology most widely adopted in European biomethane production plants is pressurized water scrubbing (PWS), which has also been considered in this study. Economic and efficiency values assumed for this technologies are derived from [23].

Since any consideration related to the environmental impact of these technologies has been included in the Italian biogas promotion schemes, the environmental balance of the system of concern, in terms of carbon equivalent emissions produced, have been excluded from the model objective function. Therefore, the greenhouse gases emission savings associated to the model optimal solutions have been calculated by adopting the emission factors indicated by the Global Emissions Model for integrated Systems (GEMIS) database [24]. The GEMIS tool is a freely available database for process or product life cycle assessment (LCA) containing the most extensive inventory of agricultural biogas processes as it adopts typical biogas plant sizes, compared to the wide ranges (e.g. “up to 50 MW”) that are used by other software packages for process or product LCA, such as [25,26].

With regard to the logistics activities considered, a special feature of biogas supply chains is that, besides input flows, an output material flow should be managed, i.e. digestate. As clarified by [18] is important that the Nitrates Directive limits on the application of manure fertilizer on cropland are respected, since some areas of the territory under investigation are classified as Nitrate Vulnerable Zones and assigned the corresponding limit of 170 kg nitrogen per hectare. For this reason, the digestate management practice has been included in the model, by considering the digestate equivalent nitrogen content as in [18].

2.3.2 Case studies description

The first case study analyzed concerns the territory of Friuli Venezia Giulia Region (FVG) excluding its mountain areas. In FVG, potentials for biogas generation from agricultural byproducts are high, especially considering co-digestion options and the use of energy crops as possible substrates. Maize is a leading crop: approximately 60% of the arable agricultural area is yearly sown with maize, with silage being extensively used as fodder. Given the dominance of breeding farms in the area, animal manures from main kinds of breeding, that is cattle, swine and chicken manure, is considered. With these assumptions, theoretical biogas potentials represented in Figure 1 are estimated.

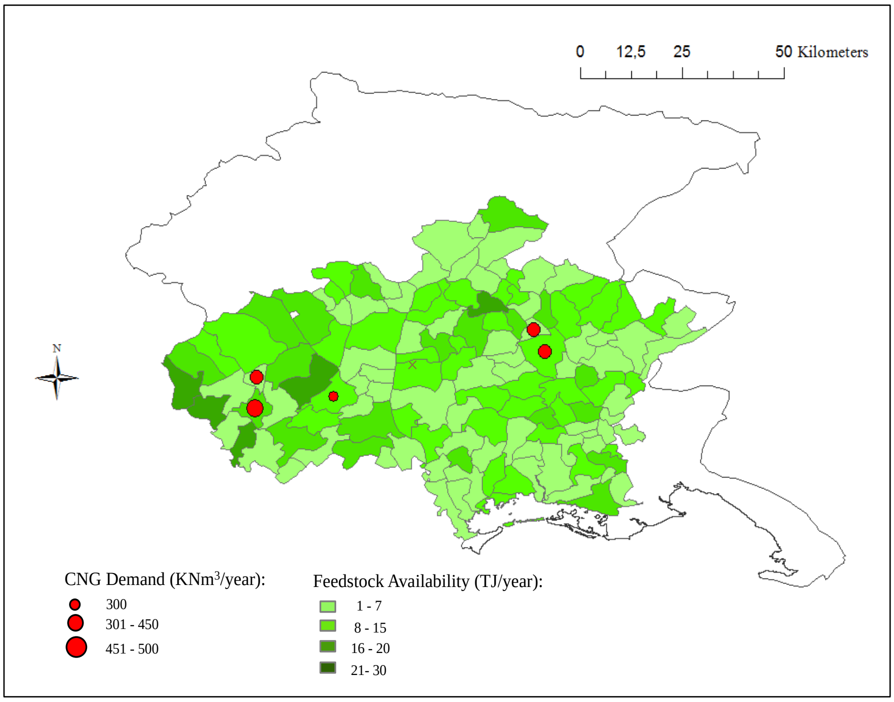


Figure 1. Feedstock availability and CBM demand level in FVG region

Figure 1 also shows the location of existing CNG refuelling stations, whose presence is very limited in FVG. Such aspect might discourage entrepreneurs to invest in upgrading technology as the production of CBM fuel would not be easily absorbed by the regional market. To validate results, and particularly to assess the influence of CNG demand levels on biogas supply chain performance, the Romagna region as the second regional case study. Romagna is a sub-region located on the northern Adriatic coast, constituted by almost 80 municipalities. This area is comparable with FVG as to technical biogas potential, which is somewhat higher and more concentrated, as represented in Figure 2, however Romagna is characterized by an high penetration of CNG as a vehicle fuel, with a total annual CNG demand of more than 20 kNm^3 (almost 4 Nm^3/km^2), distributed in 25 refuelling stations, against 5 stations only in FVG (represented as red dots in figures 1 and 2).

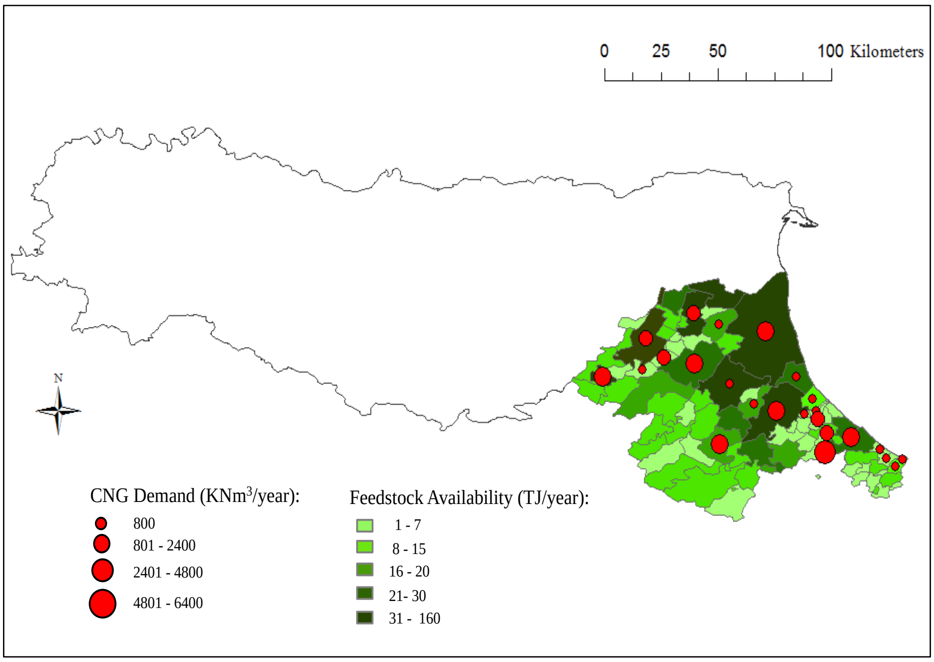


Figure 2. Feedstock availability and CBM demand level in Romagna region

2.3.3 Scenario analysis and Design of experiments (DOE)

To address the effect of current biogas promotion schemes on the model optimal technology mix and plant locations, a baseline scenario has been developed, accounting for current levels of incentives for bioelectricity production (Feed-in-Tariff for electricity, FITel), biomethane injection Feed-in-Tariff for Injection (FITinj) and biomethane production for transport application. Especially for CBM for vehicles, as the market for tradable certificates (CIC) has not been started, values estimates are highly uncertain and based on results in completely different markets. The Decree of the Minister for the Economic Development 23 April 2008, has set a minimum CIC value of 25.82 €/MWh, equal to 25 €cent / Nm^3 (AIEL, 2014), thus in our baseline scenario we set a nominal value of 600 € for certificate.

Given the high uncertainty and variability of important parameters, it is important to perform a sensitivity analysis on factors affecting profitability of biogas alternatives, and, consequently, the expected outlook of biogas technologies under future circumstances. Traditional one-factor-at-time analysis may be enlightening, but it fails to consider possible interactions between different uncertain parameters. Under an incentive framework supporting alternative utilization pathways of the same, scarce renewable resource, conflicts and interactions between different tariffs may be not negligible.

For this reason, the methodology selected for sensitivity analysis is based on factorial design, which is advocated by [27] as the most suitable methodology to answer the practical questions on which factors may cause a project (or a group of projects) to go wrong when the state of knowledge does not allow the analyst to confidently assign distributions to the model inputs [28]. As this is often the case in energy system modeling, factorial design has been used by several authors to obtain an interpretation of the importance of uncertain parameters on sustainable energy projects [16,19,29,30]. By allowing to consider the relations between different parameters affecting the system under investigation, in our case such methodology resulted particularly suitable to investigate whether there are important interaction effects in the factors affecting the potential diffusion of biogas upgrading, both for CBM and grid injection, against power generation, which was up to now the most popular, although inefficient, utilization pathway. In particular, the following five uncertain parameters were investigated:

1. demand level of CNG as a vehicle fuel in the region of concern (D);
2. maximum amount of nitrogen to be spread in the fields (N) ;
3. FIT values for biogas based electric power (E);
4. FIT values for biomethane injection (I) ;
5. market values of biomethane tradable certificates (C);

They were selected because they embrace all basic leverages of current biogas utilization support schemes (FIT for electricity generation, FIT for grid injection for heating, tradable CICs for CBM for vehicles) and territorial constraints which in a previous study on a pilot area in FVG [31] were found to limit biogas utilization potentials, i.e. the demand for CNG for vehicles and limitations on nitrogen according to Nitrate directive, which restricts digestate production and management. Although uncertain, household and industry demand for natural gas were not incorporated in the factorial design because from previous investigations on power generation in Northern Italy [4] it results that, unlike CNG for vehicles, the Italian natural gas requirements for space heating are much higher than technical potentials for biomethane generation, and thus are not a limiting factor. The factors selected were examined with values on two levels, low and high, respectively, following a full-factorial design plan, resulting in $2^5 = 32$ runs of the model. The values adopted for each factors have been summarized in table 2.

Parameter	Symbol	Unit	Low	Baseline	High
CBM demand	D	kNm^3/year	0.7 * baseline values	Current demand	1.3 * baseline values
Nitrogen spreading limit	N	Kg/ha	170 for all municipalities	According to regional deliberation 1246/2008	340 for all municipalities

FITel	E	€/kWh	0.7 * baseline values	According to Decree of 6 July 2012	1.3 * baseline values
FITinj	I	€/Nm^3	0.7 * baseline values	According to Decree of 5December 2013	1.3 * baseline values
CIC	C	€	400	600	800

Table 2 Baseline values for the considered parameters and factor design plan for two levels (low and high)

3. Results and Discussion

3.1 Baseline scenario

As summarized in table 3, the areas selected for comparison are very similar as to biogas potentials (5404 TJ in FVG against 6508 TJ in Romagna), however with a higher density in Romagna (about 752 GJ/km^2 against 1236 GJ/km^2 in FVG). Romagna has also a higher population density, which may have an impact on per capita indicators.

In spite of larger potentials in Romagna, results reported in Table 3 show that biogas production under the baseline scenario would be smaller than in FVG. Limitations on nitrates management are not a technical reason for this difference, on the contrary saturation is almost full (87%) in FVG, while stopping at 47% in Romagna. Total public investments (i.e. total subsidies yearly allocated to all utilization pathways through feed-in-tariffs or certificates) would be higher in Romagna, although smaller if considered per-capita. This would lead to more advantageous average payback time on private investment in Romagna, but the environmental performance of public investment in terms of CO_2eq emission reduction would be slightly worse than in FVG.

To explain these differences, one should consider the optimal technology mix and the optimal plant locations for FVG and Romagna, represented in Figure 3 and 4, respectively, and summarized in Table 4.

Under current level of biogas and biomethane incentives, the biogas to power option represents the preferred economic choice for FVG region (figure 3): the baseline scenario foresees the introduction of 36 small power plants, having a homogeneous capacity of 300 kW (Table 4). New upgrading facilities for biomethane injection and for CBM production are also introduced, although the biogas allocated to transport represents only 5% of the total biogas produced in FVG.

Variable	**Unit**	**Case study**

		FVG	Romagna
Area	km^2	7182	5264
N° of municipalities	Dimensionless	123	89
Population	Inh	857,822	1,179,039
Digestate spreading limit	Mt	5,10	7,6
Total biogas potential	TJ	5404	6508
Biogas potential (maize)	TJ	3512	3904
Biogas potential (manure)	TJ	1891	2603
Biogas production	TJ	1746	1105
Digestate saturation	% on digestate spreading limit	87%	47%
Public investment	M€/year	19	21
VAN	M€/year	25	62
Payback	Year	7,2	3,9
Maize utilization	% on total maize based potential	26%	19%
Manure utilization	% on total manure based potential	42%	13%
Public investment per capita	k€/per capita	23,1	18,0
GHG balance and indicators	tco_2 /year ($kgco_2$ /year) per capita ($kgco_2$ /year)/k€ public investment	-43835 - 51.1 - 2.21	-41238 35.1 -1,95

Table 3 Territorial features and optimization results in the baseline scenario

Considering the suggested plant locations depicted in figure 3, it can be noticed that biomethane injection and CBM are usually performed jointly. Comparing figure 3 with feedstock availability data represented in figure 1, it can be observed that, when locating new upgrading plants, municipalities with high biogas potentials are preferred to those characterized by high CBM demand. In fact, with the exception of one municipality, the biofuel produced in the selected upgrading plants is generally transported to the nearest refuelling station, rather than being consumed locally. The same aspects can be appreciated for Romagna case study (figure 4), in that injection is coupled with CBM production in 5 municipalities out of 7, and CBM is produced in a municipality with refueling station only in one case out of 12. In Romagna the number and overall capacity of CBM production plants in the baseline scenario is more than double than in FVG. The size of installed CBM is comparable, in fact average capacity varies between some 90 Nm^3/h in FVG and about 120 Nm^3/h in Romagna, where refueling station capacity is generally higher. For assumed efficiency and calorific values, upgrading plants of this size would correspond to average equivalent power plants of 178 kW for FVG and 232 kW in Romagna, respectively. These installations would be smaller than typical power-only plants prevailing under baseline incentive schemes, i.e. manure based plants at the upper limit of the smallest incentive size class (300 kW), which both in Romagna and in FVG remains the unique feasible configuration for the power only option.. However, CBM production is mostly coupled with injection plants of similar capacity (117 Nm^3/h) in Romagna, of higher capacity (259 Nm^3/h) in FVG. Results show that injection would thus be a complementary technology but, under current support scheme, is profitability is less constrained by the stepwise shape of feed-in-tariffs than other technologies, and benefits from positive margins also for higher shares of energy crops, characterized by higher energy density but also higher environmental and land use impacts [32] , in the feedstock mix.

The number of biogas to power plants in Romagna stops at 8, with 31% of produced biogas allocated to CBM production and 51% to power generation, against 5% to CBM and 79% to power in FVG.

Thus, in the most likely scenario under current Italian incentive schemes:

- The existing demand of CNG for vehicles is the main limiting factor for CBM diffusion;
- Nitrates constraints and available feedstock (particularly: manure) may be local limiting factors for selected territories;
- Locating plants optimally from a feedstock and nitrate management viewpoint and transporting CBM would be economically preferable, while CBM plant size is determined by typical capacities of refueling stations.
- CBM production represents the best economic choice when existing refuelling stations are widely spread in a given territory, while the biogas to power option is the least favorable technology.

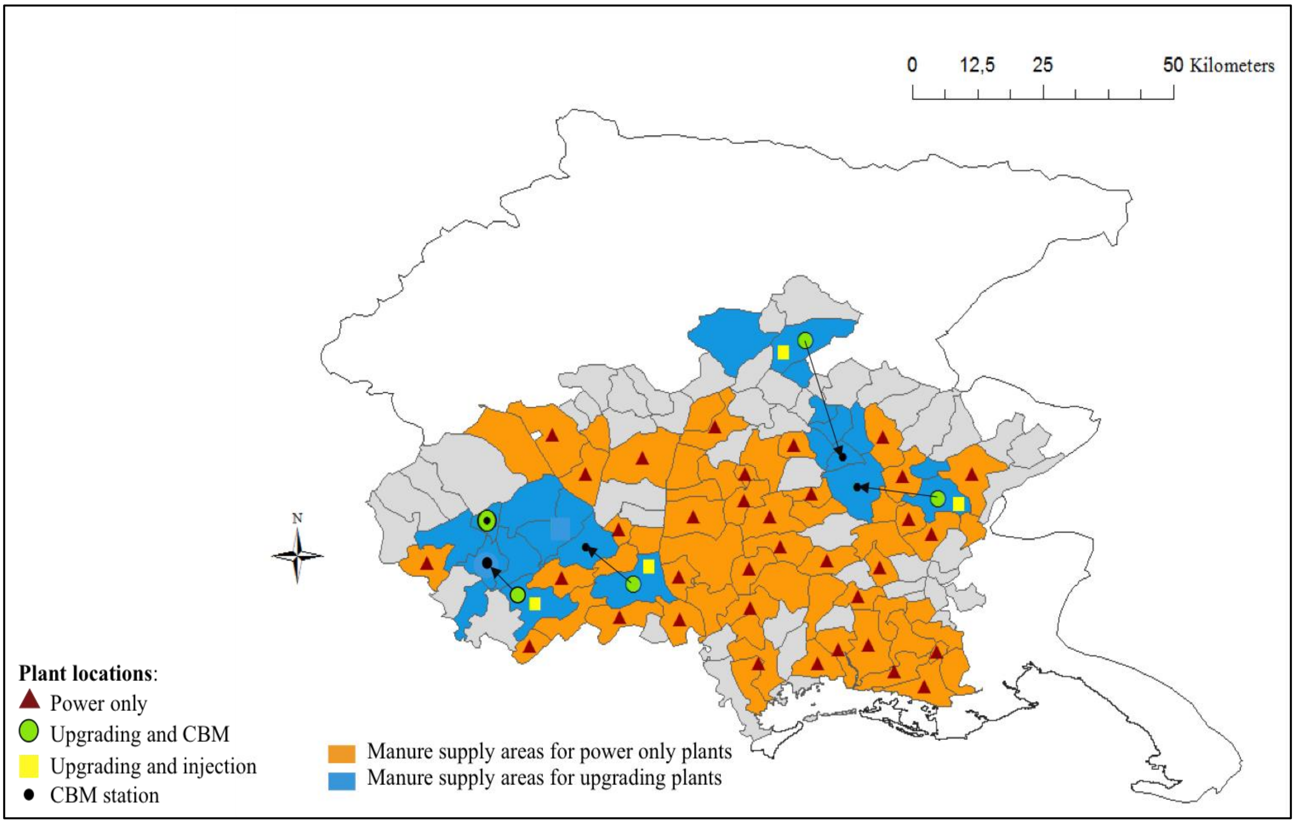


Figure 3. Optimal plants locations and manure supply areas for FVG region

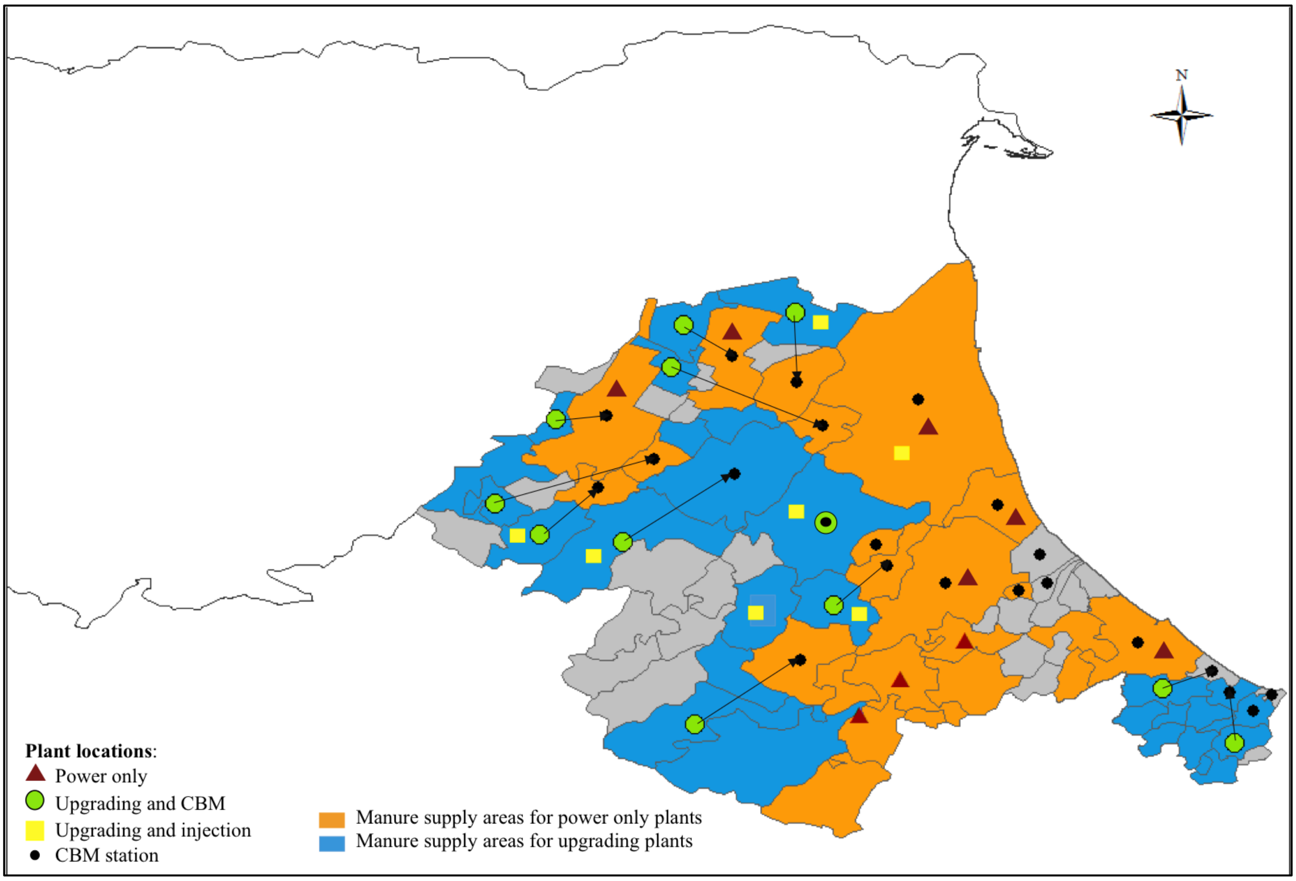


Figure 4. Optimal plants locations and manure supply areas for Emilia Romagna region

Variable	Unit	Power only		Injection		CBM	
		FVG	Romagna	FVG	Romagna	FVG	Romagna
Number of plants	Dimensionless	36	8	4	7	5	12
Total capacity installed	kW - Nm^3/h	10,800 (kW)	2,400 (kW)	1036 (Nm^3/h)	825 (Nm^3/h)	460 (Nm^3/h)	1440 (Nm^3/h)
Mean of manure share	% on total substrate weight	80%	80%	<50%	<50%	75%	75 %
Average plant capacity	kW - Nm^3/h	300 (kW)	300 (kW)	259 (Nm^3/h)	117 (Nm^3/h)	92 (Nm^3/h)	120 (Nm^3/h)
Biogas allocation	% on total biogas production	79	51	16	18	5	31
Total annual revenues	k€/year	18,147	4,032	3184	1,998	2,034	12,994
GHG balance	tco_2 /year	-33,065	-10,110	-3,674	-6,429	-7,096	-24,879

Table 4. Optimization results for the baseline scenario

The similar environmental performance of FVG, where power-only plants prevail, seems in contrast with results in literature [33]: to explain this, an additional analysis on the carbon mitigation potential of each biogas technology option has been performed and is represented in figure 5, obtained by running the model for single technologies and calculating the GHG reduction impact of allocating a growing amount of input resources to each biogas conversion technologies. For single technologies, results of the present model confirm that, for GHG emissions, producing biomethane for transport application in the installations prevailing in the baseline scenario (small size, 30% energy crops) is better than producing power, with internal use of heat only and maximum (100%) use of manure as feedstock, however the benefit is quite small. Moreover, the relationships between expected incentives and current power and natural gas wholesale prices (9 $€_{cent}$/kWh and 5 $€_{cent}$/kWh respectively) are such that a high share of incentives would be allocated to bio-methane under the baseline scenario, which would make this technology very attractive for entrepreneurs under favorable territorial situations, but also very expensive when relating public investment to the environmental outcome.

We conclude that CIC values expected here are relatively high, a policy choice that could be sensible at the start, in order to attract investors to the relatively new and highly uncertain market of CBM, but should be monitored over time.

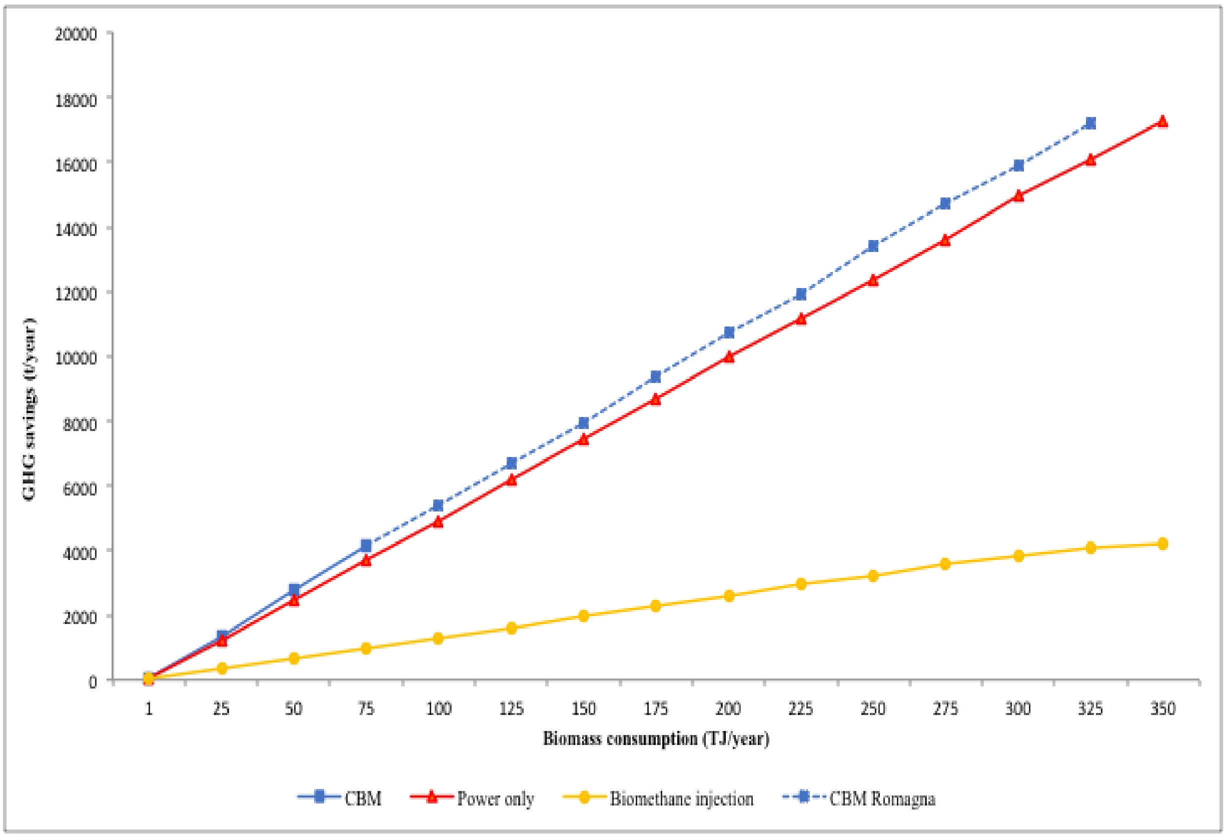


Figure 5. Trend of GHG emissions savings for each biogas technology option

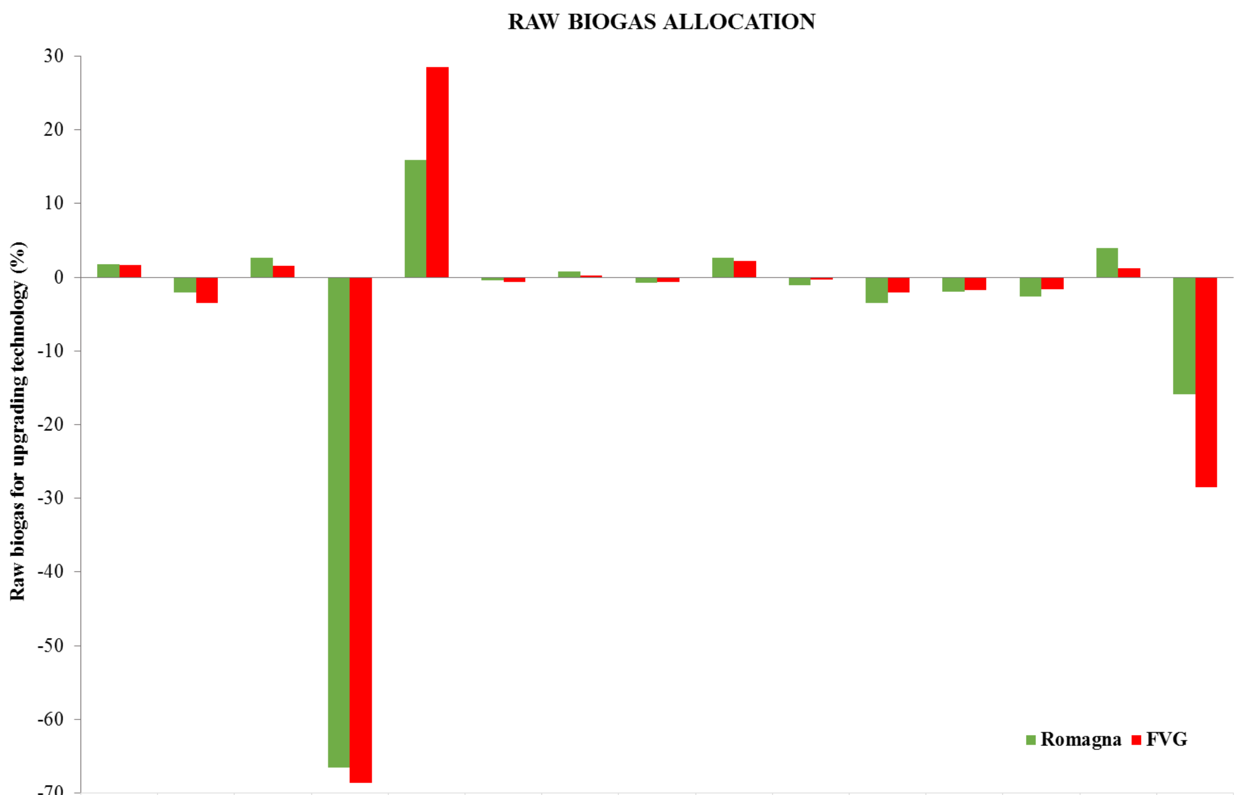
3.2 Sensitivity analysis with factorial design

In order to test the magnitude effect of the aforementioned key factors (here shortly described as C,N,D,E,I according to the symbolism of table 2) on the biogas supply chain configuration, a factorial analysis has been carried out. The impact of single and joint variations of uncertain factors on the optimal technology mix, particularly on the upgrading share, on GHG reduction potentials and on the ratio between public subsidies and private investments in biogas technologies were analyzed for the two case studies. Results are reported in figures 6-8.

Figure 6 represents the variation in the amount of biogas allocated to the upgrading (for CBM and INJ) in both case studies. Variations in values of tradable certificates (C) produce only small shifts in upgrading shares and so does CNG demand (D); their interaction is also minimal. This is especially evident in Friuli Venezia Giulia, where CNG demand is smaller and CBM allocation potentials stop at 75 TJ in the baseline scenario (Figure 5).

Sensitivity to incentives in injection (I) is much higher has a relevant effect in the optimal solution: a 30% higher Feed-in Tariff for grid injection results in 30% and 20% increases in the amount of biogas upgraded in FVG and in Romagna regions, respectively. Increases in electricity tariffs E cause the most remarkable reduction in upgrading technologies, mainly at the expense of injection, especially in FVG because of limited bio-methane potentials. This is confirmed by the significant negative interaction between E and I, meaning that the reduction in upgrading shares caused by high E is more important when I levels are high. Again, interactions of these parameters with bio-methane for transport related parameters C and D are very small or negligible.

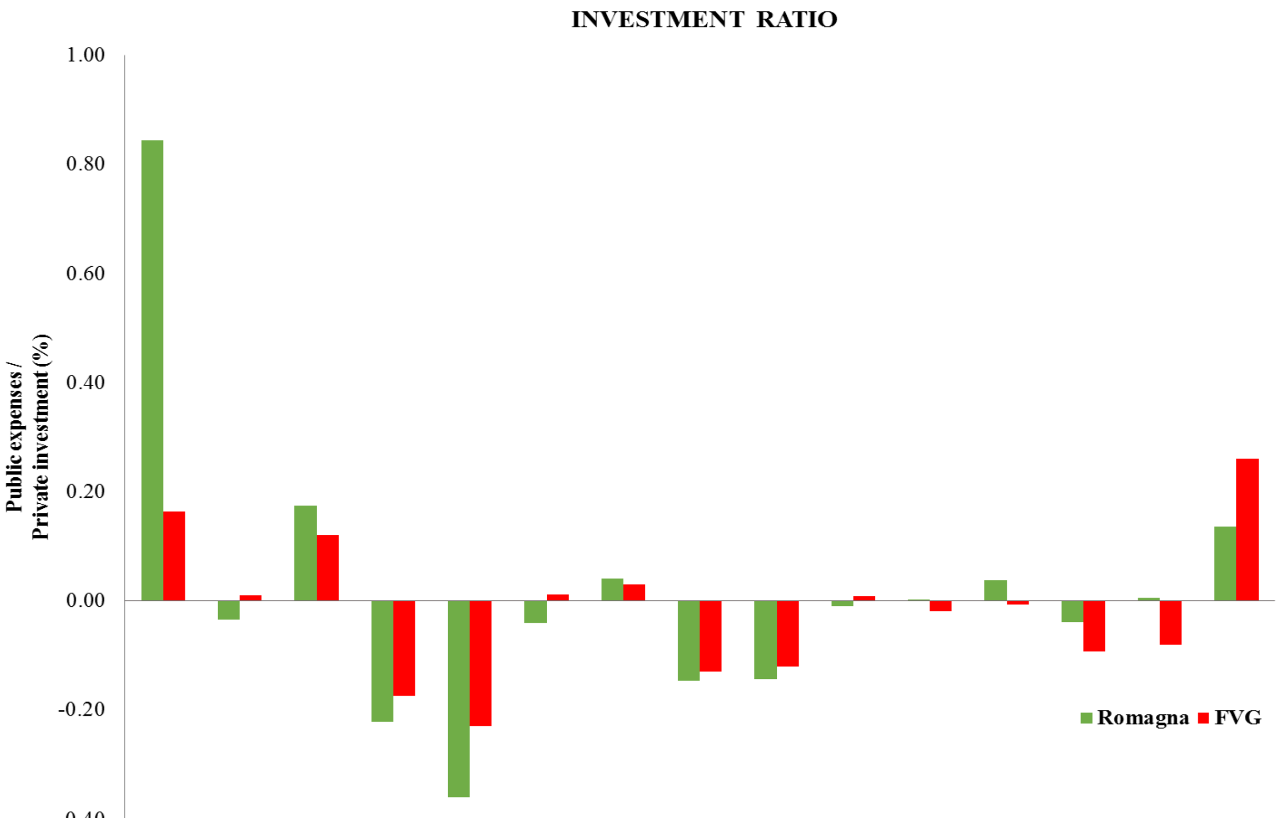
Hypothesizing higher digestate spreading limits on the Nitrate Vulnerable Zones, i.e. higher N, has a small negative effect on the adoption of the upgrading technology, i.e. it mainly fosters electricity production, and the effect is more significant in FVG, where saturation rates in the baseline scenario are closer to the limit.



	C	N	D	E	I	CN	CD	CE	CI	ND	NE	NI	DE	DI	EI
Romagna	1.73438	-2.0275	2.60438	-66.588	15.9344	-0.3819	0.73437	-0.7344	2.64438	-1.1131	-3.5081	-1.9794	-2.6044	3.92438	-15.934
FVG	1.6375	-3.5081	1.5875	-68.639	28.5425	-0.5988	0.18875	-0.6375	2.16625	-0.2687	-2.0275	-1.7088	-1.5875	1.23625	-28.543

Figure 6. Main and two factors interaction effect on raw biogas allocation

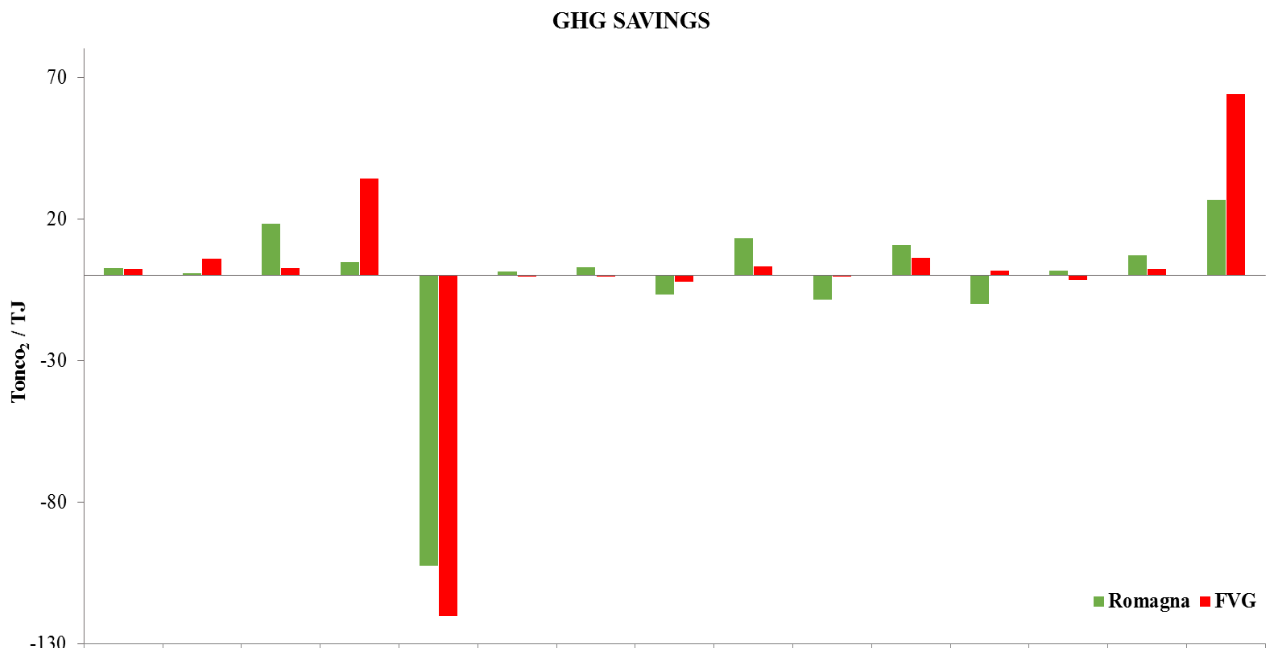
While increasing C has a limited impact on upgrading shares, it has a remarkable negative effect on the efficiency of subsidies, as can be observed in Figure 7. Investments in CBM would be profitable even at limit conditions but only through a heavy proportion of public subsidies for CBM to private investment. Increases in CNG demand D has a similar effect: thus, even when accounting for parameter uncertainty, observations at baseline scenario are confirmed, i.e. that CBM is the technology which most relies on incentives. Increasing either E or I, instead, would determine higher shares of profitable technologies in the biogas utilization mix, leading to a reduced proportion of public subsidies. Their combined effect is, however, unfavorable.



	C	N	D	E	I	CN	CD	CE	CI	ND	NE	NI	DE	DI	EI
Romagna	0.85	-0.03	0.18	-0.22	-0.36	-0.04	0.04	-0.15	-0.14	-0.01	0.00	0.04	-0.04	0.01	0.14
FVG	0.16	0.01	0.12	-0.17	-0.23	0.01	0.03	-0.13	-0.12	0.01	-0.02	-0.01	-0.09	-0.08	0.26

Figure 7. Main and two factors interaction effect on investment ratio (public expenses/ private investment)

Even as to GHG emission reduction results, reported in Figure 8, the impact of higher C on savings is negligible because of inherent limitations in market potentials. Instead, an increase in D in Romagna leads to significantly better environmental performance. It follows that policy measures directed to increase CNG market shares would be probably more effective in promoting, in turn, increased CBM production and associated environmental benefits: this, however, applies to an area where CNG market is already well developed. In FVG, instead, benefits derive from higher E. The negative environmental impact of increasing injection tariffs I is remarkable in both regions, and should be well considered by policy makers. The interaction with E is positive because at high levels of I increasing E is an effective way to divert resources from injection, which has low GHG reduction performance, to electricity production and CBM. The effect is more evident in FVG, where potentials allocated to electricity are higher because of CBM market limitations.



	C	N	D	E	I	CN	CD	CE	CI	ND	NE	NI	DE	DI	EI
Romagna	2.69	0.89	18.29	4.61	-102.33	1.50	2.76	-6.83	13.23	-8.41	10.76	-10.08	1.82	7.00	26.70
FVG	2.33	5.94	2.49	34.17	-120.13	-0.04	-0.27	-2.28	3.15	-0.15	6.25	1.81	-1.62	2.31	63.92

Figure 8. Main and two factors interaction effect on GHG emission savings

4. Conclusions and future research

In this study the economic and environmental effects of applying current Italian biogas promotion schemes has been assessed by conducting two spatial explicit case studies and by performing a factor analysis on the model main parameters.

Results showed that investing in CBM production represents the most profitable choice for entrepreneurs under current levels of bio-methane incentives, and it also leads to the highest GHG emissions savings per TJ of biogas allocated to that utilization pathway. However, from both baseline and sensitivity analysis we can conclude that, in spite of the relatively large diffusion of CNG especially in some regions of Italy, CBM is a niche product which risks to be overly subsidized, considering the limited overall environmental benefits it can yield because of inherent limitations in market size. Allocating funds to promote a further expansion of CNG would probably help CBM development and benefits more than increasing specific incentives. This could be a subject for further research, bearing in mind that only the substitution of CNG with CBM for vehicles was considered in this study, while an expansion in CNG *and* CBM markets would happen at the expenses of gas oil and gasoline, probably with further environmental benefits.

The factor analysis performed in this study also showed that growing incentives for biomethane injection would rapidly foster the adoption of upgrading solutions. However, the environmental analysis performed for both case studies suggests that such biogas utilization pathway has the least environmental benefits in terms of GHG emissions savings, and that even the power only solution, which environmental performance has been subject to growing criticism in literature [34,35], is preferable to biomethane injection. Policy makers should thus be especially careful in financing a technology which has high market potentials, would be probably welcomed by entrepreneurs in that natural gas distribution to households and industry is a solid, well developed market in Italy, but would divert both public and private funds from more efficient utilization pathways.

While CBM for vehicles has interesting strategic implications, finding a way to promote high efficiency cogeneration, with proved, large utilization shares of by-produced heat is probably the key to achieve evident economic and environmental benefits from agricultural biogas in Northern Italy. This is a challenge to policy makers, who already introduced some measures in current legislation, and to research supporting their choices, in that district heating systems are rare and should be accurately modelled from a spatially explicit perspective, to estimate technical and economic feasibility of biogas utilization. Moreover, it is really difficult to estimate heat utilization potentials at small and distributed scale: further research should be directed at using GIS to enhance knowledge and improve decisions in this framework.

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