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Original

Availability:

This version is available <http://hdl.handle.net/11390/1102084> since 2021-03-26T10:40:57Z

Publisher:

Published

DOI:10.1016/j.renene.2016.07.047

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The impact of regional factors and new bio-methane incentive schemes on the structure, profitability and CO₂ balance of biogas plants in Italy

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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

4 municipal methanization plants increased from approximately 17 TWh in 2006 to almost 36 TWh in
5 2011 [1].

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

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

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

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

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

37 premium, concluding that by introducing such measure the profitability of commercial biogas
38 projects is somewhat raised.

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

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

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

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

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

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

67 With the aim of evaluating the impact of new policies on biogas utilization pathways and relevant
68 GHG emission reduction potentials, it is assumed that plants will be built if and only if (and where)
69 they are profitable. The economic performance (particularly considering the amount of private

70 investments mobilized by public incentives) and the environmental performance in terms of GHG
71 emission balance are thus calculated at supply chain level.

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

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

82

83 **2. Material and Methods**

84 Current biomethane promotion schemes are briefly analyzed in section 2.1 and incorporated in a
85 MILP model accounting for the most relevant steps of the biogas supply chain as described in section
86 2.2. The model considers different biogas utilization pathways such as production of electricity and
87 biogas upgrading to biomethane for heating and for transport purposes. The goal is to find the
88 optimal mix of conversion technologies, plant capacities and locations under current biogas
89 promotion schemes. To this end, the methodology has been applied to the North Italian regions of
90 Friuli Venezia Giulia (Figure 1) and Emilia Romagna (Figure 2), as detailed in section 2.3. Areas
91 selected for comparison have similar biogas potentials but different market potentials for bio-
92 methane for vehicles (compressed bio-methane, CBM in the following), as they currently have
93 different compressed natural gas (CNG) demand levels and number of existing refueling
94 infrastructures. A reference scenario is defined as baseline in section 2.3, where methodological
95 details are also given on how sensitivity analysis is performed through factorial design to understand
96 which uncertain parameters (particularly: market and incentive parameters) affect the economic
97 optimum, that is to say the expected scenario under those economic circumstances.

98 **2.1 Policy framework**

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

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

106 For CBM, a tradable certificate (called CIC, as in the Italian regulation, in the following) mechanism
 107 is introduced as for other biofuels, which is based on the quota obligation for fossil fuel traders in the
 108 transport sector. The certificate size is assumed to be equivalent to 1166 Nm³, and, as summarized in
 109 Table 1, the number of certificates granted by the managing authority depends on the substrate mix
 110 with three classes based on exploited manure shares (below 70% in weight, above 70% in weight
 111 and 100% by-products). If biomethane producers become direct biomethane distributors (labelled
 112 “Own” in Table 1), rather than wholesalers to existing natural gas distributors (labelled “Third” in
 113 Table 1), they are eligible for 10 years to an increment of 50% of the certificate value.

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

116

Manure %	Natural gas injection (INJ) equivalent tariff [€/Nm ³]				Manure %	Number of tradable certificates (CICs) for compressed bio-methane (CBM)			
	Size class upper limit (Sm ³ /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

123

124 Table 1. Current bio-methane support mechanism

125

126 2.2 Modeling actual biomethane promotion schemes

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

131 The production of energy vectors is a function of biogas conversion efficiency $\eta_{s,tech}$, which is
 132 influenced by technology $tech$ and size class of the plant s , the biogas lower calorific value K_{bg}
 133 (6.2 kWh/Nm^3) and the total biogas production $ProdBg_{j,s}$ (Nm^3/year), depending on the total
 134 amount $Q_{j,t,s}$ (kWh) of feedstock of different types t adopted in the digestion process.

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

$$139 \quad ProdEvUp_{s,j} = \sum_{tech} (\eta_{s,tech} * \varphi_{tech}) * (ProdBg_{j,s} * K_{bg}) \quad (1)$$

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

$$144 \quad \sum_s ProdEvUp_{s,j} = \sum_s [\sum_f ProdEvCBM_{j,s,f} + \sum_g ProdEvINJ_{j,s,g}] \quad (2)$$

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

$$154 \quad \sum_s \sum_f ProdEvCBM_{j,s,f} = DemCBM_j + \sum_{k \neq j} DemCBM_k * binFS_{j,k} \quad (3)$$

156 Where the binary variable $binFS_{j,k}$ equals 1 if an upgrading plant is built in the j -th municipality to
 157 serve the refueling station located in k . Equation (4) imposes that each CBM production plant serves

158 at maximum one refueling station. Another simplifying assumption, considering social acceptance
159 constraints and typical sizes of plants and of municipalities, is that injection into the gas grid for
160 heating purposes is compatible with all other utilization pathways, while fuel production and power
161 generation are incompatible at municipal level: equation (5) thus imposes that a maximum of one
162 CBM or power plant can be installed in each municipality.

163

$$164 \quad \sum_{k \neq j} binFS_{j,k} \leq 1 \quad (4)$$

$$165 \quad binCBM_j + binMCI_j + \sum_{k \neq j} binFS_{j,k} \leq 1 \quad (5)$$

166

167 To be allocated to remote stations, CBM has to be transported, which has economic and
168 environmental implications. As to transport, both the possibility to inject the biomethane into a local
169 gas grid and to adopt a truck-based distribution have been considered in this study. The connection
170 through the local gas grid at a fixed cost was deemed a reasonable solution for refueling stations
171 located in the same municipality as CBM plants, since low pressure gas distribution networks exist in
172 every municipality in the areas of concern. Furthermore, existing natural gas refueling stations are
173 often located near high pressure gas transport pipes, which results in lower operational costs and
174 energy consumption. On the other hand, to connect upgrading plants to remote refueling stations
175 located in different municipalities in a flexible way, the distribution of CBM between different
176 municipalities in the area of concern has been assigned to specific trucks, such as a demountable
177 platforms, in which compressed gas cylinders are loaded and then distributed. For small volumes
178 (less than 10 MNm³/year) and small distances (up to 50 km), which characterized the territories of
179 concern as further explained in section 2.3, this process may be less expensive than distribution
180 through pipes [20].

181

182 2.3 Case studies description and scenario analysis

183 2.3.1 System boundaries

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

187 Besides these technologies, the actual biogas promotion scheme also incentivizes the production of
188 heat deriving from high efficiency cogeneration units, having an overall efficiency equal or greater
189 than 75 % [21]. In the case of biogas plants, such threshold value requires that the heat recovered
190 from the internal combustion engine is almost equal to the electric power produced. Individual cases

191 in which the produced heat is completely absorbed by private or public units (to meet high heat
192 requirements of e.g. greenhouses or a chick farms) might exist in the territory of concern, however
193 data on the location of these particular cases are not currently available. Alternatively the heat
194 produced might be distributed via district heating systems, which are very rare in the Italian territory.
195 For these reasons, and since the issue of developing new district heating infrastructure is out of the
196 scope of this study, the cogeneration option have been excluded as potential biogas conversion
197 technology.

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

203 Since any consideration related to the environmental impact of these technologies has been included
204 in the Italian biogas promotion schemes, the environmental balance of the system of concern, in
205 terms of carbon equivalent emissions produced, have been excluded from the model objective
206 function. Therefore, the greenhouse gases emission savings associated to the model optimal solutions
207 have been calculated by adopting the emission factors indicated by the Global Emissions Model for
208 integrated Systems (GEMIS) database [24]. The GEMIS tool is a freely available database for
209 process or product life cycle assessment (LCA) containing the most extensive inventory of
210 agricultural biogas processes as it adopts typical biogas plant sizes, compared to the wide ranges (e.g.
211 “up to 50 MW”) that are used by other software packages for process or product LCA, such as
212 [25,26].

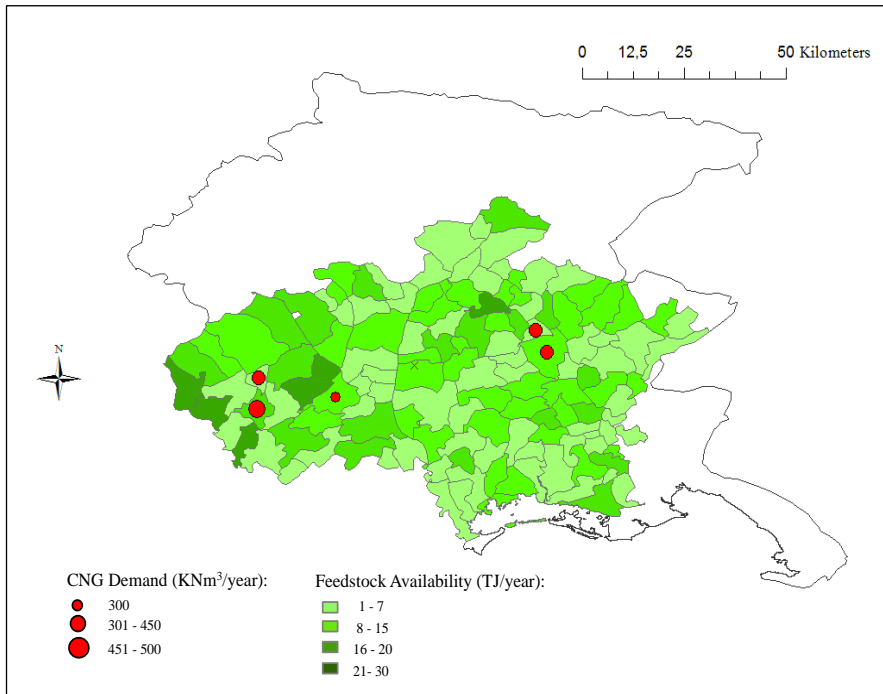
213 With regard to the logistics activities considered, a special feature of biogas supply chains is that,
214 besides input flows, an output material flow should be managed, i.e. digestate. As clarified by [18] is
215 important that the Nitrates Directive limits on the application of manure fertilizer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

220

221 2.3.2 Case studies description

222 The first case study analyzed concerns the territory of Friuli Venezia Giulia Region (FVG) excluding
223 its mountain areas. In FVG, potentials for biogas generation from agricultural byproducts are high,
224 especially considering co-digestion options and the use of energy crops as possible substrates. Maize

225 is a leading crop: approximately 60% of the arable agricultural area is yearly sown with maize, with
 226 silage being extensively used as fodder. Given the dominance of breeding farms in the area, animal
 227 manures from main kinds of breeding, that is cattle, swine and chicken manure, is considered. With
 228 these assumptions, theoretical biogas potentials represented in Figure 1 are estimated.

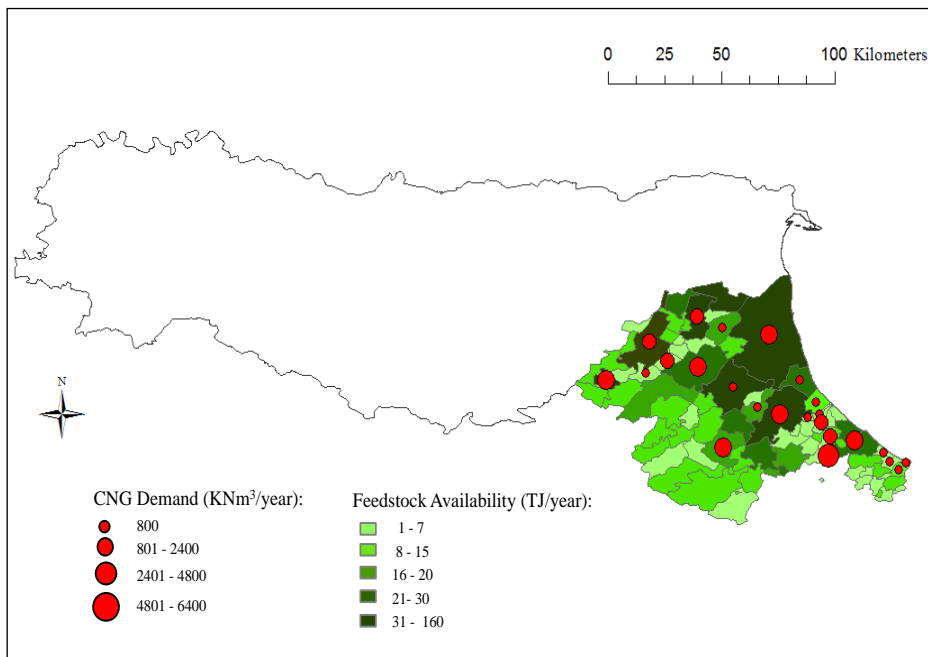


229

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

231 Figure 1 also shows the location of existing CNG refuelling stations, whose presence is very limited
 232 in FVG. Such aspect might discourage entrepreneurs to invest in upgrading technology as the
 233 production of CBM fuel would not be easily absorbed by the regional market. To validate results,
 234 and particularly to assess the influence of CNG demand levels on biogas supply chain performance,
 235 the Romagna region as the second regional case study. Romagna is a sub-region located on the
 236 northern Adriatic coast, constituted by almost 80 municipalities. This area is comparable with FVG
 237 as to technical biogas potential, which is somewhat higher and more concentrated, as represented in
 238 Figure 2, however Romagna is characterized by an high penetration of CNG as a vehicle fuel, with a
 239 total annual CNG demand of more than 20 kNm³ (almost 4 Nm³/ km²), distributed in 25 refuelling
 240 stations, against 5 stations only in FVG (represented as red dots in figures 1 and 2).

241



242

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

244

245 2.3.3 Scenario analysis and Design of experiments (DOE)

246 To address the effect of current biogas promotion schemes on the model optimal technology mix and
 247 plant locations, a baseline scenario has been developed, accounting for current levels of incentives
 248 for bioelectricity production (Feed-in-Tariff for electricity, FITel), biomethane injection Feed-in-
 249 Tariff for Injection (FITinj) and biomethane production for transport application. Especially for CBM
 250 for vehicles, as the market for tradable certificates (CIC) has not been started, values estimates are
 251 highly uncertain and based on results in completely different markets. The Decree of the Minister for
 252 the Economic Development 23 April 2008, has set a minimum CIC value of 25.82 €/MWh, equal to
 253 25 €cent / Nm³ (AIEL, 2014), thus in our baseline scenario we set a nominal value of 600 € for
 254 certificate.

255 Given the high uncertainty and variability of important parameters, it is important to perform a
 256 sensitivity analysis on factors affecting profitability of biogas alternatives, and, consequently, the
 257 expected outlook of biogas technologies under future circumstances. Traditional one-factor-at-time
 258 analysis may be enlightening, but it fails to consider possible interactions between different uncertain
 259 parameters. Under an incentive framework supporting alternative utilization pathways of the same,
 260 scarce renewable resource, conflicts and interactions between different tariffs may be not negligible.
 261 For this reason, the methodology selected for sensitivity analysis is based on factorial design, which
 262 is advocated by [27] as the most suitable methodology to answer the practical questions on which
 263 factors may cause a project (or a group of projects) to go wrong when the state of knowledge does

264 not allow the analyst to confidently assign distributions to the model inputs [28]. As this is often the
 265 case in energy system modeling, factorial design has been used by several authors to obtain an
 266 interpretation of the importance of uncertain parameters on sustainable energy projects [16,19,29,30].
 267 By allowing to consider the relations between different parameters affecting the system under
 268 investigation, in our case such methodology resulted particularly suitable to investigate whether there
 269 are important interaction effects in the factors affecting the potential diffusion of biogas upgrading,
 270 both for CBM and grid injection, against power generation, which was up to now the most popular,
 271 although inefficient, utilization pathway. In particular, the following five uncertain parameters were
 272 investigated:

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

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

290

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 5 December 2013	1.3 * baseline values
CIC	C	€	400	600	800

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

292

293 3. Results and Discussion

294 3.1 Baseline scenario

295 As summarized in table 3, the areas selected for comparison are very similar as to biogas potentials
 296 (5404 TJ in FVG against 6508 TJ in Romagna), however with a higher density in Romagna (about
 297 752 GJ/km² against 1236 GJ/km² in FVG). Romagna has also a higher population density, which
 298 may have an impact on per capita indicators.

299 In spite of larger potentials in Romagna, results reported in Table 3 show that biogas production
 300 under the baseline scenario would be smaller than in FVG. Limitations on nitrates management are
 301 not a technical reason for this difference, on the contrary saturation is almost full (87%) in FVG,
 302 while stopping at 47% in Romagna. Total public investments (i.e. total subsidies yearly allocated to
 303 all utilization pathways through feed-in-tariffs or certificates) would be higher in Romagna, although
 304 smaller if considered per-capita. This would lead to more advantageous average payback time on
 305 private investment in Romagna, but the environmental performance of public investment in terms of
 306 CO₂eq emission reduction would be slightly worse than in FVG.

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

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

315

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	-43835	-41238
	(kgco ₂ /year) per capita	- 51.1	35.1
	(kgco ₂ /year)/k€ public investment	- 2.21	-1,95

316 Table 3 Territorial features and optimization results in the baseline scenario

317

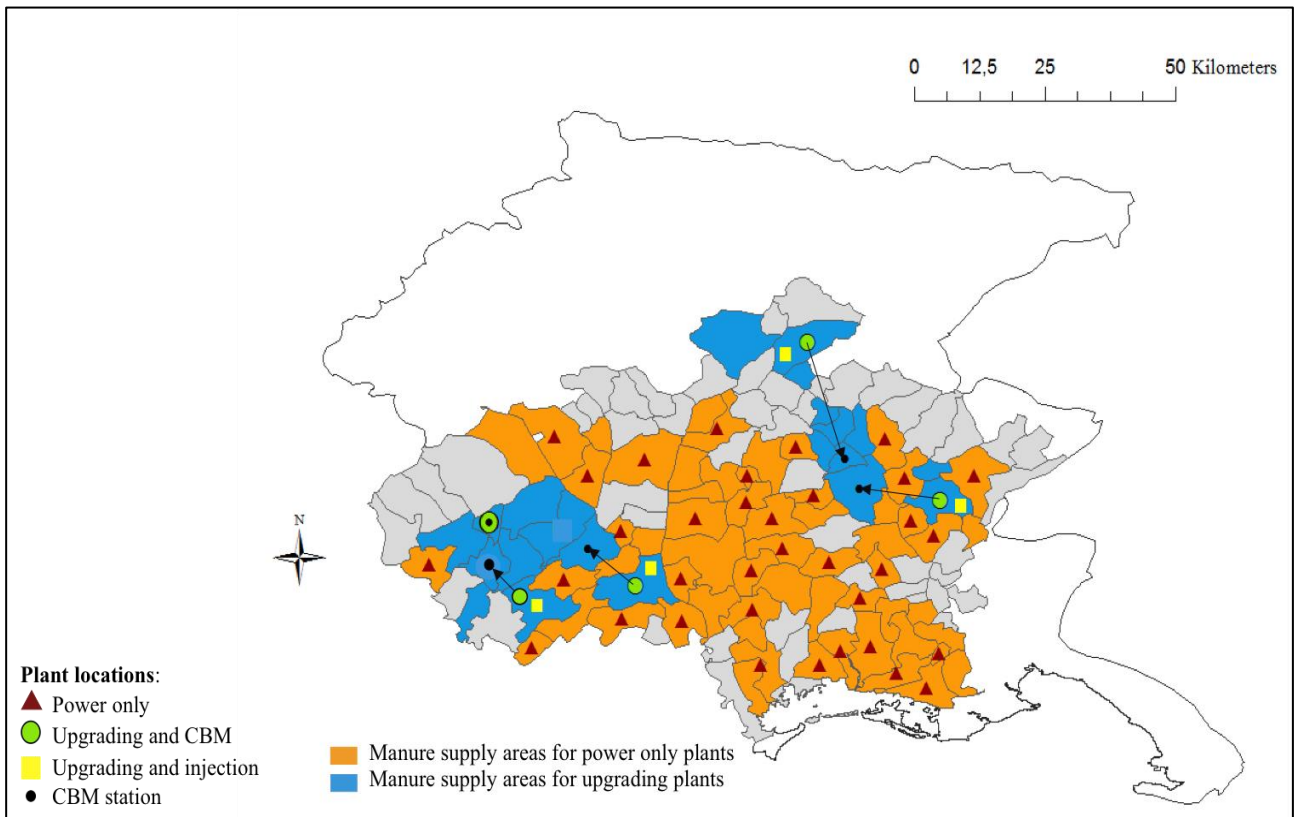
318 Considering the suggested plant locations depicted in figure 3, it can be noticed that biomethane
319 injection and CBM are usually performed jointly. Comparing figure 3 with feedstock availability data
320 represented in figure 1, it can be observed that, when locating new upgrading plants, municipalities
321 with high biogas potentials are preferred to those characterized by high CBM demand. In fact, with
322 the exception of one municipality, the biofuel produced in the selected upgrading plants is generally

323 transported to the nearest refuelling station, rather than being consumed locally. The same aspects
324 can be appreciated for Romagna case study (figure 4), in that injection is coupled with CBM
325 production in 5 municipalities out of 7, and CBM is produced in a municipality with refueling station
326 only in one case out of 12. In Romagna the number and overall capacity of CBM production plants in
327 the baseline scenario is more than double than in FVG. The size of installed CBM is comparable, in
328 fact average capacity varies between some 90 Nm³/h in FVG and about 120 Nm³/h in Romagna,
329 where refueling station capacity is generally higher. For assumed efficiency and calorific values,
330 upgrading plants of this size would correspond to average equivalent power plants of 178 kW for
331 FVG and 232 kW in Romagna, respectively. These installations would be smaller than typical power-
332 only plants prevailing under baseline incentive schemes, i.e. manure based plants at the upper limit
333 of the smallest incentive size class (300 kW), which both in Romagna and in FVG remains the
334 unique feasible configuration for the power only option.. However, CBM production is mostly
335 coupled with injection plants of similar capacity (117 Nm³/h) in Romagna, of higher capacity (259
336 Nm³/h) in FVG. Results show that injection would thus be a complementary technology but, under
337 current support scheme, its profitability is less constrained by the stepwise shape of feed-in-tariffs
338 than other technologies, and benefits from positive margins also for higher shares of energy crops,
339 characterized by higher energy density but also higher environmental and land use impacts [32] , in
340 the feedstock mix.

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

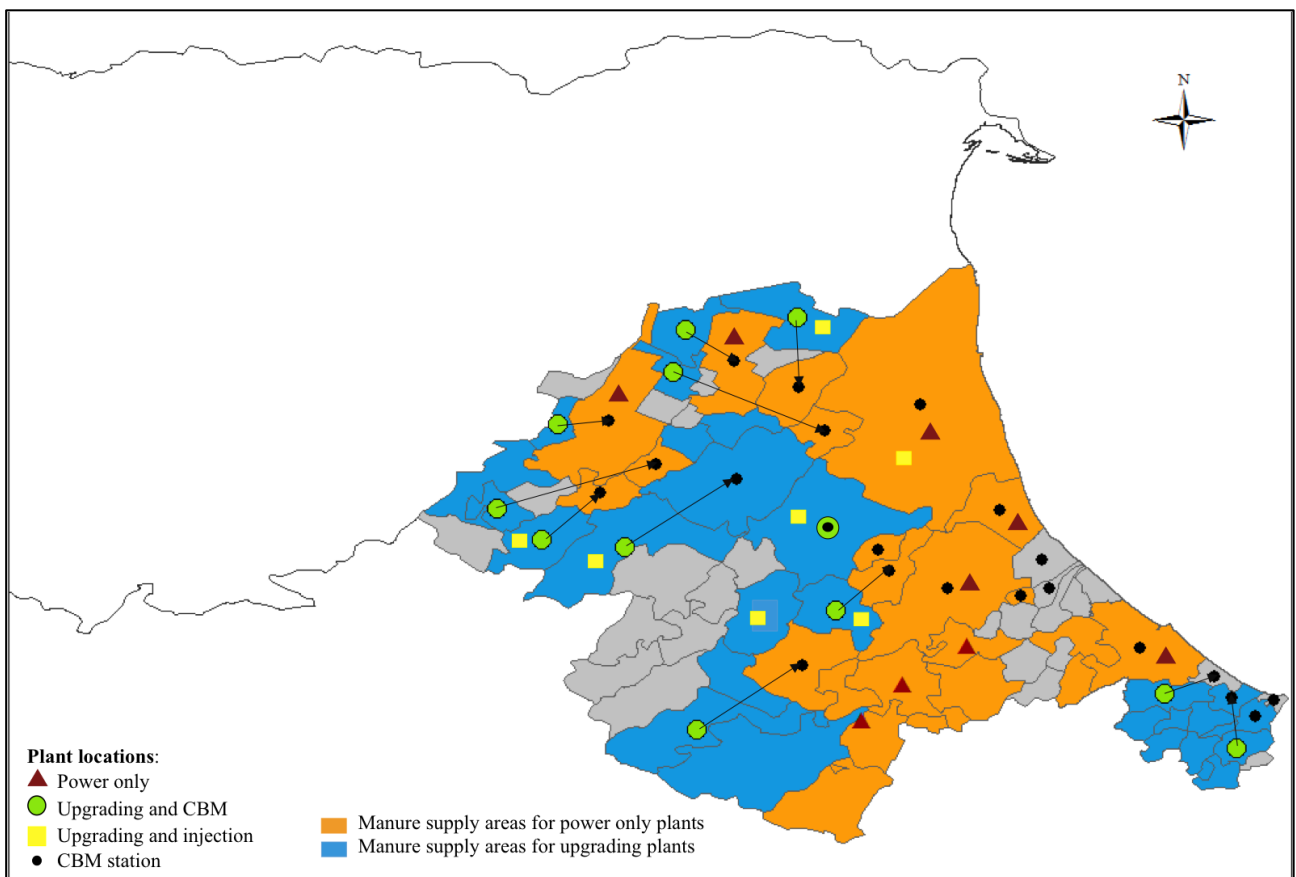
343 Thus, in the most likely scenario under current Italian incentive schemes:

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



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



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

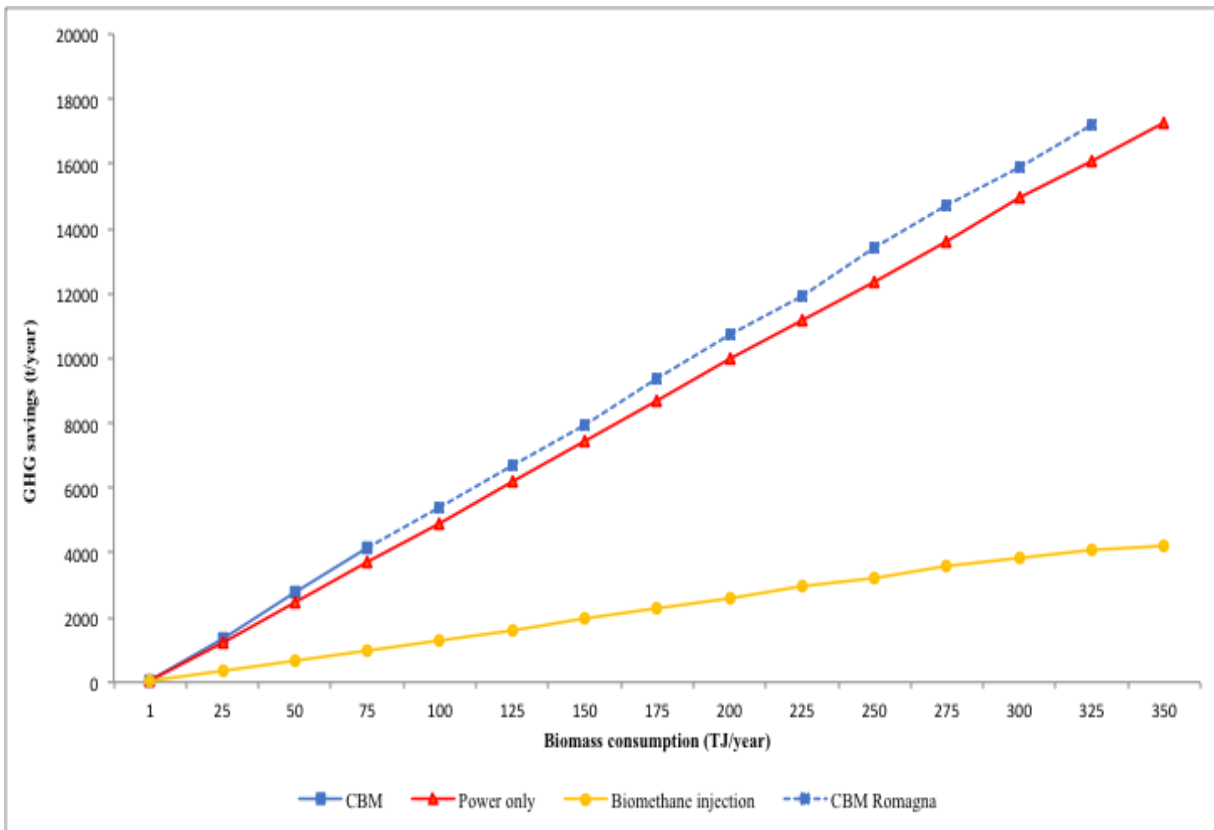
Variable	Unit	Power only		Injection		CBM	
		FVG	Romagna	FVG	Romagna	FVG	Romagna
Number of plants	Dimensionless	36	8	4	7	5	12
Total capacity installed	kW - Nm ³ /h	10,800 (kW)	2,400 (kW)	1036 (Nm ³ /h)	825 (Nm ³ /h)	460 (Nm ³ /h)	1440 (Nm ³ /h)
Mean of manure share	% on total substrate weight	80%	80%	<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

359 Table 4. Optimization results for the baseline scenario

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

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



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

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382 3.2 Sensitivity analysis with factorial design

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

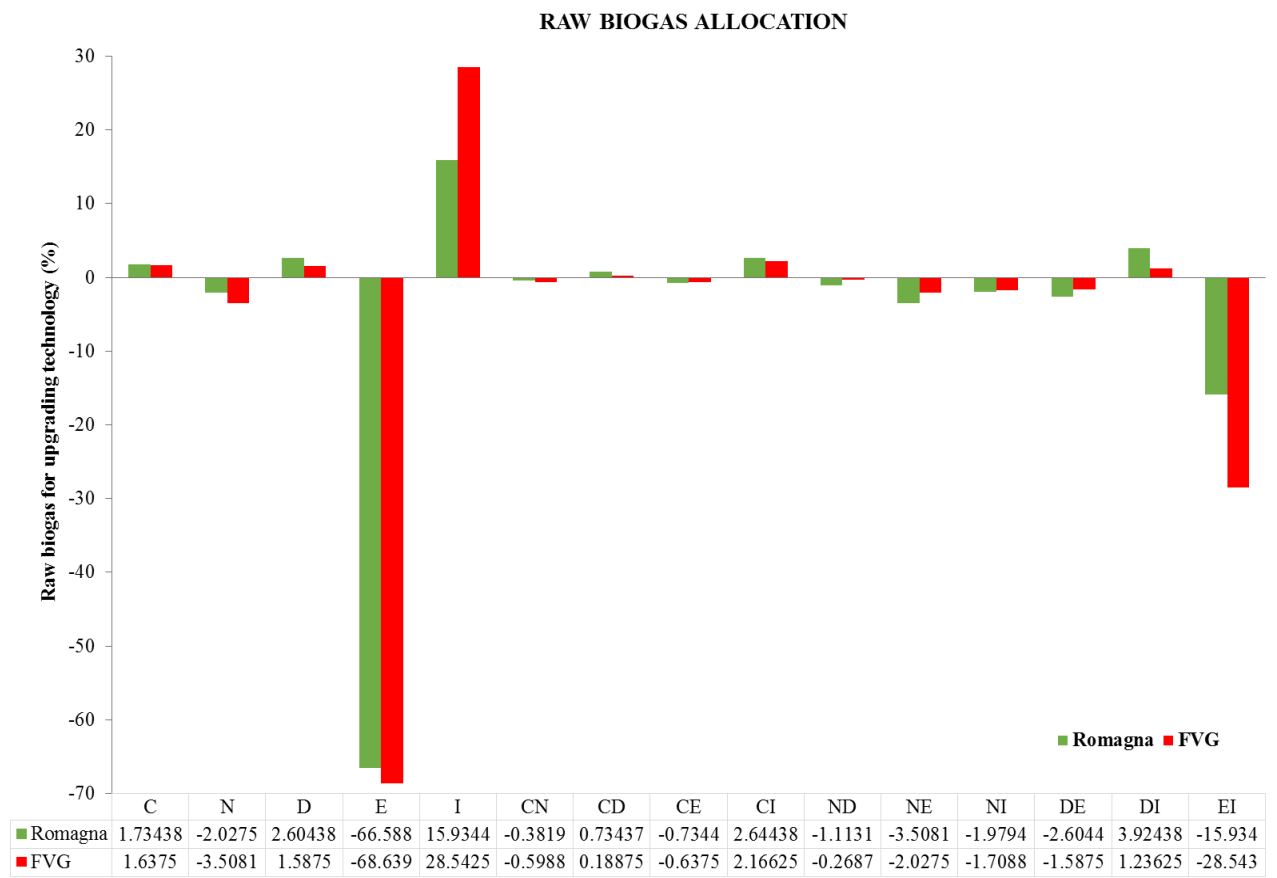
389 Figure 6 represents the variation in the amount of biogas allocated to the upgrading (for CBM and
 390 INJ) in both case studies. Variations in values of tradable certificates (C) produce only small shifts in
 391 upgrading shares and so does CNG demand (D); their interaction is also minimal. This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

394 Sensitivity to incentives in injection (I) is much higher has a relevant effect in the optimal solution: a
 395 30% higher Feed-in Tariff for grid injection results in 30% and 20% increases in the amount of
 396 biogas upgraded in FVG and in Romagna regions, respectively. Increases in electricity tariffs E cause
 397 the most remarkable reduction in upgrading technologies, mainly at the expense of injection,
 398 especially in FVG because of limited bio-methane potentials. This is confirmed by the significant
 399 negative interaction between E and I, meaning that the reduction in upgrading shares caused by high
 400 E is more important when I levels are high. Again, interactions of these parameters with bio-methane
 401 for transport related parameters C and D are very small or negligible.

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

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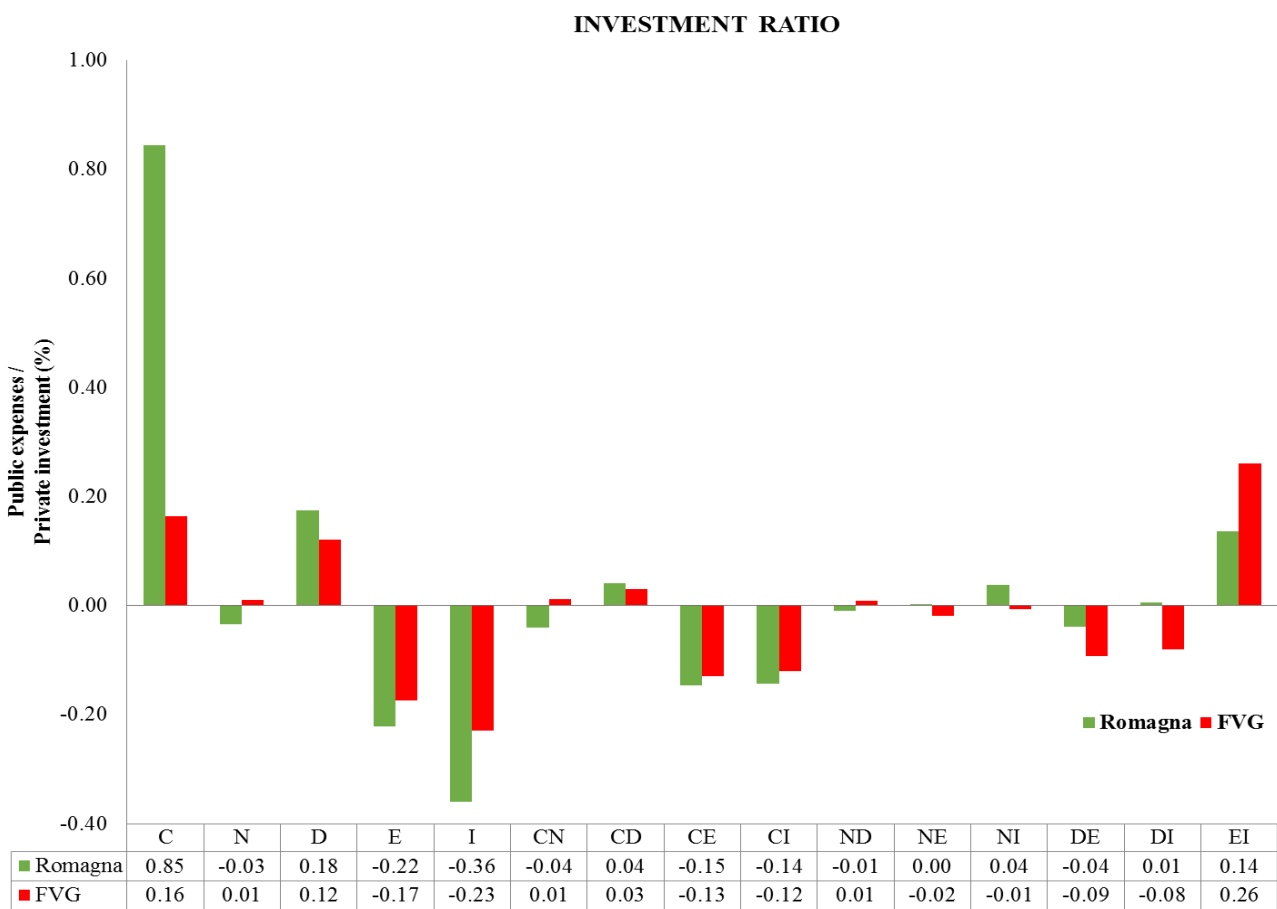
409 Figure 6. Main and two factors interaction effect on raw biogas allocation

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

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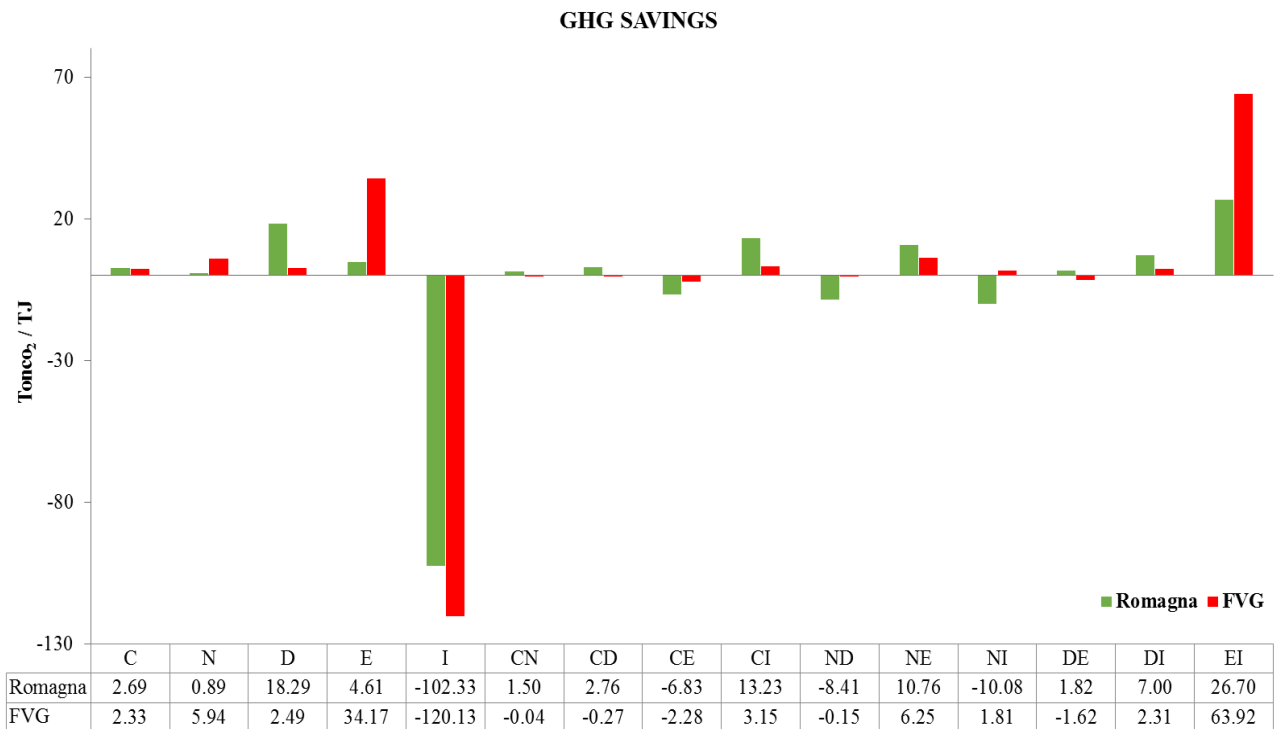
422 Figure 7. Main and two factors interaction effect on investment ratio (public expenses/ private investment)

423

424 Even as to GHG emission reduction results, reported in Figure 8, the impact of higher C on savings is
 425 negligible because of inherent limitations in market potentials. Instead, an increase in D in Romagna
 426 leads to significantly better environmental performance. It follows that policy measures directed to
 427 increase CNG market shares would be probably more effective in promoting, in turn, increased CBM
 428 production and associated environmental benefits: this, however, applies to an area where CNG

429 market is already well developed. In FVG, instead, benefits derive from higher E. The negative
 430 environmental impact of increasing injection tariffs I is remarkable in both regions, and should be
 431 well considered by policy makers. The interaction with E is positive because at high levels of I
 432 increasing E is an effective way to divert resources from injection, which has low GHG reduction
 433 performance, to electricity production and CBM. The effect is more evident in FVG, where potentials
 434 allocated to electricity are higher because of CBM market limitations.

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

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443 **4. Conclusions and future research**

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

447 Results showed that investing in CBM production represents the most profitable choice for
 448 entrepreneurs under current levels of bio-methane incentives, and it also leads to the highest GHG
 449 emissions savings per TJ of biogas allocated to that utilization pathway. However, from both baseline
 450 and sensitivity analysis we can conclude that, in spite of the relatively large diffusion of CNG

451 especially in some regions of Italy, CBM is a niche product which risks to be overly subsidized,
452 considering the limited overall environmental benefits it can yield because of inherent limitations in
453 market size. Allocating funds to promote a further expansion of CNG would probably help CBM
454 development and benefits more than increasing specific incentives. This could be a subject for further
455 research, bearing in mind that only the substitution of CNG with CBM for vehicles was considered in
456 this study, while an expansion in CNG *and* CBM markets would happen at the expenses of gas oil
457 and gasoline, probably with further environmental benefits.

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

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

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478 **Acknowledgments**

479 The Italian Ministry of Education, University and Research are acknowledged for their financial
480 support in the form of a Ph.D. Scholarship for Miss Piera Patrizio

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