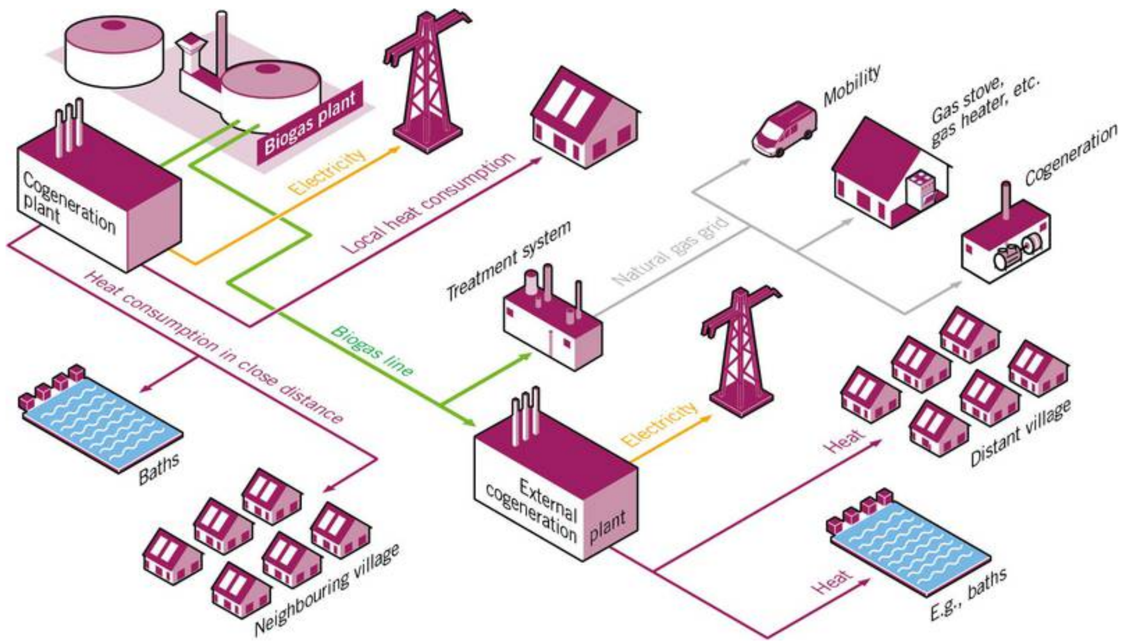
University of Udine

PhD Course in Environmental
and Energy Engineering Science

PROSPECTS FOR AGRICULTURAL BIOGAS AS A VEHICLE FUEL IN NORTHERN ITALY

PhD Candidate Piera PATRIZIO



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Author's Web Page: www.diegm.uniud.it

Author's e-mail: patrizio.piera@spes.uniud.it

Author's address:

Dipartimento di Ingegneria Elettrica
Gestionale e Meccanica
Università degli Studi di Udine
Via delle Scienze, 106
33100 Udine – Italia
tel. +39 0432 558025
web: http://www.diegm.uniud.it

Front picture:
Biogas supply chain structure
source: http://www.german-biogas-industry.com

Abstract

In recent years, Italy has become the third largest agricultural biogas producer in the world after China and Germany.

The utilization of biogas in the country is still restricted to power generation with limited use of cogenerated heat, whereas other utilization pathways focusing on biogas upgrading to biomethane remain unexplored.Given the high development of natural gas pipelines and the presence of numerous compressed natural gas (CNG) refuelling stations in Northern Italy, significant market opportunities for biogas may also arise in the transport sector.

The use of biomethane as a vehicle fuel offers several advantages compared with other biofuels, such as first-generation bioethanol and biodiesel, the most prominent of which being a more favourable energy balance and the possibility of adopting a wide variety of organic materials for its production. However, the requirement to upgrade the biogas to biomethane of adequate quality for transport fuel use, the compression of the gas for storage and transport, and the lack of refuelling infrastructure, represent significant barriers to the deployment of biogas-based vehicle fuels in many European countries.

In this thesis, prospects for agricultural biogas in Northern Italy have been explored. The focus is on its utilization as compressed biomethane for vehicles (CBM), as compared to other utilization pathways (i.e. power only option, simultaneous production of electricity and heat and injection of biomethane into the national gas grid).

The methodology considers the use of different spatially explicit optimization models to forecast future biogas supply chain structures that minimize overall costs and environmental impact. Previous and actual biogas promotion schemes and other policy instruments to foster the production of biomethane as a vehicle fuel have been included in the assessment and applied to regional as well as macro regional case studies.

The results show that upgrading biogas for transport applications carries some environmental advantages, especially compared with its utilization solely for the production of electricity. However, promoting the development of a biomethane market solely with the introduction of environmental taxes is the least effective option as the environmental benefit in terms of emissions mitigation is very little. On the other hand, the introduction of current biogas incentive mechanisms would favour the development of CMB technologies in areas with promising biomethane market potentials.

..Keep Ithaka always in your mind.
Arriving there is what you are destined for.
But do not hurry the journey at all.
Better if it lasts for years,
so you are old by the time you reach the island,
wealthy with all you have gained on the way,
not expecting Ithaka to make you rich.

Ithaka gave you the marvelous journey.
Without her you would not have set out.
She has nothing left to give you now.

And if you find her poor, Ithaka wont have fooled you.
Wise as you will have become, so full of experience,
you will have understood by then what Ithaka means.

(C.P. Cavafy)

Acknowledgments

While I was thinking on how to begin these acknowledgments, (of course the very last thing I have write in this thesis), I've started remembering lots of moments occurring during these three years. If I have to consider all the travels, cheerful and hard-working days, technical issues (laptop shutdown, hacker attack, dead keyboards) and challenges that I have experienced , I can surely say my PhD was not boring at all!
Mostly important, I had the pleasure to find along my way many brilliant, skilled and positive persons , from whom I got constant support, inspiration and friendship.
Therefore here comes the shorted list of the many thanks I wish to express:

To my supervisor Dr. Damiana Chinese, for her constant support, guidance and great scientific expertise. For all the productive brain storming moments and for the enthusiastic approach she teach me during these years. I am also thankful to my co-supervisor, Professor Antonella Meneghetti, for interesting ideas and valuable comments.

To Dr. Sylvain Leduc, my supervisor during my visiting periods at IIASA. Thanks for teaching me so much with endless patient and understanding. (If I consider the number of times I have appeared into your office with a question, I am quite sure I can walk that corridor with eyes closed!)

I am really thankful to Dr. Florian Kraxner for the valuable comments and advices I have received during my periods at IIASA.

A sincere thanks to Dr. Rentizelas, Dr. Wetterlund and prof. Mummolo, for reviewing my thesis and for the useful comments that I have received on my work.

To Arpan, Floor, Edo, Jie, Jenny, John, Oreane.. and to all friends that I've met during these years, thanks for the amazing travels, hiking, dinners, parties...for inspiring me and sharing with me part of this journey.

Thanks to Amandine, for being my french sister, for the yoga, running, sailing, painting, clubbing sessions we share to alleviate the stress of being a YSSPer.

A special acknowledgment goes to everyone who has helped me during my thesis writing (and not only)...for compensating my frequents "lack of knowledge" to: Bernard and Mauri (Matlab), John and Moonil (ArcGis) and Luca (Latex).. It's so good too have so many engineers around when you are in trouble!

Foremost to my big, enthusiastic and warm family, for being so open-minded and at the same time so Italian!

Last but not least my greatest thank goes to Alberto, for the magic... and for that contagious smile.

Contents

Outline

The thesis is structured as follows:

Chapter 1 gives a technical introduction to the potential adoption of biogas for transport applications in the Italian context. The aim of the thesis as well as the research questions are also presented here.

Chapter 2 describes the studied system and the biogas utilization pathways considered.

Chapter 3 presents the most relevant policy instruments investigated in this thesis to support the market development of biogas based energy vectors.

Chapter 4 presents a review of the methodologies mostly adopted in literature to address the topics investigated in this thesis.

Chapter 5 describes the case studies developed and presents the main techno-economic parameters adopted for modelling the biogas supply chain.

Chapter 6 presents the methodology used.

Chapter 7 provides the results obtained for each of the case studies developed.

Chapter 8 includes a brief discussion of the results. The answers to the specific research questions and the main limitation of the research are also presented.

Nomenclature

Abbreviations

AD	anaerobic digestion
AP	acidification potential
CIC	certificati di immissione al consumo
CHP	combined heat and power
CBM	compressed natural gas biomethane
CNG	compressed natural gas
DH	district heating
DOE	design of experiments
EEC	environmental external costs
EP	eutrophication potential
EU-ETS	European union emission trading scheme
FIT	feed-in tariffs
FS	fuelling stations
GHG	greenhouse gases
GIS	geographic information system
GWP	global warming potential
ICE	internal combustion engine
IPA	impact pathway approach
LCA	life cycle approach
MILP	multi integer linear programming
MINLP	multi integer non linear programming
NPV	net present value
OAT	one factor at time
ORC	organic ranking cycle
PWS	pressurized water scrubbing
RES	renewable energy source
SA	sensitivity analysis
TOE	ton of oil equivalent
UA	uncertainty analysis

Chemical symbols

CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide

H_2O	water
H_2S	hydrogen sulfide
N	nitrogen
N_2O	nitrous oxide
NH_3	ammonia
NMVOC	non-methane volatile compound
NO_x	nitrogen oxide
O_2	oxygen
PM	particulate matter
S_2	sulphur

1

Introduction

This chapter describes the context in which the Italian CBM market has developed and gives an introduction of the main technical features of biomethane as a vehicle fuel as compared to liquid biofuels. The chapter ends with the description of the research questions posed in this work.

Since the start of the twenty-first century, policy makers have recognized that biogas production can answer a number of challenges simultaneously. It can reduce the emissions of greenhouse gases (GHGs) such as methane (for example, from manure storage) and is the only mature renewable energy vector that is currently directly applicable in all of the sectors (electric power generation, heat generation and transport sector), leading to reduced impacts of pollution by waste disposal. Equally important, when animal manure is utilized as a substrate, the process upgrades the waste into a product and makes it a valuable organic fertilizer called digestate. This recognition has led to the rapid growth of the biogas sector over the last two decades, which has been promoted through legislation with various targets set worldwide for renewable energy and reduced GHG emissions.

In the last few years, Europe has witnessed a substantial growth in energy generation from biogas: the gross electricity output from decentralized agricultural plants, centralized co-digestion plants and municipal methanization plants increased from approximately 17 TWh in 2006 (Eurobserv'er, 2008) to almost 36 TWh in 2011 (Eurobserv'er, 2012). In Italy, in particular, the proliferation purpose-designed energy conversion anaerobic digestion plants from agricultural residues and crops is impressive. As shown in figure 1.1, the number of plants increased by a factor of 19 between 2007 and 2011, whereas the installed capacity and yearly electricity production increased by a factor of approximately 9 (Chinese et al., 2014).

However, as highlighted by Carrosio, 2014, most of the existing biogas plants make use of the by-produced heat only for internal purposes, i.e., to sustain the anaerobic digestion processes, and do not satisfy any external heat demand (e.g., via district heating). This implies that only a very limited share, ranging from 20% to 25% according to (Poeschl et al., 2012a), of by-produced heat is actually used, which is well below the recovery rates required to consider combined heat and power (CHP) an efficient solution from an environmental point of view (80% heat recovery according to Patterson et al., 2011).

In fact, comparing the environmental performances of different biogas pathways (Ravina and Genon, 2016), observed that if the thermal energy produced by the biogas cogenerator is not used, the GHG balance approaches zero, meaning that the avoided emissions are almost equal to the produced emissions. On the other hand, previous studies have shown that substituting fossil fuels for transport with biomethane is not only economically preferable to power generation without external heat recovery (Goulding and Power, 2013) but can also lead to a more favorable environmental balance. For instance, a study by Poeschl et al., 2010 reports a GHG savings for CBM of 1.15 $kgCO_2eq/kg$ biomethane, corresponding to -1721.8 t/y of CO_2eq. Nonetheless, as confirmed by many studies in the literature (Lantz and Börjesson, 2014; Ravina and Genon, 2016), biogas processes are often characterized by an high level of variability depending on the feedstock employed in the digestion step, the assumptions made for the biogas technology options, and the system boundaries considered.

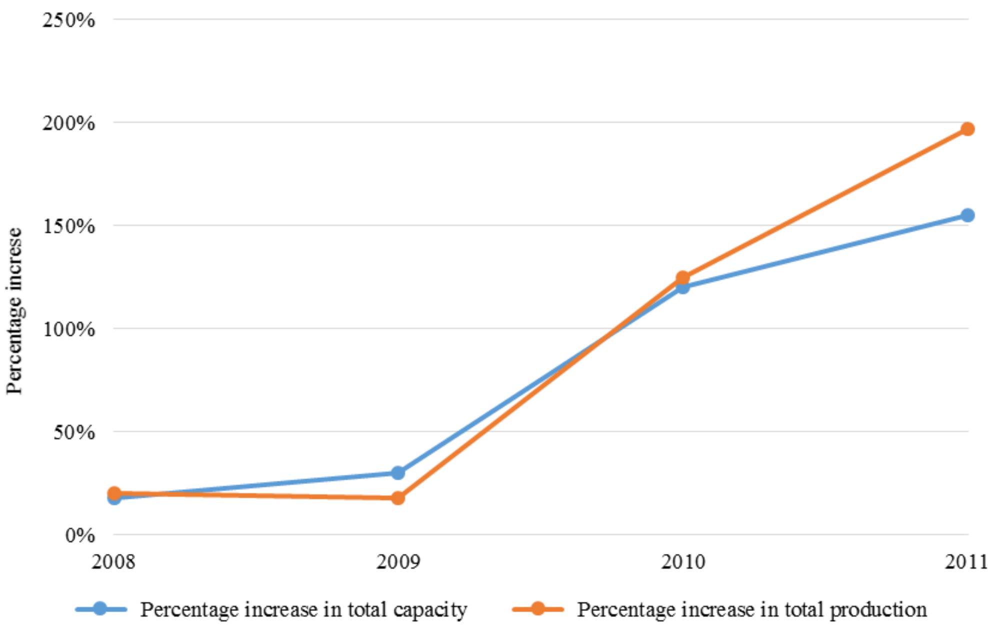


Fig. 1.1 Evolution of biogas-to-electricity plants from livestock effluents and agricultural activities in Italy compared with the 2007 scenario (Chinese et al, 2014)

1.1 Biomethane as a vehicle fuel: technical and scientific background

In the last 20 years, efforts to find a long-term and large-scale biofuel alternative to petrol and diesel for the transport sector have been intensified with a focus on liquid biofuels, such as ethanol, methanol and Fischer-Tropsch diesel, derived from wood (Ahman, 2010). However, the sustainability of the current and planned expansion of ethanol and biodiesel production is a controversial topic in many European countries.

As several studies focusing on the future prospects of liquid biofuels in Europe highlighted (Börjesson and Mattiasson, 2008; Wetterlund, 2012), the current production levels of ethanol and biodiesel from agricultural feedstocks cannot grow too much or too fast before being constrained either by economic, social or ecological reasons. The increased use of land, primary energy, fertilizers and pesticides is the main argument against the large-scale production of such first-generation biofuels, which would result in further environmental damage, including the release of soil carbon, leaching of nutrients and loss of biodiversity.

To minimize the pressure and competition for scarce land resources, an emerging development route for biofuels is a focus on utilizing woody biomass, the so-called "second generation" of biofuels (Ahman, 2010). This can be obtained either from hydrolysis and fermentation to ethanol or from gasification with downstream synthesis to, for example, Fischer-Tropsch diesel (FTD), methanol or dimethyl ether (DME). However, what can be easily seen as a major drawback of these biofuels is that they are still at a development or demonstration stage, with production costs far from being comparable with other fuel alternatives (Wetterlund, 2012).

Biomethane is a high-quality energy carrier that is fully miscible and interchangeable from a combustion point of view with its fossil counterpart, natural gas. It is a gaseous fuel with no blending limitations or end-user complications, unlike other liquid biofuels, if properly purified. Of the second-generation biofuels, biomethane is comparatively less dependent on specific technical developments, less dependent on the scale of production (as liquid second-generation alternatives all require large-scale production due to the synthesis step to meet cost standards), and has a greater feedstock flexibility and potential (Åhman, 2010). In addition, the regulated and unregulated emissions of biomethane, together with its carbon footprint, are lower than for any other biofuel (Patterson et al., 2011a; Power and Murphy, 2009). The obvious disadvantage of biomethane compared with liquid biofuels is its gaseous form, which makes the distribution, dispensing and storage of the fuel in the vehicles more difficult compared with those of liquid fuels.

Depending on the location and type of upgrading, the upgraded biomethane may be distributed in several ways: by injection to a central or local gas grid or by road in mobile units, either in a compressed or liquefied state. Used in an optimized manner, all of these have a role to play in reaching full utilization of the available biomethane potential. Methane being a major component in biomethane and natural gas makes the joint distribution and utilization of natural gas and biomethane a natural step, which has been shown through market experience to give rise to several synergies (Mathieu Dumont et al., 2013). Biogas upgraded to natural gas quality is injected into existing gas grids across Europe: IEA task 37 lists 334 upgrading facilities on their homepage (September 2015), and a majority of them inject the generated biomethane into the grid. However when considering the biomethane potential in the transport sector, additional barriers apart from the absence of a distribution grid come into play, which often justify the minimal adoption of such biofuel in some European countries.

1.2 The Italian scenario

Uusitalo et al., (2014) highlighted that the major limiting factors of adopting biomethane in the transport sector can be grouped into technological, economical and policy issues. Technological aspects are related to the potential to produce biomethane in a certain territory and to the availability of distributing infrastructure such as gas grids and refuelling stations. Economical aspects refer to the market potential of biomethane, especially the fuel market conditions and the viability of gas-fuelled vehicles. Political aspects are related to the targets to increase the adoption of biogas technology in the transportation sector, which can be affected by different national and regional support mechanisms. Alternatively, such aspects may also represent significant opportunities for the growth of the biomethane market in a certain region, as in the case of the Northern Italian scenario.

Figure 1.2 highlights the evolution of the primary energy production from biogas energy vectors in some EU countries such as Germany, Italy, the United Kingdom and Sweden for the years 2009-2012. All of these countries have experienced a growth in the

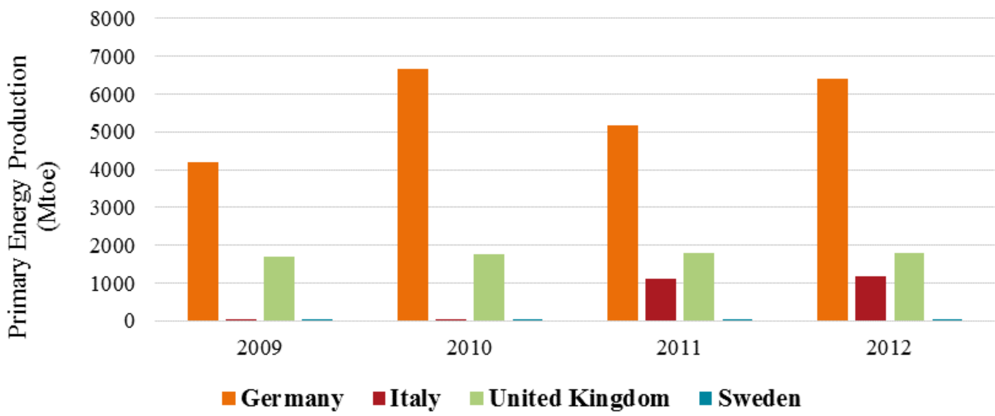


Fig. 1.2 Biogas annual production in (Mtoe) in the leading European countries

adoption of biogas technology in the last few years, mostly dedicated to the production of electricity or combined heat and electric power (CHP), but they differ in the penetration level of the upgrading technologies in the national market. As highlighted in the figure, Germany clearly leads the biogas European market; with a total of 8700 installed plants in 2012, the country contributes 53% of the European primary energy biogas production.

Of these plants, 84% are based on the co-digestion of crops and slurry (animal waste), and 161 plants upgrade the biogas to biomethane. Germany is followed by the United Kingdom, with 1.8 Mtoe biogas production in 2012. Landfill is the main feedstock in the UK, with a share of 84.6% of the total production. A special case is represented by Sweden, in which, despite the small contribution of the transport sector to the total European biogas market (production of 0.13 Mtoe in 2012), 30% of the biogas is upgraded as vehicle fuel.

With a total primary energy biogas production of 1180 Mtoe in 2012 (10% of the total European production), the Italian biogas sector has recently increased its role in the European biogas context. However, no upgrading facilities have been installed in its territory, despite the favourable economic framework for such. In fact, the country is characterized by an annual biogas potential of up to 5.6 MNm^3/year, which is nearly 50% of its annual national natural gas production. Thus, upgrading the biogas may represent a significant opportunity to reduce the share of natural gas in the national energy mix, especially considering that future distribution networks delivering biomethane may be easily implemented by exploiting the existing national gas grid, which has a pervasive coverage of the national territory.

The number of natural gas vehicles in the country also represents a positive indicator of the possibility to boost the production of biomethane for transport: as reported by Uusitalo et al., 2015, in recent years, Italy had the fastest increment in the number of gas-operated vehicles, with an annual average growth of 0.23%. In 2012, the country had more than 746,000 vehicles powered by natural gas on its roads (equal to almost 11 vehicles per 1000 inhabitants, as depicted in figure 1.3) , representing 75% of Europe's gas-fuelled entire car fleet, according to data from the Natural Gas Vehicle Association (NGVA Europe, 2012).

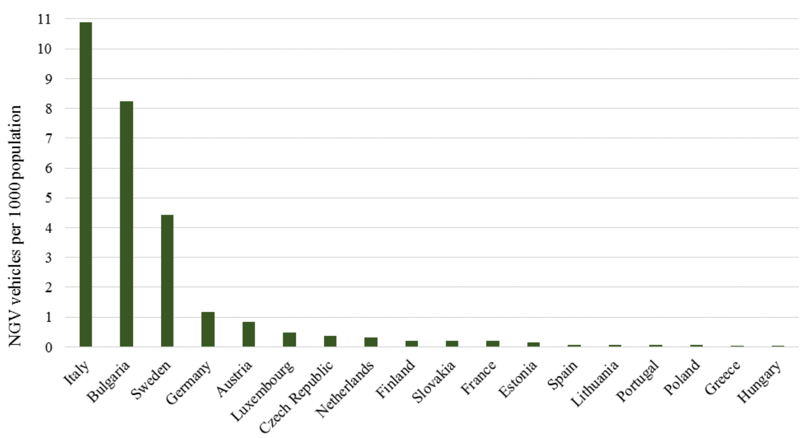


Fig. 1.3 Pervasiveness of NGV vehicles in European countries (source: NGVA Europe 2012)

The well-developed refuelling infrastructure network includes 1,060 stations, of which 90% are located in the northern part of the country. The monthly sales of natural gas as a vehicle fuel amount to 80 million Nm^3, with compressed natural gas (CNG) being favorably taxed compared with traditional fossil fuels, especially gasoline, on which the tax is among the highest in the EU. As shown in figure 1.4, the Italian CNG selling price in 2012 represented 34% and 40% of the gasoline and diesel prices, respectively.

Despite this favorable techno-economic framework, no upgrading facilities converting the biogas produced into biomethane have being installed in the national territory so far because Italy was one of the last European countries to adopt supporting mechanisms for biomethane applications. Until a few years ago, only electricity generation plants of selected size classes (e.g., below 1000 kWel) have been heavily subsidized, whereas the long-awaited incentive program for biomethane grid injection and biomethane for transportation started only in December 2013.

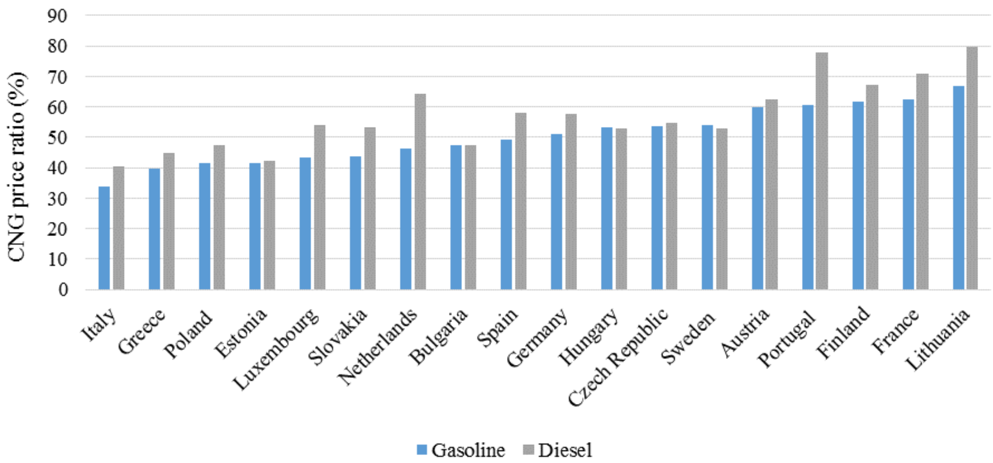


Fig. 1.4. CNG price ratio as compared to conventional fossil fuels

1.3 Scientific background and research questions

As shown in previous sections, biogas technologies can be adopted in several utilization pathways, leading to different supply chain configurations, economic performances and environmental effects. As mentioned by Lantz et al., (2007), the market potential of biomethane is affected by several factors, acting either as incentives or barriers, and thus, understanding the environmental and economic sustainability of biogas utilization pathways requires a supply chain approach to consider the different actors involved, such as municipalities, farmers and energy companies.

Several studies in the literature deal with the market potential of biomethane by comparing different biogas utilization pathways at the supply chain level. This analysis is generally carried out from an environmental (Börjesson and Berglund, 2006; Buratti et al., 2013; Hahn et al., 2015; Jury et al., 2010; Patterson et al., 2011b; Pierie et al., 2015; Pöeschl et al., 2012a) or economic prospective (Wu et al., 2015) and is usually performed for reference plants (Berglund and Börjesson, 2006; Pöeschl et al., 2012b) rather than for regions and under a number of assumptions, e.g., feedstock mix (Jury et al., 2010; Pierie et al., 2015) and feedstock supply distance limits (Buratti et al., 2013).

Moreover because the potential development of biogas technologies in a region is strongly affected by regulatory issues such as incentive mechanisms and tax exemptions, biogas policy schemes have been extensively investigated in the literature, generally concerning a particular aspect of the biogas supply chain such as biogas plant configurations, biogas conversion technologies or biomethane distribution. Lantz et al., (2007) investigated different policies and policy instruments that can influence the potential expansion of Swedish biogas systems, with a special focus on those affecting the utilization of biogas, concluding that extensive policy is needed for biogas systems to develop.

Within the same context, several recent studies assessed the impact of policy mechanisms in fostering the replacement of fossil natural gas with biomethane. Börjesson and Ahlgren, (2012) 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. Bekkering et al., 2013 and Eker and van Daalen, (2015) analysed the effects of existing policy schemes in Netherland, considering the natural gas grid option alone while excluding the biomethane for transport option. An extensive analysis of biomethane support schemes affecting the economic feasibility of different biogas plant configurations has been produced by Budzianowski and Budzianowska, (2015), who also analysed the presence of a climate policy instrument in the form of a carbon mitigation premium. The market development of biogas for transport under existing policy mechanisms has been studied by Fallde and Eklund, (2014), who addressed how Swedish biogas production has been influenced by its societal and technological context.

The aforementioned papers contribute to underlining the policy and regulatory issues connected with the development of biogas technologies in a certain region. However, none of them assessed the impact of supporting policy choices on the capital and operational performance of the biogas supply chain.

The aim of this thesis is to investigate the potential of CBM in the Italian scenario and identifying under which policy and economic frameworks it may represent a preferred economic choice among other biogas utilization pathways by adopting a spatially explicit approach and by analysing the constituent steps of its supply chain. The environmental effect of promoting the production of such biofuel is also investigated and compared with the environmental performance of other biogas-based energy vectors (i.e., cogenerated electricity, heat for domestic purposes and biomethane for injection) and its corresponding fossil alternatives, considering a range of carbon and non-carbon emissions produced along its supply chain.

Furthermore, this thesis aims to investigate the key parameters affecting its market development in a certain region, by conducting specific case studies in areas where some techno-economic barriers (e.g., the scarcity of refuelling infrastructure or unfavorable fuel market conditions) may prevent its adoption at a regional level. The thesis is focused around the following research questions:

1. Under what circumstances can the promotion of biogas as a vehicle fuel be a feasible choice compared with other utilization pathways?

2. What levels of economic policy support are needed to make biomethane economically attractive?

3. What are the environmental implications of the use of CBM in the region of concern?

The analysis has been conducted by assessing the economic and environmental feasibility of different biogas supply chain configurations and considering different policy instruments. The abovementioned political, technical and economic issues related to the development of the biomethane market have been investigated with specific case studies.

2

Technical background

This chapter gives an overview of the agricultural biogas supply chain, describing the main biogas technologies studied in this thesis, with a special focus on the upgrading options commonly used for converting the raw biogas into biomethane. A technical introduction to the digestate, a secondary output flow of the anaerobic digestion process, is also given.

2.1 The biogas supply chain

Biogas is produced in biogas plants by the bacterial degradation of biomass under anaerobic conditions. Different categories of biomass can be employed in the digestion process and are usually categorized by their origin, including substrates of farm origin, such as liquid manure, feed waste, harvest waste and energy crops; waste from private households and municipalities, such as separately collected organic waste, market waste, expired food and food waste; and industrial by-products, such as glycerine, by-products of food processing and waste from fat separators.

In this thesis, agricultural biogas will be considered, with animal manure and energy crops being the main feedstocks. As with fossil natural gas, the main component of biogas that determines its energy content is flammable methane (CH_4). Depending on the substrate digested in the biogas plant, the methane content of the biogas fluctuates between 50% and 75%. The second main component of biogas is carbon dioxide (CO_2), with a share between 25% and 50%. Other components of biogas are water (H_2O), oxygen (O_2) and traces of sulphur (S) and hydrogen sulphide (H_2S).

After the digestion process, the raw biogas can be exploited within different utilization pathways, as described in Fig 2.1. Traditionally, biogas has been used as fuel for boilers to produce heat or for the cogeneration of heat and electrical power in combined heat and power plants (CHP). In this latter case, electricity is generated by burning fuel (natural gas or biogas), and then a heat recovery unit is used to capture heat from the combustion system's exhaust stream. This heat can be converted into useful thermal energy, usually in the form of steam or hot water.

After purifying the raw biogas by adopting an upgrading technology that removes any presence of carbon dioxide, the so-called biomethane can be used in all applications commonly fuelled by natural gas. Thus, it can be injected into the natural gas grid and used for household applications such as cooking and heating, and it can be adopted as

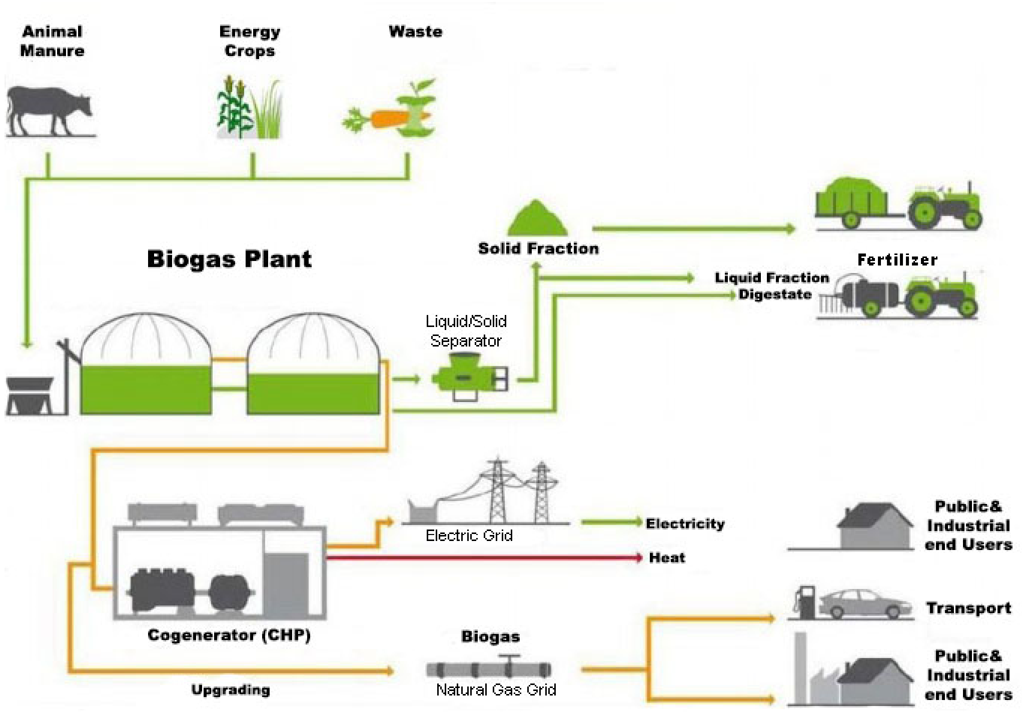


Fig. 2.1 The biogas supply chain analysed in this thesis

compressed biomethane (CBM) in transport applications.

2.2 Raw biogas production and conversion

Biogas can be obtained through a variety of anaerobic digestion processes that are usually classified by their main process parameters, such as temperature ranges, digester configuration and feedstock mix. In this thesis, a continuous mesophilic digestion process (having a temperature range of 35-40° C) is assumed as the core of the biochemical process, as it is used in most Italian biogas plants because of its lower energy requirements for digester heating and the stability of the process parameters.

The optimal digester design and configuration are a function of the feedstock characteristics and may be dry or wet, batch or continuous, one-step or multi-step, and one-phase or multi-phase. In general, when considering the co-digestion of agricultural slurries and crops, as in this case, a continuously stirred tank reactor is employed as a mixing system for pre-processing the substrates (Nizami and Murphy, 2010). Apart from the digester, the biogas plants may include different raw biogas conversion technologies and additional equipment according to the final biogas utilization pathways, with techno-economic parameters that need to be accounted for when addressing the optimal configuration of the plant.

Before biogas is injected into the natural gas grid or used as a vehicle fuel, it needs to be upgraded to biomethane, primarily by removing any trace of carbon dioxide. Through this, it is possible to achieve a higher level of the gas heating value while at the same time meeting the national standard requirement (generally represented by the Wobbe index). Several methods for biogas upgrading are commercially available and have been extensively reviewed in the literature (Patterson et al., 2011). Their economic and environmental performances are generally assessed by considering key parameters such as energy requirements (i.e., water or electric power) and methane losses as methane is a greenhouse gas that is 21 times stronger than CO_2.

2.2.1 Biogas upgrading technologies

The major task for the production of biomethane is removal of CO_2. Upgrading technologies can be roughly assigned to four main groups:

- Adsorption;
- Absorption;
- (gas) Permeation;
- Cryogenic upgrading.

The six most widespread technologies are pressure swing adsorption, water scrubber (or pressurized water scrubber), physical absorption (using organic solvents), chemical absorption (using organic solvents), high-pressure membrane separation and cryogenic upgrading.

Table 2.1 compiles the key parameters of these six upgrading technologies, as reported by Beil and Beyrich (2013).

As the same authors clarified, pressurized water scrubbing (PWS) is one of the best solutions in terms of efficiency (generally calculated in terms of methane recovery rate) and economic performance and this is also confirmed by its wide utilization on the global scale. Water scrubbing is an absorptive method for biogas upgrading using only the inorganic solvent water. In this process, CO_2 and other acidic (e.g., H_2S) and basic (e.g., NH_3) gas components are absorbed in parallel. Unlike other upgrading methods (e.g., pressure swing adsorption or chemical adsorption), a precision desulphurization is not necessary because H_2S is adequately removed from the biogas in the absorption column. Typical methane concentrations in the biomethane flow are lower than 96% (Beil and Beyrich, 2013; Börjesson and Ahlgren, 2012). After the condensate separation, the raw biogas normally passes through two compression stages up to approximately 4 - 8 bar.

	PSA	**Water scrubber**	Physical absorption	Chemical absorption	Membrane separation	Cryogenic upgrading
Electricity demand (kWh/Nm^3)	0.20 - 0.30	**0.20 - 0.30**	0.23 - 0.33	0.06 - 0.17	0.18 - 0.35	0.18 - 0.35
Temperature process heat (C)	Not specified	**Not specified**	40 - 80	106 - 160	Not specified	Not specified
Operative pressure (bar)	1 - 10	**4 - 10**	4 - 8	4	7 - 20	10 - 25
Methane recovery rate (%)	90 - 98	**98 - 99.5**	96 - 98	99	85 - 98	98 - 99
Desulphurization required	Yes	**No**	No	Yes	Yes	Yes
Water demand	No	**Yes**	No	Yes	No	No
Demand of chemical substances	No	**No**	Yes	Yes	No	No

Tab. 2.1 Main technical parameters of biogas upgrading technologies

2.2.2 Biogas utilization pathways

As highlighted in figure 2.2, the following conversion process has been considered in this thesis:

1. *Combined heat and power (CHP) generation*: Biogas-to-CHP represents the most common utilization in many European countries such as Germany, Sweden and Austria. The electricity is produced using an internal combustion engine (ICE) and is fed into the national grid, whereas the heat, which is partly used in the AD process control, may be consumed via district heating networks.

2. *Power generation with ORC process*: As highlighted previously, the Italian scenario is characterized by a proliferation of power-only biogas plants, with no external use of the heat produced. Thus, such a plant configuration has been accounted for in this thesis, also considering the opportunity of bottoming it with an organic Rankine cycle process, (see Pöeschl et al., 2010) to enhance the electricity production while recovering heat wasted by the ICE.

3. *Biogas upgrading to biomethane and injection*: The injection facility is composed of a feed-in station, which is the link between the upgrading technology and the public gas network. It also generally includes the following sub-systems: compression of the biomethane to the target pressure, or gas pressure regulation when fed into a low-pressure grid; monitoring of the gas characteristics (Wobbe index or heating value); odorization of the biogas; and network connection via a pipeline.

4. *Biogas upgrading to biomethane and compression for transport application*: When adopting biomethane as a vehicle fuel, an additional equipment system is needed to compress the biomethane to a pressure of 200 bar, making it compatible with the distribution stations. Thus, according to the transportation mode selected, the compressor may replace the feed-in station, when the biomethane is transported by road, or it may be located in the proximity of the refuelling station in the case of gas grid injection.

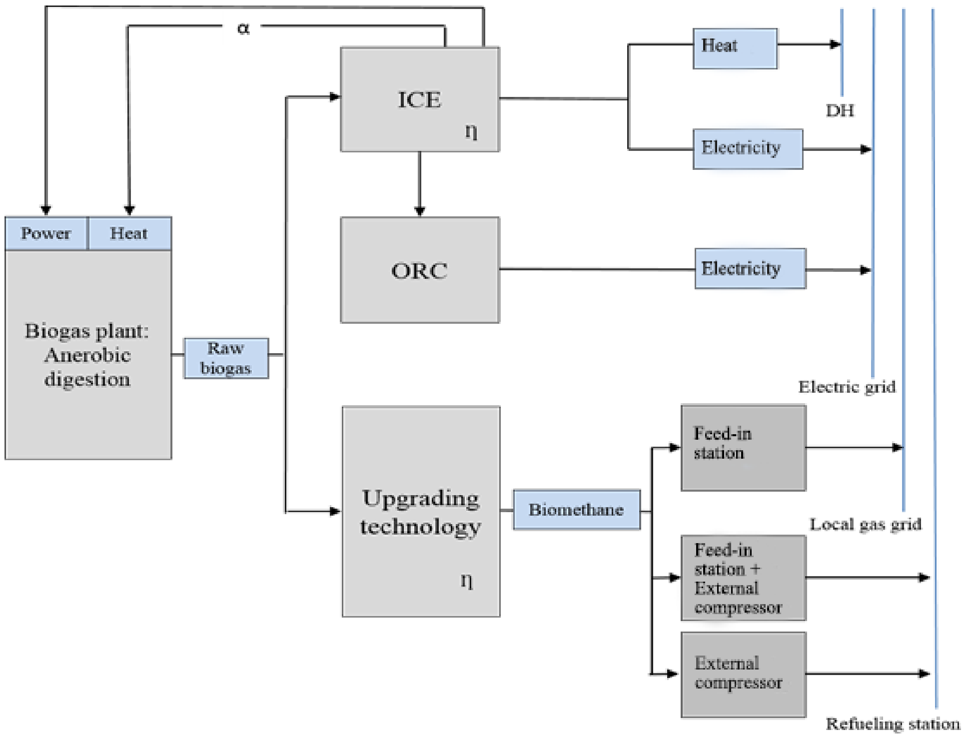


Fig. 2.2 Biogas utilization pathways

2.2.3 Energy vectors distribution

The final products deriving from various biogas conversion technologies are delivered to users through specific energy infrastructures. Their presence in proximity of the biogas plants represent an important factor that need to be consider when assessing the feasibility of a biogas supply chain, both in terms of environmental as well as economic point of view.

This is especially true when considering alternative biogas utilization pathways such as biomethane for transport application: the absence of distributing networks such as natural gas grids and CNG refuelling stations might restrict its adoption in a certain territory, as several authors have pointed out (Lantz et al., 2007; Mathieu Dumont et al., 2013; Uusitalo et al., 2014).

For CBM distribution, two main options are available: the injection of biomethane to a central or local natural gas grid and truck-based distribution using different types of mobile units. Whether one of these options is economically preferable depends on technical parameters such as the amount of biomethane to be transported and the proximity of an existing refuelling station.

A report issued by the Swedish Gas Association investigates the relation between the transport distance and transported volumes for different distribution alternatives (Benjaminsson and Nilsson, 2009), concluding that for larger volumes (more than 10 MNm^3/year), a local gas grid always represent the best alternative, whereas for distances up to 50 km, it is preferable to adopt specific trucks to avoid extra cost for the feed in station.

2.3 Digestate management

Digestate, which is the digested effluent of the biogas production process, consists of the residual feedstock materials after the extraction of biogas through anaerobic digestion. Because of its content of easily accessible macro- and micronutrients, the digestate is a valuable crop fertilizer, suitable to be used in the same way as raw animal slurries. Recycling as fertilizer is considered the most sustainable utilization of digestate, as it is able to provide benefits for the environment, as well as to help in the preservation of limited natural resources such as mineral resources, such as nitrogen, phosphorus and potassium.

The digestate quality, in terms of the amounts of nutrients, is primarily determined by the composition and quality of the feedstock used in the AD process. However, the digestate characteristics are specific to each substrate mix and can vary even between batches from the same digester and within the same batch of digestate during storage. Table 2.2 reports the main organic characterization of some selected feedstocks (Crpa, 2012). Because it is the mineral nitrogen component of the digestate that is mainly available to crops after land application, a distinction is generally made between the total amount of nitrogen and the proportion of nitrogen in the form of ammonium.

The quantities of nutrients that are supplied to a digester in the feedstock are the same as those in the digestate. However, the AD process can alter the chemical structures in which the nutrients are present (for instance, some of the organic nitrogen is converted into ammonium during the digestion process), according to the technical characteristics of the digester, the temperature at which the digestion process takes place, and the substrate mix. For this reason, the nutrient content of the digestate is generally directly empirically determined after the digestion process by considering its total nitrogen content.

In this thesis, according to the substrates under analysis and the digestion process described in the previous section, total nitrogen contents of 3.8 kg/t and of 3.9 kg/t have been used for digestates deriving from cattle and swine manures, respectively, whereas a value of 4 kg/t has been derived for energy crops.

Feedstock		TS %	Total N	NH_4–N	P	K
Sewage	Dairy cow	6	3.0	2.0	0.5	2.1
	Pig	4	4.0	2.5	0.9	7.5
Manure	Poultry: Layer manure Broiler litter	 30 60	 16.0 30.0	 3.2 12	 5.7 10.9	 6.7 4.2
	Farmyard manure: Cattle Pig	 25 25	 6.0 7.0	 0.6 0.7	 1.5 3.1	-
Energy crops	Grass silage	25-28	3.5-6.9	6.9-19.8	0.4-0.8	4.2
	Maize silage	20-35	1.1-2	0.15- 0.3	0.2-0.3	4.2

Table 2.2 Nutrient content (kg/m^3 fresh weight) of some feedstock commonly used in co-digestion.

Depending on its end use and on the requirements related to it, the digestate can be used as it is produced (whole digestate), or it can be further refined through a number of treatments and technologies. This thesis considers digestate separation to be the reference digestate processing technology because it is the most adopted methodology due to its simplicity and relatively low costs (Delzeit and Kellner, 2013; Rehl and Müller, 2011), consisting merely of separating the liquid and solid fractions of the digestate using decanter centrifuges or a screw press separator. Whereas the latter is mainly used in the case of high-fibre content digestates, such as in the mono-digestion of energy crops, decanter centrifuges are used in manure co-digestion (as in our case) and also in municipal or industrial waste treatment plants. There are also more complex processing technologies, with various degrees of technical maturity. Common to all is that they provide volume reduction and separation of the valuable nutrients and fibres from the high volume of water contained in the whole digestate.

The storage, transport, handling and application of digestate as a fertilizer results in significant costs for farmers compared with its fertilizer value due to its large volume and low dry matter content. For the most common use of digestate as agricultural fertilizer, several authors (Epp et al. 2008, Pöeschl et al. 2012, Delzeit et al. 2013) recommend an average transport radius of 5 to 15 km from the biogas plants. However, some environmental restrictions may limit its spreading in the proximity of the biogas plant, especially in areas with a high concentration of agriculture and problems of over-fertilization.

3

Biogas promotion schemes and other policy instruments

This chapter analyses the magnitude of different policy instruments in supporting biogas development in the Italian energy context. This are:feed-in tariffs, tradable certificates, carbon pricing mechanism and monetization of externalities. An analysis of previous and current Italian biogas incentive schemes has also been carried out, with a special focus on the supporting schemes dedicated to biomethane for transport applications.

3.1 Policy instruments to support biogas development: a comparison

RES promotion in the EU has been mostly based on two main mechanisms: feed-in tariffs (FITs) and tradable certificates. FITs are subsidies per energy unit generated, paid in the form of a total quantity (tariff) or as an amount on top of the wholesale energy price (premium) combined with a purchase obligation by the utilities. Tradable certificates are permits issued for every energy unit of RES, allowing generators to obtain additional revenue from the sale of energy (i.e., two streams of revenue).

Demand for such certificates generally originates from an obligation on energy distributors to surrender a number of permits as a share of their annual consumption (quota), or otherwise they would pay a penalty. Their price strongly depends on several factors, including the levels of the quota and the penalty and the duration of the obligation (Del Rìo, 2010). Among existing policy mechanisms to stimulate the deployment of green energy, FIT policies are the most widely implemented are thought to be the most promising of all, accounting for a larger share of renewable energy propagation than any other policy support scheme (Del Rìo; Mendoça et al., 2009).

However, in recent years, FIT mechanisms have been the subject of growing criticism in the literature (Gawel et al., 2014; Lehmann and Gawel, 2013). The major concern raised with respect with RES support mechanisms is that they are not linked to the emission reductions achieved with the use of the renewable technologies but with the cost of their deployment. If the support guarantees the economic operation of renewable energies, these will be deployed by market actors. Hence, if the feed-in tariffs and price premiums are sufficiently high, the share of renewable energies will increase, and the renewable target can be met. Thus, this instrument is not able to achieve a specific emission reduction target, as the amount of emissions is not limited but only related to the energy produced via the different renewable technologies. Feed-in tariffs are efficient tools to support the technology development and market introduction of renewable energy technologies, such as biogas, but may not be suited for achieving dedicated emission reduction targets (Del Rìo and Mir-Artigues, 2014).

In addition to the aforementioned instruments, the European Union Emission Trading Scheme (EU-ETS) is a key component of the EU climate policy (European Parliament, 2003b, 2009b). The system has been in place since 2005, with the objective of reducing the GHG emissions in a cost-efficient way by promoting measures with the lowest mitigation cost. Thus, by penalizing the utilization of fossil fuels for energy production and conversion through the introduction of a tax on carbon emissions, it may represent an efficient measure to boost the development of biogas. However, many critical issues lie behind the use of EU-ETS as an efficient tool to promote the adoption of renewable sources for energy production.

In addition to the fact that, as several authors noted, the EU-ETS emissions cap came out of a political negotiation process and was not set at an efficient level (Lehmann, 2012), energy production processes usually generate a consistent amount of non-carbon emissions that are not incorporated in such allowances. Thus, carbon taxes do not adequately reflect the environmental impact associated with the production of a certain energy vector because they do not account for other relevant environmental burdens generated along its supply chain.

This is especially the case for biogas-based energy vectors, whose production may lead to several non-carbon environmental burdens such as land use, traffic, and local emissions from the intensive use of fertilizers. To account for such environmental effects, a useful toll is represented by the external cost methodology.

The energy externalities are expenses imposed on society by the environmental disadvantages generated from energy conversion that are not reflected in the prices of energy commodities (e.g., electric energy, vehicle fuels and domestic heat). The externalities arising from the environmental impact of energy production are significant in most EU countries, especially with regard to electric energy production, and reflect the dominance of fossil fuels in the energy generation mix: from 2005 - 2010, the average external cost of electricity production in the EU was about six €cent/kWh (Streimikiene and Alisauskaite-Seskiene, 2014).

Because it allows the inclusion of several different pollutant emissions in the quantification of the environmental impact of a certain energy source, such a methodology may be an important instrument for renewable energy systems planning, considering also that by monetizing such environmental burdens, it can be easily integrated into economic optimization models. Therefore, including the environmental burdens of energy production processes, for instance by incorporating a LCA analysis in the optimization procedure as proposed by (Vassaro, 2015), might allow to model energy polices more effectively.

3.2 Previous biogas support mechanisms

The state of biogas production and utilization in the Italian countryside is set within the context of the institutional framework and its incentives and obligations. The first incentives for electricity generation from agricultural biogas were introduced in Italy in 1992, with the resolution known as CIP6 (Provvedimento CIP6/1992, April 29, 1992), when ENEL, which is the national, publicly owned electricity board, still acted as the direct enforcer of government energy policies. However, it was with the introduction of Law 99/23 July 2009 and subsequently the Decree of the Minister of Economic Development 6 July 2012 that biogas production received a real boost in Italy, shaping the structure of the biogas market as well as the organizational form characterizing the biogas plants (Carrosio, 2014).

3.2.1 Law 99/23 July 2009

The first substantial rise in agricultural biogas production in Italy dates back to the early 2000s. The main motivation was the introduction of tradable green certificates in the framework of Legislative Decree 79/99 of February 19, 1999, which transposed European Directive 96/92/EC into Italian Law and implemented a quota obligation-based renewable energy support mechanism. The regulation of the agronomic use of livestock effluents, which was implemented between 1999 and 2006 to transpose European Directive 91/676/EC, also contributed to the development of digesters.

However, it was not until the introduction of the feed-in tariff in 2008 and its final determination at 280 €/MWh with Law 99/23 July 2009 that agricultural biogas production received a real boost, mirrored by the three-figure percent growth reported in table 1 for the years 2010 and 2011. Green certificates were also partially modified by the same regulations by extending to 15 years their validity period, whose original narrowness had led to the highest prices in Europe (Haas et al., 2011), and by differentiating their value by technology, e.g., introducing a banding factor of 1.8 for bioenergy from short supply chains (supply radius below 70 km). As a result, based on data from the GSE on certificate buyback prices and on power wholesale prices between 2011 and 2013, as reported in Table 3.1, the average remuneration for bioenergy is 223 €/MWh.

It is thus clear that, while the TGC option was also theoretically available for plants below the feed-in tariff eligibility threshold of 1 MW, the feed-in tariff was clearly preferable for both increased profitability and lower risk. Recommendations on RES support reported in the literature (Haas et al., 2011) suggest that distortions may arise when the profitability expected at low risk (as in the case of FITs) is higher, resulting in higher additional costs ultimately paid by consumers.

In a recent analysis of the Italian biogas market based on neo-institutional theory, Carrosio (2013) observed that in recent years, very similar typologies have become dominant in Italy, with plants having an installed capacity of 999 kWe using a mix of animal feedstock and energy crops as substrates. From an organizational viewpoint, Carrosio (2013) classified them as "entrepreneurial farms", which do not have significant connections with local communities and do not make use of the heat they produce. He noted that such isomorphic processes result in economic and environmental inefficiencies, par-

	Law 99/23 July 2009		**Decree of the Minister of Economic Development 6 July 2012**		
Incentive form	Feed In Tariff and Green Certificates		Feed In Tariff and Feed In Premium		
Substrate based tariff differentiation	None, but an additional incentive was introduced for Green Certificates issued to plants fed with short biomass supply chains (radius below 70 km).		Different tariffs apply depending on the share of crops to animal by-products from farming and the food industry (if it is below 30%, the system is considered energy crops based). An additional premium applies to plants with capacity between 1 and 5 MW using selected non-food energy crops as substrates.		
Capacity limitations and classes	Plants with power capacity up to 999 kW are eligible for Feed In Tariffs.		Five size classes are introduced. Feed In Tariffs apply to plants with power capacity up to 1 MW, above 1 MW Feed In Premiums apply.		
Time horizons	15 years		20 years		
Incentive value	Feed In Tariff for plants up to 999 kW (€/MWh)	280	Size class	Energy crops (€/MWh)	Animal by-products based (€/MWh)
	Green Certificates (€/MWh)	223 €/MWh Average GC buy-back value plus average power wholesale price 2011-13, including banding factor 1.8	1-300 kW	180	236
			301 – 600 kW	160	206
			601 – 1000 kW	140	178
			1001-5000 kW	104	125
			>5000 kW	91	101
Additional premiums	Green Certificates and Feed In Tariffs can be combined with additional incentives, particularly capital grants from other sources, if plants are owned by farmers.		Additional premiums are introduced for high efficiency cogeneration from energy crops, or cogeneration with district heating from animal by-products based plants, and for plants adopting technologies for fertilizer production via nitrogen recovery.		

Table 3.1 Previous biogas supporting mechanisms

ticularly increasing the cost of corn products for fodder, leading farmers to enlarge their livestock herds to produce more manure from digesters and increasing the emissions from the transport of biomasses from farther areas to supply oversized plants.

Although previous support schemes had been effective in promoting investment, changes were required, as an intense debate about the costs and effectiveness of incentives became an issue in the Italian media. At a time of economic stagnation, public opinion focused on the allegedly high costs of the renewable energy support charged to consumers. Actually, RES-E targets have been fixed as shares of the total gross consumption of electricity, whose growth was below forecasts due to the decline of the Italian GDP from 2008 onwards and particularly the decrease in industrial production. However, the absolute values of, e.g., solar electricity production and biogas electricity production, were also larger than expected, although the second was still well below the 2020 targets.

3.2.2 Decree of the Minister of Economic Development 6 July 2012

In this climate, the Decree of the Minister of Economic Development 6 July 2012 introduced an incentive structure more in line with those in force in Germany, Austria and the Netherlands (Hahn et al., 2010). In fact, as summarized in Table 3.2, the new biogas support policy include:

- A stepped, technology-specific feed-in tariff, which is presented in the third column of Table 3.2;

- An augmented tariff for plants using a minimum share of 30% manure, resembling similar bonuses or constraints in Austria and Germany;

- An additional bonus for high-efficiency cogeneration of 40 €/MWh, compared with 30 €/MWh under the German EEG 2009 and 20 €/MWh in Austria;

- High-efficiency cogeneration plant eligibility for an additional bonus of 40 €/MWh if they adopt nitrogen recovery technologies to produce fertilizers;

- Special bonuses for plants with capacities between 1 MW and 5 MW using only non-food energy crops (20 €/MWh); a further bonus, to be determined with a successive decree, is proposed for plants between 1 MW and 5 MW enabling proven GHG emission reduction compared with reference values.

The new policy also entails a phase-out of green certificates; plants commissioned before 2012 will obtain proceeds from the sale of green certificates until 2015, at which point they will be substituted by a fixed feed-in premium calculated, for bioenergy and biogas plants, using current banding factors and equations, with reference to current wholesale power prices. In general, the 2012 incentive scheme is significantly more complex than previous ones. The basic tariffs are more generous than the corresponding incentives in other countries (Hahn et al., 2010), and cogeneration is encouraged with higher bonuses, rather than being requested as an eligibility constraint.

3.3 Actual biomethane supporting mechanism

To support the development of biofuel production in European countries, two main promotion mechanisms have been established by member states: a tax exemption, which represents an indirect subsidy of biofuels, and a direct governmental obligation to make a quota of biofuels available for consumption.

At the national level, the Italian government has combined these two instruments to sustain the adoption of biofuels, as described in table 3.2, which summarizes the national biofuel policy development until 2013. By that time, the national policies supported only the production of biodiesel, and bioethanol, while the CBM incentive program was introduced only in December 2013.

The first measures date back to the early 1990s and were aimed at reducing the final cost of biodiesel; it was a total tax exemption for the production of a maximum amount of 125,000 tonnes of biodiesel in 1995 that became a 20% reduction of the excise in 2006 for 250,000 tonnes until 2009. The reduction of the excise duty was changed by Law n. 191 of 2009, which lowered the maximum amount to 18,000 t of biofuels, subject to tax reduction. This policy measure, however, ended in December 2010.

The first biofuel obligation quota in Italy was introduced in 2007, with Law n. 296 of 2006, which established a mandatory quota of biofuels that fossil fuel traders (obligated subjects) must enter into the market.

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

To support biomethane injection, a stepped feed-in tariff was introduced, with a distinction between three feedstock mix classes, considering the percentage of manure employed (i.e., below 50% in weight, above 50% in weight and 100% by-product mix), and 4 size classes, as highlighted in table 3.3.

For CBM, a tradable certificate (CIC) mechanism was 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 equal to 1166 Nm^3, and the number of certificates depends on the substrate mix with three classes depending, as for biomethane injection, on the total amount of manure adopted (below 70% in weight, above 70% in weight and 100% by-products). A distinction is also made in case the CBM producer, rather than exploiting the natural gas grid, becomes a direct CBM distributor, which would make him eligible for 10 years to an increment of 50% of the certificate values.

As the market for biogas certificates has not been started, value estimates are highly uncertain and are based on results in completely different markets. In particular, the Decree of the Minister for Economic Development 23 April 2008 set a minimum value of 25.82 €/MWh, equal to 25 €cent $/Nm^3$ (AIEL, 2014). Additional incentives, in the form of supplementary certificates, are also introduced to support the construction of new refuelling stations (FS in the table).

Year	Policy measure	Policy instruments
1995	Excise exemption for 125.000 t of biodiesel	Legislative Decree n. 504 of 1995
2001	Excise exemption for 300.000 t of biodiesel	Law n. 388 of 2000 (Finanziaria 2001)
2005	Excise exemption for 200.000 t of biodiesel	Law n.311 of 2004
	Objectives: 1% in 2005 and 2.5% in 2010	Law n 128 of 2005 (implementation of Directive 2003/30)
2006	Excise reduction for 200.000 t of biofuels	Law n. 266 of 2005 (Finanziaria 2006)
	Mandatory blending rate for biofuels derived from the "agrifuel chain": 1% of diesel and gasoline of the previous year. The percentage must increase by one point each year until 2010.	Law n. 296 of 2006 (Finanziaria 2007)
2007	Excise reduction for 250.000 t of biofuels: 70.000 t assigned to the agrifuel chain and 180.000 t form non agrifuel chain.	Law n. 296 of 2006 (Finanziaria 2007)
	Obligation quota: 1% in 2007 and 2% in 2008 on the basis of energy value	
2008	Obligation quota: 3% of the total consumption of diesel and gasoline of the previous year on the basis of energy value	Law n. 244 of 2007 (Finanziaria 2008)
2010	Excise reduction for a maximum of 18.000 tons	Law n.191 of 2009
	Obligation quota: 3.5% in 2010; 4% in 2011; 4.5% in 2012	Decree 25 January 2010
2011	Obligation quota: 5% in 2014	Legislative decree n.28 of 2011
	Sustainability criteria and rules to verify the compliance to the criteria	Legislative Decree n.55 of 2011

Table 3.2 Biofuel policy development in Italy. Data taken from (Finco, 2013; GSE 2014)

3.4 Carbon Prices

Carbon pricing refers to any government policy that puts a price on carbon emissions and can take the form of a tax or a market-based mechanism, such as an emissions trading scheme. The fundamental difference between a carbon tax and a carbon market is the market variable that the mechanism fixes, price or quantity. Cap-and-trade has

Feedstock %	Natural gas injection equivalent tariff [€/Nm3]				Feedstock %	Number of tradable certificates for CNG			
	Size class upper limit (Sm3/h)					New FS		Existing FS	
	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 3.3 Actual biomethane supporting mechanism

one key environmental advantage over a carbon tax in that it provides more certainty about the amount of emissions reductions that will result and little certainty about the price of emissions (which is set by the emissions trading market). A carbon tax provides certainty about the price but little certainty about the amount of emissions reductions. Since Finland introduced the world's first carbon tax in 1990, many governments have implemented or proposed some form of carbon pricing.

The EU-ETS is a 'cap and trade' system that has been in place in Europe since 2005 and works by capping the overall GHG emissions of all participants in the system. It currently comprises the energy-intensive industries and electricity and heat producers, covering approximately 40% of total EU CO_2 emissions. The EU-ETS legislation creates allowances that are essentially rights to emit GHG emissions equivalent to the global warming potential of 1 tonne of CO_2, equivalent (tCO_2eq). The level of the cap determines the number of allowances available in the whole system.

After a first pilot phase from 2005 to 2008, in which the cap was largely based on estimates, as there were no reliable emission data available, the cap was redesigned to decrease annually from 2013, reducing the number of allowances available to businesses covered by the EU-ETS by 1.74% per year. This allows companies to slowly adjust to meeting the increasingly ambitious overall targets for emissions reductions.

Each year, a portion of the allowances are given to certain participants for free, in intensive carbon emissions sectors where there is a potential risk that production (and pollution) could shift to countries with less ambitious emissions reduction actions (causing the carbon leakage phenomenon), whereas the rest are sold, mostly through auctions. At the end of a year, the participants must return an allowance for every tonne of CO_2eq they emit during that year. If a participant has insufficient allowances, then it must either take measures to reduce its emissions or buy more allowances on the market. Participants can acquire allowances at auction or from each other.

The price of emission allowances has considerably varied in the last 5 years, reaching a maximum value of 22 EUR/tCO_2eq in 2011 (April) and a minimum of 4 EUR/tCO_2eq in 2014 (March).

3.5 External costs

External costs arise from the economic consequences of an activity that are imposed on society but are not explicitly accounted for by the economic agents in their decision-making process. The relevance of recognizing, assessing and internalizing external costs is increasingly acknowledged by economists and policy makers in the context of sustainable development goals (Ciemat, 2000; Eyre, 1997; OECD, 2003).

In the energy sector, a wide range of external costs may arise, in particular from the health and environmental impacts of emissions, exploitation of natural resources, and production of waste. Impacts on natural ecosystem, and agriculture, as well as global environmental impacts, such as climate change induced by greenhouse gases, remain external costs of energy systems in so far as they are not paid for by energy producers and consumers (Eyre, 1997).

External costs are generally estimated by damage assessment, which in turn can be conducted by two broad methodological approaches usually described as 'top-down and 'bottom-up. Top-down analyses use highly aggregated data, for example, national emission and national impact data, to estimate the damage costs of particular pollutants. However, this approach does not easily allow for the consideration of variation in impacts due to location or time.

In contrast, the bottom-up methodology uses technology-specific emissions data for individual locations. These are used with pollutant dispersion models, detailed information on the distribution of receptors, and thoroughly reviewed dose-response functions to calculate the physical impacts of the emissions from a certain production process. Even where monetary valuation is not possible, there is an assessment of the impacts, enabling them to be considered by policy makers.

With regard to energy production processes, from the early 1990s, the European Commission supported the development and application of a framework for assessing the external costs of energy use. In the ExternE (Externalities of Energy) project series, the bottom-up impact pathway approach (IPA) was developed, improved and applied for calculating externalities from electricity and heat production. Two air transport models are also included to cover both the local and regional ranges. (van Essen et al., 2011) The principal steps of the IPA methodology can be grouped as follows:

1. Emission: specification of the relevant technologies and pollutants, e.g., kg of oxides of nitrogen (NOx) per GWh emitted by a power plant at a specific site;

2. Dispersion: calculation of increased pollutant concentrations in all affected regions, e.g., incremental concentration of ozone;

3. Impact: calculation of the cumulated exposure from the increased concentration, followed by the calculation of the impacts (damage in physical units) from this exposure using an exposure-response function, e.g., cases of asthma due to this increase in O_3;

4. Cost: valuation of these impacts in monetary terms, e.g., multiplication by the monetary value of a case of asthma.

For the calculation of the damage costs, ExternE uses the EcoSense software package. This software combines atmospheric models with databases for receptors (e.g., land use and agricultural production), dose-response functions that relate the quantity of a pollutant that affects a receptor (e.g., amount of NOx absorbed by the soil) to the physical impact on this receptor (e.g., loss of soil properties), and monetary values. The result is a quantitative assessment of the external costs arising from the production of a certain energy source (e.g., electricity production) using a certain energy conversion technology (e.g., nuclear power plants) within a precise geographical area.

4

Methodology definition

In this chapter the methodological approaches generally adopted in literature for biomass and biogas supply chain modelling have been reviewed. A research journey into the most significant methodologies for assessing the environmental impact of bioenergy systems is also conducted. Finally, the methodology developed in this work is described and justified.

4.1 Biogas and biomass supply chain modelling

Because of the emphasis placed by international policy makers on bioenergy and biofuels as a means to reduce greenhouse gas emissions and because of the multiplicity of decisions required to structure new, bio-based energy systems, biomass supply chain design has become a central topic in bioenergy and biofuel research in the last decade. No less than seven review papers on biomass-to- energy and biofuel supply chain optimization have been published in leading journals in the last five years (Awudu and Zhang, 2012; De Meyer et al., 2014; Gold and Seuring, 2011; Mafakheri and Nasiri, 2014; Mota et al., 2015; Sharma et al., 2013; Yue et al., 2014). Considering the results of these reviews and the challenges for future research and practice highlighted by their authors, there seems to be general consensus on following facts: aa

- Mixed Integer Linear Programming (MILP) is the most widely used methodology (De Meyer et al., 2014; Sharma et al., 2013), especially for decisions on location (Mafakheri and Nasiri, 2014), technology selection, capital and investment, production planning, and inventory management.
- In the light of the policy and regulatory issues, there is still very limited research on the assessment of the impact and supporting policy choices on the capital and operational performance of biomass supply chain (Mafakheri and Nasiri, 2014).
- Most research is focused on ligno-cellulosic biomass from forestry or energy crops, which can be used for heat and power production or for liquid biofuel production in second generation bio refineries (Wetterlund, 2012). While the anaerobic digestion path is considered in the review framework of some authors (Sharma et al., 2013), none of the reference they examine deals with biogas supply chains.

Indeed, in the field of biogas, traditional engineering economics approaches are mainly used, e.g. to simulate the operation of single, exemplary plants (Gebrezgabher et al., 2010; Taleghani and Shabani Kia, 2005) and to determine the optimal plant size (Gan and Smith, 2011; Walla and Schneeberger, 2008) or the optimal timeliness for crops harvesting (Capponi et al., 2012; Gunnarsson et al., 2008) by repeated simulation and sensitivity analysis on continuous variables. When researching literature on biogas supply chains, optimization is more often meant to improve the performance of individual plants (Gueguim Kana et al., 2012; Thorin et al., 2012) or sections of supply chains (Bekkering et al., 2010), rather than to analyze or design supply chains as a whole. Based on an extensive review of literature, few model based approaches for analyzing biogas supply chains as systems exist to date:

1. Stürmer et al. (2011) introduced a non-linear programming model to analyze the impact of alternative substrates, machinery chains, and field distances on total substrate costs of a 250 kWel and a 500 kWel biogas plant. The model minimizes total substrate costs subject to land which is available in different distant land circles around the plants and is not spatially explicit.

2. Delzeit et al (2012) introduce a spatially explicit simulation framework, which includes a linear programming model for transport cost minimization and an iterative determination of the locations and substrate types for biogas generation.

3. The German tariff and support scheme is also studied by (Sorda et al., 2013), who couple an agent based simulation model for investment decisions with GIS data to estimate additional economic capacity potential for selected German regions.

4. Most recently (Bojesen et al., 2015) evaluate the capacity expansion potential for biogas in Denmark determining optimal location and production capacity by combining a location-allocation model with a production constrained spatial interaction model.

4.1.1 Spatially explicit approach

Many, if not most, management decisions concerning the environment management and the energy policies affect and are affected by the characterization of a certain landscape e.g. in terms of land use issues, resources availability and physical boundaries. Understanding and modelling the spatial patterns of landscape processes at several different scales is critical to effective environmental management. Economists, too, are increasingly adopting spatial analytical and spatial econometric techniques to study questions such as the geographical targeting of policies, regional clustering, technology diffusion, and the causes and consequences of land-cover change (Moran, 2010). The most common reason to adopt a spatial approach is the necessity to have the collected data georeferenced, that is, a precise location on a lat/long (latitude/longitude) so that the information collected is place-based precisely.

A model is spatially explicit when it differentiates behaviors and predictions according to spatial location (Goodchild and Janelle, 2004), and when the data are geolocated as part of the analysis. This is important in studies where the spatial characteristics of the input data are important in assessing the success of the model in predicting outcomes, as in the case of supply chain optimization of bioenergy systems. In biogas supply chain analysis, as in most bioenergy supply chain models, the modeling efforts are complicated by the fact that biogas can be produced and delivered at different scales and using various feedstock, technologies, distribution modes, resulting in a large number of potential supply pathways. 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 (Höhn et al., 2014). 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 (Fiorese and Guariso, 2010; Sliz-Szkliniarz and Vogt, 2012) and for biogas plant location analysis (Höhn et al., 2014).

4.2 Infrastructure development modelling

A major limitation of the MILP models, relies on their computational rigidity, since non linearities functions often occurring when describing complex systems such as bio-energy systems, need to be transformed with additional computational programming efforts. Such issues are generally solved by setting boundaries conditions in the model (and thus increasing the amount of variables) or by excluding from the optimization procedure some aspects of the supply chain under investigation. In addition, as highlighted by Rentizelas et al. (2009) , the linearity condition is generally maintained by investigating cases or scenario of interested while assuming that some conditions, such as the energy demand level or the size classes of the plants, are pre-determined. To this end, since part of this thesis investigates the possibility to expand the market of biomethane for transport application in a certain region, different approach was required.

As mentioned in previous chapters, a particular feature of gaseous fuels such as CNG or CBM and hydrogen is represented by the need of specific refuelling infrastructure for their distribution. Thus, when assessing the feasibility of expanding their presence in a certain region, such fuels face the challenge of persuading investors in refuelling stations to attain a satisfactory station-to-vehicles ratio (Yeh, 2007).

Few studies investigate this subject from either a modelling or an empirical perspective. Most empirical (Collantes and Melaina, 2011; Yeh, 2007) or model based (Struben and Sterman, 2008) studies are performed at a national or international scale, so they give substantial strategic insights but cannot be immediately used at the detailed, local planning level to guide the site and capacity definition of refuelling stations.

On the other hand, the use of operations research models for location planning of service stations is widely spread in literature. Most applications concern future hydrogen based supply chains (Bersani et al., 2009; Kuby and Lim, 2005; Kuby et al., 2009; Lin et al., 2008; Stephens-Romero et al., 2010), while a single example handling CNG filling stations is reported (Frick et al., 2007). (Upchurch et al., 2009) present a review of models for optimal location of alternative-fuel stations and summarize three general approaches to locate refueling stations optimally, i.e.:

- Variants of the p-median model, where demand is associated with a set of nodes i and allocated to service facilities j to minimize the total distance travelled by consumers to facilities.
- Traffic count or VMT methods, based on road traffic data, try to maximize the traffic passing by stations but risk to locate stations on several adjacent links of high volume freeways, rather than spreading stations, because they tend to double count the same trip by the same drivers more than once if they travel multiple links.
- Flow intercepting location models, including the flow refuelling location model by (Kuby and Lim, 2005) are path based models, where basic units of demand are not points, nor network links but flows on paths across network representing travelled route. The representation is realistic, but the method requires a data matrix of traffic flows from origins to destination, which is not available for all regions and geographic scales.

For each of these approaches, several variants of objective functions could be conceived, but competition factors, such as profitability of single service stations, are seldom taken into account. Profitability, in terms of net present values, is explicitly considered as an objective function only by Hugo et al. (2005), who deal with the strategic planning of whole supply chains, with special focus on locating refineries, and by (Bersani et al., 2009), who aim at maximizing net present values of a network of fueling service stations.

However, to overcome the chicken and egg dilemma, the profitability of service stations is a key issue: in fact, empirical research has shown that, in cases of successful market penetration of alternative transport fuels, refueling infrastructure mostly grew through private investment (Collantes and Melaina, 2011). Therefore, understanding which options for technology, capacity and location planning would be most desirable for potential investors, who aim at maximizing their profits, allows to gain insight on the future evolution of alternative fuel distribution systems and on their chances to thrive or decline.

4.3 Environmental analysis

A parallel literature stream dealing with biogas technologies focuses on the environmental and energy performances of the biogas supply chain by addressing its environmental impact in terms of positive and negative emissions produced. Greenhouse gas (GHG) emissions are often considered a satisfactory index for environmental assessment, and it is common practice in energy systems planning to evaluate environmental impact only in terms of CO_2 equivalent emissions reductions, especially when considering alternative energy production sources (Ostergaard, 2012; Patrizio et al., 2015; Starr et al., 2015). In many cases, the assessment is conducted by comparing the uses of different raw materials (Fuchsz and Kohlheb, 2015), supply chain configurations (Novosel et al., 2014) or utilization pathways.

However, addressing the environmental impact only in terms of carbon dioxide equivalent emissions might be misleading when it comes to biogas based energy vectors, which production generates a consistent amount of local airborne pollution (Pöeschl et al., 2012b). In order to account for additional environmental burdens in energy system planning (which are also often a major concern to local communities) , several authors propose the monetization procedure, that is, incorporating the so-called external costs in the optimization procedure, by adopting a LCA approach.

The external cost methodology, which follows the impact pathway approach (IPA), allows to monetize the environmental damage associated with emissions of a wide range of pollutants, which can be consequently incorporated in the model objective function. In other words,the externalities arising form a certain energy production process can be calculated in a tree-step procedure:

- Specification of the quantities of the relevant pollutants emitted and of the location of the pollution sources by adopting a life cycle analysis (LCA) approach;
- Conversion of welfare losses resulting from general emission impacts into monetary coefficients using specific database;
- Assessment of the external costs of the system of concern by weighting air pollutant emission according the monetary coefficients previously obtained.

As highlighted by Eyre (1997), the task of quantifying externalities arising from energy conversion technologies is hindered by several factors related to the methodology, including dependence on a specific technology and its location, uncertainties in the causes and nature of impacts to health and the environment, and a lack of suitable economic valuation studies. Nonetheless, the use of monetary values makes the estimation of the environmental damage caused by energy conversion processes more comprehensible in the market place and thus can be more efficiently included in energy decisions.

Moreover, as highlighted by Mirasgedis and Diakoulaki (1997), in spite of the difficulty of determining monetary values for all environmental impacts and of the many uncertainties in the valuation procedure, it is possible to estimate a significant part of the externalities associated with different energy sources and power generation technologies and thus to identify the most advantageous among them. Hence, even if the absolute values are still debatable, the comparative examination of externalities calculated for different energy sources allows for reconsidering existing pricing mechanisms.

4.3.1 Life Cycle emissions

The assessment of the overall emissions generated among biogas supply chains is generally conducted using a life cycle analysis (LCA) approach (Berglund and Börjesson, 2006; Jury et al., 2010; Lansche and Müller, 2012), which is a valid methodology because it allows considering various impact categories such as the global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical creation potential (POCP), toxicity and use of energy.

The results may vary depending on the method used, such as the applied system boundaries and the source of the data used for the analysis. The results may also vary depending on the assumptions made regarding the technical performance of the biogas system and the production of the process energy carriers required. The overall environmental impact also depends on how the biogas is utilized, on the energy carriers replaced, and on the assumptions made regarding the utilization of the digestate.

In most LCA studies on biomethane as a fuel, the analysis is limited to the following airborne emissions: CO_2, CH_4, N_2O, NH_3, NMVOC (non-methane volatile organic compounds), SO_2, NO_x (nitrous oxides), and PM_{25} (particles with diameter smaller than 10 μm). CO_2, CH_4, and N_2O, generally called greenhouse gases, are the main causes of global warming because they trap heat in the atmosphere. Several human activities may cause the release of these gases into the air: in particular, carbon dioxide is released through burning fossil fuels, solid waste, trees and wood products and also as a result of certain chemical reactions (e.g., manufacture of cement); and methane is emitted during the production and transport of coal, natural gas, and oil, from livestock and other agricultural practices, and by the decay of organic waste in municipal solid waste landfills; and nitrous oxide is mostly emitted during agricultural and industrial activities, as well as during the combustion of fossil fuels and solid waste.

Particulate matter, which is also known as particle pollution or PM, is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulphates), organic chemicals, metals, and soil or dust particles. "Fine particles", such as those found in smoke and haze, are 2.5 micrometres in diameter or smaller. These particles can be directly emitted from sources such as forest fires, or they can form when gases emitted from power plants, industries and automobiles react in the air.

The emissions of SO_2, NO_x, NMVOC and NH_3 are especially related to local environmental problems and may cause three important environmental effects:

1. *Acidification*: The acid deposition of sulphur and nitrogen compounds stems mainly from SO_2, NO_x and NH_3 emissions. The effects of acidification are expressed in a number of ways, including the defoliation and reduced vitality of trees, and declining fish stocks in acid-sensitive lakes and rivers (European Environmental Agency, 1998). SO_2 and NO_x can be oxidized into sulphate (SO_4^{--}) and nitrate (NO_3^-), either in the atmosphere or after deposition, respectively resulting in the formation of two and H+ ions. NH_3 may react with H^+ to form ammonium (NH_4^+), and upon nitrification in the soil, NH_4^+ is oxidized to NO_3^-, resulting in the formation of two H^+ ions (Wark and Warner, 1981)

2. *Photochemical smog*: Photochemical smog is caused primarily by NMVOC and NOx, and the main so-called secondary pollutant is ozone (O_3). The photochemical reactions in the atmosphere are very complex, but it can overall be concluded that in a European context, nitrogen oxide emissions are responsible for much of the ozone formation in thinly populated areas of the countryside. In the more densely populated areas, especially close to towns, ozone formation is enhanced by NMVOC emissions (Holten-Andersen et al., 1998). Photochemical smog constitutes, as does acidification, so-called transboundary air pollution. This means that the ozone spreads across national borders in Europe. In pure air, ozone has a lifespan of

several weeks and can therefore mix into the air and disperse over virtually the whole of the northern hemisphere before it is chemically degraded or physically removed. Harmful effects are seen both on vegetation and man.

3. *Eutrophication*: Eutrophication expresses itself in enhanced nutrient loading in ecosystems, such as forest, grasslands, fjords, lakes and open marine areas. The two main pollutants contributing to the atmospheric deposition of nutrients are NH_3 and NO_x. The greatest effects of the atmospheric deposition of nitrogen compounds are seen on ecosystems that are vulnerable to nitrogen loading. Examples of such systems are heath bogs and dry grasslands. Exceedance of critical loads with regard to eutrophication has resulted in altered compositions of animal and plant species in these areas and in decreasing species numbers.

Beside such local impacts, SO_2 and NO_x also have geographically wider impacts as they contribute to the formation of acid rain, which threatens ecosystems and vegetation in particular.

4.4 Uncertainty management

Uncertainty and sensitivity analyses study how the uncertainties in the model inputs affect the model's response. Uncertainty analysis (UA) quantifies the output variability while Sensitivity Analysis (SA) describes the relative importance of each input in determining this variability (Campolongo et al., 2011).

The goal of SA is to characterize how model outputs respond to changes in input, with an emphasis on finding the input parameters to which outputs are the most sensitive. Thus, such approach can be used for addressing the following issues:

- Testing the robustness of the results of a model or system in the presence of uncertainty;
- Increased understanding of the relationships between input and output variables in a system or model;
- Uncertainty reduction: identifying model inputs that cause significant uncertainty in the output and should therefore be the focus of attention if the robustness is to be increased (perhaps by further research);
- Searching for errors in the model (by encountering unexpected relationships between inputs and outputs).

Sensitivity analysis methods can be broadly classified into local and global methods (Campolongo et al., 2011). Local sensitivity measures, often referred to as One At a Time (OAT) measures assess how uncertainty in one factor affects the model output keeping the other factors fixed to a nominal value. The main drawback of this approach is that interactions among factors can not be detected, since they become evident when the inputs are changed simultaneously. Global measures offer instead a comprehensive approach to model analysis, since they evaluate the effect of a factor while all others are varying as well, exploring efficiently the multidimensional input space.

4.4.1 Local sensitivity analysis: OAT

One of the simplest and most common approaches to sensitivity analysis is that of changing one-factor-at-a-time (OFAT or OAT), to see what effect this produces on the output. OAT customarily involves moving one input variable, keeping others at their baseline (nominal) values, then, returning the variable to its nominal value, then repeating for each of the other inputs in the same way. Sensitivity may then be measured by monitoring changes in the output, e.g. by partial derivatives or linear regression. This appears a logical approach as any change observed in the output will unambiguously be due to the single variable changed.

Furthermore, by changing one variable at a time, is possible to keep all other variables fixed to their central or baseline values and thus increasing the comparability of the results (all "effects" are computed with reference to the same central point in space).

When the sensitivity of several parameters is considered for one alternative using a single measure of worth, it is helpful to graph percentage change for each parameter versus the measure of worth by using the spider-plot tool. This approach makes explicit the impact of variability in the estimates of each factor of concern on the economic measure of merit (Sullivan et al., 2015).

Despite its simplicity , this approach does not fully explore the input space, since it does not take into account the simultaneous variation of input variables. This means that the OAT approach cannot detect the presence of interactions between input variables.

4.4.2 Scenario analysis

Scenario analysis may represent an useful approach when applied in energy policy modelling since it can provide a picture of future alternative states of an energy system in the absence of additional policies ("reference" or "baseline" scenarios). In this way scenarios are a device to assess the impacts of an energy system on the environment, and to point out the effectiveness of environmental policies in avoiding these impacts (Alcamo, 2008). In addition, scenario analysis can illustrate how alternative policy pathways may, or may not, achieve an environmental target and they can identify the robustness of a particular environmental policy under different future conditions. This is important because "background" factors such as market conditions, change in consumption habits or other trends might affect the success of an environmental policy.

As clarified by (Sullivan et al., 2015) the simplest way to conduct a scenario analysis is to consider three estimates of the key parameters affecting the model results : a pessimistic, a most likely, and an optimistic estimate (O-ML-P estimating technique) . Depending upon the nature of a parameter, the pessimistic estimate may be the lowest value (e.g. low value of carbon tax) or the largest value (such as high external cost value of pollutant emission).

4.4.3 Global sensitivity analysis: Design of experiments

The major drawback with the aforementioned methods is that any possible interaction between the factors cannot be detected since they cannot evaluate the effect of an element while all others are varying as well, exploring efficiently the multidimensional input space (Campolongo et al., 2011). When several variables influence a certain characteristic of a system, the best strategy is then to design an experiment so that valid, reliable and sound conclusions can be drawn effectively, efficiently and economically.

In a designed experiment, deliberate changes in the input variables (or factors) are made in order to determine how the output varies accordingly. Moreover, the objective of a carefully planned designed experiment (DOE) is to understand which set of variables in a process affects the performance most and then determine the best levels for these variables to obtain a sustainable output.

One of the most commonly used experimental design is represented by factorial design, which allows performing a series of experiments (runs) with different combinations of values of the factors to be investigated. The number of experiments needed, depend on the number of factors since a full factorial designed experiment consists of all possible combinations of levels for all factors. Thus, the total number of experiments for studying k factors at 2-levels is 2^k. How the method works is illustrated by an example, where the issue is how the result Y is affected by the two factors, a and b. The behaviour of the result is investigated at two levels of such two factors, high and low level according to Table 4.1. Thus 2^2 runs must be performed, each experiment with a combination of the

Run	*a*	*b*	Results
1	Low	High	Y_1
2	Low	Low	Y_2
3	High	Low	Y_3
4	High	High	Y_4

Table 4.1 Full factorial design plan for two factors and two levels as in (Sundberg G., 2000)

factor values. The effect from each factor on the result can be calculated as the average difference between the sum of the result where the factor is high and the sum result with low level, as showed expressed in the following equation:

$$E_a = 0.5\Big[(Y_3 + Y_4) - (Y_1 + Y_2)\Big] \tag{4.1}$$

Where E_a represent the effect from factor a, with the result from 4 runs it is possible to calculate, not only the single factors effect, but also their interaction. It is possible to estimate whether the factors affect the result independently on the level of the other factors. In the same way, the interaction effect AB is calculated as the average difference between the sum of the result where the factors a and b have the same level (high/low) and the sum of the result where the factors level differs.

4.5 Rationale for methodology selection

As highlighted in previous section, MILP is a well established method that can combine technical and economic data of a studied bio-energy system, and use it to determine optimal strategies that minimize the cost for the system. A MILP problem contains the objective function that is to be minimized or maximized, continuous and integer variables and boundary conditions, representing restrictions that limit the possible solution space. The integer variables can be used to consider a choice, for example if a new plant is built or not, or if a facility is operating or not, in these cases they can assume only the value 0 or 1 (binary variables).

In this thesis two MILP models have been adapted for optimizing biogas supply chains namely the BIOGASregio model and the BeWhere model. Given the fact that biogas to energy schemes are geographically dependent, a spatial explicit approach was required, thus a GIS based assessments has being used to determine the biogas potential of various feedstock streams and to find the optimal locations of biogas facilities and the optimal allocation of biomass feedstock, energy infrastructure and energy demands. Similarly to other studies on large scale bioenergy supply chains, when considering the North Italian scenario this work employs a simplified grid-based spatial representation in which the grid cell is used to represent the location of potential production facilities and energy demand (Natarajan et al., 2014; Wetterlund et al., 2012a). Conversely, for smaller areas (as it is the case of Friuli Venezia Giulia region) it was possible to apply the model at a municipal level, meaning that for all the input data the exact geographical location have been considered.

At the same time, when investigating the potential expansion of CBM market in a certain region, a different modelling approach was required in order to deal with non-linearities often occurring when considering attraction factors. Therefore a MINLP model has been developed to identify sites and characterizations of new potential CBM refuelling stations in the region of concern by evaluating their attractiveness under different market circumstances. The model results have been subsequently used as input data in the MILP model BIOGASregio.

The probable range of values of the models output have been examined by applying sensitivity analysis, a common way to explore the robustness of a model optimal solution. In particular, scenario analysis was developed for assessing the impact of different policy instruments in fostering the adoption of biomethane as a vehicle fuel as compared to other biogas utilization pathways. Thus changing in the following parameters, which after a first screening have been found to be significant in the models output, have been considered:

- Biogas and biomethane incentive levels
- Magnitude of environmental policy instruments, in the form of carbon prices
- Geographic extension of the environmental impact (i.e. local and global effects)

In addition to investigate whether there are important interaction effects in the factors affecting the adoption of biomethane as a vehicle fuel, a DOE analysis has been carried out. The following five variables were assumed to be of particular relevance to the model results, since they represent important energy market leverage:

- CBM demand level in the region of concern (D_{CBM});
- maximum amount of digestate to be spread in the fields (N_{max});
- feed in tariff values for biogas based electric power ($FITel$);
- feed in tariff values for biomethane injection ($FITinj$);
- market values of biomethane tradable certificates (CIC);

Such factors 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 BIOGASregio model.

5

Case studies description and data

After a description of the case studies developed, this chapter considers the main techno-economic parameters characterizing each of the steps in the conversion chain, from biogas feedstock to end products. The technical aspects of the energy infrastructure for the distribution of the biogas energy vectors are also investigated, with a special focus on the infrastructure required for dispensing the biomethane for transport.

5.1 Rationale for case studies selection

As mentioned in the introduction, almost 800 power plants based on agricultural biogas were operating at the end of 2012 in Italy, with a total capacity of 650 MW. Most of these plants, which produce almost 70% of total Italian domestic biogas consumption, are located in the Po valley, a large flat area located in northern Italy , which comprises the highest concentration of industrialized regions in the country and also boasts long-standing animal breeding and agroindustrial supply chains (e.g. Parma ham and Parmesan cheese).

With a total length of 250,000 km the Italian natural gas grid has a widespread coverage of the national territory, especially of northern Italy. Thus, the technical barriers to injecting biomethane into the natural gas grid and using it for heating purposes are expected to be particularly low in this area, which implies that this option could be advantageous from an economic viewpoint, even if it is thought to be less beneficial from an environmental perspective than other biogas utilization pathways.

It should also be mentioned that the northern Italian scenario hosts more than 60% of CNG refuelling stations of the country, meaning that significant market opportunities for biomethane market development might arise also in the transport sector.

Having a huge biogas potential, mostly deriving from intensive farming activities and a high presence of energy infrastructure for grid injection and CNG distribution, the Northern Italian territory resulted particularly interesting to address the main purpose of this thesis that is to assess the economic and environmental performances of different biogas utilization pathways, also taking into account the actual territorial distribution of existing infrastructure and potential feedstock.

With this aim, the environmental and economic feasibility of different biogas supply chain configurations in the region of concern have been investigated by introducing two environmental policy instruments: carbon pricing and external costs (case study III and case study IV in table 5.1).

While the market penetration of CNG in Northern Italy is remarkable and the number of service stations is expanding, some area of the territory are still characterized by a lack of biomethane distributing infrastructure that prevent the development of such fuel as a competitive fossil fuel substituted. This especially applies to the case of Friuli Venezia Giulia (FVG) , an Italian region with about one million inhabitants located at the border with Austria and Slovenia, as shown in figure 5.1.

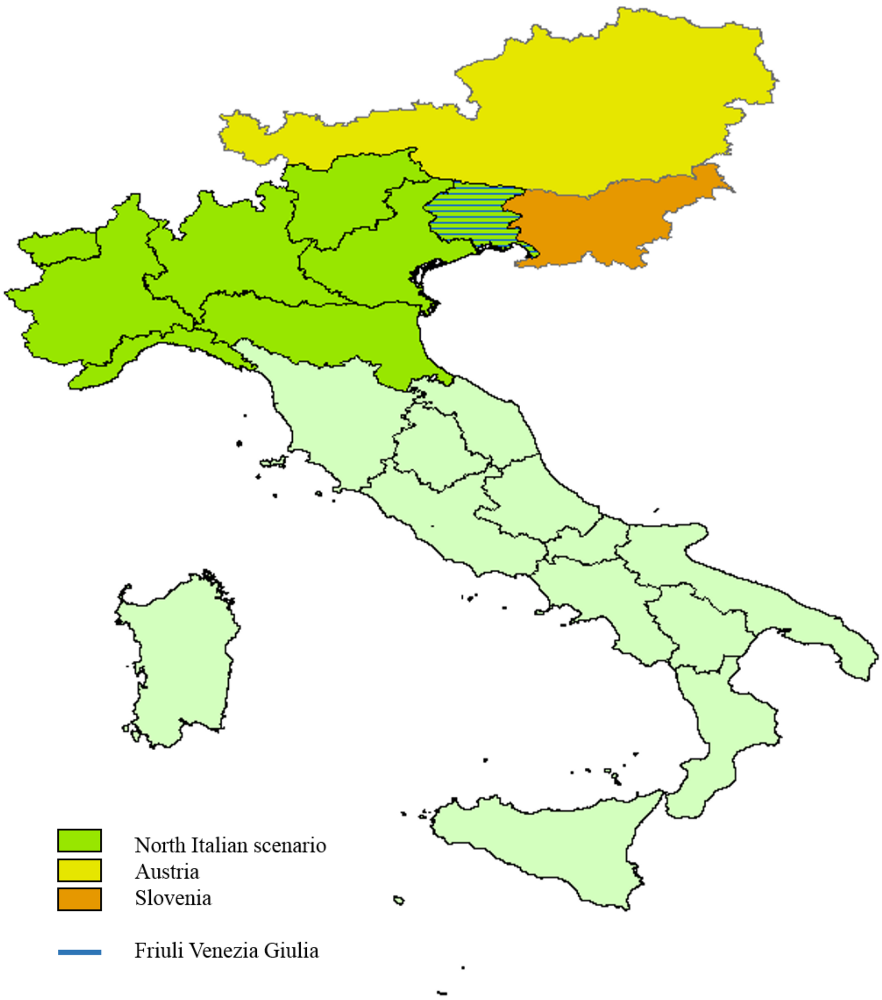


Fig. 5.1. Geographic dimension of the analysis

Even though a (limited) number of methane vehicles have been acquired by private and public owners as a result of national incentives some years ago, differences in price and tax structures in bordering countries make refuelling abroad the most attractive option for many customers. Historically, taxes on fuels have been significantly lower in neighbouring countries (especially in Slovenia) than in Italy, which generates a flow of refuelling commuters. To reduce this flow, the regional government of FVG used to finance a system of pricing zones depending on distance to borders, which was modified in 2011 due to objections by the European Union on the grounds of distortion of economic competition between countries.

Given its peculiarity in terms of high biogas potential, lack of CNG infrastructures and historically unfavourable CNG market conditions, the Friuli Venezia Giulia territory resulted particularly suitable to assess the economic impact of policy instruments targeted for the production of biogas. Therefore, such region has been taken as a reference scenario to investigate the potential adoption of biomethane technologies through the application of previous and current Italian biogas promotion schemes (case studies I and II, respectively).

Policy instrument / **Geographic dimension**	Environmental tax		Biogas promotion scheme (Feed in Tariff)		
	External costs	Carbon price	Past	Actual	Modelled
Regional level			*Case study I*	*Case study II*	
Macro-regional level	*Case study IV*	*Case study III*			*Case study IV*

Table 5.1. Policy instrument and geographic dimensions of each case study presented in this thesis

5.2 Techno-economic indicators

5.2.1 Feedstock availability and logistics

Animal manure is generally considered an excellent feedstock substrate for anaerobic digestion, as it naturally contains anaerobic microorganisms. However, due to its low dry matter content, which results in a relatively low methane yield (ranging from 260 to 450 Nm^3 of biogas per ton of volatile solids), animal manure is generally used in co-digestion with other substrates, such as energy crops. Thanks to its high availability in the Northern Italian agricultural area, maize and sorghum are the most frequently used energy crops in the majority of the existing biogas plants. Unlike manure, they are characterized by a high biogas potential, which make them particularly suitable for anaerobic digestion purposes.

However, their use as biogas feedstocks requires some specific technological steps prior to digestion: harvesting, pre-processing and ensiling. At the same time, the cultivation requires a high input of fertilizers, pesticides and energy for harvesting and transport, which considerably reduces the environmental sustainability of their use for biogas.

The feedstock substrates considered in this thesis derive from the agricultural sector, which accounts for the largest potential for biogas feedstocks in Northern Italy (Patrizio et al., 2015). These feedstocks consist mainly of animal manures collected from farms (from cattle, pigs and poultry) and of energy crops, such as maize silage and sorghum. As in similar works (Pantaleo et al., 2013), only animal solid waste has been considered in this thesis, representing approximately 90% in weight of the overall animal waste, whereas sewage has been neglected due to its low energy density. Having specific a volatile solid content and biogas yield, each of the substrates carries a specific biogas potential,as described in table 5.2.

Parameter	Manure			Energy crop		Unit
	Cattle	Swine	Chicken	Maize	Sorghum	
Dry Matter	25	25	30	35	38.9	%
Volatile Solid	75	82	75	95.5	91.1	% of Dry Matter
	15.0	16.4	15.0	29.1	28.7	%
Biogas yield	260	450	260	600	590	Nm^3 / t VS
Average feedstock production	0.087	0.064	0.04	60	65	t/t living weight/day * t/ha

Table 5.2. Characteristics of the biogas feedstock adopted in this thesis. Data taken from (Crpa, 2011)

Considering the entirety of the municipalities in the area of concern, we obtain gross biogas potentials of 80 PJ/year and of 24 PJ/year for energy crops and animal feedstocks, respectively, which are mostly located in the Po area, as Figure 5.2 shows.

After being collected, the feedstock needs to be transported to the biogas plants for

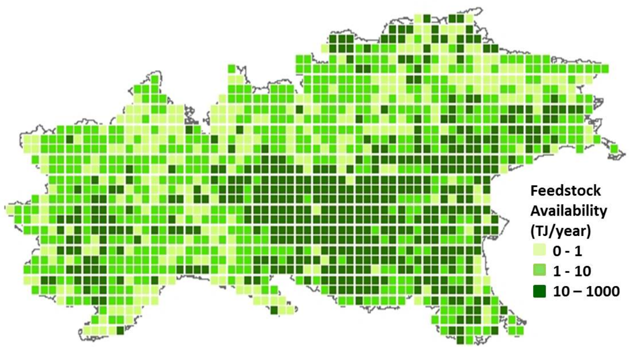


Fig. 5.2. Spatial distribution of feedstock availability

digestion. The Italian national transport infrastructure is suitable for truck and tractor-trailer transport throughout the area of concern, including the alpine municipalities.

Table 5.3 summarizes the procurement and logistics costs of the selected feedstock, considering both values found in the literature and values based on personal communication and estimates from experts and local farmers. The manure purchase cost is commonly set to zero, as this is generally the case when the biogas power plants are owned by farmers. However, to consider the high demand for animal manure in the last few years, which is mainly due to the rapid growth of biogas plants in the region, we set such costs in the range of 4-6.5 €/t. The costs of cultivating and harvesting the selected energy crops include direct costs (e.g., seed and fertilizer costs), field machinery operation costs, and ensiling costs. The values used are 36.8 €/t for maize silage and 27.8 €/t for sorghum silage, which are in line with the values reported in the literature (Gissén et al., 2014, Informatore Agrario 2011, CRPV 2011).

The vehicles used for the transport of feedstock differ according to the characteristics of the transported materials. In particular, most of the local farmers interviewed reported the use of a tractor trailer for transporting the solid fraction of manure, having a capacity varying according to the size of the plant. Thus, an average capacity of 14 t and an average transport cost of 0.20 €/t km have been taken as reference values for the logistical activities of animal manure. Maize and sorghum are assumed to be transported from the field to the biogas plant in a hauler having an average capacity of 38 m^3, in line with (Delzeit and Ressourcenökonomik, 2008), who also reported comparable loading and unloading costs (1.5 €/t), as well as transport costs (0.266 € for each kilometre).

5.2.2 Plant and conversion technologies

Table 5.4 presents the efficiencies that have been considered for the selected technologies. In particular, for the cogeneration technology, a distinction has been made between the heat and power efficiencies, with both referring to a range of plant sizes (kW), as the

Parameter	Typology (t)	VALUES		
		Literature	Adopted	Unit
Animal manure purchasing cost	Swine manure	0	4.1	€/t
	Cattle manure		5.5	
	Chicken manure		6.5	
Cultivation and harvesting cost	Maize silage	33.3 - 37	36.8	
	Sorghum silage	21.7	27.8	
Loading and unloading cost	Energy crops (silage)	1.5- 2.9	1.78	
	Animal manure	1.8	2	
Transport cost	Energy crops (silage)	0.08 - 0.26	0.145	€ / t km
	Animal Manure	0.19-0.24	0.20	

Table 5.3 Procurement and logistics costs for the selected feedstock

tariff incentive schemes for electricity generation distinguish between size classes. When considering the power-only option, the electric efficiencies of the ICE and the ORC and waste heat to power output ratios (α=1.2666) have been derived from the literature (Pantaleo et al., 2013). The power plant electric self-consumption has been fixed at 11% according to the Decree of the Minister of Economic Development 6 July 2012, whereas the heat self-consumption has been set at 25% based on literature data (Poeschl et al., 2012).

The plant operating hours are 8000 h/year according to manufacturer data and literature data (Poeschl et al., 2012). As table 5.5 shows, direct labour costs vary in the range of 15,000 - 80,000 €/year, assuming an average labour cost of 40 k€/person, two full-time workers for operating a larger power plant (more than 1 MW) and part-time workers for smaller ones. For consistency, the maintenance cost and insurance cost of each conversion technology have been calculated as functions of the gross electric energy produced using values derived from the literature (Walla and Schneeberger, 2008) and from interviews with local plant managers. A maintenance cost of 0.031 €/kWh and a 0.008 €/kWh insurance cost have been calculated as functions of the gross electric energy produced using values derived from the literature (Pantaleo 2013, Walla et al. 2008) and from interviews with local plant managers.

The capital costs of the selected technologies are given in table 5.6 and have been calculated as year equivalents, considering a time horizon of 15 years and accounting for their sizes, which are limited with reference to the biogas input flows. For the PWS technology, data related to the cost components were derived from the Vienna University of Technology, which considers a reference value of 0.91 for the upgrading process efficiency. The same source has also been used to determine the costs of grid injection stations, which include pipe connections and the additions of odorizers and propane.

Core technology		SIZE (S) Unit	SIZE (S) Value	EFFICIENCY	
				Electricity	Heat
I	ICE	KW	300	0.3	0.28
			1000	0.33	0.31
			2000	0.36	0.34
				ICE	ORC
II	ICE + ORC	KW	300	0.32	0.18
			1000	0.35	
			2000	0.38	
III	Upgrading technology + feed in station	Nm^3/h	151	0.507	
			504		
			1008		
IV	Upgrading technology + feed in station / compression	Nm^3/h	151	0.507	
			504		
			1008		

Table 5.4 Technical efficiencies of the considered technologies

Plant operational costs			
Parameter	**Size (S)**	**Value**	**Unit**
Labor cost	S ≤ 300 kW	15,000	€/year
	300 <S ≤ 1000 kW	40,000	
	S > 1000 Kw	80,000	
Maintenance cost	Undefined	0.031	€/kWh
Insurance cost	Undefined	0.008	€/kWh

Table 5.5 Operational cost coefficients

5.2.3 Digestate managment

Digestate is applied as fertilizer in the fields in the same way and using the same equipment as the spreading of animal manures and slurries. The most suitable methods of application are the same as those used to apply raw untreated slurry. To reduce the amount of pollutants released into the air, the equipment used should minimize the surface area exposed to the air and ensure the rapid incorporation of digestate into the soil

<table>
<tr><th colspan="2" rowspan="3">Core technology</th><th rowspan="3">Unit</th><th colspan="4">Capital cost</th></tr>
<tr><th colspan="2">Digester</th><th colspan="2">Core technology</th></tr>
<tr><th>Fixed part
MEUR/ Year</th><th>Size-dependent part
EUR/ S</th><th>Fixed part
MEUR/ Year</th><th>Size-dependent part
EUR/S</th></tr>
<tr><td>I</td><td>ICE</td><td>KW</td><td rowspan="4">642.136</td><td rowspan="4">2634.4</td><td>89.314</td><td>716.44</td></tr>
<tr><td>II</td><td>ICE + ORC</td><td>KW</td><td>842.097</td><td>895.41</td></tr>
<tr><td>III</td><td>Upgrading technology + feed in station</td><td>Nm^3/h</td><td>945.916</td><td>156.72</td></tr>
<tr><td>IV</td><td>Upgrading technology + feed in station / compression</td><td>Nm^3/h</td><td>960.362</td><td>173.6</td></tr>
</table>

Table 5.6 Investment costs functions for the selected technologies

(Beil and Beyrich, 2013). For these reasons, as recommended by several studies, digestate is generally applied with trailing hoses. Because the amount of digestate available for spreading in the fields depends on its fertilizing value, the logistics costs generally refer to the total amount of mineral nitrogen transported (kg). For the digestate spreading cost, in particular, a value of 0.6846 €/kgN is estimated based on farmer experience, whereas the capital costs for storage are accounted for in the digester investment cost curve.

As mentioned in chapter 2, the digestate contains a high nutrient content of nitrogen, which can pose a threat to the environment and in some cases to the fertility of the soil itself. To prevent loss of nutrients and pollution problems, the European Nitrates Directive (91/676/EC) on fertilizers, by designating as "nitrate vulnerable zones (NVZs)" areas of land that drain into polluted waters, restricts the application of fertilizer from animal manure on cropland to 170 kg nitrogen per hectare within such areas. Such strict legislative frameworks, which seek to protect the environment, may necessitate the transport and redistribution of nutrients away from intensive areas. In particular. In the case of Friuli Venezia Giulia region, with the regional deliberation n. 1246/2008, 68 out of the 131 considered municipalities were identified as Nitrate Vulnerable Zones (NVZs) and assigned the corresponding limit of 170 kg Nitrogen per hectare on the application of manure fertilizer on cropland. For remaining useful agricultural area of the region (ordinary zones), a limit of 340 kg Nitrogen per hectare was imposed by the regional deliberation. Considering such nitrate constraints and a maximum arable land freely available for spreading equalling 10% of the useful agricultural area currently sown with maize, we obtained the estimates of maximum permissible spreading quantities of digestate for each feasible location in the area of concern, as represented in Figure 5.3

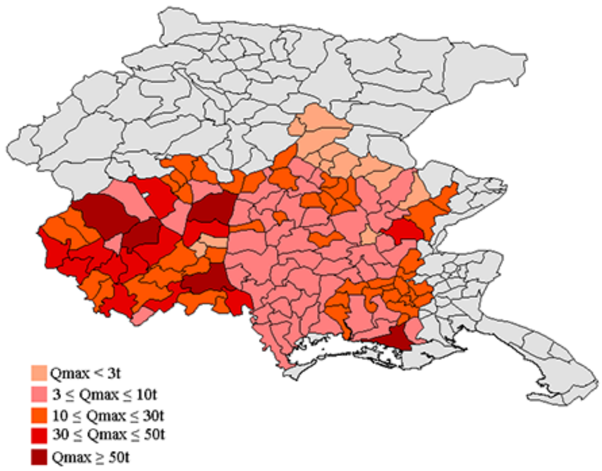


Fig. 5.3 Nitrogen limits for digestate spreading (Qmax)

5.2.4 Energy infrastructure

Table 5.7 highlights the energy infrastructure that have been accounted for in this thesis, which presence in the territory under investigation have been mapped by coupling national and regional database with a GIS software.

The electricity generated from the biogas plant, controlled under priority dispatch benefits, is assumed to be completely distributed to the electricity grid. The costs of connection to the electricity grid are considered homogeneous and have been incorporated within the economic parameters of the CHP plants. The heat produced via co-generation, which is partly used in the AD process control, is assumed to be consumed via an existing district heating network. The hypothesis is that new biogas to power plants should be coupled with an efficient external heat exploitation infrastructure. Thus, CHP plants have been dimensioned as in (Schmidt et al., 2011) by considering the heat demand within a 15 km radius and assuming an average pipeline loss coefficient of 15%, which is based on data from (Agcm, 2013).

As shown in Figure 5.4, there are local gas distribution networks in virtually every municipality in the Po Valley, and these often coexist with district heating networks (green grid points in the figure), which play a minor role compared with those in other European countries (Agcm, 2013). Individual cases of district heating systems in the absence of gas grid networks are rare, generally restricted to mountain areas and are

Energy Infrastructure	Technical constraint	Biogas Energy vector	Losses %
National electric grid	None	Electricity	None
Existing DH System	Maximum distance from the plant: 20 km	Heat	15%
Local gas grid	Operative pressure: 60 bar	Biomethane for heating purposes	4%
		Biomethane for vehicles	4%
Existing road network	Maximum travelling distance from the plant: 50 km	Biomethane for vehicles	None
Existing refueling stations	Average capacity: 0.85 MNm^3/year Operative pressure: 220 bar	Biomethane for vehicles	None

Table 5.7 Energy infrastructure considered in this thesis

so small that, at the aggregation scale utilized in this study, their effects are negligible. Only some areas within alpine regions (red grid points in Figure 1) lack access to both natural gas and district heating (DH); here, gas, oil, and wood biomass are the main fuels used to meet the household heating demand.

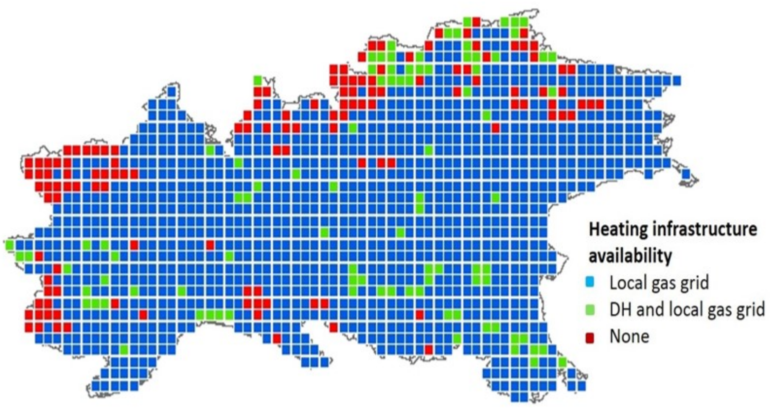


Fig. 5.4 Spatial distribution of heating infrastructure

Both alternatives have been considered in this thesis. In particular for the truck-based distribution, we assume the use of a demountable platform, in which compressed gas cylinders are loaded and then distributed by truck to the existing refuelling stations within a maximum supply radius of 50 km. The loading capacity of such a truck has been fixed to 3,000 Nm^3, which accounts for the total weight limit, which usually does not exceed 60 tonnes

5.2.5 Building new CNG/CBM refuelling stations

As mentioned in the introduction, the growth of the Italian biomethane market for transport application might benefit from the possibility of exploiting existing refuelling infrastructure, having a widespread presence in the northern part of the country (figure 5.5). Moreover, the actual policy scheme designed for promoting biomethane utilization in the country encourages investment in new refuelling CBM infrastructure and through specific incentives for their construction. This aspect, together with the incentives introduced for the production of biomethane for transport, may represent a very promising opportunity for regions characterized by low rates of biomethane market penetration.

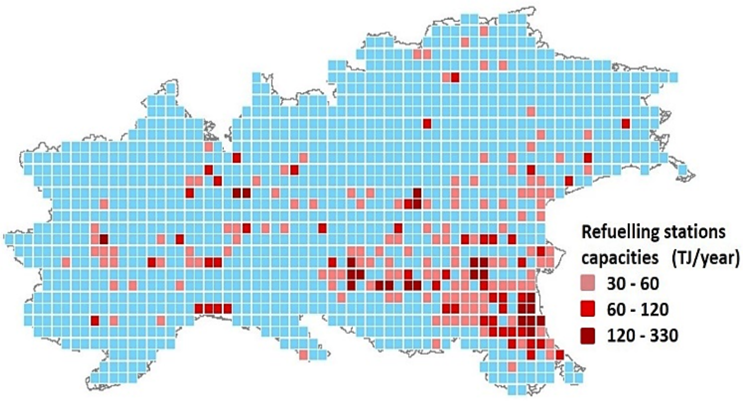


Fig. 5.5 Spatial distribution of CNG station (Federmetano, 2014)

Depending on the way the CBM is distributed, by natural gas grid injection or by truck, the FS configuration may require different subsystems. In general, the following units are recognizable: a single or multi-stage compressor, CBM storage units having a maximum capacity of 3,000 Nm^3, and a dispensing unit operating at a pressure of 220 bar. The investment required varies according to the size and the operating pressure of the refuelling stations.

The main important factors affecting the location of a new station are the traffic flow and the possibility of easily accessing natural gas distribution lines (Melaina, 2007) stated that because the costs of connection are high (ranging from 180 €/m to 250 €/m) the distance from the station to the point of connection with the distribution line is generally less than one kilometre, although it could be up to four kilometres.

Depending on the possibility of connecting to a national or local gas pipeline, a CNG or equally a CBM station may operate at a pressure of 40 bar (high-pressure FS) or 4 bar (low-pressure FS), respectively. In the latter case, an additional compression step is needed to reach the target pressure of 220 bar. Figure 5.6 highlights the relationship between the annual costs, expressed as the sum of the operating costs and the annual capital cost, and the distance from the natural gas pipeline for several FS capacities.

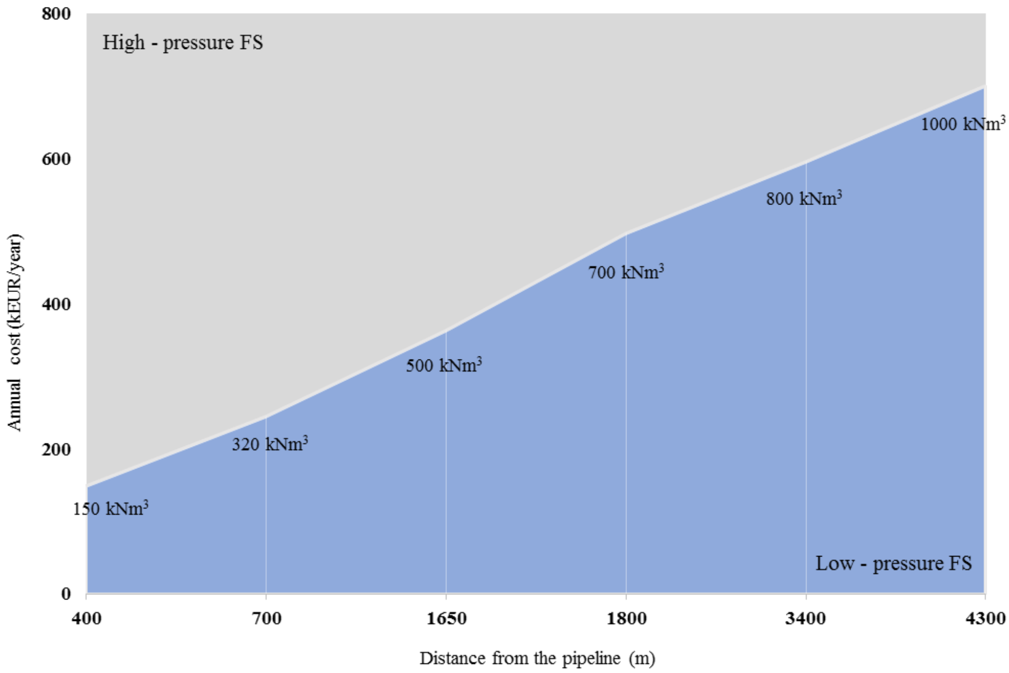


Fig. 5.6. Break-even distances form the pipeline for different FS capacities

The values on the x-axis represent the break-even distance from the national gas pipeline up to which building a high-pressure FS, and thus reducing the compression operations, is economically preferable. For higher distances, connecting to the national grid would generate extra costs. The choice of connection is also size-dependent, in that for larger capacities, the connection costs would be compensated by the economy of scale.

6

Modelling the biogas supply chain

This chapter describes the optimization models adopted as well as the environmental analysis conducted for assessing the economic and environmental feasibility of the biogas supply chains under investigation.

6.1 The BeWhere model

BeWhere is a geographically explicit MILP model designed for analysis of optimal locations for bioenergy conversion facilities, in particular for biofuel production. The model has been developed in the commercial software GAMS and is solved using CPLEX. Originally developed from jointly collaboration of International Institute for Applied Systems Analysis (IIASA, Austria) and Lulea University of Technology (Sweden), the model has been adopted for regional (Leduc et al., 2010a; Schmidt et al., 2012) and national studies (Leduc et al., 2010b, 2009; Natarajan et al., 2014) as well as at European scale (Wetterlund et al., 2012b).

The BeWhere model combines the use of MILP with heuristic criteria of variables research and boundary condition setting within a database, directly coupled with GIS software. It was thus particularly suitable for geographically extended studies like this one, in which the northern Italian area was analysed. The model also takes into account a wide range of economic parameters related to the performances of biomass plants, allowing biogas technology options to be evaluated at a supply chain level under environmental and economic considerations.

The objective of the model is to minimize the total cost of the complete biofuel supply chain, from feedstock procurement and logistics, including biomass harvest, biomass transportation, conversion to biofuels, transportation and delivery of biofuel, and sale of excess heat and co-produced electricity. Fossil CO_2 emissions are also included in the assessment, by applying a carbon price on the supply chain emissions, including a negative cost for offset emissions from replaced fossil energy carriers. The model chooses the least costly pathways from one set of feedstock supply points to a specific production plant and further to a set of biofuel demand points. For a more detailed description of the BeWhere model, see Leduc (2009) and Wetterlund (2012). The model had previously been implemented for ligno-cellulosic forest residues (wood waste, crop residues, and ligno-cellulosic industrial waste) as potential substrates. Biogas is generally obtained from the process of anaerobic digestion, which may be carried out with various plant typologies characterized by different costs and process parameters. To participate in anaerobic digestion, feeding substrates, are required to comply with several technical features (like humidity, nitrates contents, and methane yield) and also to have a low lignin content, which makes wood substrates unfeasible for such a purpose. During my visiting period at IIASA, the BeWhere model has thus been developed to accommodate the specific biogas substrates of the area of concern, feedstock transport, biogas conversion technologies and energy infrastructure in accordance with the data described in chapter 5.

In order to limit calculation times, the region was divided into grid cells with a 0.1 degree resolution (10 x 10 km), which have been considered as both supply point for biogas feedstock, demand point for energy (electric energy, heat and transport fuels), and potential location for biogas plants. Furthermore, to enhance the environmental analysis by including additional airborne emission generated along the supply chain, the external cost methodology has been included in the model, firstly by evaluating the amount of airborne emissions generated in each process step and subsequently by associating their damage costs.

6.2 The BIOGASregio model

Similarly to the BeWhere, the BIOGASregio is a MILP optimization model specifically designed for identifying the optimal site, size and technology mix of a biogas plant, under different market conditions. The market scenario is modelled through the introduction of different policy incentives, according to actual and previous policy schemes defined in chapter 3.

The model has been developed at the University of Udine in 2013 and was originally developed for assessing the economic feasibility of biogas to power options, as described in Chinese et al, 2014. During my PhD I have further developed the model by including other biogas utilization pathways (such as biomethane injection and CBM production) and by introducing the most recent national biogas promotion schemes in the optimization process. Further model developments also refer to the adoption of the DOE technique to test the robustness of the obtained results.

Being specifically targeted for analyzing the effect of certain policy instruments, such model has been implemented at a smaller scale, which allowed to adopt less geographical aggregated data as for the BeWhere model. In addition, since any consideration related to the environmental impact of the biogas technology has been included in such policy schemes, the BIOGASregio model deals with a pure economic cost minimization, without considering any environmental policy instrument (i.e. carbon taxes or external costs).

The model objective function is characterized by the following generic form:

$$Max \sum_{Bp} \sum_{j} \Big(R_{Bp,j} - C_{Bp,j} \Big) \tag{6.1}$$

Where the first summand represent the total annual revenues deriving from the adoption of a specific biogas utilization pathway Bp for the plant located in the jth municipality and the second term includes the economic costs generated along the biogas supply chain. These are: logistics and procurement costs of the selected feedstocks, operational and annual capital costs related to the biogas plant according to the biogas utilization pathway selected, digestate management costs and the infrastructure costs required to distributing the biogas energy vectors in the market.

As expressed by equation (6.2) total annual income is a function of total annual production of the selected energy vector $Evector_{Bp,j}$ (being electricity, biomethane for injection or for transport application), and of marginal revenues, given by feed in tariffs or wholesale prices Tar_{Bp} depending on support scheme structure. The production of such energy vectors (equation (6.3)) is a function of the biogas conversion technology efficiency $\eta_{Bp,s}$, the biogas lower calorific value K_{bg} (kWh/Nm^3) and on the total biogas production $Prod_{bg_{j,s}}$ (Nm^3/year) , which accounts for the total amount $Q_{j,t,s}$ (in kWh) of animal by product and energy crop type t adopted in the digestion process, having specific volatile solids VS and biogas yields Y. Furthermore equation (6.5), ensures that the plant size limitation $Smax$ is respected.

$$R_{Bp,j} = Evector_{Bp,j} \cdot Tar_{Bp} \tag{6.2}$$

$$Evector_{Bp,j} = \sum_{s} \left(\eta_{Bp,s} \cdot Prod_{bg_{j,s}} \right) \cdot K_{bg} \tag{6.3}$$

$$Evector_{Bp,j} = \sum_{t} \left(Q_{j,t,s} \cdot VS_t \cdot K_{bg} Y_t \right) \tag{6.4}$$

$$Evector_{Bp,j} = \sum_{t} Smax \cdot bin_{j,Bp,s} \cdot tf \tag{6.5}$$

A special feature of biogas supply chain modelling is that, besides input flows, an output material flow should be managed, i.e. digestate, whose volumes and costs are significant. According to the assumptions made in section 3.3, the BIOGASregio model considers the digestate storage in tanks and the application of untreated manure on agricultural land, at the same time ensuring that limits on manure N/ha stipulated by the local implementation of Nitrates Directive are respected. Mass flow balances are thus more conveniently expressed in terms of equivalent nitrogen content using digestate production coefficients D_t and nitrogen content coefficients N_t of each feeding substrates t, as expressed by equation (6.6) where the digestate mass flows between municipalities $Q_{i,j}^{N_{dig}}$ are also accounted for.

Equation (6.7) sets the Nitrates Directive boundary for each jth municipality, ensuring that the digestate spread in the jth municipalities $Q_j^{N_{spread}}$ is lower than the specific spreading limit $Q_j^{maxN_{spread}}$ assigned for that municipalities

$$\sum_{t} Q_{i,j} \cdot D_t \cdot N_t + \sum_{i \in A(i,j)} Q_{i,j}^{N_{dig}} = Q_j^{N_{spread}} + \sum_{k \in A(j,k)} Q_{i,k}^{N_{dig}} \tag{6.6}$$

$$Q_j^{N_{spread}} \leqslant Q_j^{maxN_{spread}} \tag{6.7}$$

To assess the impact of different policies, former and forthcoming biogas incentive schemes have been modeled with proper constraints in different model versions in order to highlight the effect of changes in bioenergy promotion schemes.

6.2.1 Modelling biogas to power promotion schemes

Both Law 99/23 July 2009 and the Decree of 6 July 2012 basically introduce stepped tariffs for the production of electricity from biogas alone, which can be modeled with special ordered sets of binary variables (Williams, 1999) introducing corresponding constraints. However, while Law 99/23 July 2009 discriminates between plant sizes which correspond to the introduction of either Feed In Tariffs or Green Certificates, the 2012 policy scheme additionally makes a distinction on the substrate mix adopted in the digestion process.

For the incentive scheme set until 2012, plants up to 999 kW may opt for Feed In Tariffs whereas incomes for larger plants, benefit from Green Certificates and from selling power at an average market electricity wholesale prices.

The set of equations (6.8-6.11) imposes that the generated electricity El_j^{NET} is either sold as El_j^{FI} at the Feed in Tariff Tar_{el}^{FI} or as El_j^{GC} at average tariff Tar_{el}^{GC} equivalent to Green Certificates; equations (6.10) and (6.11), in particular, constrain power sales to fall under either the first or the second tariff class XT_j^{FI} and XT_j^{GC} while respecting the plant size limitation S_j^{PLANT} (kW).

$$El_j^{NET} = El_j^{FI} + El_j^{GC} \tag{6.8}$$

$$R_{el,j} = El_j^{FI} \cdot Tar_{el}^{FI} + El_j^{GC} \cdot Tar_{el}^{GC} \tag{6.9}$$

$$XT_j^{FI} + XT_j^{GC} \leqslant 1 \tag{6.10}$$

$$S_j^{PLANT} \leqslant 999 \cdot XT_j^{FI} + M^{plant} \cdot XT_j^{GC} \tag{6.11}$$

The new tariff scheme is primarily depending on the feedstock mix used in the digestion process and on plant size. Equation (6.11) represents the case of simultaneous utilization of energy crops Q_J^{ecp} and animal byproducts Q_J^{byp}, specifying that the tariff for energy crops based power generation Tar_{el}^{ecp} applies when total share of animal byproducts is smaller or equal to the 30% of total substrates. Mathematically:

$$\left\{Q_J^{ecp} - \left[\left(Q_J^{ecp} + Q_J^{byp}\right) \cdot 0.3\right]\right\} - \left(M \cdot XB_j\right) \leqslant 0 \tag{6.12}$$

imposes the 30% share limit to energy crops mass flows when XB_j equals 0, which implies that XB_j must be 1 when energy crop flows exceed the limit share. Five size classes, here represented by sets s, are introduced for stepped tariffs. For each size class, corresponding binary variables $XS_{s,j}^{PLANT}$ have been introduced, equaling 1 when capacity S_j^{PLANT} of the jth plant is lower or equal to the upper capacity bound S_s for size class s and higher than the upper capacity bound $S_s - 1$ for size class $s - 1$. Logical equations (6.12) to

(6.14) guarantee that each feasible plant falls within a single size and substrate bonus class and that only plants with $XB_j = 1$, i.e. those meeting substrate composition bounds, are eligible for the corresponding tariff.

$$\sum_s XT^{ecp}_{s,j} + XT^{byp}_{s,j} \leqslant 1 \tag{6.13}$$

$$XB_j \leqslant \sum_s XT^{ecp}_{s,j} \tag{6.14}$$

$$\sum_s XT^{byp}_{s,j} \leqslant 1 - XB_j \tag{6.15}$$

6.2.2 Modelling biomethane promotion schemes

The decree of 5 December 2013 promotes the upgrading of biogas to biomethane through the introduction of different incentive levels depending on the utilization pathway (either injection of biomethane in the gas grid or production of CBM), plant capacity and feedstock mix. Thus, to assess the effect of the introduction of such new policy scheme in the biomethane market development, the BIOGASregio model has been further develop to accommodate three different upgrading technologies, having a specific range of sizes and efficiencies.

Due to the complexity of such model configuration, in order to limit the computational efforts, a simplification has been introduced with regard to the biomass input flows: while the previous version of the model discerns between different manure typology, in this latter case an aggregated average animal manure potential have been considered, accounting for the manure mix available municipal level.

A specific parameter characterizing the upgrading processes, is the methane recovery factor ϕ representing the CH_4 content (%) of the biomethane after the purification process. Thus, general equation (6.3) has been transformed in the following form:

$$Evector_{up,j} = \sum_{s,tech} \Big(\eta_{s,tech} \cdot \phi_{s,tech} \Big) \cdot \Big(Prod_{bg_{j,s}} \cdot K_{bg} \Big) \tag{6.16}$$

where $bin_{j,s,tech}$ is a binary variable specifying if the upgrading technology $tech$, having a specific size s, is adopted in the jth plant. The upgraded biomethane $Evector_{up,j}$ may be further injected into the grid or used as a vehicle fuel, as defined by equations (6.16) while at the same time equation (6.17) force the system to select only one of the biomethane utilization pathways.

$$Evector_{up,j} = \sum_f EvectorCBM_{j,f} \cdot binCBM_j + \sum_g EvectorINJ_{j,g} \cdot binINJ_j \tag{6.17}$$

in which f and g are sets accounting for the feedstock mix adopted for the production of biomethane for transport and for injection respectively, since the tariff scheme impose to specify the percent of manure utilized in the digestion process. The same sets can be found in the computation of the annual incomes, expressed in the following equation:

$$R_{up,j} = \sum_{f} EvectorCBM_{j,f} \cdot Tarcbm_f + \sum_{g} EvectorINJ_{j,g} \cdot Tarinj_j \tag{6.18}$$

6.3 Building new refuelling station: a MINLP model

As explained in chapter 4, to explore potential expansion of the CBM market in Friuli Venezia Giulia region, a MINLP model has been developed, which main goal is to estimate whether and where entrepreneurs are likely to invest in CBM refuelling stations under different market scenarios, assuming that their rational behaviour is directed to attain maximum profits.

In order to formulate the decision problem, two main assumptions have been introduced:

- Based on previous break-even analysis, it is assumed that in the municipalities characterized by the presence of gas pipeline only high-pressure refuelling stations (FS) should be built;
- The location of the four existing CNG stations is fixed and their costs are treated from an external viewpoint like the costs of new stations;
- A maximum of one refueling station can be built in each municipality.

The basic variables of the problem are defined as follows:

- $FS_{i,t}$ $i = 1, .., N$: binary variable associated with the ith municipality. Specifically, $FS_{i,t} = 1$ when a station is located in the ith considered municipality, otherwise $FS_{i,t} = 0$;
- $t = 1, 2$ index associated with the refueling station type low pressure or high pressure FS;
- S_i: size of the ith fuel station in kNm^3/year;
- P_i: annual equivalent profit of the ith station, in €/year
- Δ_{ij}: binary variable representing the fraction of demand associated with the jth municipality to be served by a fuel station located in the ith municipality.

The parameter D_i represents the CNG demand in each municipality, calculated by adopting an econometric model, since data on monthly sales of CNG are available regional level and are not discriminate between different sites. Other relevant parameters are the binary parameter HP_i, equalling 1 if the ith municipality is served by a gas pipeline, 0 otherwise, and the distance $dist_{ij}$ between municipalities i and j. The objective function is to maximize the sum of annual equivalent profits of all stations, as shown in equation (6.19):

$$MAX \sum_i \Bigg\{ P_{CNG} \cdot D_i - f \cdot \sum_t \Bigg(C_{FSfix_i} \cdot FS_{i,t} + C_{FSvar_{i,t}} \cdot S_i \Bigg) - sum_t \Bigg[D_i \cdot (C_{el_{i,t}} + C_{main_{i,t}}) \Bigg] - C_{hr_i} \Bigg\} \tag{6.19}$$

where f is the capital recovery factor of a series of uniform amounts, in this case for an interest rate of 7% for 15 years, while other cost and sale price parameters are summarized in section 2.6 of this thesis .

All cost functions are obtained interpolating data obtained by CNG station constructors or managers for at least three different plant capacities. Maintenance costs, in particular, are calculated as a function of capital cost investment, expressed in general terms by equation (6.20).

$$C_{main_{i,t}} = \begin{cases} \mu & for \quad S_i \leqslant Sth \\ \alpha \cdot \Bigg(C_{FSfix_i} \cdot FS_{i,t} + C_{FSvar_{i,t}} \cdot S_i \Bigg) + \delta & for \quad Sth \leqslant S_i \leqslant Smax \end{cases} \tag{6.20}$$

Where Sth represent the threshold size (equal to 350 $kNm^3/year$) below which maintenance costs are assumed equal to a fixed value μ, and Smax is the upper bound size of the model, corresponding to 2000 $kNm^3/year$, which is imposed by equation (6.21).

$$S_i = FS_{i,t} \cdot Smax \tag{6.21}$$

Equations (6.22) and (6.23) aim at determining the capacity Si of the service station located in the ith municipality according to equation (6.20). In particular equation (6.22) express S_i as a weighted sum of demand in the municipality of concern and of demand in other municipalities, which can be partially diverted to the ith station depending on attraction factors (equation (6.23)) related to distance decay functions (equation (6.24)) as indicated in (Frick et al., 2007) and in (Bersani et al., 2009).

With respect to those references, we do not fix a minimum number of stations, as it is our aim to find it through system optimization. On the other hand, the truncation condition we introduce with equation 5 influences the relative distance between stations, in that it imposes that, above a maximum distance d_{max}, (equal to 20 km and corresponding to the maximum daily travelling distance for 80% of European drivers) the attraction of customers to the fuel station drops to zero.

$$S_i = \sum_j \Bigg(\Delta_{i,j} \cdot D_j + D_i \cdot FS_{i,t} \Bigg) \tag{6.22}$$

$$\Delta_{i,j} = \begin{cases} \frac{attr_{j,i} \cdot FS_{j,t}(1-FS_{j,t})}{\sum_i attr_{j,i} \cdot FS_{j,t}} & dist_{ij} \leqslant dmax \\ 0 & dist_{ij} > dmax \end{cases} \tag{6.23}$$

$$attr_{jt} = \frac{1}{t_{ij}} \qquad i = 1, ..., N \qquad j = 1, ..., N \tag{6.24}$$

6.4 Environmental indicators

Following the IPA methodology developed within the ExterneE project, the external costs associated with the emissions of each biogas utilization pathway have been estimated and compared with its corresponding fossil alternative in a three-step procedure. First, the GEMIS database (Fritsche and Schmidt, 2007) was used to identify and quantify the airborne emissions released in each step of the biogas supply chains. Subsequently, the pollutant-specific damage cost factors were estimated using the EcoSenseLE tool. The environmental external cost (EEC) of each energy vector is finally calculated by multiplying the amount of each pollutant arising from the production of 1 GJ of each end-product (e.g., chemical, electric power, heat feeding district heating networks) by its damage cost factor (€/g). Comparing GEMIS with other software packages for process or product life cycle assessment, not only it is freely available, but at the moment of the study, it also possesses the most complete inventories for agricultural biogas processes. The GEMIS software includes the main key energy, material, and transport processes for more than 50 countries and was extended to cover the EU-25 and EU-28 for the years 2000, 2010, 2020, and 2030.

6.4.1 Emissions assessment

To quantify the emissions produced among the biogas supply chain, the system under investigation has been divided in 4 main steps, as highlighted in figure 6.1: farming, feedstock logistics, anaerobic digestion (AD) for the production of raw biogas, and the conversion of biogas to the end energy vectors. Such steps have been analysed by considering their corresponding background processes and their associated emissions, according to the GEMIS database. For consistency, such data have also been compared with those of other studies addressing the environmental impact of the biogas supply chain.

Step I: Farming In this step, the emissions considered refers to maize and sorghum cultivation and harvesting and to manure collection in the farm-based biogas plant. The calculations consider direct emissions from tractor and field machinery operations, including the provision of chemical fertilizers and the digestate management activities, assuming its spreading in the proximity of the biogas plants. For simplicity, the energy crops are assumed to be cultivated on existing agricultural land traditionally assigned for their production, which means that the soil does not change its occupation. In this way, any direct land use change (dLuc) emissions could be excluded, which are mainly caused by modifications in the carbon soil content, as for (Boulamanti et al., 2013; Jury et al., 2010). According to GEMIS, the culture of 1 ha maize over 1 year needs 53.8 kg of P, 56 kg of K and 345 kg of Ca. Such values also include the use of digestate to replace part of the nitrogen fertilizers required for the cultivation. The main assumptions in GEMIS are that the fraction of N as ammonium in digestate represents 65% of its weight, which is an average of the literature data for digestate from manure fermentation and that 120 kg of digestate is annually spread in the field, complying with the maximal legal amount of organic nitrogen fertilization.

Step II: Feedstock logistics Biomass transport to the biogas plant is assigned to a truck trailer with an average capacity of 14 t, based on a gasoil price of 1.1 €/l. Distances between the supply sources and the production plants have been calculated by a GIS-based transport network model. In this way, rather than deriving overall emissions from an average fuel consumption for reference distances as in GEMIS, a specific database for the quantification of the external costs in the transport sector has been used.

Step III: Anaerobic digestion A detailed literature review of studies dealing with methane emissions from biogas production was performed by (Beil and Beyrich, 2013), who reported that limited emissions during digestion are generally considered, ranging from 0.02 to 0.07% of the total methane production. Accordingly, a reference value of 0.43 g/Nm^3 has been considered, corresponding to 0.06% of the total methane production.

Step IV: Biogas conversion technologies Processing the raw biogas to obtain a renewable energy vector such as electricity, heat or biomethane may cause losses of methane, generally classified as uncontrolled losses (Börjesson and Berglund, 2006). However, as the same authors noted, due to difficulties in measuring and quantifying the net losses of methane from biogas production, such data are uncertain and limited. (Liebetrau et al., 2010) analysed the greenhouse gas emissions of ten representative agricultural biogas plants located in Germany with an average installed capacity of 500 kW. He found that the cogeneration unit was the second major source of methane emission along the biogas production chain. Methane leakages ranged from 0.175% to 3.72% of the utilized methane, mostly depending on the equipment employed and the maintenance level of the engines. When considering the biogas-to-CHP process, the GEMIS database sets the losses of methane to 1% of the raw biogas, which can be considered consistent with other sources found in the literature (Liebetrau et al., 2010; Ravina and Genon, 2016). Methane losses during purification can range from 1% to 4% of purified biogas and specifically from 0.5% - 2% of purified biogas when the water scrubber technology is selected (Beil and Beyrich, 2013). Thus, given that purification technology is rapidly evolving and lower losses are expected in the near future, a central value of 1% has been choose, in line with the value indicated in GEMIS.

6.4.2 External cost evaluation

EcoSenseLE is an online tool for estimating external costs due to emissions of a typical source (e.g., power plant, industry, transport) or all sources of a sector in a EU country or group of EU countries. It is a parameterized version of EcoSense, based on European data for receptor (population, crops, building materials) distribution, background emissions (amount and spatial distribution), and meteorology. The cost calculation is based on the ExternE exposure-response function and monetary values, and a user-defined valuation of mortality and greenhouse gas emissions is possible.

Although global warming is certainly among the priority impacts related to air pollution, this impact category is not covered by EcoSense because of the very different mechanism and global nature of the impact.

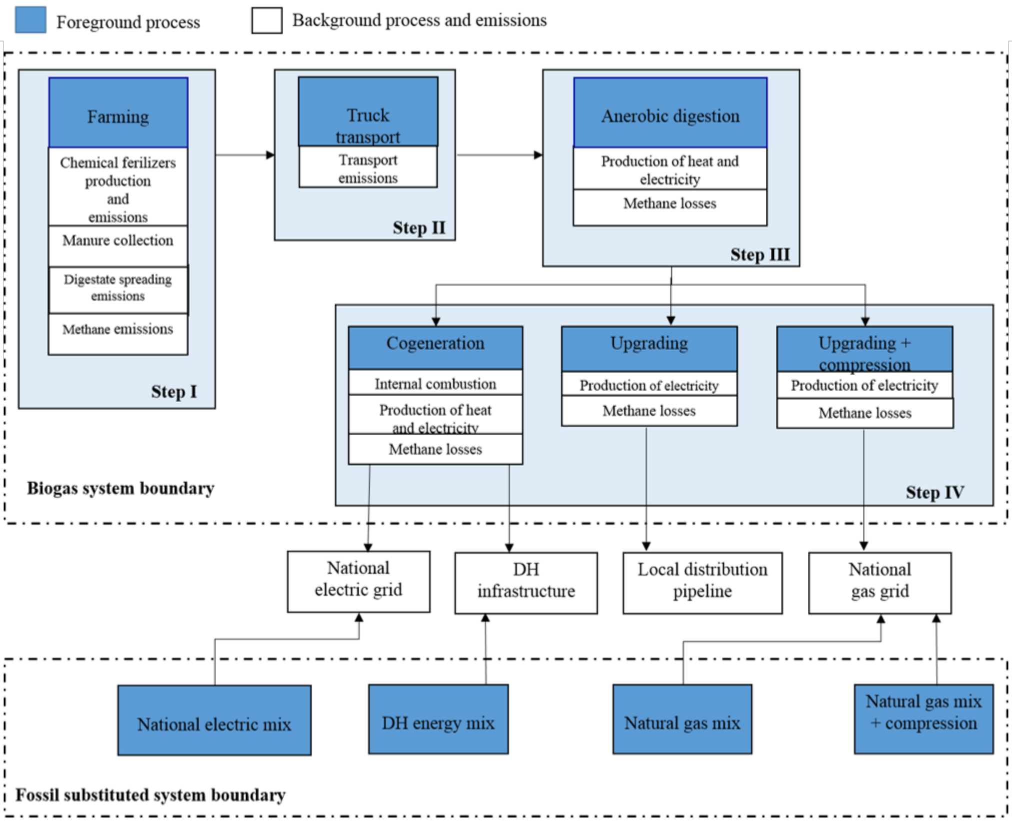


Fig. 6.1. Biogas System and Fossil Substituted system Boundaries

Carbon prices resulting from CO_2 emissions trading represent the development of the avoidance costs in the least cost path towards the 2050 target and are found to gradually increase from 15 €$/tCO_2$ in 2010 to 65 €$/tCO_2$ in 2030 (European Commission, 2011). Various recent studies have moved away from the avoidance cost and instead use external cost factors based on damage costs. At the same time, improved insight into the impacts of global warming has led to higher estimates of these damage costs.

According to Bickel et al., 2006, the external cost factor for CO_2 should depend on the year of emission. For emissions in the following decades, increasing external cost factors are recommended: 26 €$/tCO_2$ for 2010-2019, 32 €$/tCO_2$ for 2020-2029, and 40 €$/tCO_2$ for 2030-2039. Following the damage cost approach, a central value of 26 €$/tCO_2$ has been adopted.

With regard to the fossil energy vectors considered in this study, determining the exact location of the pollution sources is not always possible (e.g., 90% of the Italian natural gas demand is met by imports from several countries, including Russia, the Netherlands and Algeria). Thus, average European (EU27) damage cost factors have

Energy source	N_20	CO_2	CH_4	NO_X	SO_2	NMVOC	NH_3	PM_{10}
Fossil	7.24	0.026	0.575	7.06	6.75	1.06	12.71	15.2
Biogas	7.24	0.026	0.575	3.66	4.26	1.89	11.28	18.2

Table 6.1 Damage cost factors for fossil and biogas based energy sources (€/kg)

been used instead, as table 6.1 highlights.

Conversely, in this study, the locations of the feedstock and the energy infrastructures have been mapped in a spatially explicit way, which allows considering national Italian data from EcoSenseLE when calculating the damage cost factors of the biogas energy vectors

6.5 Energy indicators

As for the emission assessment, the GEMIS database has been used for quantifying the energy consumption occurring along the biogas supply chain. Table 6.2 summarizes the main value adopted in this thesis, accounting for the electric energy, heat and gasoline demands and considering the same process steps identified in previous section.

Field machinery operations are assigned to a tractor having an operating time of 2500 h/year and a specific fuel consumption of 10.5 MJ/km. The electricity consumption considered for the anaerobic digestion (for pumping, stirring, etc.) was 4% of the amount of energy in the biogas produced, which corresponds to 0.15 kWh/Nm^3 of raw biogas. For comparison, the electricity consumption in anaerobic digestion reported in the literature varies between 0.12 and 0.27 kWh/Nm^3 (Buratti et al., 2013; Lantz and Börjesson, 2014). The same authors reported a specific thermal energy consumption between 0.60 and 0.85 kWh/Nm^3 of biogas, in line with the value of 0.70 kWh/Nm^3 indicated by GEMIS. The electricity demand for the biogas purification can range from 3% - 6% of the energy content in the biogas produced (Lantz, 2012), depending on the compression required. Within the system boundaries considered in this study, the biomethane is supposed to be injected into a low-pressure gas network (4 bar), so the specific electric demand has been estimated as 0.23 kWh/Nm^3, which is in line with (Lantz and Börjesson, 2014).

A major compression is required when the purified biogas is used as a vehicle fuel as it is assumed to be transported to an existing refuelling station with an operating pressure of 200 bar. Thus, when considering the CBM technology, the use of a centrifugal compressor is assumed according to the technical information founded in GEMIS, which leads to an additional electric demand of 0.53 kWh/Nm^3 of purified gas, in line with (Jury et al., 2010).

To allow aggregation operations, the energy flows occurring along the biogas supply chain have been considered by means of a common physical unit of account, used to measure all energy produced, processed and consumed, so-called ton of oil equivalent

(TOE) .

Step	Activity	Technology/equipment	Energy vector	value	Unit
I	Field machinery operation	Tractor	Diesel fuel	10.5	MJ/km
II	Transport of feedstock	Hauler	Diesel fuel	10.5	MJ/km
III	Anerobic digestion	Continuously stirred tank reactor	Electricity	0.15	kWh/Nm^3
			Heat	0.70	kWh/Nm^3
IV	Biogas upgrading	PWS technology	Electricity	0.23	kWh/Nm^3
	Compression	Centrifugal compressor	Electricity	0.53	kWh/Nm^3

Table 6.2. Energy consumptions occurring among the biogas supply chain

7

Results and discussion

This chapter presents the main results obtained for each of the case studies presented. The analysis have been differentiated according to the geographic context considered.

7.1 The Friuli Venezia Giulia scenario

The results of case study I refer to the application of the incentive schemes for the production of bioelectricity alone, in terms of biogas plants locations and feedstock mixes. The economic (e.g. changes in public expenses for bioelectricity support) and the social consequences (e.g. reduction in labour costs and thus in employments positions) of applying such policy instruments in the territory of concern have also be addressed. The prospects for the development of the CBM fuel in the region have been analysed in case study II by comparing the economic performance of different biogas utilization pathways under their corresponding supporting mechanisms.

In order to overcome the chicken and egg dilemma, introduced in the first chapter of this thesis, the CBM demand adopted in this case study has been previously calculated by means of the attraction model described in chapter 4. Subsequently a sensitivity analysis on the main model parametershave been conducted, which have found to influence the adoption of the biogas technologies, in order to observe changing in the model optimal solution at environmental level (i.e. total GHG reduction), economic level (i.e. ratio of public investment) and energetic level (i.e. reduction in total primary energy consumption).

It should be remembered that, as just only one district heating system exists in the region, the CHP option has been excluded as potential biogas utilization option from case study I and II.

7.1.1 Previous policy schemes and cogeneration support: Case study I

In the first case study, in order to assess the economic effects of previous and actual biogas energy policies at regional level, four scenarios of analysis were created. The previous support scheme (PSS) scenario has features and constraints of the 2009 tariff scheme, while in the future support scheme (FSS) scenario energy prices are differentiated by plant classes and feedstock mix, according to the 2012 tariff scheme. It is also interesting to consider two cost minimization scenarios, named CM_PSS and CM_FSS, where a mandatory share of electricity production is imposed, corresponding to the economic potentials calculated by the optimization procedure for scenarios PSS and FSS, respectively.

In this way, we identify minimum costs supply chains configurations and estimate minimum production costs to obtain the same energy output, which would lead to maximum profits in absence of stepped in tariffs, so to highlight the impact of incentive mechanisms on the optimal size of biogas plants and on energy costs. The main results for the analyzed scenarios are summarized in Table 7.1.

Changes in optimal solutions between PSS and FSS scenarios

In the PSS scenario the additional economic potential reaches almost 38 MW, that is more than 4 times as much as existing total capacity (at the moment 4 biogas to power plants exist in the territory), and 38 new plants would be feasible, with an average size of 998 kW and virtually no variance: the homogenization process described in literature is thus confirmed by the model. In the FSS scenario, the additional capacity would be 5.1 MW (that is about 60% of the existing one) spread over seventeen 300 kW plants. Hence, homogenization seems probable also in future, although stopping at a smaller optimal capacity. Although economically viable from an NPV viewpoint, the implementation of such additional capacity seems unlikely looking at other profitability indicators. Average payback time would increase from 3.6 years in the PSS scenario to almost 9 years in the FSS scenario, and the IRR estimated by sensitivity analysis as shown in figure 7.1 would decrease from more than 30% (PSS) to 7% (FSS). The assumption of 15 years investment duration may be restricting in evaluating the FSS scenario, in that we neglect incentives between the fifteenth and the twentieth year. Infact, figure 7.1 (second x-axis, referring to years) shows that the increment in NPV when considering the 20 year time horizon in the FSS scenario is significant (reaching about 18 million €in 20 years, against almost 1.8 million €in 15 years over the examined area). Nonetheless, considering the profitability chances investors were accustomed to under the PSS (the NPV over 15 years being almost twice as much as investments, with the PSS, and is less than 3% of investments, under the FSS, see Table 7.2), attracting new investors under new conditions seems very challenging.

Thus, the potential annual net electricity production of 95 GWh under the FSS scenario (compared with 328 GWh with PSS), contributing with less than 1% to regional RES-E targets, may even be optimistic. Consequently, the reduction in public expense for bioelectricity support within the examined boundaries, which declines from about 77 million €in the PSS scenario to less than 11 million Euro in the FSS scenario, might be more remarkable, in that even the restricted number of economically feasible plants would not be actually commissioned under the future scenario. While it may be desirable that subsidies to non cogenerative plants are abated, given the little environmental benefit deriving from such technology option as compared to other biogas utilization pathways, a social drawback is the reduction in labor costs and ultimately in jobs.

	Variable	Unit	PSS	CM_PSS	FSS	CM_FSS
TECHNICAL INDICATORS	**Number of power plants**	dimensionless	38	15	17	4
	Total power capacity	kW	46,170	46,170	13,372	13,372
	Mean of manure share	% on total substrate weight	20.3%	59.2%	100%	100%
	Average plant capacity	kW	998	2.430	300	1,672
	Average supply area (maize silage)	km²/plant	96	197	-	-
	Average supply area (cattle manure)	km²/plant	124	202	215	469
	Average area for digestate spreading	km²/plant	61	76	89	80
	Saturation of digestate spreading areas	% on maximum permissible nitrogen input	99.3%	98.6%	61.6%	51.9%
ECONOMIC INDICATORS	**Average power production cost**	€/kWh	0.209	0.187	0.185	0.171
	Total annual revenues	k€/year	7,753 93,650	75,184 9,018	17,797	11,360
	(thereof from power sale)		(23,931)	(23,931)	(6,931)	(6,931)
	Direct labor cost	k€/year	1,800	955	550	400
	(Indirect labor cost)	k€/year	(13,968)	(10,913)	(3,019)	(2,766)
	Total Investment cost	k€	188,102	171,394	62,796	51,089
	Net Present Value	k€	319,138	220,093	1,793	-620
	Payback	year	3.6	4.25	8.85	>15 years

Table 7.1. Optimization results under defined scenarios

Table 7.2 presents direct labor costs estimated as explained in chapter 5. Indirect labor costs are estimated as a proportion of maintenance costs (we assume that 40% of maintenance costs derive from consumable materials and spare parts, adapting cost factors reported by Karellas et al., 2010), of maize silage production costs, feedstock transportation and management costs and of digestate management and transportation costs.

Assuming an average worth of one man year of employment equal to 40000 €, al-

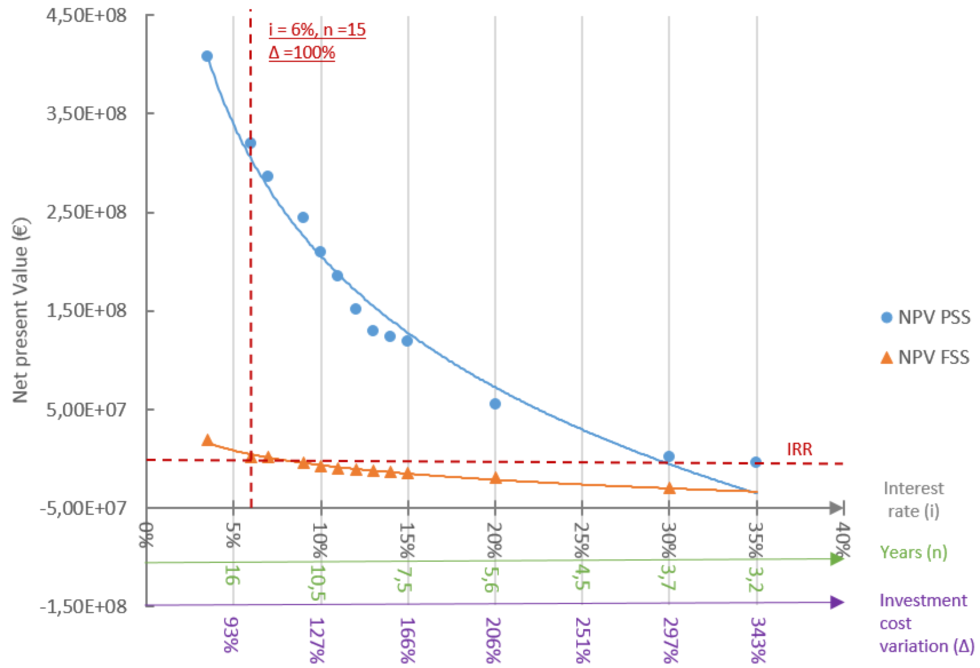


Fig. 7.1 Sensitivity analysis of NPV with respect to factors affecting annual equivalent capital costs

most 350 man years were created under the PSS against about 75 man years under the FSS. Dividing by net electricity production, it means 1.06 man years/GWh under the PSS, against 0.8 man years/GWh under the FSS. The first value is in good agreement with employment factors of 1.27 man years/GWh estimated by Thornley et al. (2008) for biomass power plants, as we did not consider indirect labor for equipment design, manufacturing and installation.

The significant reduction in job creation under the FSS mainly depends on the exclusion of maize from feedstock. As shown in Figure 7.2, the contribution of maize production, which accounts for more than 50% of operative costs in the FSS scenario, becomes nil in the PSS scenario.

In fact, besides reducing the additional potential for non cogenerative agricultural biogas plants by a factor of almost eight, the new tariff system also minimizes chances for maize as a substrate. As reported in Table 7.1, under the old scheme the average weight share of manure was about 20% in the optimized solution, with 80% coming from maize silage, with a total substrate production of about 687 kt/year. Under the new tariff scheme, viable biogas plants would use animal manure as single feedstock and, given its low energy density a total quantity of about 256 kt/year is required in the FSS scenario to produce less than 30% of the electricity produced in the PSS scenario. The estimated optimal solution with 100% manure based plants is an extreme, depending on the fact that our linear programming model cannot account for positive synergisms that improve biogas yield in co-digestion of different substrates, but it indicates that maize production for biogas generation is not affordable under the new support scheme.

Figure 7.2 shows that the enhanced use of animal manure as substrate results in a higher impact of biomass and digestate transportation and management on total costs. In spite of plant size reduction, the surface of feedstock supply and digestate spreading areas grows.

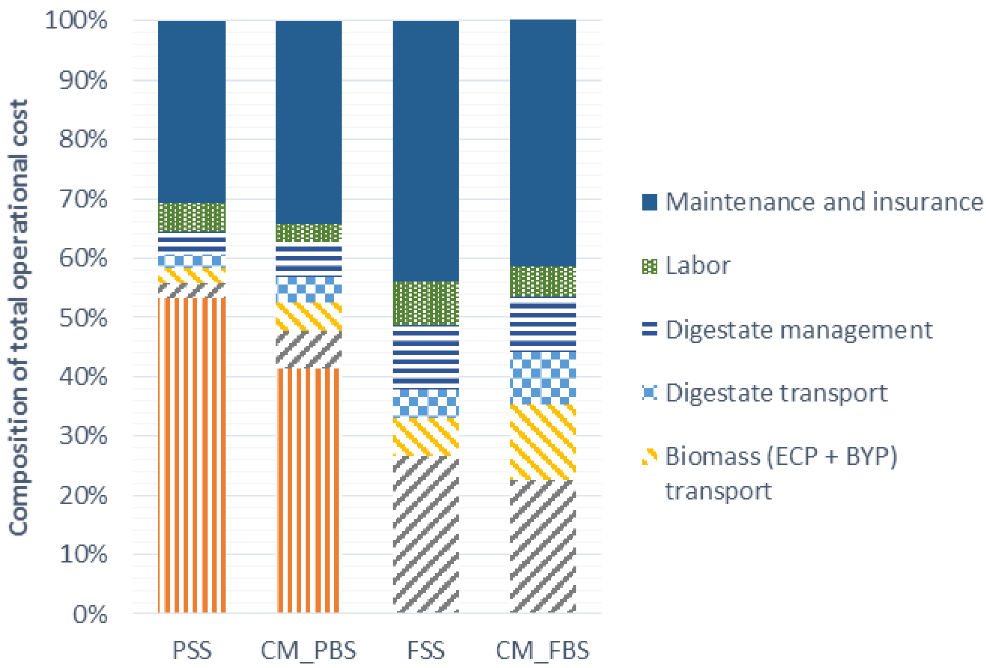


Fig. 7.2 Operational cost structure under different scenarios

As reported in Table 7.1 and highlighted graphically in Figures 7.3 and 7.4, in the case of cattle manure average supply areas increase from 124 km^2 under the PSS to 215 km^2 under the FSS. Also areas for digestate spreading increase from 61 km^2 under the PSS to 89 km^2 under the FSS: this is a consequence of the lower energy density of manure as feedstock, which results in larger input and byproduct quantities, as found also in similar work by Delzeit and Kellner (2013). Compared with feedstock supply, areas for digestate management are smaller and it is usually easier to respect distance limits for net environmental benefits (e.g. 95 km for cattle manure and 19 km for maize silage according to Pöschl et al., 2012). Nitrates Directive constraints for digestate spreading calculated with our assumptions are a limiting factor under the PSS (saturation is almost

100%): more advanced digestate management techniques would have been an interesting option in that case. Under the FSS, saturation decreases significantly; the viability of techniques for nitrogen content reduction in digestate could be evaluated at the light of specific incentives in the FSS, but there would be probably less pressure to adopt them as fewer plants would be commissioned.

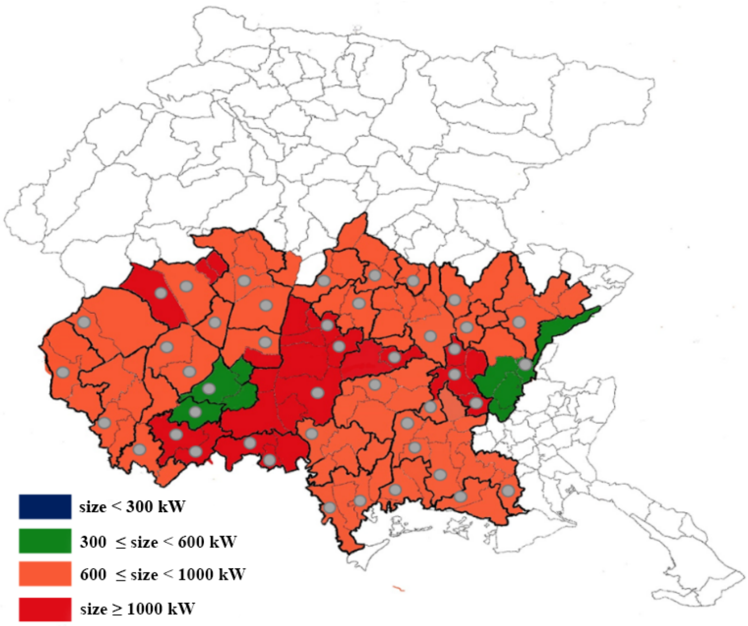


Figure 7.3 Plant locations, capacities and cattle manure supply areas - PSS Scenario

Changes in optimal solutions between profit maximizing and cost minimizing scenarios

Pursuing the minimization of electricity production costs as in the CM_PSS and CM_FSS scenarios would be rational, in that target bioenergy shares would be obtained at highest economic efficiency. However, it would be undesirable under many respects: table 7.2 shows that large size plants would be built and manure would be preferred as feedstock (a 5.1 MW manure based plant is the only additional plant built in the CM_FSS scenario), with a remarkable expansion of feedstock supply areas (469 km^2 in the CM_FSS scenario compared with 215 km^2 in the corresponding FSS scenario, which takes tariffs into account).

Digestate disposal area remains almost unchanged, because substrate consumption is lower thanks to better efficiency. In fact, larger plants may not only reap economies of scale, but also benefit from higher power generation efficiency, because larger and slower

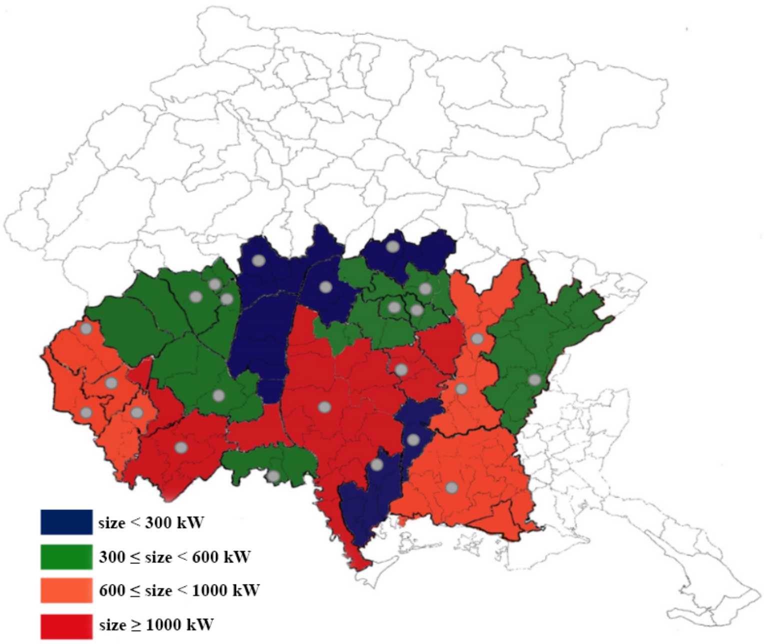


Fig. 7.4 Plant locations, capacities and cattle manure supply areas - FSS Scenario

internal combustion engines are more efficient and because the minimum capacity for technical and economic feasibility of ORC bottoming cycles can be achieved.

Optimal sizes and combinations of technologies depend on local feedstock availability, optimal solutions include only bottoming cycles with a power capacity of at least 500 kW, which can be sustained by heat recovery from ICEs with a power capacity of at least 2900 kW. Such large plants are, however, only introduced in cost minimization scenarios, which do not account for feed in tariffs in their objective function.

This implies that, both under the previous and the future biogas support schemes, better efficiency and lower specific costs do not compensate for reduced values of tariffs (or of TGCs, in the CM_PSS scenario) introduced for larger capacities. Because of lower revenues from support mechanisms, net present values are significantly smaller and payback times are longer under cost minimization scenarios than under corresponding profit maximization scenarios. Under the CM_FSS scenario, the investment does not even pay off, even though the electricity production cost is at its minimum, with 0.171 €/kWh.

Such cost estimates agree well with those by Pantaleo et al. (2013) and are somewhat higher than those by Walla and Schneeberger (2008), mainly because of higher estimated capital expenditures, based on Italian market conditions. Walla and Schneeberger reference dates back to 2008, but given moderate inflation in the last few years and considering similarities between our region and Austria, as well as geographical proximity, it is likely that previous Italian incentive schemes have contributed to higher plant costs. The FSS may change this, in that, as shown in Figure 5, examining the third x-axis (investment cost variation) we observe that a capital expense reduction of about 20% would be needed to significantly improve NPV under the future support scheme.

Comparing profit maximization and corresponding cost minimization scenarios, is clear that the estimated increase of leveled electricity costs due to support mechanisms is moderate: under the PSS, average electricity cost grows by about 12%, from 0.187 €/kWh in the CM_PSS to 0.209 €/kWh in the PSS scenario, while under the FSS average electricity costs grows by about 8%, from 0.171 €/kWh to 0.185 €/kWh under the CM_FSS and the FSS scenarios, respectively. Outcomes of these additional expenses would be higher investments (more than 16 million €under the PSS, about 12 million €under the FSS), more direct and indirect jobs (for a total of about 4 million €/year under the PSS, about 0.4 million €/year under the FSS), and smaller plants, which usually benefit from higher social acceptance.

It should be highlighted that cost minimization - which is likely to be pursued in case of flat feed in tariffs - is associated with higher variability of optimal size, while stepped feed in tariffs cause homogenization of plant capacity under both support schemes.

7.1.2 New refueling infrastructure development in Friuli Venezia Giulia

Based on what mentioned in the introduction, the lack of CNG penetration in the regional market is mainly due to the limited number of fuel stations in the territory, and consequently, to the limited number of CNG vehicles.

In August 2010, in order to overcome the chicken and egg dilemma, a legislative decree has been issued by the regional government (L.R.14/2010), relating to subsidies' disbursement for the establishment of CNG fuel stations in the region. Such subsidies were proposed in the form of outright grants for maximum value of 50% of the total construction expenditure.

In order to quantify the potential effect of such subsidies in the choice of theoptimal location and capacity of the additional refueling infrastructure, the MINLP model presented in chapter 4 has been adopted, and four scenarios of investigation have been created:

(a) At current demand levels, with no subsidies;

(b) At current demand level, with the 50% capital grant foreseen by the regional government;

(c) With double demand level, with no capital grants to stations;

(d) With double demand level and 50% capital grant.

The results are presented in figure 7.5, in which the presence of the high pressure gas pipeline have also been mapped.

The analysis of the current scenario (a), leads to conclude that only four stations would be sustainable at current conditions with no subsidies, meaning that the actual distribution of refuelling infrastructure in the region is sufficient to fulfill the CNG demand (indeed, the total capacity of such FS is nearly equivalent of the existing ones, as figure 7.6 shows).

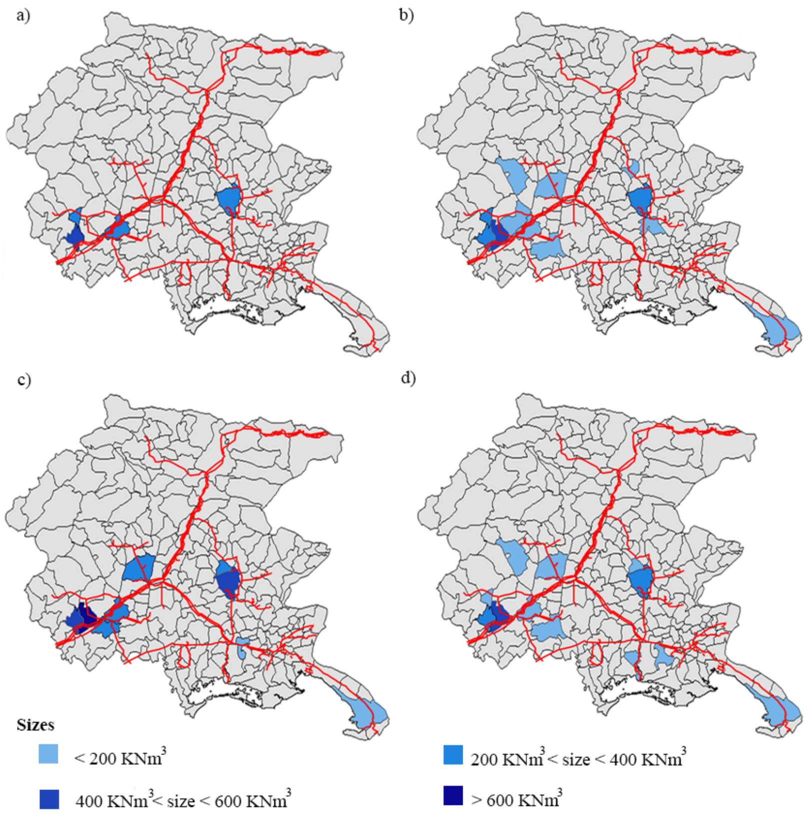


Fig. 7.5 Sizes and locations of prospected refuelling stations

On the other hand, the effect of subsidies, under both present (b) and increased (d) demand level foresees a proliferation of up to twelve micro-plants with an average capacity of 140 kNm^3/year and 160 kNm^3/year respectively. Such configuration does not adequately capture the expected rational behavior of the investors especially given the average plant sales at national level, which can be estimated at about 940 kNm^3/year. To this respect, an average plant capacity of 350 kNm^3/year is already viable at the financial conditions we assume (i.e. 7% interest rate for 15 years).

To this end, increasing the number of CNG vehicles alone (scenario c) seems the most technical feasible option, as it would lead to overall smaller investments (which however would not benefit from any public co-founding) but an increment of the average capacity

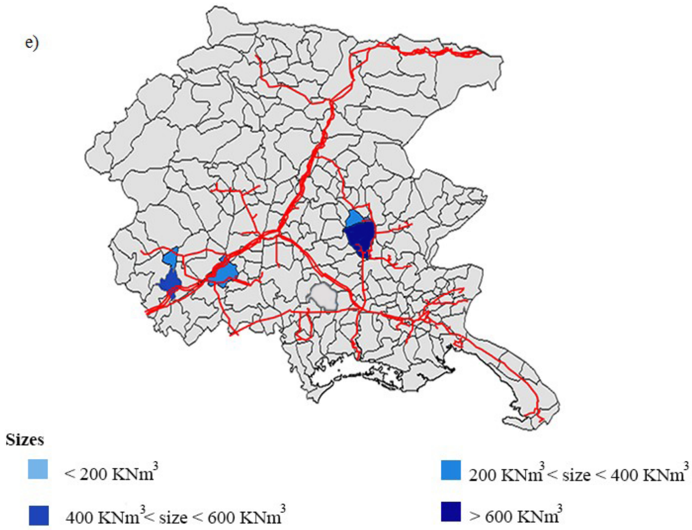


Fig. 7.6 Sizes of prospected refuelling stations (reference scenario)

(almost 450 kNm^3/year). Post-analysis discussion with constructors who provided cost data pointed out that, based on experience, a minimum size of about 400 kNm^3/year should be economically feasible. This size is smaller than the national sales average, probably due to the more recent practice of upgrading existing gasoline refueling stations - which requires less investment - rather than building standalone stations selling CNG only, which was common practice in the Nineties due to competition and legislation barriers.

Moreover, looking at the results obtained for each scenario, two main conclusions can be gathered with regard to the location of the potential refuelling stations. Firstly the fact that the presence of the high pressure pipeline is a determinant of the siting strategy: only in scenario (b) and (d) two stations with LP connection are installed, which is consistent with their very low average capacity. In addition, even under the presence of public subsidies, entrepreneurs are more likely to choose location close to the existing refuelling stations, while other areas result unexplored. This fact however can be seen as a natural consequence of the chicken and egg dilemma, meaning that areas with high CNG vehicle numbers would still represent the favorite choice.

The capacities and locations of the prospected refuelling stations have been adopted in case study II so to consider different levels of CBM in the region of concern. Since the results of the public grants introduction (scenario b and d) have been deemed as unrealistic based on the above discussion, they have been excluded from the analysis.

7.1.3 New policy schemes and biomethane promotion: case study II

Including all the potential biogas utilization pathways in the BIOGASregio model (with the exclusion of the CHP technology, for the aforementioned reasons), the biogas to power option is confirmed the preferred economic choice.

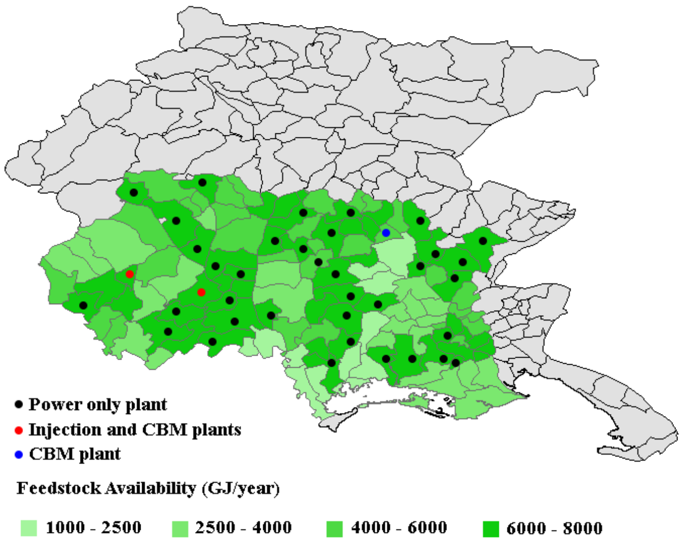


Fig. 7.7 Optimal plant locations under given scenario

The baseline scenario, accounting for the current biogas promotion schemes and considering the results of scenario e) as CBM demand level, foresee the introduction of 42 small power plants, having an homogeneous capacity of 300 kW, in line whit the results obtained in the FSS scenario of case study I. On the other hand, the increment of total power capacity (passing from 5,100 to 12,600 kW) can be perceived as a natural consequence of the biomass flow simplification described in chapter 4, leading to smaller area with higher energy density. New upgrading facilities for biomethane injection and for CBM production are also introduced; although the biogas converted to biomethane represent only 13% of the total biogas produced in the area of concern.

Considering the suggested plant locations depicted in figure 7.7, it can be noticed that injection is always jointly performed with CBM in area characterized by higher biogas potential rather than higher CBM demand. In fact, comparing figure 7.6 and 7.7 it can be noticed that the two municipalities at higher CBM demand, due to the scarcity of feedstock availability, are never selected. In other terms, fulfilling the CBM demand and thus investing in additional capacity, would incurs extra transport and procurement costs, which under the current circumstances, is not economically feasible.

Thus, under such level of biomethane incentives, the CBM technology represent the

Group	Variable	Unit	Power only	INJECTION	CBM
TECHNICAL INDICATORS	Number of plants	dimensionless	42	2	3
	Total capacity installed	kW - Nm^3/h	12,600 (kW)	126 (Nm^3/h)	264 (Nm^3/h)
	Mean of manure share	% on total substrate weight	80%	70%	70%
	Average plant capacity	kW - Nm^3/h	300 (kW)	63 (Nm^3/h)	89 (Nm^3/h)
	Biogas allocation	% on total biogas production	71	11	16
	Saturation of digestate spreading areas	% on maximum permissible nitrogen input		92%	
ECONOMIC NDICATORS	Total annual revenues	k€/year	21,172	741	2,226
	Public expenses	% of total investment		67	
	Net Present Value	k€		13,533	
	Payback	year		8.32	
OTHER INDICATRS	GHG balance	Kg$_{CO_2}$ /year	-38,576	-906	-2,269
	Primary energy balance	TOE/year	-16,776	- 541	-656.81

Table 7.2 Optimization results for baseline scenario

second best choice, especially considering the lower size of the injection facilities (which are 30% smaller than the CBM plants as table 7.2 shows).

The overall preference of smaller capacities for each technology option, can also be explained by considering the digestate saturation level (92%) indicating that the feedstock utilization, and thus the optimal size of the plants, is constrained by the spreading limits imposed in each municipalities. The high level of land saturation its explicable by considering the higher utilization of manure as feedstock (reaching the 80% in case of the upgrading plants) which in turns indicate that, increasing the consumption of energy crops, and thus reducing the amount of digestate to be managed, is not economically feasible .

Since the reference scenario foresees a mix of biogas technologies, the net present value as well as the revenues obtained in such configuration is not comparable with the value obtained in table 7.1 for the FSS scenario. However, considering the aggregated indexes, it can be noticed that the combined introduction of different incentives schemes results in a smaller payback, due to a higher investment profitability.

Scenario analysis

As mentioned in chapter 4, after a first screening process, five key parameters have been choose for conducting a sensitivity analysis on the model optimal solution. In particular, to assess their magnitude effect on the optimal technology mix, two additional scenarios (worst case scenario and best case scenario) have been carried out, as table 7.3 describes. Main results have been summarized in table 7.4.

In the worst case scenario, when the subsidies level for biomethane injection and for bioelectricity are 30% lowered, only to 2 CBM plants are feasible, is spite of the higher incentive cut (34%) applied for such option. Thus, the current structure of CBM incentive scheme, which also support the construction of additional refueling stations, promotes the upgrading to biomethane for transport application as the most robust solution in terms of expected profitability. On the other hand, the restriction on digestate spreading and the lower CBM demand are found to have any impact in the model optimal solution, since under such incentive levels, any other investment in biogas technologies is economically practicable.

The injection technology, which represent the worst economic choice under present circumstances, sees a sharp growth in the best case scenario: a 30% increment of the FITs for biomethane production would foster the installation of additional 37 injection facilities (corresponding to the production of more than 44,000 kNm^3 of biomethane for heating purposes) compared to the baseline scenario.

Parameter	Symbol	Unit	worst case	baseline	best case
D	D	kNm^3/year	Scenario (a)	Scenario (e)	Scenario (c)
N_{max}	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

Table 7.3 Main values of the key parameters for each scenario of analysis

Similarly, also the number of biogas to power plants grows, although the smaller size (300 kW) remains the unique feasible capacity to be installed. The choice of such reference size, rather than the effect of low biogas subsidies, seems to be a natural consequence of the digestate land saturation under such scenario: even with generous digestate spreading permits (340 kg/ha of nitrogen to be distributed) only the 1% of the total agricultural area is still available for digestate management.

Looking at the economic performances of such scenario, an overall lower public investment ratio can be appreciated, meaning that introducing abundant subsidies for each biogas conversion technology would certainly attract more investors, thanks to the increased profitability of such solutions. However, it should be clarified that the annual regional investment required in this scenario, would entail a public expenses of more than 60 €/year for each person, which seems far to be acceptable by public opinion.

	Variable	Unit		worst case	baseline	best case
TECHNICAL INDICATORS	Number of plants	dimensionless	Power only	0	42	60
			Injection	0	2	39
			CBM	2	3	9
	Total capacity installed	kW	Power only	0	12,600	18,000
		Nm^3/h	Injection	0	126	5,636
			CBM	181	264	605
	Average plant capacity	kW	Power only	0	300	300
		Nm^3/h	Injection	0	63	144
			CBM	90	88	68
	Mean of manure share	% on total substrate weight	Power only	0	70%	43%
			Injection	0	80%	60%
			CBM	80%	80%	78%
	Biogas allocated to CBM production	% on total biogas production		100	16	3
	Saturation of digestate spreading areas	% on maximum permissible nitrogen input		1%	92%	99%
ECONOMIC NDICATORS	Total annual revenues	k€/year		1,107	24,139	78,471
	Private investment	k€/year		1,377	25,518	116,882
	Public subsidies	k€/year		860	17,027	67,525
	Public expenses ratio	% of total investment		62	67	57
	Net Present Value	k€		265	13,533	287,034
	Payback	year		3.20	8.32	2.72
OTHER INDICATRS	GHG balance	$Kgco_2$ /year		-1,559	-41,751	-104,806
	Primary energy balance	TOE/year		-451	- 17,973	-51,578

Table 7.4 Optimization results for the scenario considered

Design of experiments

The DOE analysis has been carried out to test the combined effect of the aforementioned key parameters (here shortly described as C,N,D,E,I according to the symbolism of table

7.3) . The goal in this case was to assess which indicators would effect most the optimal solution in terms of economic profitability and of environmental performance of the overall system, and which effect would derive from their combined variation. Results are reported in figures 7.8-10.

Increasing the level of biogas incentives for electricity (E) and for biomethane production (C,I) would surely attract more private investments in biogas technologies: both the single and combined growth of such indicators would reduce the public investment ratio as depicted in figure 7.8. In particular, the injection technology would be perceived as the most attractive investment (in spite its bad environmental performances that will be further described in case study III).

However, the joint growth of parameters C and I is least effective in terms of upgrading plants installation: beside the injection technology, when also the CBM production becomes highly profitable, a conflicting relation between the two technologies emerges, limiting the increase of private investment in both technologies. Heavily subsidizing the production of electricity alone is also least effective, mainly because of the higher level of private investment required for each biogas to power solution.

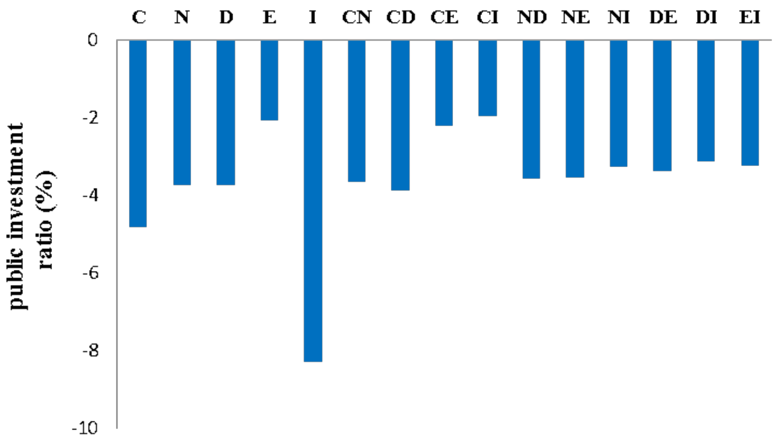


Fig. 7.8 Public investment variation

Important hints on the subsidizing effect on the digestate land saturation can be gathered when considering the effects on GHG balances and on primary energy consumption depicted in figure 7.9 and 7.10.

Each indicator contribute to reduce the GHG emissions of the chain, as the substitution of fossil energy vectors would certainly led to negative emission balance. However, looking at the NE interaction in both figures 7.9 and 7.10, it is clear that the installation of 60 power plants encountered in the best case scenario is the main cause of the 99% land saturation. In fact increasing FITs for electricity production would simultaneously increase the profitability of the biogas to power option, allowing the introduction of an higher share of energy crops (in fact the ratio of manure adoption in such stops at 43%

under such plant configuration) and thus increasing the land requirement for digestate spreading.

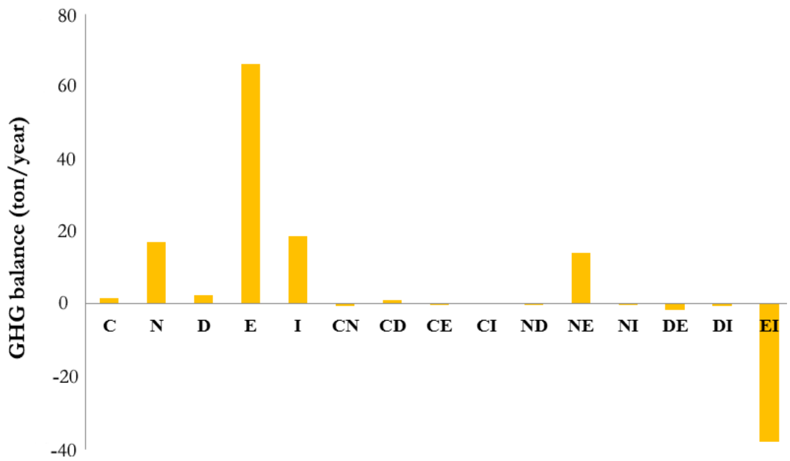


Fig. 7.9 GHG balance variation

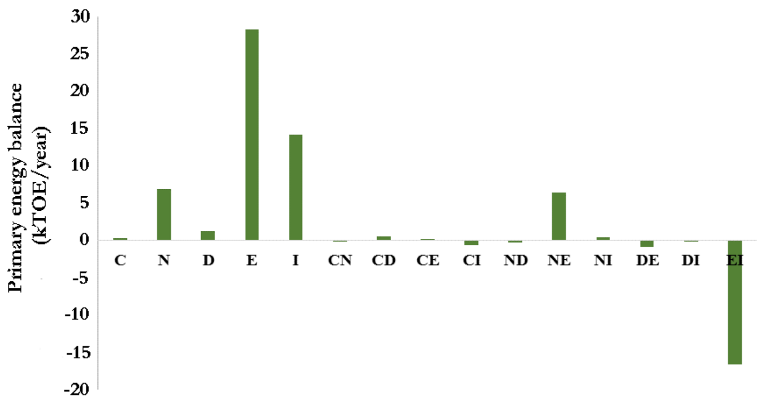


Fig. 7.10 Primary energy balance variation

Figures 7.9 and 7.10 also suggest a very small positive effect of the level of CIC for biomethane production on the overall energy and environmental balance. Again, this fact is not mainly due to limited environmental benefits of CBM solution, but rather depends on the limited CBM demand in the region of concern. In fact the resulting 605 Nm3/h of CBM produced in the best case scenario, are very small compared to the corresponding injection capacity (5,636 Nm3/h) but sufficient to meet the CBM demand level of the overall territory. Thus, rather than being constrained by its market profitability, the adoption of such technology in the region, is constrained by a low rate of CNG vehicles.

7.2 The North Italian scenario

In case study III and IV the environmental and economic impact of adopting the CBM in Northern Italy has been assessed and compared to other utilization pathways. In addition it is also investigate whether the environmental taxes introduced in chapter 2 might efficiently foster the development of such transport fuel. To this end, in order to compare the environmental benefit of each solutions, the most relevant indicators have been expressed in Joule.

In case study III, the carbon price mechanism is compared with other options such as price premiums on biomethane or electricity costs. In this way, the biogas utilization pathways have been addressed with respect to both their economic efficiency and their contribution to GHG emission reduction.

Conversely, in case study IV, three different policy options have been analyzed: a baseline with no internalization of external costs, a global emission oriented policy focused on the external costs of GHG emissions and a full emission oriented policy, which also internalizes the costs of the main air pollutants. In order to quantify the contribution of the greenhouse gases to the overall externalities, beside the scenario accounting for the local as well as the global effects of the airborne pollutants (full scale scenario), an additional scenario (global scale scenario) has been carried out, for which CO_2 equivalent emissions alone have been considered.

Thus, in the baseline scenario, production costs are internal costs only, while in the global scale scenario they include GHG external costs, internalized through e.g. carbon taxes, and in the full scale scenario they include also the external costs of other emissions, whose impact is mainly local. In this way it is possible to determine the most feasible technology mix, both in terms of economic profitability and environmental impact reduction, when the externalities are partially or totally internalized and when they are neglected. For the three scenarios, a sensitivity analysis to changing feed-in-tariffs for each bioenergy vector considered in the study has been performed.

7.2.1 Carbon price application: case study III

In order to derive the optimal mix of biogas conversion technologies under different climate change mitigation scenario several levels of carbon price have been applied to the model, ranging from 12 €$/tCO_2$, (corresponding to the average CO_2 allowance price under the EU ETS in 2011), to a maximum value of 120 €$/tCO_2$.

Figure 7.6 highlights the trend of the annual net cost for new plants introduced by the optimization procedure in the area of concern (continuous lines in the figure). Net costs account for all cost components of each technology option reduced by the income obtained under the current level of market sale prices of their energy output. Costs are compared with incomes deriving from the emission reduction for each option under the corresponding CO_2 price (dashed lines). It can be seen that, for lower carbon prices, no additional biogas plants are installed.

The first selected technology is CHP, with the first plant installed at 15 €/tCO_2. With increasing carbon prices, CHP plants grow in number until the value of 70 €/tCO_2 is reached, when the first upgrading plant for CBM production is introduced into the optimal mix. Above this value, the number of CBM plants increases and 32 facilities are set up when the carbon price reaches 120 €/ tCO_2.

The calculation with the CO_2 price set to 100 €/ tCO_2 has been chosen as a reference scenario for further analysis. In this scenario, an additional 490 CHP plants are installed; the optimal solution also includes nine CBM facilities, while the injection technology option is neglected.

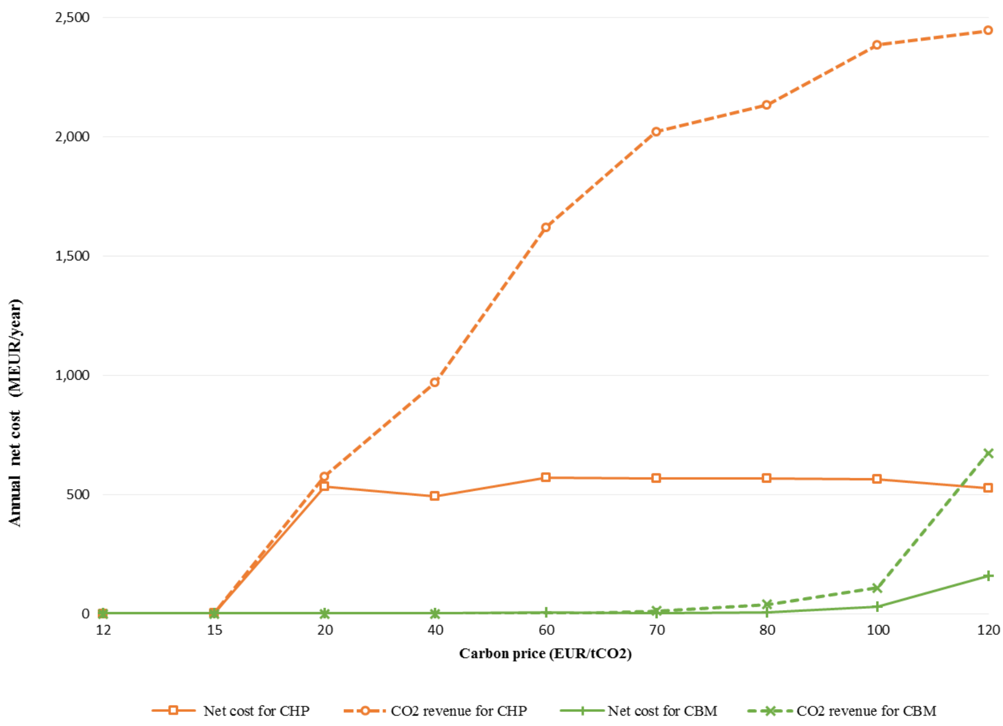
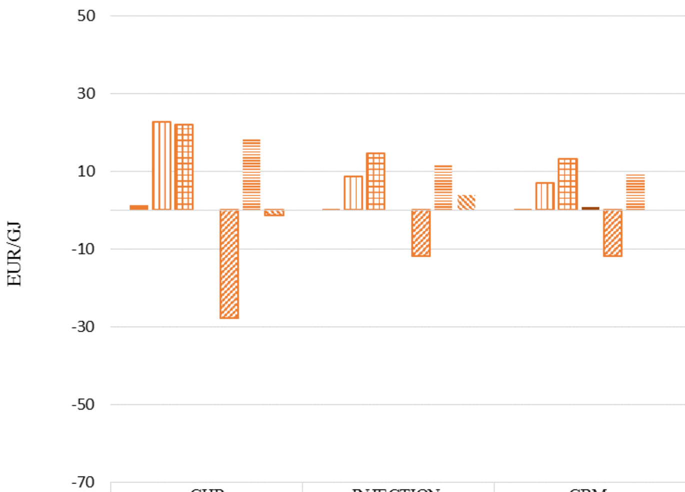


Fig. 7. 11 Economic performance of each option under different carbon cost levels

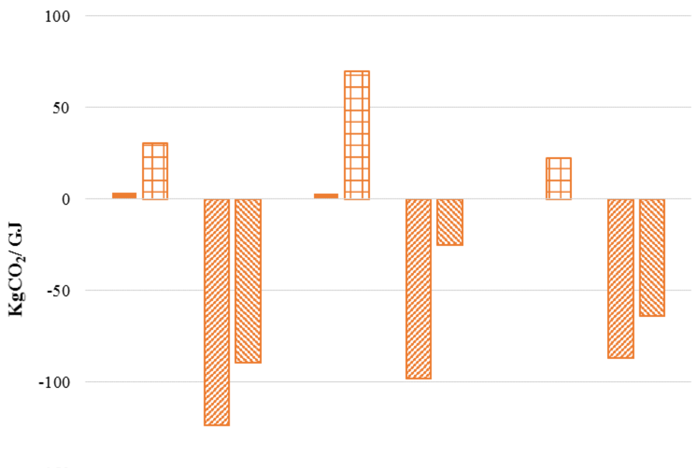
The choice of the optimal technology mix can be clarified by analyzing Figure 7.12 and Figure 7.13, where a breakdown analysis of costs and direct emissions, respectively, is performed. To also obtain a comparable cost breakdown for injection, which is clearly suboptimal and never selected, the model has been separately forced to consider the injection technology by imposing a minimum level of 5% of the total heat demand to be satisfied via injection into the gas grid. When considering the economic impact of each option, CHP is found to be the most expensive technology in terms of both production and transportation costs.

Power generation also benefits from the most advantageous market conditions due to high electricity wholesale prices in Italy (27.7 €/GJ, resulting in a net revenue of 55 €/GJ when sales of cogenerated heat are accounted for); nevertheless, these do not compensate for higher CHP costs, leading to a net cost of 18.41 €/GJ. However, when considering environmental benefits, the application of carbon prices, which are accounted for in the objective function of the model, make CHP the most favorable option, with a net cost of -1.4 €/GJ or equivalently a net profit of 1.4 €/GJ. CBM generation gives the next best performance, with a net profit of 0.20 €/GJ, due to its smaller environmental benefits (a net GHG emission reduction 64 $kgCO_2$/GJ against 89.39 $kgCO_2$/GJ for CHP, as shown in Figure 7.13), which are not balanced by lower production and logistics costs. Biomethane injection into the gas grid is unprofitable because it shows the least favorable environmental impact (a net balance of -25 kg of CO_2 equivalent per GJ of natural gas), mainly because propane has to be added to the biogas during the upgrading process to meet heating value requirements for natural gas distribution. CBM production is the next best from a GHG emission reduction perspective.



	CHP	INJECTION	CBM
Biomass procurment	1.23	0.01	0.01
Biomass transport	22.79	8.56	7.05
Production	21.94	14.61	13.20
Byproduct transport	0	0	0.81
Income	-27.77	-11.77	-11.77
Net cost	18.19	11.41	9.30
Net cost with CO2 price	-1.41	3.91	-0.20

Fig. 7.12 Average cost breakdown for each technology option (for a CO_2 price equal to 100 €/tCO_2)



	CHP	INJECTION	CBM
Biomass transport	3.59	3.16	0.46
Production	30.72	70.05	22.23
Byproduct transport	0	0	0.1
Avoided	-123.70	-98.22	-86.70
Net balance	-89.39	-25.01	-64.00

Fig. 7.13. Direct emissions breakdown for each technology option (for a CO_2 price equal to 100 €/tCO_2)

Sensitivity to market prices and opportunities for expanded biofuel production

In the current analysis and under the CO_2 price levels being considered, the superior environmental performance of the CHP technology is the main reason why the biofuel market share increases only when the CHP expansion limit has been reached. This is confirmed by analyzing the sensitivity of the optimal technology mix (expressed in terms of total investment costs to variations in electricity and CNG wholesale prices) to explore opportunities for expanding biomethane production shares with specific incentives.

Figure 7.14 illustrates the investment cost variation (in terms of share) for each selected option when different prices of electricity (continuous lines) and natural gas (dashed lines) are applied. (The CO_2 price is set to 100 €/ tCO_2).

Reductions in electricity price lead to a coerresponding percentage increment in investment in CBM, while low variations are expected for CHP. In spite of higher costs, the CHP technology, thanks to its higher GHG reduction potential, is not only more profitable, but also less sensitive to reduction in power wholesale prices. On the other hand, even the moderate percentage reduction in total investment costs for CHP determined by power price reduction, mobilizes resources for the development of biomethane generation.

The same trend can be observed for the natural gas wholesale price (dashed lines),

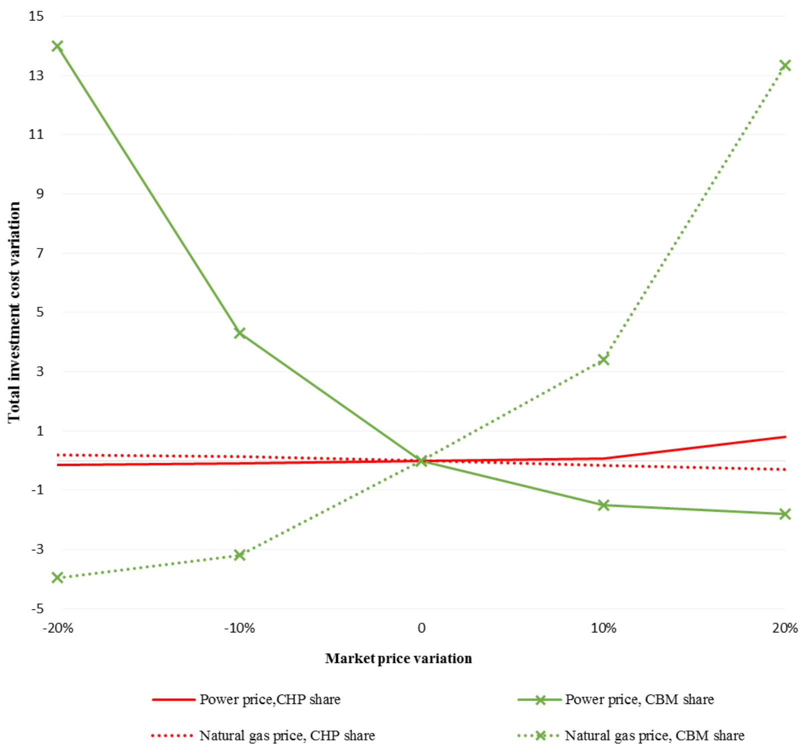


Fig. 7.14. Sensitivity analysis of market wholesale prices (for a CO_2 price equal to 100 €/tCO_2)

whose increment determines a corresponding percentage increment of total investments in CBM, while marginally affecting CHP development because of resource reallocation. This indicates that, while generic incentives for GHG emission reduction would continue to boost power generation coupled with significant heat exploitation, the strategic objective of expanding biomethane for vehicle use could be achieved even with moderate but specific subsidies on its wholesale prices, which would only slightly alter prospects for environmentally beneficial CHP plants with external heat exploitation.

Changes in optimal plant locations and feedstock supply

Figure 7.15 shows selected locations for additional biogas plants in the reference scenario. Observe that new plants are also located in some alpine areas, where heat demand is more intense and district heating already exists. However, the most remarkable proliferation of CHP units can be observed in the proximity of existing biogas power plants (i.e., in the Po valley area which is characterized by high feedstock availability).

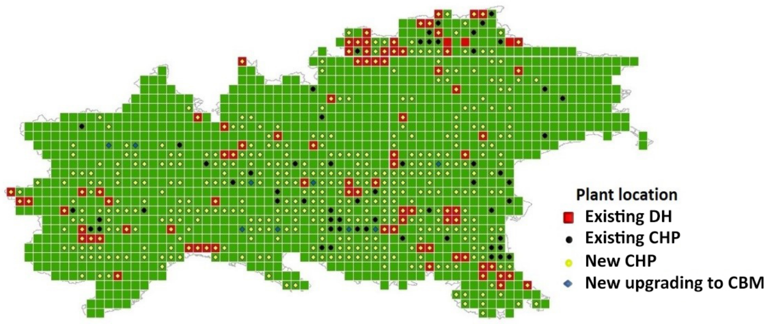


Fig. 7.15 Location of prospected CHP and CBM plants

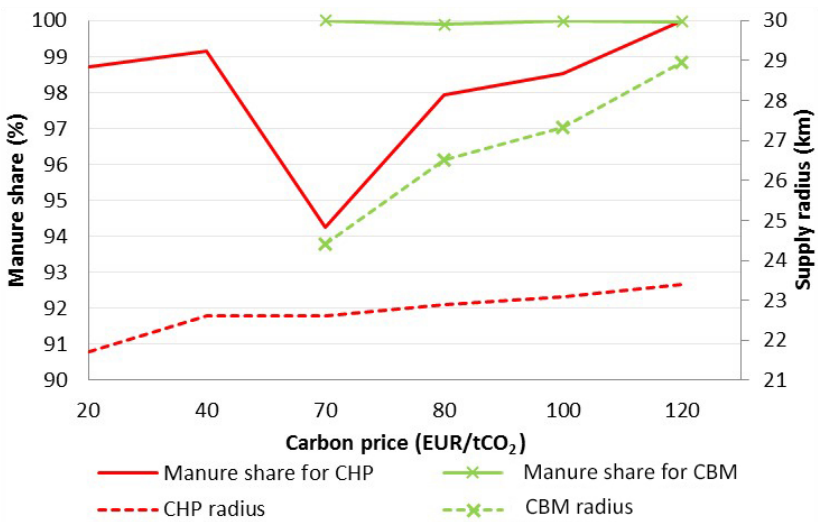


Fig. 7.16: Manure share and supply radius variations under different carbon cost levels

Feedstock is shown to be a key parameter when locating new biogas facilities. In particular, CBM production plants are always manure-based, while, as shown in Figure 7.16, profitability of CHP plants is high enough to allow the partial use of energy crops. The share of manure substrates in CHP plants (simple continuous line) decreases at 70 €/ tCO_2, when manure is partially reallocated to the CNG plants (crossed continuous line).

In this way, lower cost biomass is reserved to the upgrading process, enabling its viability. Subsequently, when the carbon price increases, the highest share of manure for both technologies is reached for long supply distances (dashed lines referring to the secondary axis in the figure), as major transport costs are supported by higher incomes from GHG savings.

7.2.2 External costs application: case study IV

In case study IV, when no feed-in-tariffs are introduced, average national wholesale price for each energy vector, i.e. power, heat from district heating, natural gas for heating and CNG, have been assumed as reference market prices, as reported in table 7.5 which summarizes most important quantitative parameters and results of the analysis.

At current market prices, no additional plants are found to be installed in the region of concern, both in the baseline as well as in the global or full scale scenarios. This means that, while each biogas energy vector presents lower external costs than its corresponding fossil alternative, both when considering the full scale and the global scale scenario, benefits are too small to make up for additional production costs of biogas based alternatives. As shown in table 7.5, in fact, the externalities contribute with a minimum amount to the total expenditure, representing in each option less than 10% of the internal cost.

The feed in tariffs required to start production are generally much higher than current energy market prices: in the baseline scenario, break-even values in the case of biomethane production equal 25.9 €/GJ for CBM and 27.9 €/GJ for injection, as costs for network connection and propane addition required for heating purposes overtake savings in compression costs. Such values are more than double of current market value of fossil alternatives (11.8 €/GJ). In other words, to achieve a minimum production of 140 TJ of biomethane, corresponding to the installation of one biogas plant, a feed-in-tariff of 16.1 €/GJ for biomethane injection and of 14.1 €/GJ for CBM would be needed. Larger premiums would be required to make more installations affordable, these break-even values reflect production costs for plants located in most favourable situations in terms of biomass logistics and connection costs.

In spite of larger production costs, the CHP option, although unfeasible under current market conditions, requires smaller incentives because the joint production of heat and electricity gives a double source of income. Thus, a feed-in-tariff of 38.1 €/GJ for power or alternatively of 27.3 €/GJ of heat would be enough for the model to allow a minimum production of 25 TJ from one CHP plants. Premiums to add to market prices would thus equal 10.4 €/GJ for power or 5.1 €/GJ for heat.

In the global scenario, when the external costs of GHG are internalized, reductions in the break-even tariffs are recognizable for each alternative: internalizing the carbon emissions would require a minimum feed in tariff of 26.8 €/GJ (premium of 15.1 €/GJ) for biomethane injection and of 23.1 (premium of 11.2 €/GJ) for CBM. Minimum feed-in-tariffs decrease for each technology in the global scenario, thus implying that all options entail net benefits from GHG emission reduction at assumed levels of external costs. This is confirmed by the carbon emission saving reported in Table 7.5 in terms of tonnes of carbon equivalent emission savings per energy unit of renewable energy, which is favourable for each option, although with lowest efficiency for biomethane generation options.

When considering also the total production of pollutants, the environmental efficiency of the biomethane energy vectors decreases, especially in the case of biomethane injection.

		Electricity			Heat			CBM			Biomethane for injection		
Scenario		Baseline	Global scale	Full scale	Baseline	Global scale	Full scale	Baseline	Global scale	Full scale	Baseline	Global scale	Full scale
Energy vector market price		27.7			22.2			11.77			11.77		
Bio internal cost		58.2			55.4			25.9			27.9		
Bio external cost	EUR/GJ	0	1.3	4.3	0	0.9	3.6	0	0.6	2.9	0	0.6	2.9
Fossil External cost		0	3.6	6.5	0	2.2	2.8	0	1.9	3.0	0	1.6	2.4
Break-even feed-in-tariff		38.1	31.6	30.8	27.3	25.4	24.6	25.9	23.1	24.2	27.9	26.8	28.5
CO_2 balance	tco_2/GJ	0.138			0.141			0.052			0.042		

Table 7.5. Economic analysis for each biogas energy vector

In fact, with a value of 28.5 €/GJ, the break-even tariff is even higher than in the baseline scenario, suggesting that when internalizing whole pollutants emissions, the use of biogas for heating purposes would entail higher external costs than its fossil alternatives. It is thus interesting to study how external costs of biogas generation change depending on feed-in-tariffs, and how the environmental impact varies when the external costs are partially (global scale scenario) or totally (full scale scenario) internalized.

External costs of baseline scenario

Pursuing the minimization of the biogas production cost alone, the CHP would be the most favourable biogas utilization pathway: with a feed in tariff of 13.4 €/GJ, three additional CHP plants are selected. At the same time, increasing natural gas price would firstly promote the production of CBM, rather than its injection into the gas grid. In fact, at a natural gas price of 25.9 €/GJ, the model selects 5 biogas plants producing vehicle fuel, while the injection of biomethane into the gas grid is feasible only at a price level of 28.6 €/GJ due to its higher supply chain costs.

Figure 7.17 highlights the effect on external costs and the primary energy reduction, of subsidizing either the production of electricity or of biomethane, by applying specific feed-in-tariffs named FITel and FITgas respectively. Public investment corresponding to such tariff levels, calculated as total feed-in-tariffs for power and gas, is reported on the horizontal axis, while reduction of external costs and fossil fuel consumption is reported in percent terms on the vertical axis.

When no incentives are applied, the value of the total externalities is approximately 4,000 M€/year, which is due to the fulfilment of the energy demands by adopting fossil energy sources. Fostering the substitution of fossil methane with a biogas based alternative, and applying increasing feed-in-tariffs on the production of biomethane (FITgas), would weakly contribute to lowering such level of externalities. When external costs are not internalized (red dotted lines in figure 5.17), it can be noticed that very little variations occurs, regardless the amount of the annual investment in the biogas upgrading technology: only when a total expenditure of 24 M€/year is introduced, a reduction of 0.03% of total externalities is registered (equal to 12 M€/year) .

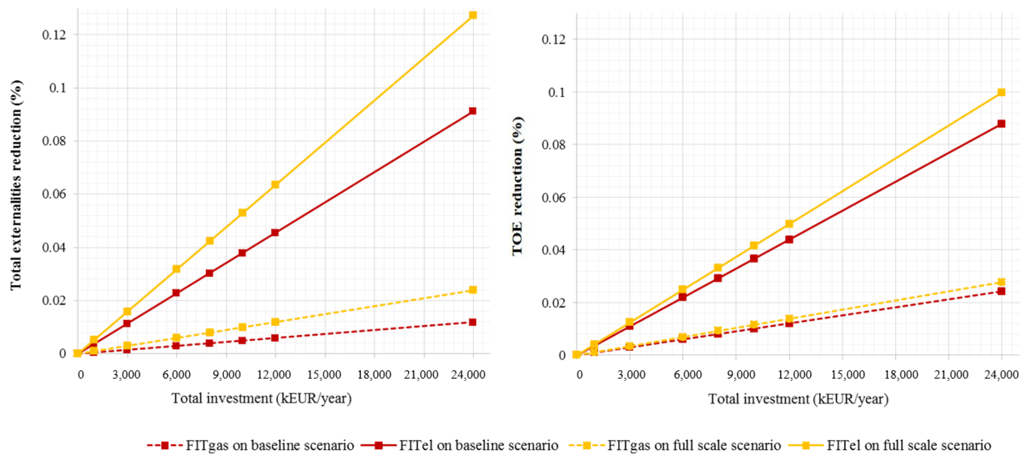


Fig. 7.17 Total externalities variation according to the application of Feed in Tariffs

Different considerations can be drawn for the total externalities trend when the production of biogas based electricity is subsidized (red continuous line in the figure): with investments of almost 6 M€/year in the CHP technology, the same reduction of total external cost is obtained, whereas increasing FITel would lead to a total reduction of 0.13%.

Small reductions in the overall energy consumption can be appreciated in both cases (red lines of the right figure) since even with high levels of investment, the energy consumed by the system decreases of 1% with the application of FITel (from 90 MTOE to 89.1 MTOE) and of 0.1% with the introduction of FITgas.

However, considering that the national Renewable Energy Action Plan (nREAP) have set for 2020 a reduction of the national primary energy consumption equal to 3% of the value registered in 2010 (passing from 165 MTOE to 158 MTOE),it is clear that such reduction of 0.1%, which seems negligible in absolute terms, would strongly contribute to reach that target. Introducing FITel always leads to a major reduction of the total externalities, which decrease by 0.1% when the investment is set to 24 M€/year), rather than in the case of promoting the upgrading technology, with increasing FITgas values.

7.2.3 Environmental impact of partial and total internalization of the external costs

Yellow lines of figure 7.17 shows that, when the external costs are accounted for in the objective function, achieving the same primary energy and external costs reduction, would require smaller incentives both for natural gas and for electricity, since the externalities generated from biogas energy vectors are always lower than their fossil alternatives.

While in figure 7.17 effect of changing one factor at a time on aggregate indicators is shown, figures from 7.18 to 7.23 highlight the variation in the model key parameters under different combination of energy market prices, ranging from 5 to 25 €/GJ for natural gas and from 30 to 50 €/GJ for electricity. In addition, since results of one-factor-at-time sensitivity analysis reported in Table 7.5 highlight that a natural gas price around 26 €/GJ is a threshold value, corresponding to the first adoption of the upgrading technology, a deeper analysis of the model behaviour around such value has been conducted here. Thus, we adopted an additional range of natural gas prices, varying from 25 €/GJ to 29 €/GJ.

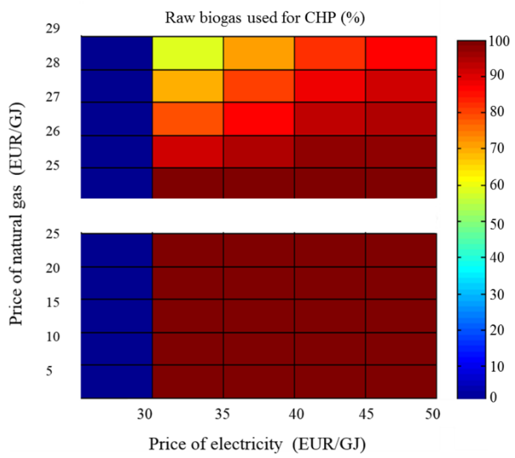


Fig. 7.18 Raw biogas used (%) for CHP in the full scale scenario for different combination of energy market price

Figure 7.18 and 7.19 show the allocation of raw biogas when the external costs of all the pollutants are accounted for in the model objective function (full scale scenario). The colour gradient varies from blue to red, as expressed in the scale, according to the share of raw biogas allocated to the production of CHP (figure 7.18) and to the production of biomethane (figure 7.19).

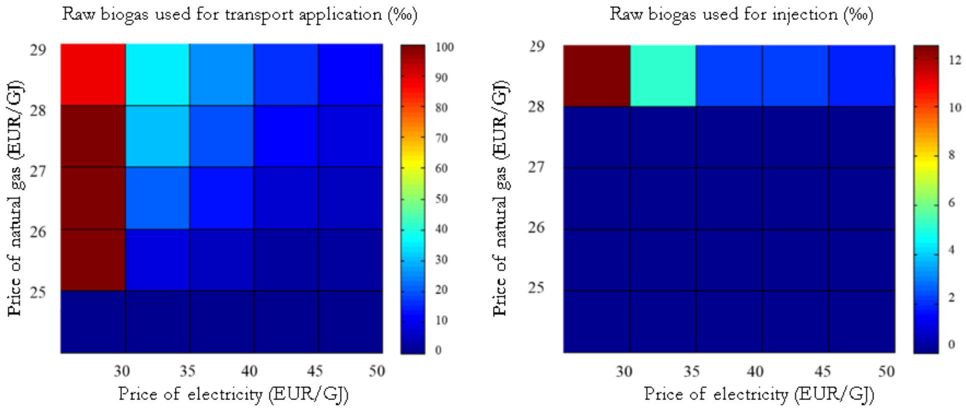


Fig. 7.19 Raw biogas used (%) for CBM (left) and for biomethane injection (right) in the full scale scenario for different combination of energy market price

In this scenario, an overall dominance of the CHP technology can be identified (majority of green to red colours in figure 7.18), while the use of biogas for the production of CBM is preferred only in case of higher natural gas prices and disadvantageous electric power market conditions (i.e. for an electricity price lower than 30 €/GJ). This is even truer when considering the injection technology: raw biogas starts to be allocated to biomethane for heating production only above a natural gas price of 28.8 €/GJ.

The way external costs influence this behaviour can be deduced from figure 7.20, where the scales express the total (left) or the partial (right) externalities reduction. The most remarkable reduction of the total externalities occurs along the horizontal axis (with squares colours shifting from blue to red), rather than the vertical one, meaning that increasing the electric market price and consequently the use of CHP technology has the best environmental benefits. Conversely, installing CBM plants induces substantial improvement only in terms of carbon emissions: production of biomethane alone, which occurs when an electric price of 27.7 €/GJ is applied, leads to a 0.1% reduction of carbon externalities (square colours shifting from dark blue to light blue).

It is thus clear that, due to the good environmental performance of the biomethane in terms of CO_2 reduction, a more promising scenario for biomethane would occur when the sole carbon externalities are internalized.

Comparing figure 7.21 with figure 7.18, lower shares of the CHP technology can be appreciated for each electricity price level, meaning that more raw biogas is allocated to the production of biomethane for each combination of energy market prices. In fact, for a natural gas price of 28.6 €/GJ, the possibility of injecting biomethane in the gas grid is also promoted, since 14 additional biogas plants for the production of biomethane for injection are installed (in line with the break-even tariffs expressed in table 7.5). In fact looking at the left part of figure 7.22, higher utilization of raw biogas for such technology

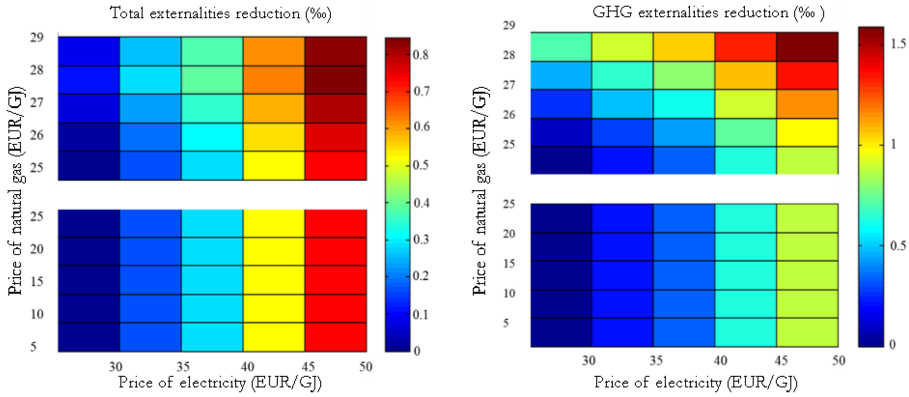


Fig. 7.20 Total (left) and GHG externalities reduction (right) in the full scale scenario for different combination of energy market price

can be appreciated, compared with the previous scenario (left part of figure 7.19).

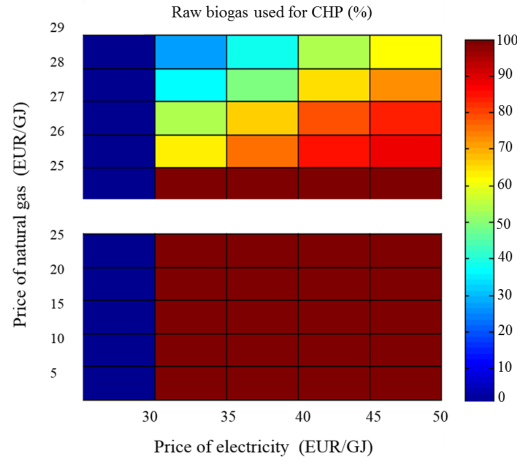


Fig. 7.21 Raw biogas used (%) for CHP in the global scale scenario for different combination of energy market price

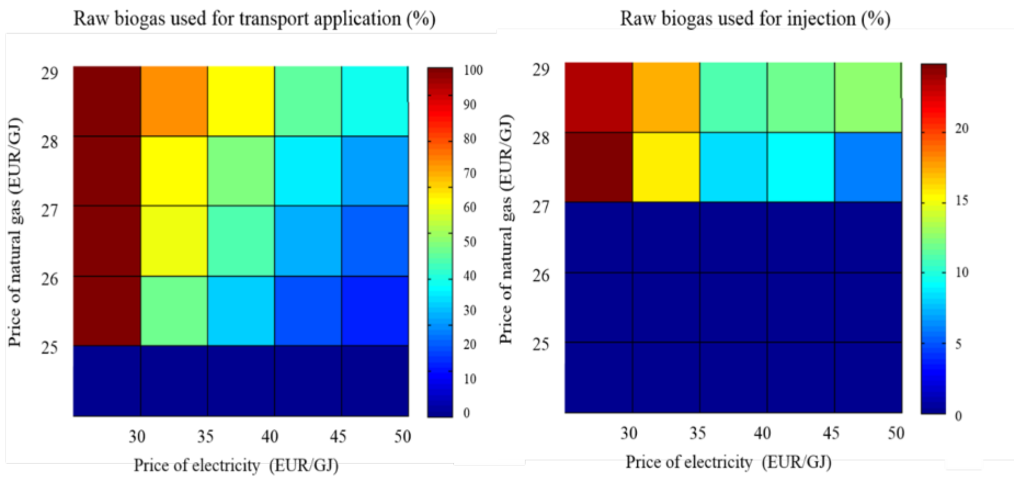


Fig. 7.22 Raw biogas used (%) for CBM injection (left) and for biomethane for transport application (right) in the global scale scenario for different combination of energy market price

This fact, however, leads to considerable changes in the total externalities balance: the right part of figure 7.23 shows that, while the values of the carbon externalities decrease as high natural gas prices are applied (with colours passing from blue to red), the introduction of the injection technology has a negative effect in terms of total emissions. In fact, the left figure shows a shift from warm colours (third upper line) to cold colours, meaning that the overall externalities reduction is smaller.

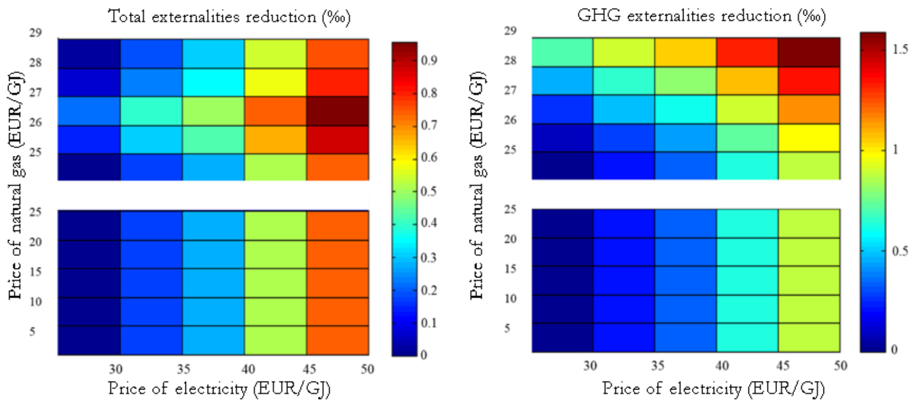


Fig. 7.23 Total (left) and GHG (right) externalities reduction in the global scale scenario for different combination of energy market price

The trends of the total and GHG externalities, as well as the high break even fossil tariffs found for each scenario, can be explained by considering the marginal external cost of dispatching the raw biogas for each utilization pathway. Such cost can be calculated by increasing feed-in-tariffs for single energy vectors or, equivalently, by imposing fixed increments in production levels assigned to each utilization pathway, while conversion to other energy forms is kept constant at given production levels. Marginal external costs of biogas conversion to different utilization pathways result basically independent from production levels in the ranges considered in this work, and equal average values reported in figure 7.24 for total (green) and GHG (red) externalities.

It is confirmed that, considering external costs of carbon alone, all the biogas utilization pathways are favourable, and CHP has the best performance. Conversely, when also externalities from local emissions are considered, the environmental advantage over fossil alternatives decreases in all the cases, and in case of biomethane injection it turns negative.

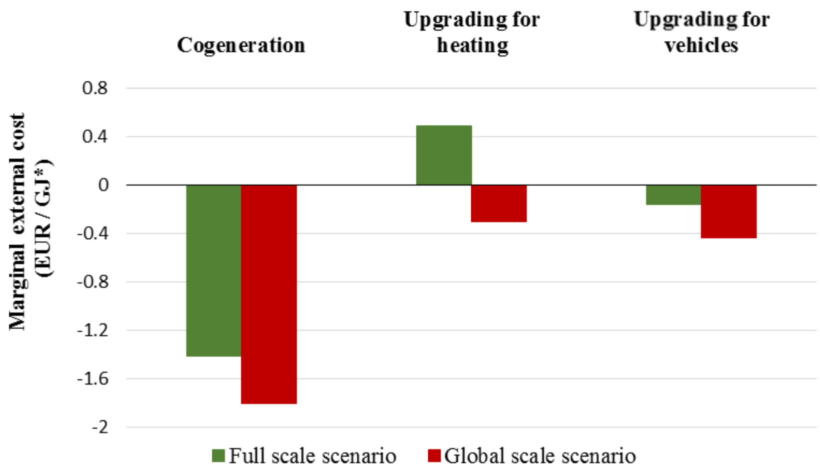


Fig. 7.24 Marginal external cost of the biogas energy vectors in both scenarios (the marginal external cost refers to GJ of raw biogas)*

Since local emissions have such an adverse impact on external costs of biogas production and since they constitute the major concern of residents when biogas projects are proposed, it is interesting to highlight the different contribution to the total externalities of each production step diagramming the results in figure 7.25.

It can be noticed that, farming activities (Step I) generate high emissions per MJ biogas, especially regarding non carbon emissions such as NO_x, SO_2 and particles. This is mainly caused by the usage of chemical fertilizers (corresponding to 47%, 63% and 46% of the total NOx, SO_2 and particles emissions, respectively, according to GEMIS database) and by high diesel consumption occurring during field operations (corresponding to almost 6% of the energy content of the raw biogas produced).

The second cause of external costs is transportation of biomass, which mainly causes local emissions of NO_x. The grounds of local concerns about this issue, which is a main cause of opposition to new plants, appear acceptable. Conversely, the external costs of anaerobic digestion (step III) are almost negligible, and external costs of energy conversion (step IV) are quite small, especially in the case of upgrading.

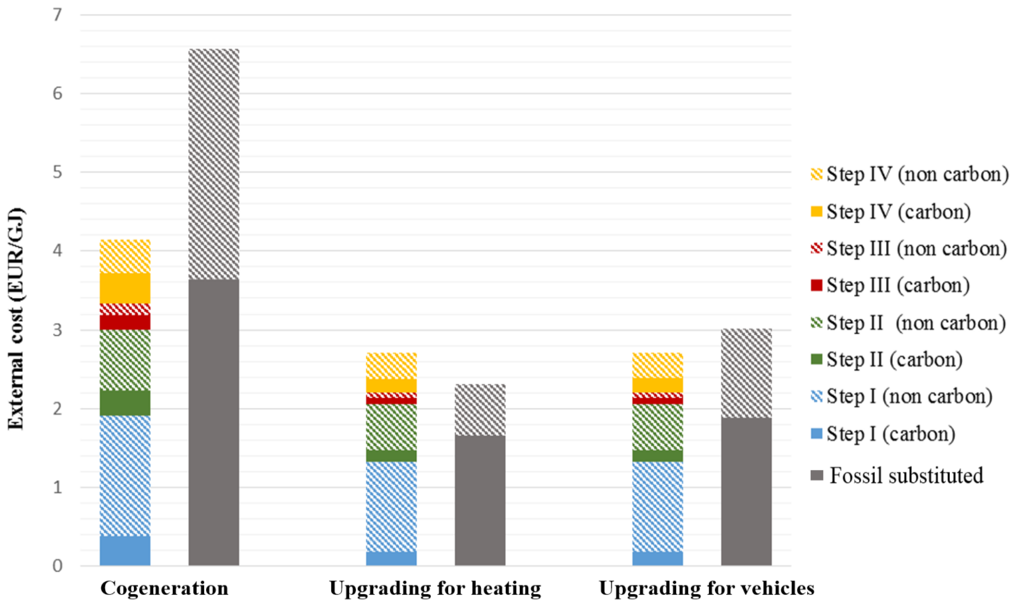


Fig. 7.25 Contribution to the external cost of each biogas process step for the energy vectors considered in the full scale scenario

Upgrading may thus appear particularly attractive in terms of social acceptance because of its limited emissions, in that no additional combustions from stationary engines are introduced in regional systems. However, Figure 7.25 confirms that not only marginal but also average external costs from total emissions generated for the production of fossil energy vectors (grey bars) are higher than the biogas based alternatives and that benefits are especially high in the case of electricity. Given the high contribution of fossil fuels to the Italian generation mix, biogas based CHP is environmentally more favourable, both when considering the CO_2 equivalent emissions and the totality of pollutants. Fossil methane for vehicles has the second worst performance in terms of total emissions, which is mainly due to different steps required for delivering the product to the filling stations (e.g. compression to 220 bar and transport).

8

Concluding Remarks

The concluding chapter presents the answers to the research questions posed in the introduction, as well as some considerations on the most important factors affecting the potential expansion of CBM market in northern Italy. Suggestions for further research are also included.

8.1 General conclusions

In this thesis two MILP optimization models have been utilized to assess the prospect of adopting the agricultural biogas as a vehicle fuel in Northern Italy. The potential development of the CBM fuel has been addressed by comparing the environmental and economic performances of the biogas utilization pathways when different policy instruments are introduced. Such methodology has been applied to four case studies differing for the policy instrument considered and for the geographic dimension investigated.

The analysis of Friuli Venezia Giulia scenario (case study I and II) was specifically targeted to analyze the effect of real incentive schemes for agricultural biogas generation and conversion to power and to biomethane.

The northern Italian territory was selected as a reference scenario (case study III and IV) to investigate the effect of the adoption of environmental taxes, e.g. in the form of carbon prices or external costs, on the CBM technology development for a wider energy system. The pervasive distribution of energy infrastructure (such as DH, regional and national gas grids and CNG refuelling stations) and the high biogas potential characterizing such territory, allowed to compare the environmental and economic performance of the biogas based energy vectors.

8.1.1 Effect of different policy measures in the promotion of the biogas technologies

With regard to the effectiveness of the aforementioned policy instruments, given the results presented in chapter 7, the following conclusions can be drawn.

I) Promotion of the biogas to power solution alone:

The homogenization process observed in Italy (Carrosio, 2013), was determined by support schemes in force until 2012, which made such configuration the most profitable even when capital costs were relatively high, compared with references from neighboring countries (Walla and Schneeberger, 2008).

Conversely, the adoption of the new support schemes highlighted that the cut in feed-in-tariffs introduced in 2012, which was milder for small scale manure based plants and more severe for energy crops based plants around 1 MW, will leave hardly any room for entrepreneurial farms as they used to be.

Based on model estimates, additional electricity generation potentials would be reduced to 13% of potentials under the previous support schemes in the examined area. Similarly, it has been estimated that public expense for biogas incentives would be reduced by a factor of 7, and job creation would be reduced by a factor of 4.7. While small scale manure based plants appear more desirable from an environmental viewpoint (Bacenetti et al., 2013), it was shown that new incentives, even if linked to smaller optimal capacities, may significantly expand surface areas of affordable manure supply, resulting in unfavorable Primary Energy Input Output ratios (Poschl et al., 2012).

II) Simultaneous introduction of actual subsidy schemes for cogeneration and biomethane production

When introducing subsidies for each biogas utilization pathways, according to the policy schemes currently in place in Italy, the biogas to power solution still represent the preferred economic choice for entrepreneurs. Such preference is mainly triggered by the duplicability of the solution (as bioelectricity distribution does not require investment in additional infrastructure), rather than by the economic convenience of such option.

The current level of biomethane tradable certificates (which have been set equal to 400 €) allows the installation of few upgrading plants for CBM production and the construction of new refueling stations.

Thus, under current biomethane promotion schemes, the development of CBM is affordable, even thought it would still be limited in area with high biogas potentials to overcome additional feedstock transport costs.

In addition, results revealed that the new refuelling stations would be installed in proximity of the existing CBM plants: smaller decentralized refuelling infrastructure, connected with a single biogas facility, are more profitable than big centralized units served by multiple upgrading plants.

III) Carbon price application

The current level of carbon tax (12 €/tonCO_2) is too little to promote the production of the biogas based energy vectors. Results of case study III showed that the feedstock available in northern Italy is sufficient to guarantee a relevant expansion of biogas plants for heat and power production, when the carbon price value is higher than 50 €/tonCO_2.

On the other hand, the development of CBM plants, which represented the main target of the analysis, should be specifically subsidized (i.e. with a subsidy price mechanism rather than with a carbon price based mechanism) in order to become competitive.

Moreover, when analysing optimal locations selected by the BeWhere model, an inhomogeneous plant distribution can be observed, with high concentration of plants in areas with both great manure substrates availability, and in proximity of existing district heating systems. These are exactly the areas where most existing biogas power plants are located. Such phenomenon might lead to relevant environmental and social acceptance concerns.

In particular, given the extensive utilization of animal by-products for anaerobic digestion emerged in the case study III, managing waste output flows (i.e. digestate, whose disposal is already restricted by specific national directive) might become crucial.

IV) Internalization of external costs

Under present energy market conditions, the partial or total internalization of the external costs have limited impact on further development of biogas alternatives, since the benefit of producing biogas-based energy vectors (in terms of local and total emissions reduction) is very small compared to their overall production costs.

Introducing premium prices on electricity or biomethane production would firstly favour the cogeneration technology both when the pure internal cost and the external costs of GHG and pollutant emissions are considered.

Such preference is mainly caused by the favourable market condition characterizing the bioelectricity production (as the fossil electricity is highly costly as compared to fossil natural gas) and the higher environmental benefit connected with the simultaneous production of heat and power. However, it should be remembered that the CHP technology has been included in the BeWhere model under the assumption of an efficient heat exploitation, since each biogas CHP plant has been coupled with an adjacent district heating network.

Moreover, given the relevant contribute to the local airborne emissions of the transport activities reducing the feedstock supply radius might induce significant improvement to the final environmental balance.

8.1.2 Effect of technical constraints in the promotion of the biogas technologies

I) Infrastructure availability

The presence of energy infrastructure is essential for the economic and environmental feasibility of the biogas technologies. Results of case study III showed that some alpine municipalities might benefit from a wider diffusion of biogas plants, in that additional cogeneration activities would be installed in the area. However, looking at the location of district heating infrastructure in the territory of concern, it can be noticed that the additional plants are mostly located in areas already served by the DH systems (e.g. South Tyrol municipalities). Thus, in order to obtain a more homogeneous development of biogas facilities, by serving additional undiscovered areas, a wider extension of energy infrastructure is needed.

Similar conclusions can be gathered when considering the CBM adoption: case study II has demonstrate that, even when introducing high levels of CBM incentives, the total feasible production of such biofuel is constrained by the number of gas fuelled vehicles in the territory, and in turn, by the availability of CNG or CBM refuelling stations.

II) Digestate spreading limits

By imposing a maximum amount of digestate to be spread in the fields, the Nitrate Directive in force in the country, limits the maximum amount of biogas to be processed. This is especially the case of cogenerative and biogas to power solutions. In fact, results of case study II highlight that the generous public subsidies introduced by recent policy schemes, which foresee a proliferation of bioelectricity plants in the territory, become least effective when the digestate constraints are accounted for.

In light of such considerations important hints for decision makers arise: biogas incentive mechanisms need to account for existing environmental obligations that might overtake the overall environmental benefits of the biogas solutions.

III) Fossil fuels market prices

Fossil energy market conditions have a significant impact in the profitability of the biogas technologies. Since the MILP optimization models considered in this study account for the market competition between biogas energy vectors and their corresponding fossil alternatives, it has been demonstrated that current energy prices discourage investments in biogas plants.

This is especially the case of biomethane production: the Italian natural gas market price (equal to 11.7 €/GJ or equally to 0.50 $€/Nm^3$) is too low to persuade private actors to invest either in injection or CBM technologies as the resulting expenditures would not be reflected in a convenient selling price. On the other hand, the sensitivity analysis on energy market prices conducted in case study III, highlights that the CHP technology, thanks to its higher emission reduction potential, is less sensitive to reduction in power wholesale prices.

This aspect suggests that the strategic objective of expanding the adoption of CBM could be achieved even with specific subsidies on its wholesale prices, which would only slightly alter prospects for environmentally beneficial CHP plants with external heat exploitation.

8.2 Answer to the specific research questions

I) Under which circumstances producing the CBM can be a feasible choice, as compared with other utilization pathways?

Results showed that the production of CBM is not economically feasible without the presence of public subsides. Upgrading to biomethane for transport application is surely less costly than adopting cogenerative technologies, which are also constrained by the need of DH infrastructure for the distribution of heat.

On the other hand installing additional biogas to power plants in northern Italian scenario, not only gives the least environmental benefit in terms of emission reduction, but would also incur in some technical barriers (such as digestate spreading limit and utilization of higher shares of energy crops), as the existing installed capacity is already high.

Injecting the biomethane, would certainly be favoured by the presence of an homogeneous distribution of the natural gas grid in the territory, but the current level of natural gas price and the bad environmental performance of such solution, discourage its adoption from an economic and environmental point of view.

The introduction of a carbon tax, would be feasible for promoting the CBM production, but at higher costs (results revealed a minimum carbon price of 80 €/ton to adopt such technology) and only as a second best choice (as the CHP solution would firstly be favoured). On the other hand, a wider adoption of the CBM technology entails the resolution of some existing technical issues, since the production of such biofuel would not be absorbed by the existing CNG market.

II) What levels of economic policy support are needed to make the biomethane economically attractive?

The current biomethane promotion scheme is sufficient to install a few number of CBM plants in Norther Italy. The minimum level of Trading Certificates for CBM production has been calculated as 400 €.

Table 8.1 summarizes the amount of subsidies required for implementing such technology in the area under investigation, depending on the minimization approach assumed.

III) Which would be the environmental implications of the use of agricultural biogas as a vehicle fuel in the region of concern?

Both case study III and case study IV highlight that the production of CBM carries some environmental benefits as compared with natural gas. However the resulting GHG

Parameters addressed	Policy instrument	Unit	Value
Economic costs	CIC	€	400
	Fitgas	€/ GJ	14.1
Economic costs and GHG emissions	Carbon price	€/ ton	80
	Fitgas	€/ GJ	11.3
Economic costs and airborne pollutants	Fitgas	€/ GJ	12.4

Table 8.1. Threshold values for each policy instrument

emission mitigation is too low to make such solution attractive under current carbon market.

In addition, results showed that, when the main airborne emissions are considered in the assessment, each biogas technology induces high amounts of non carbon emissions, mostly in terms of NO_x and particulates. Such negative environmental performances are mainly introduced in the first steps of the biogas supply chain, because of the use of chemical fertilizers and the transportation activities occurring during the farming activities. To this end, installing small CBM plants and thus reducing the supply radius and the share of energy crops in the feedstock mix, might improve the overall environmental balance of such solution.

8.3 Research limitations and further development

Like every model, the optimization models adopted in this thesis are based on assumptions and simplifications, in part due to computational requirements and in part depending on the features of available data. In particular with regard to the geographical scale of case study I and II, it should be mentioned that the choice of adopting a regional dimension was driven by two main reasons:

- The complexity of the subsidies structure, which required to study a limited geographic area (and thus to manage a smaller amount of data) in order to reduce the computational efforts and to overcome additional mathematical simplifications.
- The presence of some technical barriers affecting the regional FVG fuel market, and the so called chicken and egg dilemma related to the interconnection between gas vehicles number and CBM demand level, which might constrain the adoption of the CBM fuel.

A further development of the analysis for the Friuli Venezia Giulia scenario would be the introduction of other policy instruments (e.g. environmental taxes such as carbon prices or external costs) to validate the results obtained in the macro-regional case studies and to compare the environmental performances of the biogas utilization pathways in that region.

Furthermore, an important issue that has not been tackled in this study is the potential expansion of the energy infrastructure for domestic heat distribution (such as DH systems and regional gas pipelines). Including such aspect with a spatially explicit approach in the economic and environmental assessment of the biogas technologies would led to important conclusion. On a first place, specific measures to address inequalities in the territorial distribution of new plants might arise. Secondly, including the costs of investing in the aforementioned heating infrastructures in the optimization process, would make the cogeneration option less competitive as compared with the CBM technology.

With regard to the MINLP model that has been built to simulate the construction of additional refuelling infrastructure, collecting further information through empirical research would be a necessary step to increase the validity of the obtained results. In particular, given the demonstrated effect of the attraction function, data collection of actual or stated refuelling behaviour of CNG vehicle drivers would be needed. Especially considering that the empirical research on refuelling behaviour (characterizing the modelling assumptions of this model) is focused on gasoline and on the US market.

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