A Techno-economic Assessment of the Generation and Usage of Biogenic Gases in Chile as a Substitute of Natural Gas

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En el claro de la luna
Donde quiero ir a jugar
Duerme la Reina Fortuna
Que tendrá que madrugar

Habanera de
Silvio Rodríguez

Drei Verwandlungen nenne ich euch des Geistes: wie der Geist zum Kamele wird, und zum Löwen das Kamel, und zum Kinde zuletzt der Löwe

Also sprach Zarathustra
Friedrich Nietzsche

Keep a clean nose,
Watch the plain clothes
You don't need a weather man
To know which way the wind blows

Subterranean Homesick Blues
Bob Dylan

Abstract

As energy is essential to modern societies, attempts to diversify its primary sources, integrate cleaner, more efficient and cutting-edge conversion technologies as well as foster development through the exploitation of indigenous supplies have become an imperative for sustainability. This being so, use of biomass for energy purposes can play a relevant role on the road to a secure energy supply. Preliminary studies indicate that the bioenergy potential of Chile based on biochemical conversion of biomass (i.e. anaerobic digestion) stands at approximately 35 PJ y^{-1} (data from 2007), typical for a country of Chile's population, area and climate. Nevertheless, the contribution of bioenergy to the energy matrix continues to be modest, a fact attributable to a lack of research into its viability. There is evidence that methodologies for assessing the technical potential of biomass are relatively well-developed. However, it is in the literature addressing the economic potential of biomass on all scales (regional, national & continental), where inconsistencies and lack of methodological rigour can normally be found.

Because the biochemical conversion of residual biomass can significantly contribute to achieving energy security goals with positive environmental externalities, this study uses a novel techno-economic holistic approach to calculate the economic potential of biomass in Chile. The pathway of electricity generation via direct combustion and that of upgraded biogas produced as bio-substitute natural gas (Bio-SNG) for injection into the gas grid were assessed and compared. In each case, namely the *biogas-to-energy* and *biogas-to-BioSNG* routes, were evaluated employing proven technologies.

The primary data necessary for the potential analysis was gathered from a variety of sources, and afterwards sorted in such a way that the geographical distribution could be distinguished across the country at county level. Additionally, the sources of biomass were classified into the following sectors: i) municipal solid waste; ii) wastewater treatment; iii) livestock farming; and iv) agriculture. Finally, relevant technical and economic data was drawn from existing literature to model the potential analysis. Through a mathematical procedure relying on limits of potential (i.e. physical limit, geographical limit, technical limit and economic limit), supply-cost curves were constructed to estimate the representative generation cost of both secondary energy end-products as well as their technical and economic limits. The results of the technical potential were then integrated into a geographical information system (GIS) to show the energy distribution nationwide. Finally, a cross-assessment comparison was conducted with the cost distribution of electricity and the cost distribution of Bio-SNG being balanced against the price of electricity and the price of natural gas respectively, with the aim of elucidating the economic attractiveness of the two options.

By applying this method, it was found that municipal solid waste offers the largest economic potential for electricity generation when recovering landfill gas (1.1 $TWh_e y^{-1}$) or when processing unsorted municipal residue through a *waste-to-energy* route (2.1 $TWh_e y^{-1}$). Wastewater treatment plants and livestock sectors bring a similar economic potential for electricity generation (approximately 0.8 $TWh_e y^{-1}$ for each one), while the potential from the agricultural sector is slightly higher (1.1 $TWh_e y^{-1}$). The option of co-digesting feedstock from the livestock farming sector (manure) and agricultural sector (annual crop residue) is feasible to some extent, and it can appreciably improve the economics of biogas processing when compared to mono-digestion. Moreover, the wide range of biomass technical potential gives rise to a representative generation cost ranging from 11.0 ct€ kWh_e^{-1} to 25.0 ct€ kWh_e^{-1}. For the option of production of Bio-SNG, the largest economic potential was found in the

agricultural sector (280 MM Nm^3y^{-1}), and the smallest in waste water treatment (19 MM Nm^3y^{-1}). The economic potential from municipal solid waste (224 MM Nm^3y^{-1}) and the livestock farming sector (134 MM Nm^3y^{-1}) is still significant. It was noticed that the representative generation cost ranges from 9.5 € $MMBTU^{-1}$ to 98 € $MMBTU^{-1}$, thus severely restricting the commercialisation, based on the present price of natural gas. The energy potential was observed to be highly concentrated in only some administrative regions of Chile. For municipal solid waste, wastewater treatment and livestock farming sectors, the greatest economic potential is located in the XIII region (Metropolitan), whereas that of the agricultural sector is predominantly distributed among the VI, VII and IX regions.

In the light of these results, it is observed that the option of producing electricity appears to be more advantageous than that of producing Bio-SNG, since a larger number of biogas-based projects may run profitably under the current energy-market conditions. These conclusions remain true irrespective of government subsidy or lack thereof. This suggests that a macro-policy for the generation and enhancement of biogas should have as the bedrock of implementation, firstly, the promotion of electricity generation as the main conversion route, and secondly, increased energy generation from the existing sources which are economically competitive without subsidy.

This research did not take into consideration aspects such as implementation or public attitude. The assessment of the commercial potential was beyond the scope of this thesis, and it should be undertaken in further research. Additionally, environmental penalties or social compensation were not included in the assessment, so the conclusions arising from the presented analysis would change to some extent if these aspects were incorporated. Changes in the energy market triggered by larger introduction of liquefied natural gas (LNG) into the energy system or modifications in indexing in the short-term may also modify quantitatively some findings.

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Christian BIDART

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Nomenclature, Acronyms and Symbols

Acronyms and units

$A_{i,j}$:restriction on source *j* of limit *i*

AD :anaerobic digestion

BAT : best available technology

Bio-SNG : substitute natural gas from biomass

BOD : biochemical oxygen demand

BTE : biogas-to-energy

BTU : biogas-to-upgrade

CAS : conventional activated sludge

CHP : combined heat and power

COS : carbonyl sulphide

ct€ :euro cent

FM : fresh matter

g : gramme

GIS : geographical information system

GWh$_e$: gigawatt electric

GWh$_{th}$: gigawatt thermal

ha : hectare, equal to 10,000 m^2

hab : inhabitants

i : interest rate (%)

kWh$_e$: kilowatt-hour electric

kWh$_{th}$: kilo-watt-hour thermal

LHV : lower heating value

LGTE : landfill gas-to-energy

LGU : Landfill gas for upgrading

MLVSS : mixed liquor volatile suspended solids

MMBTU : one million British thermal units, 1 MMBTU = 293.29 kWh$_{th}$

MSW : municipal solid waste

MM : abbreviation of million

mqq : metric quintal, equal to 100 kg

Nm^3 : normal cubic meter

R : revenues

T : Tera (10^{12})

t : metric tonne (1,000 kg)

TS : total solids

VS : volatile solids

VOC : volatile organic compound

VSS : volatile suspended solids

WTE : waste-to-energy

WwT : wastewater treatment

WwTP : wastewater treatment plant

w_b : wet basis

Greek symbols

π_f : physical limit (theoretical potential)

π_g : geographical limit (geographical potential)

π_t : technical limit (technical potential)

π_e : economic limit (economic potential)

Π_t : total technical potential

Π_e : economic potential

η_e : electrical efficiency

θ_H : mean hydraulic retention time (h)

θ_c : mean cell retention time (h)

$y_{i,j}$: index i and j of a variable y

γ, δ : correlation factors

1. Introduction

Energy is an essential resource for modern industrial societies, which are characterised by an intensive consumption of raw materials and energy goods as well as by high levels of organisation, complexity and evolution into more integrated and complex forms. The historically fossil fuel-based society is now confronting a major challenge derived principally from economic growth, scarcity of non-renewable resources and steady demand of raw materials, all which are concomitantly linked to problems such as global warming, uncertainty of fuel supply and the massive generation of waste products and pollutants associated with industrial activity (Ayres 2007). These matters are of the highest interest and preoccupation in public discussion and political decision making as well as in society at large, which has a major stake in decision making, transparency and equality. These concerns can be seen as driving forces and political pressures that might redefine understanding and thinking in the future, and influence strategies for development and decision making based on knowledge and co-governance (Light 2006).

The possibility of using resources which will not compromise the development of future generations, and simultaneously offer beneficial externalities beyond merely economic, has gained increased interest in last decades. In these terms, renewable energy resources, or just *renewables*, (i.e. biomass, wind power, hydropower and geothermal) are expected to play a key role in the future; their development and integration are seen as a pivotal scheme which the energy systems of post-modern societies will be structured around. However, the exact mechanisms linking energy to social development is uncertain since the social development issue has been traditionally seen as separate from the economic and energy, or has been limited to the correlation between economic growth and increased consumption.

Energy from biomass, also know as bioenergy, had supplied the vast majority of the world's energy needs until the fossil era began in the 1800s (Klass 1998). With the first oil shock of the 1970s, biomass regained interest among governments and policymakers who recognised in it a resource that offers advantages, principally for local availability and the possibility of reducing energy dependency. Following this realisation, biomass and its fuel derivatives have been seen as alternatives both to reduce reliance on crude oil and cut down on carbon dioxide emissions while promoting and maintaining economic development, particularly in rural areas

(Marques & Fhinhas 2012). Today, biomass is the fourth largest energy resource in the world, after natural gas, coal, and crude oil, and is estimated to comprise about 10-15% of global primary energy consumption (Faaij 2006). When compared with renewable energy sources such as hydropower, solar, wind and geothermal, biomass supplies 48% of total renewables (data from 2011). Considering solely Europe, the most significant contribution of biomass is expected to be obtained from the waste sector, and only in the long-term, with major technological advances, will bioenergetic crops provide the largest share.

Chile is one of the countries with the potential to develop renewable energy, mainly due to its diverse geography and well-distributed natural resources which include a wide variety of renewables such as wind, geothermal, solar, hydropower and biomass (Bennett 2009). These conditions offer a remarkable opportunity to harness renewable energy so that the international, historical dependency on fossil fuel supplies can be reduced, the energy mix improved and Research, Development & Innovation (R+D+I) can be promoted by developing technology-based projects. Nonetheless, renewable energy has been incorporated for a relatively short time, being supported for first time in 2004 through the introduction of concrete measures, mainly for the electricity sector (National Commission of Energy 2012[a]). Since then, an incipient macro policy on renewables has been improved by strengthening the regulatory framework for electricity generation, stipulating a biofuel blending quota for transportation and supporting investment and funding research & development (R+D) projects.

In spite of the achievements reached thus far, there is a lack of reliable information on renewable energy resources in Chile and an indeterminate impact on the energy system and society. In addition, uncertainties regarding technologies, their cost and performance have become barriers to promoting and implementing renewables in the country.

Taking account of the challenges faced by Chile in regard to the introduction of renewables, and more specifically bioenergy or more efficient and environmentally-friendly ways of using biomass, this research sets out to assess the potential role of biomethane as a biogenic gas for the substitution of natural gas in the country. The research was conducted by identifying and characterising resources that may meet certain conditions to develop energetic projects and for which there is currently insufficient or unreliable information to make investment decisions or to elaborate a comprehensive policy from the state. Methodologically, the emphasis is placed on a comparative assessment with a systemic orientation on technologies that may be suitable for the conversion of biomass to other forms of energy, on the economic aspects of the proposed evaluations, as well as on the possibilities of processing (routes of conversion) and their implications.

This research is structured as follows. Firstly, a discussion (critical review) of bioenergy potential studies at different geographical scales (i.e. global, continental and national level) is put forward to identify germane investigations in the field and gaps in the research. Secondly, the main figures, infrastructure, and suppliers of the Chilean energy system are presented. Later on, a discussion of how the natural gas market functions and how its organisation affects the cost structure is included. Afterwards, the methodology applied to conduct the potential analysis and the economic assessment is described. This section underlines theoretical background on which the methodological approach is conceptualised as well as limitations that it imposes and how the results must be understood. Hence, the subsequent section addresses the characterisation and evaluation of the conversion technologies for the biomass transformation, cleaning up and distribution of end products. The main economic figures to be used for the assessment are included in following section, and presented in a way that enables the calculations to economic indicators. In the seventh section, the five sectors that make up the research framework (i.e. residue from wastewater treatment plants, municipal solid waste, livestock farming, agricultural residue and co-digestion) are assessed (see Figure 3). Lastly, a concluding section compares and discusses the main findings and proposes a general policy towards the generation and use of biomethane from residue for the whole country.

1.1 Motivations of the Research

The increasing interest in energy derived from residue for energy generation is heavily motivated by the possibility of implementing a more sustainable strategy for waste management; one in which an environmental problem can be worked out indirectly as an energy generation issue rather than a waste control one. This *waste-to-energy approach* then offers significantly more advantages and positive social and political externalities than an isolated waste treatment strategy, which has the sole purpose of reducing the impact of wastes on the environment by changing its aggregate state, generally resulting in a high cost that might prevent it from running sustainably.

On a more technical perspective, the combustible gases produced from biodegradable residue (i.e. methane or hydrogen) currently receive special attention in that they offer better handling possibilities in regard to transport, storage, burning (Gilschrist 1977), processing and synthesising (Kolbitsch, *et al.* 2008; Haghighi *et al.* 2007; Benito, *et al.* 1992), as well as the reduction of nitrogen oxide emissions (Lee, *et al.* 2010). The high potential for their efficient use in motors and engines is another aspect that makes them even more attractive (Kuthar, *et al.* 2005). An additional key advantage is the opportunity to feed biogenic gases into existing energy distribution systems, considering a previous treatment, cleaning and upgrading to a quality that is equivalent to commercial gases, in this way achieving efficient distribution and use (Pöschl, *et al.* 2010; Jonsson, *et al.* 2007). This concept offers new chances for promoting the generation of biogenic carriers from renewable resources, an idea also supported by the fact that bionergetic technologies have a dynamic development worldwide, and more efficient and competitive processes are expected to be available in the medium-term (CERT 2009).

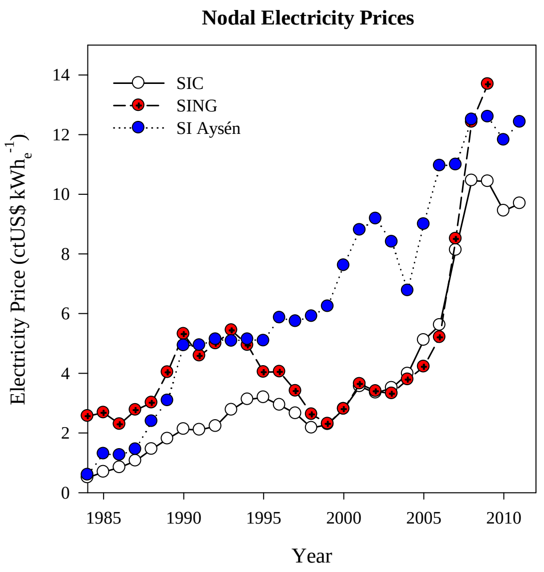

Figure 1.1. Evolution of nodal price in the three main electric system of Chile.
Source: National Commission of Energy (NCE 2011[b]).

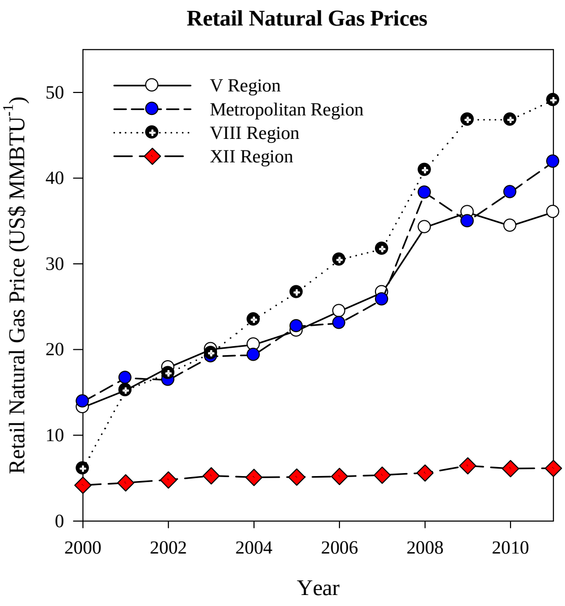

Figure 1.2. Retail natural gas price in four administrative regions of Chile.
Source: National Commission of Energy (NCE 2011[c]).

Additionally, the steady increase in the cost of energy in Chile is coupled with the above-mentioned socio-environmental and technical motivations, and could become a driving force for organic *residue* to become *by-product*, with a trade price that might reflect their energy value, and, consequently, inter-market competition. By way of illustration, Figure 1.1 shows the annual average increase in nodal price of the country’s three main electrical systems in the last period. Electricity price rose dramatically in the past five years, reaching 14 ctUS$ MWh_e^{-1} in 2006. Similarly, Figure 1.2 presents the evolution of retail natural gas price, which exhibits a 35-45 US$ $MMBTU^{-1}$ price range for 2011[1]. In a broader context, Chile has one of the highest industrial average electricity prices in the southern region (14.14 ctUS$ kWh_e^{-1}), only overtaken by Brazil (18.27 ctUS$ kWh_e^{-1}), but substantially higher than any of the neighbouring countries, i.e. Argentina (5.44 ctUS$ kWh_e^{-1}), Bolivia (6.45 ctUS$ kWh_e^{-1}) and Peru (5.91 ctUS$ kWh_e^{-1}), or countries such as Paraguay (4.85 ctUS$ kWh_e^{-1}) and Uruguay (11.73 ctUS$ kWh_e^{-1}), which have considerably lower rates of electricity consumption. A similar tendency is observed in the residential and commercial average electricity price for the same countries (data from 2011) (Olade 2010).

In sum, for the environmental, social, economic and strategic motivations discussed below, there is strong evidence for encouraging the subsequent generation and use of biogas as an energetic carrier into the Chilean energy system.

1.2 Studies of Potential of Biomass – A Critical Review

The potential of biomass for energy utilisation, bounded to some extent by spatial location (regional, national and worldwide), has been evaluated in several studies (Berndes, *et al.* 2003). Most of these studies have aimed at estimating the potential biomass being used for the generation of electricity, and, to a lesser degree, for liquid or gaseous fuel production. Considering the main motivation of this study, the follow-up discussion is focused primarily on relevant studies devoted to the assessment of potential biomass for the generation of renewable methane as an end-product, or as an intermediate for obtaining another sort of secondary energy (i.e. electricity). Furthermore, prime studies are analysed critically in this section in order to identify differences, strengths and weaknesses of the employed methodologies as well as gaps in the research, which are highlighted by the authors for further analysis. Finally, the results are compared to identify the main factors that influenced them.

1.2.1 Assessments at Worldwide Level

- **de Vries *et al.* (2007)**

Methodologically, the authors established the definition of theoretical potential, geographical potential, technical potential and economic potential, principally from the recommendations

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[1] This excepting the southern XII Region, where a subsidy mechanism still operates.

of the World Energy Council report (WEC 1994). For four scenarios, the demand for food and biomaterials was calculated by using the IMAGE 2.2 model (*Integrated Model to Assess the Global Environment*), to assess zones that can cover the demand. Once the zone was designated, the surplus agricultural land was calculated. Additionally, an economic analysis was carried out, and a GIS (Geographical Information System) with a resolution of approximately 3,000 km^2 (named *pixel*) was used as the control area. However, no residues were taken into consideration.

Table 1.1 summarises the results of the potential analysis for the four scenarios contemplated in the research, i.e. A1 (maximal food trade), A2 (low food trade), B1 (high food trade) and B2 (very low food trade). The geographical potential was calculated by introducing energy plantations into surplus agricultural land after covering human demand for food and materials, and by excluding protected, urban and natural areas. The technical potential was then calculated by applying conversion efficiencies on the geographical potentials previously estimated.

Table 1.1 Geographical and technical potential of energy from biomass estimated by Vries *et al.* (2007).

	Geographical Potential (EJ y^{-1})		Technical Potential (EJ y^{-1})	
Scenario[2]	Year 2050	Year 2100	Year 2050	Year 2100
A1 maximal food trade	2,365	4,014	475	810
A2 low food trade	1,120	1,422	227	288
B1 high food trade	1,624	2,516	328	508
B2 very low food trade	1,159	1,746	234	353

The worldwide amount of primary energy was 400 EJ in 2000, so under the scenarios A1, B1 and B2 the potential of biomass *would be in principle* sufficient to fulfil the current demand for primary energy. However, for the projected scenarios and with the projected demand for primary energy for the year 2050, the potential of biomass makes up between 30% and 60% of the consumed energy. The worldwide amount of electricity consumption for 2000 was 15 PWh$_e$; therefore, the technical potential calculated could cover the current electricity consumption, according to the authors.

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[2] Because if the number of parameters involved in the building up scenarios, it was only included in the table the way in which was addressed in the original publication.

The geographical distribution of biomass are scattered throughout the world with the main sources concentrated in southeastern Asia, ex-Soviet Union, South America and North America. In general terms, all countries in the eastern part of Europe show relatively low potentials, and for the year 2050, under the four scenarios, their biomass potential accounts for only 10% to 20% of energy consumption.

Finally, an economic assessment was conducted for the production of electricity from biomass. With a control area of approximately 3,000 km^2 in surface, the location of a conversion plant that uses the available biomass was considered. The transportation, labour, maintenance & operation cost as well as the cost of production for energy crops and total cost of electricity production was estimated.

Since the cost of transportation and production are different for each zone, this difference was considered and projected for each scenario. The reference conversion technology used in the assessment corresponds to an Integrated Gasification Combined Cycle (IGCC) with an electric efficiency of 51-53% for the year 2050 and an installed capacity in the 11-560 MW$_e$ range. It is observed that the minimum cost of generation oscillates around 4 ct€ kWh$_e^{-1}$, and the technical potential shrinks by 20-50%, depending on the scenario, when economic constraints were considered.

- **Smeets *et al.* (2007)**

Although methodologically akin to de Vries *et al.* (2007), Smeets *et al.* (2007) included agricultural, forestry and industrial residue in their assessment. Furthermore, the authors proposed a model that enabled the optimisation of the assignment of land, categorising it as either for traditional plantation or energetic crops, in order to simultaneously address food and material demand, and, additionally, maximise energetic potential.

The residues from the agricultural and forestry industry were calculated by using residue-to-crop production ratios and sustainable rate removal ratios (amount of residues that can be used in an environmentally-friendly way after harvesting). The results were then integrated into a GIS with a control area of roughly 3,000 km^2, although neither economic modelling nor an estimation of the generation cost of end-products was performed. Despite using the limit hierarchy for potential analysis, the economic potential was not calculated.

Table 1.2 shows the results of the potential analysis for the year 2050 and the percentage of energy that it represents compared to total consumption. The fraction of the primary energy was calculated by considering three probable consumption pathways of primary energy for each scenario by 2050; therefore, the results are presented as a range of percentages. It is possible to observe that the worldwide potential of biomass represents between 40% to 260% of the primary energy to be consumed in 2050.

The zones with higher potential correspond to sub-Arabic Africa, South America and countries of the former Soviet Union. Countries located in Western Europe exhibit a low biomass potential, and depending on the scenario and consumption of primary energy assumed for 2050, biomass represents from 10-50% of the total consumption of primary energy, more concentrate in the 20% to 30% range.

Table 1.2. Geographical and technical potential of energy from biomass estimated by Smeets *et al.* (2007).

Scenario 2050	Potential ($EJ\ y^{-1}$)	Primary energy 2050 (%)
Scenario 1	367	40-60
Scenario 2	610	60-100
Scenario 3	1,272	120-210
Scenario 4	1,548	150-260

For Smeets *et al.* (2007), the key factor of bioenergy's success lies in the management of food production. An advanced agricultural system that employs the best available technology and is implemented worldwide, developing countries included, will increase biomass potential substantially. The rise in productivity would be supported by the introduction of more land for crops, and the higher productivity of traditional crops as well.

Table 1.3. Geographical and technical potential of energy from biomass estimated by Smeets *et al.* (2007).

Scenario	Energy crops ($EJ\ y^{-1}$)	Forest residues ($EJ\ y^{-1}$)	Industrial and agricultural residues ($EJ\ y^{-1}$)	Total ($EJ\ y^{-1}$)
Scenario 1	215	85	76	376
Scenario 2	455	76	79	610
Scenario 3	1,101	76	96	1,273
Scenario 4	1,272	200	96	1,568

- **Bauen *et al.* (2004)**

Bauen *et al.* (2004) offer research with significant differences compared to the two previous ones. Bauen *et al.* (2004) made a series of assumptions which considerably simplified the calculation for the potential of biomass in the year 2020. Methodologically, the study did not use the definitions of physical, geographical, technical or economic potential. Aside from this, the calculations were made assuming surplus agricultural land and that 5% of the arable land devoted to energy crops, without any major justification.

The calculations were conducted by applying average productivities for energy crops. For agricultural and forest residues as well as for biogas, residue-to-crop production ratios and removal rate factors were used, and applied to statistical information on wood production, agricultural production and livestock. In contrast with the previous studies, GIS tools were not included nor was economic analysis. Because the electricity generation cost is estimated from case studies, the economic potential was not calculated.

The potential estimated by Bauen *et al.* (2004) for biomass in the year 2020 is 60 EJ y^{-1}. Whereas 42.5 EJ comes from energy crops, 17.5 EJ comes from residue, and makes up 15% of the total primary energy consumed in 2020. Assuming an electric conversion efficiency of 35%, this potential represents approximately 25% of the electric energy by 2020.

- **Preliminary Concluding Remarks**

From the three analysed studies, it is observed that for all the cases the primary energy predicted for each scenario increases with reference to the length of time under evaluation; the further in time the end year is from the reference evaluation time, the greater the primary energy predicted.

The studies show major differences in results, which can be attributed to the significant number of parameters and assumptions involved in the calculations (e.g. population growth, land productivity, the usage or non-usage of residues, improvement of conversion efficiency in the future and maturity of technology).

In spite of the disagreement over the potentials, the results are consistent in showing that the greatest biomass potentials are located on South America, southeastern Africa and countries in the former Soviet Union; thus developing countries. The potentials of the countries that compose central Europe is significantly lower and no more that 20-30% of the primary energy consumed in the reference year.

Other reasons for the differences observed in the studies arise from aspects such as the land modelling. The evolution of land for food production and for fuel was not considered, nor was the possible effect on food prices because of the demand for biofuels. In a similar way, agricultural productivity and the improvement of technology was not justified in most cases, despite being key factors for the biomass potential assessment. Another highly relevant aspect is the environmental impact or constraints of introducing large areas of arable land for energy production. This aspect is even more significant because, although not explicitly indicated by the authors, intensive agricultural production systems were assumed in all of the studies. Environmental impacts like loss of biodiversity, soil erosion, water availability and vulnerability to climate change were not contemplated, even in the studies that incorporated the most sophisticated models.

In the majority of studies the economic potential was not incorporated, which may drastically penalise the technical potential. This aspect will be discussed in more detail later in chapter 4.

1.2.2 Assessments at European Level

- **Ericsson & Nilsson (2006)**

The biomass assessment was carried out at the EU-25 level[3], with the addition of Ukranie and Belarus. Forest residues, forestry by-products, as well as crop residues were included. Municipal solid waste and used wood were not considered.

The assessment was made using international statistics (instead of local statistical sources), with scenarios built by combining hypotheses about land use, crop productivity and residue-to-crop production ratios. As far as the forest industry is concerned, a residue-to-stemwood ratio of 0.15-0.3 was assumed for coniferous trees, whereas 0.1-0.2 was assumed for

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[3] Bulgaria and Cyprus are not included since at the time of being published the article were not member yet.

deciduous. For the forest by-products, it was assumed that 75% of the roundwood is turned into final products, and the remaining fraction is turned into bark, sawdust, wood chips and black liquor. Concerning crop residues, wheat straw, barley, rye and maize were included. A residue-to-crop production ratio of 0.25 was assumed for wheat straw, and 0.22 for maize. These values consider that only 25% of the residues could be harvested because of environmental restrictions, and that 33% of the harvested straw was used in animal husbandry. Besides this, it was assumed that within the next 20-40 years the cereal maize yield would increase between 40% and 100%, based on the statistical tendencies.

For energy crops, the species intended for future use were not identified, and the productivity yield was estimated to be 50% higher than the wheat yield in each country of the EU-25. The assumption was based on the use of wheat productivity as an indicator of the agro-climatic and socio-economic conditions of each EU-25 member, as well as their agricultural policies.

Table 1.4. Potential supply of biomass energy in Europe estimated by Ericsson and Nilsson (2006).

Scenarios(*)	Forest biomass (EJ y^{-1})	Crops residues (EJ y^{-1})	Energy crops (EJ y^{-1})	**Total (EJ y^{-1})**
Scenario 1	1.8	1	1.8	**4.6**
Scenario 2a	1.8	1.1	5.6	**8.5**
Scenario 2b	2.4	1.1	7.2	**10.7**
Scenario 3a	1.8	0.7	15.4	**17.9**
Scenario 3b	2.4	0.7	19.9	**23**

(*) Scenarios are constructed by combining the conditions of crop yields, use of land and residue-to-crop production ratios, principally.

Table 1.4 lists the main results and is organised according to scenario. Based on Ericsson and Nilsson's (2006) assessment, the largest potential lies in energy crops, with exception of the first scenario, in which residues still contribute significantly to the total biomass energy supply. The countries that, in general terms and depending on the specific scenario, contribute to the biomass supply in a greater degree are France, Germany, Spain, Poland, Romania and Ukraine.

In the study, a methodology based in limits (theoretical limit, technical limit, economic limit, etc.) was not used. GIS tools were not employed and no economic evaluations were performed.

- **Kaltschmitt and Weber (2006)**

Kaltschmitt and Weber's (2006) study was limited to the biomass potential of the EU-15. The calculations were made presumably using statistical data, this base on the fact that there is no explicit information about the methodology. By assuming residue-to-crop production ratios and productivity factors, the technical potential of woody residues (3.2 EJ y^{-1}), straw (0.49 EJ y^{-1}) and energy crops (1.76 EJ y^{-1}) were calculated, although the employed parameters were not informed. For the estimation of energy crops, the authors assumed that 15-20% of the arable land could be used for growing energy crops within the EU-15; nevertheless, this assumption was not justified, and the exact percentage was not indicated either. The study concludes that the main source of biomass will come from forest residues, with France, Germany, Finland and Sweden as the major contributors.

The assessment did not incorporate either potential limits (theoretical, geographical, etc.), economic evaluation or GIS tools.

- **de Wit & Faaij (2010)**

The study covered the EU-27 plus Ukraine, and it assessed the biomass potential of dedicated bioenergy crops (i.e wood, grass, starch, sugar and oil crops as well as agricultural and forestry residue). The information was expressed as the primary energy content of the raw feedstock. An analysis based on three scenarios (baseline, low estimate and high estimate) was proposed, and the assessment was projected from the year of the study (2010) until 2020 and 2030. The primary information was gathered from databases and an extensive literature review.

The evaluation adopted an economic assessment that led to the estimation of technical potentials and cost of production by using supply-cost curves. The major cost associated with plantations dedicated to bioenergy production were fertilisers, labour, land, capital and miscellaneous cost; forestry and agricultural included collection of residues from the field, intermediate field transportation and transportation to an end-use site. For the forestry residue, the cost of procurement was estimated as the marginal production cost of chips from felling residue for a particular area.

The largest biomass potential comes from arable land, and is present in countries such as Ukraine, France, Germany, Poland, Romania and Spain in the long-term. Large variations in the potentials are observed, depending on the sort of crop, kind of land and geographical location. Whereas the energy potential of energy crops on arable land varies from 1.6 to 14.1 EJ y^{-1} (range for the low and high scenarios), the energy potential of herbaceous lignocellulose crops varies from 1.5 to 4.3 EJ y^{-1}.

The assessment incorporated both potential limits (theoretical, geographical, etc.), economic evaluation and GIS tools to visualise surplus land potential for the production of biomass by 2030 and the production cost. The cost was expressed as primary energy of first or second generation feedstock supply only; therefore, there was no evaluation of the cost of production for an energy carrier such as methane or electricity, for instance. In spite of the differences between scenarios, and the differences between the previously described studies, the research outcomes are consistent with showing Ukraine, France, Germany, Poland, Spain and Hungary as the countries with the largest potential.

Table 1.5. Potential supply of biomass energy for EU-27 estimated by M. de Wit and Faaij (2010).

Scenarios(*)	Energy crops (arable land) (EJ y^{-1})	Energy crops (pasture land) (EJ y^{-1})	Agricultural residues (EJ y^{-1})	Forestry residues(**) (EJ y^{-1})	**Total (EJ y^{-1})**
Low estimate	1.7	1.5	3.1	1.4	**7.7**
High estimate	12.2	4.3	3.9	5.4	**25.8**

(*) Scenarios are constructed by considering an increase in productivity in western European countries, an increased share of arable land, modernisation of the agricultural sector and better agricultural management.
(**) Felling residues and stem.

- **Panoutsou *et al.* (2009)**

The study aimed at mapping the technical potential of residual biomass feedstock for the EU-27, which means that energy crops were not included in the evaluation. The biomass was categorised according to sectors, with the cost of supply and potential listed at member-level. Trends in biomass availability for the time-scenarios 2000, 2010 and 2030 were taken as proxy for annual growth (an increase in agricultural residue as a consequence of increased agricultural production, etc.).

The previously mentioned biomass sectors are as follows: agriculture (i.e. crop residue, livestock waste), forest (i.e. wood fuel, forest residue), industry (i.e. woody residue from pulp & paper industries, black liquor) and municipal solid waste (MSW) (i.e. landfilled and nonlandfilled waste, sewage sludge). Table 1.6 provides the technical potential per scenario and by sub-classification.

Table 1.6. Potential supply of biomass energy in Europe (EU-27) estimated by Panoutsou *et al.* (2009).

Scenario	Agricultural residue (EJ y^{-1})	Manure (EJ y^{-1})	Forestry by-products (EJ y^{-1})	Industrial residue (EJ y^{-1})	Sewage sludge (EJ y^{-1})	MSW (landfill gas) (EJ y^{-1})	MSW (incineration) (EJ y^{-1})	**Total (EJ y^{-1})**
2000	1.37	0.69	1.76	0.54	0.09	0.21	0.30	**4.96**
2010	1.51	0.76	1.95	0.60	0.10	0.20	0.80	**5.91**
2020	1.67	0.84	2.15	0.66	0.11	0.10	1.41	**6.94**

The cost of supply for biomass was included for refined wood fuels, solid agricultural residue and industrial residue, which ranged from 0.58 € GJ^{-1} to 4.1 € GJ^{-1}, depending on the country and the kind of that. For instance, in the western European countries the cost of crop residue ranges from 1.4 € GJ^{-1} to 6.45 € GJ^{-1}, whereas in central and eastern European countries it varies from 1.5 € GJ^{-1} to 2.65 € GJ^{-1}.

According to Panoutsou *et al.* (2009), the countries with the largest amounts of biomass are Germany, United Kingdom, Estonia, Italy and France, with Scandinavia and northern members possessing higher forestry potential of biomass. No economic evaluations were done to estimate the cost of generation for secondary energy, no GIS were used either.

1.2.3 Assessments at National Level

- **Spain - Gómez *et at.* (2010a)**

Gómez *et al* (2011a) have produced a leading research on biomass potential analysis and renewables, with special emphasis on the utilisation of virgin and residual biomass (Gómez, *et al.* 2010a-c; Gómez, *et al.* 2011b). An evaluation of the potential and cost of electricity generation via anaerobic digestion of sludge from waste water treatment plants, organic fraction of municipal solid waste (MSW) and manure, as well as for the incineration of MSW, was carried out by employing supply-cost curves and then integrating the obtained results into GIS. The waste-to-energy technologies evaluated by Gómez *et al.* (2010a) were conventional anaerobic digestion plus internal combustion engines and MSW incineration. According the above-mentioned study, the most economical option is the incineration of MSW, which offers a cost of generation of 4.6 ct€ kWh$_e^{-1}$ and the largest energy potential (15 TWh$_e$ y^{-1}). The cost of generation from the remaining biomass sources varies from 5.1 ct€ kWh_e^{-1} to 11 ct€ kWh_e^{-1}, with energy potentials in the 0.4 to 4.0 TWh y^{-1} range.

Although not explicitly indicated in the study, Gómez *et al.* (2010a) assumed a centralised conversion system for manure processing in each control area so that the biomass can be converted (anaerobically in this case) and then used for electricity generation. Thus, it was assumed that all the manure available from different farms located in each county was transported at a negligible cost. Similarly, it was assumed that only a single incineration facility processes the total amount of MSW generated in each county. For the evaluation of the conversion of wastewater sludge, an anaerobic digestion plant that serves each county was assumed; however, only 68% of wastewater treatment is made of anaerobic systems (del Río 2007), and the total number of plants in operation (66 for 2007) is notably lower that the total number of counties (more than 300).

The above-mentioned simplifications led to an overestimate, in some cases, of the technical potentials, and, consequently, to an underestimate of the cost of production. Nevertheless, Gómez *et al.*'s (2010a-b) research attempted to systemically evaluate the waste-to-energy issue from a standpoint aimed at providing economic information by using the best available information, and with a strong technology-comparison orientation instead of evaluating the waste generation issue on an environmental angle, which is the traditionally chosen way. Only the electricity generation option was assessed, without considering the generation of biomethane as an energy carrier when anaerobic digestion is used as the conversion process.

- **Germany – Kaltschmitt *et al.* (2008)**

This study centered on the technical potential of agricultural (only herbaceous residues), forestry residues and its by-products, and energy crops for energy utilisation. Although no additional information was given (i.e. yields, residue-to-crop production ratios, etc.), statistical information was used to conduct the estimations. In spite of identifying the informed potentials as technical ones, a methodology based on limits of potential (theoretical, geographical, technical, etc.) was not used, and it is observed that there is a confusing definition of the meaning of “constraints”, which, according to Kaltschmitt *et al.* (2008), should be included in the technical limit, hence restricting the biomass potential.

Table 1.7. Potential supply of biomass in Germany estimated by Kaltschmitt *et al.* (2008).

Herbaceous residues (PJ y^{-1})	Wood-residue$^{(*)}$ (PJ y^{-1})	Miscellaneous residues (PJ y^{-1})	Landfill gas (PJ y^{-1})	WwTP (PJ y^{-1})	Energy crops $^{(**)}$ (PJ y^{-1})	**Total (PJ y^{-1})**
61-102	563	124-139	19.5	15-21	236	**455-533**

(*): Considered for thermo-chemical conversion only.
(**): 2 million hectares assumed.

Finally, Kaltschmitt *et al.* (2008) complement the discussion with market information of current use of biomass in Germany. However, there was no use of geographical information systems and no economic assessments were done.

- **India - Rao *et al*. (2010)**

The potential biogas generation from residues was assessed by Rao *et al.* (2010) by accounting for municipal solid waste, crop residue, agricultural waste, wastewater sludge, manure and industrial waste. Energy plantations were not included in the study. According Rao *et al.* (2010), biogas can contribute to the reduction of the electricity deficit in India, 11.436 MW_e or 13% of the peak demand for 2006 since the capacity of biogas generation from biomass accounts for approximately 5% of the technical one, and is estimated at 40,737 MM m^3 y^{-1}.

In spite of the promising technical potential, there was no segregation of data, which limits the evaluation of biogas generation to a commercial scale; therefore, the study was inconclusive. Furthermore, there was no use of limits in the potential analysis (geographical, technical, economic, etc.), and neither GIS tools nor economic analysis was included.

1.2.4 Assessments at National Level for Chile

- **Seiffert *et al.* (2009)**

This study aimed at assessing biomethane by the anaerobic and thermo-chemical conversion pathways from agricultural and forestry residue as well as energy crops. Statistical information was used for the estimation of technical potential by assuming availability factors, although there is not explicit information about the methodology or other assumptions.

Despite the remarkable differences between the Chilean and European forestry system, the authors calculated an *overall technical potential* of forestry biomass as the sum of unused felling residue and unexploited annual growth, following the methodology proposed by Thrän *et al.* (2006). This approach is, however, mistaken, because industrial plantations are harvested in Chile yearly and afterwards generating logging residue independently from firewood, which comes principally from native forest, a resource not exploited commercially, but informally. Seiffert *et al.* (2009) estimated that the annual logging residues are approximately 22 MM t y^{-1} (420 PJ y^{-1}), without taking into account circumstances in which these forestry by-products are not available. Bidart *et al.* (2010) estimated that annual logging residue are available at amount of no more than 1.7 MM t y^{-1}, leading Seiffert *et al.* (2009) to overestimate the biomass potential by over ten times the order of magnitude. Based on this information, Seiffert *et al.* (2009) concluded that forestry residue account for 72% of the national biomethane energy potential (212 PJ y^{-1}). Residual wood from the processing industry and agricultural residue respectively contribute 22% (47 PJ y^{-1}) and 6% (13 PJ y^{-1}) to the national potential.

For the assessment, the availability and future expansion of the natural gas net distribution was defined as a technical constraint. This is a questionable premise, since the technical generation of biomethane is not restricted by the injection into an existing network (so it is not a technical constraint, but a distribution step). Seiffert *et al.* (2009) did not include either sludge from wastewater treatment plants or landfills in the assessment, two promising sources for biomethane generation and customary practices in other countries with advanced biomethane policies (AEBIOM 2009). No economic evaluation was conducted, and a GIS energy map was used to pinpoint biomass distribution at a regional scale, with a resolution larger than 50,000 km^2.

Table 1.8. Potential supply of biomethane in Chile estimated by Seiffert *et al.* (2009).

Scenario	Forest Residues (PJ y^{-1})	Industrial Residues (PJ y^{-1})(*)	Agricultural Residues (PJ y^{-1})	Energy Crops (PJ y^{-1})	**Total (PJ y^{-1})**
Biomethane potential (2005)	151.6	46.5	13.4	0.2	**211.7**
Increased supply scenario (2015)	294.8	112.4	21.5	0.4	**429.0**
Stable supply scenario (2015)	162.3	55.6	13.5	0.1	**231.5**

(*) residue from wood processing industry.

Based on a scenario analysis, Seiffert *et al.* (2009) claimed that between 45% and 84 % of the national consumption of natural gas can be substituted for biomethane in a relatively short space of time (by 2015). Although the most advanced countries in biogas usage have not been able to replace beyond 3% of natural gas supply by using fermentative biogas (Mozaffarian, *et al.* 2004; EIA 2012), and the world's largest and most advanced SNG project via thermo-chemical conversion of forestry biomass, GoBigas in Sweden, aims to generate 10 TWh y^{-1} (36 PJ y^{-1}) by 2020 (Jönsson 2011), which would represent only approximately 17% of the current natural gas consumption in Chile (217 PJ in 2011), no comments about this are added by the authors.

The study lacks methodological rigour and contains methodological pitfalls, and, as previously mentioned, the potential was miscalculated; therefore, its conclusions are doubtful.

- **Chamy *et al.* (2007)**

In this study, an analysis of the residual biomass available at a national level for biogas production and the generation of electricity through CHP technology was performed. Methodologically, a classification for the biomass was proposed which was split up into dry biomass and wet biomass. The former was made up of swine and cattle manure, domestic wastewater and industrial liquid residues, whereas the latter was made up of forestry biomass, agro-industrial residue, residue from beverage industry, sludge from wastewater treatment plants, animal waste (slaughterhouse waste, fat, meat, etc.) municipal solid waste and poultry manure.

Table 1.9. Potential supply of biogas in Chile estimated by Chamy *et al.* (2007).

Livestock farming (PJ y^{-1})	Agricultural residue (PJ y^{-1})	WwTP (PJ y^{-1})	MSW (PJ y^{-1})	Industry (PJ y^{-1})	Others (PJ y^{-1})	**Total (PJ y^{-1})**
14.6	8.6	5.8	3.5	1.9	0.7	**35.2**

For the estimation of residue, residue-to-crop production ratios, typical yields and statistical data mainly taken from Germany and Sweden were applied because of the lack of more specific information for Chile. Table 1.9 summarises the main results, which are expressed as primary energy. According to these figures, livestock farming offers the highest potential, accounting for 42% of the national biogas potential. Agricultural residue makes up 25% of the total, and the digestion of sludge from wastewater treatment plants (WwTP) is 10%. Although there is a detailed segregation of residual biomass from the beverage industry (spent-used fruits, alcoholic fermentation, milk industry, etc.), all of them account for less than 4%. Similarly, residue from animal processing and pruning and weeding residue together make up less than 2% of the total potential.

Although the limits for potential (theoretical potential, technical potential, available potential, economic potential) were elaborated upon, their definitions are ambiguous and there is an unclear interpretation regarding their sense and scope. Similarly, economic potential was tackled by Chamy *et al.* (2007) as an issue of economic profitability; however, aspects of the market (price of energy, etc.) are not relevant in this stage of the analysis. The cost of production for electricity via CHP was estimated from a case study; therefore, the economic limit of each sector was not estimated. In addition, GIS systems were not incorporated.

- **Concluding Remarks of studies at European and National Level**

Thus far, most of the research on energy potential at the national level has been focused on the estimation of technical limits, without paying much attention to economics. More importantly, there are few studies focused on the potential of biomethane generation at the national level with an estimation of the cost of production and calculation of economic limits; or studies that tackle the problem of waste-to-energy comparatively and with special attention to economics (i.e. economic potential, cost of production); or to a comparative assessment of technologies.

The discrepancies found between the Seiffert (2007) and Chamy's (2007) studies are undeniable (when comparing corresponding sectors). The principal cause of these differences is the lack of consistent methodologies by both authors, and the incorrect interpretation of the functioning of some productive sectors by Seiffert (2007).

The rough estimates in Chamy's (2007) research need increased precision, which can be attained by improving primary information and by properly developing more rigorous and consistent methodologies. Nevertheless, these rough calculations indicate that the main resources for biogas generation are the livestock farming sector (manure from dairy and swine), agricultural residue, sludge from wastewater treatment plants and municipal solid waste, with the contribution of industrial residue being virtually marginal. Based on these preliminary outcomes, the aforementioned sectors will be assessed across the country as the main sources of biomass for energy generation.

After examining the previous studies, neither were found to face the problem of biomethane generation exclusively as a problem of upgraded fuel generation for injection into the distribution network, or for any other use which is not necessary in the direct generation of electricity. Being so, there are no studies aiming at a comparative analysis of the options for electricity generation from biogas, and a second alternative of upgrading for the production of a gaseous carrier with the same standard of natural gas to be injected into the gas network.

1.3 Methodological Approach

The methodological approach of the research has a systemic orientation closely following the principles of general system theory in which more important than the component units of a system is the totality and consistency of them (Skyttner 2001). In this sense, framework, inputs, outputs, component interactions as well similarities and dissimilarities between routes of conversions, technologies, benefits and impacts, are highlighted and analysed. The main emphasis is put on comparing these routes of conversions, technologies and their operating scales as well as the characterisation of energy potentials in economic terms (i.e. the necessity of subsidies, ranges of potentials out of economic scale, etc.).

Primary and secondary information to conduct the assessment will be collected from official government entities, technical reports or similar sources with sufficient reliability. When this information is not directly available, it will be built by gathering it from indirect sources such as environmental impact assessment reports, censuses carried out by public entities, information delivered from private companies or through semi-formal surveys given to experts directly involved.

The technical data to be gathered will describe the performance of conversion technology, principally investment, operation and maintenance cost, energy efficiencies, annual capacity (i.e. operating hours per year), physicochemical characterisation of the biomass processed (heating value, composition, humidity, etc.) and quality of end-products.

All the obtained information will be analysed to evaluate its statistical and technical consistency. Furthermore, case-to-case criteria will be developed to determine the conditions of applicability, ranges of validity and errors associated with the information. Preliminary results will be obtained by using primary and secondary sources and will be used as indicators to corroborate the reliability of the methods by comparisons with fully-informed case studies.

1.4 General Objectives, Framework and Scope

This research aims to investigate the potential of generation for renewable methane as a source of energy, assessing the possibilities of producing either an upgraded gaseous fuel or its direct use for the generation of electricity.

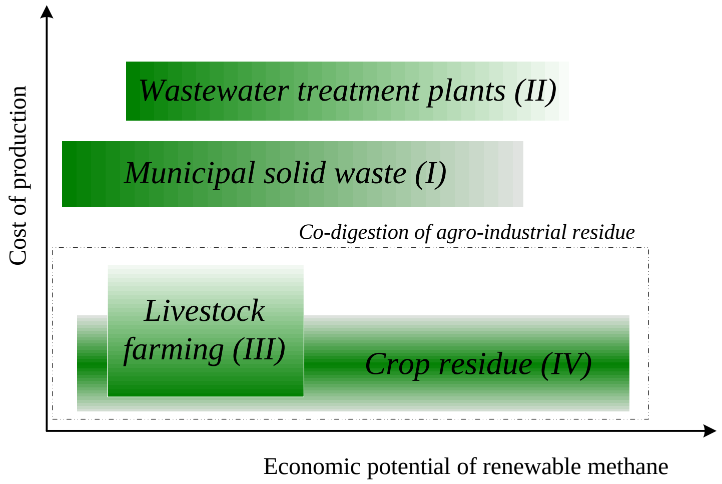

Figure 1.3. Renewable methane road-map and the five sector to be considered: municipal solid waste (I), wastewater treatment plants (II), livestock farming (III), crop residue (IV) and co-digestion (V).

The biomass that will be evaluated as raw material for the generation of biomethane is that which can be treated via anaerobic conversion or that from which methane is currently released and was originated anaerobically. These resources are classified in sectors which set up the scope of the analysis. They are identified across this study as: (i) *municipal solid waste (MSW)*; ii) *waste water treatment plants (WwTP);* iii) *livestock farming* and iv) *crop residue*. Because of the possibility of assessing the simultaneous use of manure and agricultural residue via co-digestion, a fifth sector named as *co-digestion of agro-industrial residue* has been added.

Through this assessment it will be possible to evaluate and identify sources of high potential, their cost and opportunity to be employed at economic scale. The assessment is conducted at the national level in Chile so that the entire geographical area of the country conforms to the framework of analysis. The selected frame for the analysis has then specific aspects such spatial distribution of substrates, local investments and conditions of the energy distribution systems, among others, that will be incorporated. However, these developed methodologies as well as the economic and technical information can be used for the assessment of other countries or regions.

The assessment considers the complete chain of value of the main products, starting with the collection of feedstock and ending with the use of the energy carrier to be fed into the corresponding energy distribution network.

1.5 Specific Objectives

The specific objectives of the research are the following:

- To organise and characterise digestible biomass through sectors which are suitable for the generation of renewable methane by state-of-the-art technologies.

- To conduct potential analyses based on a theory of energy potential for renewables that considers an aggregated, structured and interwoven set of limits.

- To identify and analyse state-of-the-art technologies adequate for the conversion of residual biomass to energy as well as their main economic and technical features, all which can provide reliable information to perform a techno-economic potential analysis.

- To build geo-spatial renewable methane maps from the abovementioned sectors by using computing-based tools.

- To finally propose a comprehensive policy towards the realisation of the economic potential of renewable methane generated from biomass in a systematic and orderly fashion.

2. The Chilean Energy System

This section aims to briefly outline the energy matrix of Chile, the main characteristics related to the demand of energy and dependence on imported fuels as well as the state of development of renewables. Although the goal of this section is not to review the energy system in great detail, this information will provide a context for the understanding of the results of the potential analysis that was conducted in later sections in order to frame the outcomes in the energy context of the country.

2.1. Introduction

The total primary energy consumption of Chile was 1,045 PJ y^{-1} for 2009 (National Commission of Energy 2010), and, as can be observed in Table 2.1, the energy mix relies predominantly on fossil fuels; hence, oil accounts for 43%, coal 16% and natural gas 12%. Renewables, made of hydropower, biomass and wind, account for 29% of the total.

Table 2.1 Chile's energy balance 2008 and 2009 (National Commission of Energy 2010).

Supply	2008 (PJ y^{-1})	2009 (PJ y^{-1})	Variation 2008-2009 (%)
Oil	462	445	-3.6
Natural gas	104	126	21.3
Coal	183	167	-8.6
Hydropower	87	90	3.8
Wind	0.1	0.3	107.3
Biomass (fire wood)	214	214	0.2
Biogas	0.0	0.3	-
Total (PJ y^{-1})	1,049	1,043	-0.6

Due to the introduction of natural gas from Argentina between 1997 and 2004, a significant fraction of coal and oil displacement was observed in that period. However, the disruptions in supplies from "*over the Andes*", which began in 2004, implied a reduction in the share of primary energy consumption of natural gas and higher reliance on oil (EIA 2009) although this tendency has changed in recent years due to the introduction on liquefied natural gas (LNG). This aspect in particular will be discussed in more detail in further sections.

2.2 Energy Demand

Energy consumption reached 1,000 PJ y^{-1} in 2009, accounting for 36% in the industrial sector, 37.4% in the transportation sector (mostly in on-road transport) and 26.6% in the commercial-residential sector (National Commission of Energy 2010). The public sector accounts for approximately 0.7% % of the total energy demand. A characteristic feature of the national matrix is a substantial share of biomass in the form of firewood, which is used for heating. In 2009, this fuel represented approximately 50% of the residential and commercial sector and 15% in the industrial sector (EIA 2009).

2.3 Import Dependence

One distinctive aspect of the energy sector in Chile is the virtually total dependency on fuel imports. As a result of this, the country is permanently experiencing vulnerability to price and supply fluctuations, thus coming up against a slavish dependence upon the international markets. In contraposition to Argentina, Peru, Bolivia, Brazil and other such countries in the region with abundant indigenous resources (Olade 2011), Chile only has a limited amount of fossil fuels, which are located principally in the Magallanes Region. The supply of natural gas came almost exclusively from Argentina until 2004, when the economic crisis of that country forced the introduction of LNG to fulfil the energy demand. Concerning oil, the estimated import reached 11,160 MM m^3 during 2009 (National Commission of Energy 2010), principally imported from Brazil, Ecuador, Angola and Colombia, with a net national production of 216 MM m^3.

2.4 Electrical Sector of Chile

2.4.1 Electrical System

Because of Chile’s distinct and uneven geography, the country’s, energy markets are regionally independent; this is particularly significant for the electricity systems and the main natural gas grids, which operate autonomously. In addition to this singularity, the country has faced severe (and even dramatic to some extent) energy supply interruptions in last decade, including severe droughts, a sustained gas supply cut from Argentina (since 2004) and one of the strongest earthquakes in recorded history in March 2010; the earthquake was particularly damaging to the electricity networks and refineries, leading to continuous black-outs for a significant period of time.

In Northern Chile the mining industry is the dominating consumer of energy and operates by using the *Sistema Interconectado Norte Grande (SING)* for the transmission of electricity. This system is essentially thermal-based. The central region, which is the most densely populated area of the country, operates on the more hydro-dependent *Sistema Interconectado Central (SIC)* electricity grid. In the southernmost part of Chile the systems in *Aysén* and *Magallanes*, both hydro-rich regions, are not connected to the rest of Chile in terms of electricity and gas.

2.4.2 Electricity Production

The majority of Chile's electricity supply, and potential (De la Torre, *et al.* 2010), still relies on hydroelectricity, with the importance of conventional thermal sources progressively increasing. In 2009, Chile had a total installed electricity generating capacity of 16.15 GW and electrical production of 61,038 GWh_e[1] (National Commission of Energy 2010). As previously described, thermo-power provides the largest share of Chile's electricity supply, contributing 66 % in 2009 (EIA 2009). In the last decades, Chile's generation mix has changed substantially. In 1990, electricity generation was based mostly on hydropower, which accounted for 55% of the total. Along with the supply of natural gas from Argentina between 1997 and 2004, its share in electricity generation rose from 1% to 33% (EIA 2009), thus partially replacing coal and oil. Afterwards, and because of the restriction in supply[2], this situation started reversing, returning to the previous pattern of greater use of oil-based fuels for thermo-generation.

2.5 Natural Gas

The consumption of natural gas reached 3,219 MM $Nm^3\,y^{-1}$ in 2009 of which 920 MM $Nm^3\,y^{-1}$ was used for electricity generation (National Commission of Energy 2010); the commercial, public and residential sector consumed 595 MM $Nm^3\,y^{-1}$ for the same period. Domestic gas

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[1] It includes imports from Argentina of 1,348 GWh_e

[2] More details about the supply of natural gas from Argentina and the Argentinean crises in the forthcoming sections.

production supplies only the Magallanes Region at a relatively constant rate of approximately 1,900 MM Nm^3 y^{-1} in 2009 (Sernogeamin 2012). The gas was mainly used to feed the gas-based methanol plant, which is currently being relocated to the US, Geismar, due to the lack of feedstock and more competitive prices (Hydrocarbon Processing 2013). During 2012, the gross consumption of natural gas reached 5,063 MM Nm^3 y^{-1}, with an indigenous production of 1,233 MM Nm^3 y^{-1} (EIA 2014).

The natural gas market scenario is experiencing strong changes at the time this chapter is being written (June 2013). Modifications in the supply of LNG are under discussion and negotiations between distributers and suppliers are taking place, in addition to modifications in the way of indexing price. Because of its importance and dynamism, more detailed information regarding these issues is provided in Chapter 3.

2.6 Coal

Chile has recoverable coal reserves of 3,640 MM t, which are distributed in Arauco (140 MM t), Valdivia-Osorno (500 MM t) and Magallanes area (3,000 MM t). In 2009, the country consumed 5.7 MM t (National Commission of Energy 2010), while producing 517 M t (Sernageomin 2012). Domestic coal production is located in the Lota and Coronel area (Arauco) and in the extreme south on Tierra del Fuego. The country has two mines, which are operated by Empresa Nacional del Carbón (Enacar) and La Compañía Carbonífera San Pedro de Catamutún (CCSPC), respectively.

The level of coal consumption has tended to fluctuate as the power sector, the country's largest coal consumer, uses the fuel largely as a backup to hydropower or mixed with imported coal. In this role, it is possible that coal consumption might rise in the coming years, especially if the unreliability of natural gas imports continues. In 2009, most imports came from Australia, followed by Indonesia and Colombia.

2.7 Oil

In 2009, oil accounted for 445 PJ y^{-1}, equivalent to 43% of the total primary energy consumption of the country (see Table 2.1). As mentioned earlier, the indigenous production is lower than 2% of the internal demand (216 MM m^3), making the country a net importer.

The transportation sector consumed 358 PJ y^{-1} in 2009, while mining (copper, iron, nitre and others) consumed 68 PJ y^{-1} for the same period. The total consumption reached 445 PJ y^{-1} in 2009 and a decline in import volume was observed.

2.7 Renewables

Renewables (i.e. hydro, geothermal, solar as well as biofuels and waste) comprised 67% of the domestic production of primary energy in 2009 (EIA 2009). After oil, biomass is the second most important source of primary energy accounting for 21% of primary energy matrix. Hydro-electricity contributed 30% of the country's installed capacity, and biomass made up approximately 3% of thermo generation (419 MW_e). By the end of 2007, wind energy was not part of the electrical system generation although in 2008 the total capacity reached 20 MW_e (EIA 2009), and today (May 2013) the installed capacity has risen to 273 MW_e (Financial News 2013[d]). Photovoltaic energy still has a modest installed capacity of 2.5 MW_e. Nevertheless, it will increase in near future due to projects under construction. Consequently, considering all sorts of renewable energy and only for electricity generation, it is expected that at the end of 2013 the total installed capacity will reach 1,300 MW_e (Financial News 2013[d]).

Because of the topography and natural conditions, the potential for renewable energy is diverse and significant (EIA 2009). Firstly, 10% of Chile's volcanoes are currently active, so a substantial potential for geothermal energy exists. Similarly, strong and continuous wind across the country makes wind energy another important source of energy. Due to the geographical conditions of the south area of the country, hydro will continue playing a significant role in electricity generation in that area. Finally, as a result of the more than 4,000 km coast line, Chile might have the largest potential for wave (tidal) energy in the world.

Owing to its higher stability and cost of production, biomass will continue leading the matrix of renewable energy; an imminent increase in wind energy, on the another hand, is expected, not only due to a steady reduction in production cost for this technology but also resulting from the substantial number of projects that are in the environmental assessment phase, which will consist of roughly 3,000 MW_e once they are installed (Financial News 2013[d]).

3. Fundamentals of the Natural Gas Market

In this section the main features of the natural gas market are discussed. Additionally, information related to prices and infrastructure of natural gas in Chile is provided, thus framing the economics of this industry and the main drivers that are setting the short and medium-term conditions for the commercialisation of this energy carrier.

3.1. General Background

Before the 1970s, natural gas was considered only as a by-product of the oil industry without an intrinsically commercial value and was not expected to attract significant investments. Nevertheless, energy security, concern about greenhouse gas emissions and outstanding advances in the transportation of natural gas as well as its cleanliness as a fuel has converted it to the leading fossil fuel of today and a commodity with an international trade market. From an international point of view, the largest proven reserves of natural gas are located in the former Soviet Union and in the Middle East (Gilardoni 2008; Guo 2005) although with a modest performance in the latter[1]. The largest producers and simultaneously consumers are the former Soviet Union and United States; the former Soviet Union has an approximate production of 681 billion $Nm^3\ y^{-1}$ and United States 592 billion $Nm^3\ y^{-1}$ (data from 2012), whilst the United States doubles the consumption of the Soviet Union with an approximate demand of 722 billions $Nm^3\ y^{-1}$ (BP 2013).

As noted by Essandoh-Yeddu (2012), the increasing consumption of natural gas induced a rise in price, principally in United States, from 3.33 US$ $MMBTU^{-1}$ to 8.85 US$ $MMBTU^{-1}$ for the 2002-2008 period. However, the global financial crisis in 2008 suddenly reduced consumption, thus triggering up a drop in price to 2.89 US$ $MMBTU^{-1}$ in 2009. In Asia the contrary occurred, with prices rising steadily in last decade[2], from 4.27 US$ $MMBTU^{-1}$ to 16.75 US$ $MMBTU^{-1}$ approximately. The same tendency is observed in England, with prices growing from 3.24 US$ $MMBTU^{-1}$ to 11.03 US$ $MMBTU^{-1}$ for the same period (2002-2012) (BP 2013).

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[1] With a reserve-to-production ratio 15:1 (order of magnitude); North America and South and Central America exhibit approximated reserves-to-production rations of 2 and 4.1, respectively (PB 2013), pg. 21.

[2] Values expressed as CIF price of liquefied natural gas (LNG).

The natural gas market is a complex collection of entities such as producers, transporters, regulators, sellers, buyers and brokers, who collaborate or compete across different segments of the supply chain (Essandoh-Yeddu 2012). Despite of the complexity of this market and its interactions, three main components are recognised on the supply side: *producers, pipelines* and *local distribution companies* (Pirog 2004). At the same time, the consumption market is split up and each of its segments tends to pay a differentiated price. Normally, the consumers of natural gas are categorised as *residential consumers*, *commercial consumers*, *industrial consumer* and *electricity consumers*, with the former paying the highest price, and the latter, the lowest.

3.2. Transportation of Natural Gas

In the existing natural gas market, the centres of production are normally located a long way away from those of consumption, thus long distance means of transportation are necessary. Besides, the storage of natural gas is associated with technical problems and is more expensive than that of crude oil (EA 2012), so the need for transporting it to a destination is practically compulsory after it is produced from a reservoir (Mokhatab 2006). There are a variety of means for the transportation of natural gas to the centres of consumption (see Figure 3.1), including pipelines, liquefied natural gas (LNG), compressed natural gas (CNG), gas-to-solid (GTS) and gas-to-liquid technologies (Mokhatab 2006; Wang 2009; Kidnay & Parrish 2006). The option of transporting natural gas is related to distance for the delivery, cost, technical-feasibility, distance of conveyance, demand as well as economic risks and possible terrorist activity, geo-political stability of the supply region and long-term trade embargoes (Speight 2007). Because of the lower intensive cost and higher capacity in comparison with others means, overland pipelines is the dominant way of terrestrial conveyance and distribution of natural gas. Szoplik (2012) noticed that the demand of natural gas from municipal receivers and industry has increased substantially over time, and this has also stimulated the development and delivery of natural gas through pipeline networks, which have become more and more complex in terms of design and operation.

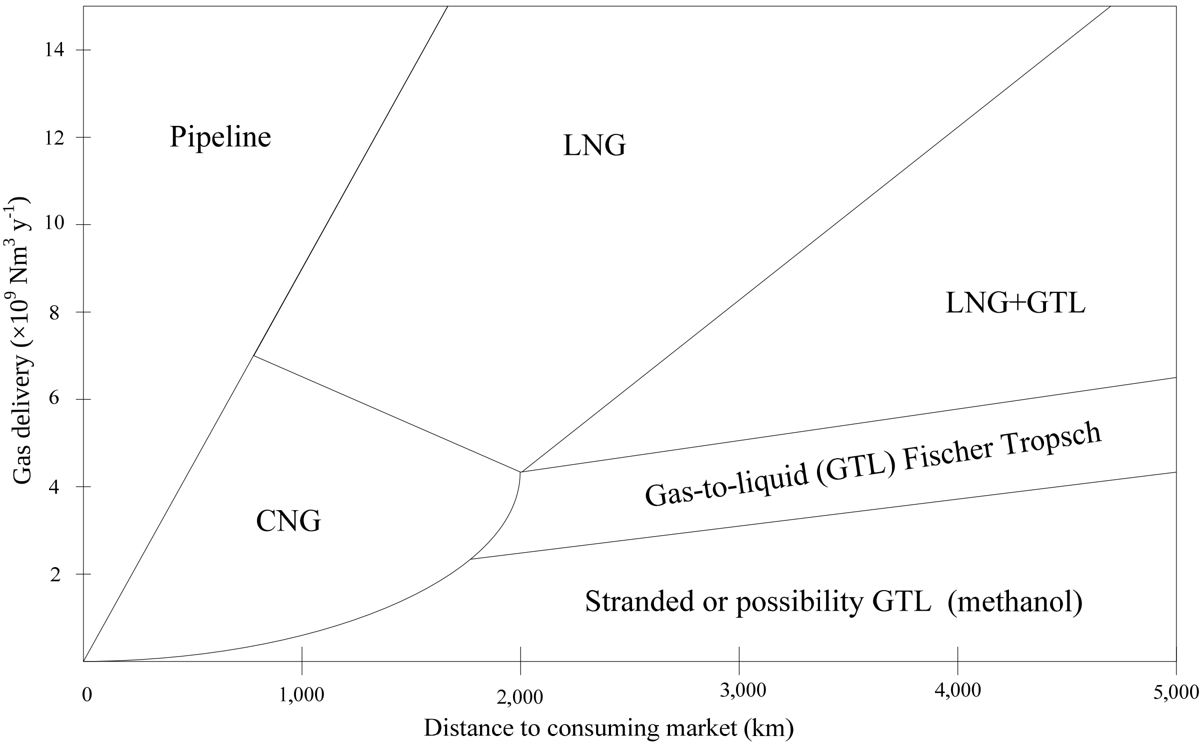

Figure 3.1. Economically preferred options for natural gas transportation. Adapted from Wang (2009).

Because pressure pays an essential role for the transportation of natural gas, the network distribution systems are normally classified using this variable. As pinpointed by Hansch (2006), there are three levels of pressure for pipeline systems: high pressure grid (1-10 MPa), medium pressure grid (10 kPa to 0.1 MPa) and low-pressure grid (lower than 10 kPa). More recently, Szoplik (2012) listed four types of distribution systems: high pressure pipelines (higher 1.6 MPa), middle pressure pipelines (from 10kPa to 0.5 MPa), increased middle pressure pipelines (from 0.5 MPa to 1.6 MPa) and low pressure pipelines (lower than 10 kPa).

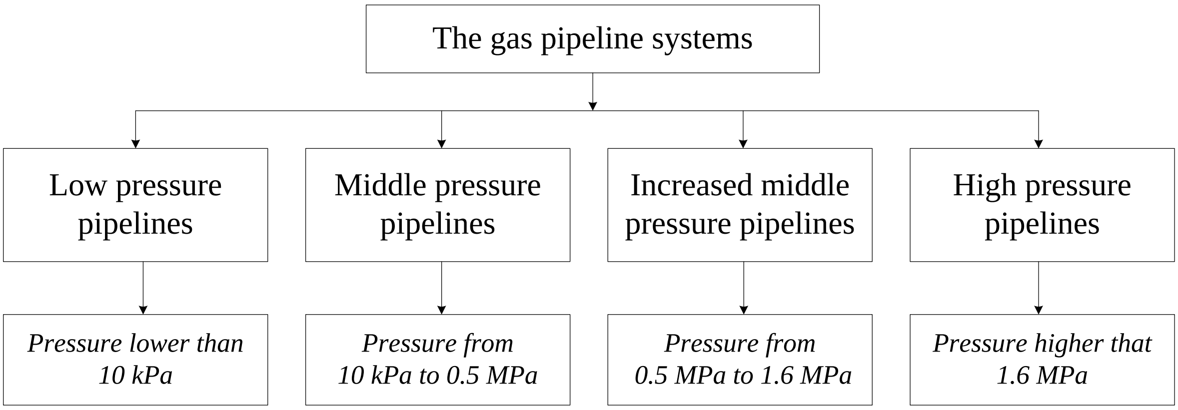

Figure 3.2. Main sorts of gas pipeline networks. Adapted from Szoplik (2012).

3.3. Infrastructure of Natural Gas in Chile

3.3.1 Liquefied Natural Gas (LNG)

Currently, there are two LNG terminals operating in Chile. These are *Quintero* and *Mejillones* terminals, the former located in the central region and the latter in far north of the country. Both are supplied with LNG from different markets (EIA 2012) and can be classified as small-medium capacity in the context of worldwide LNG terminals in operation.

Quintero terminal has operated since 2009 and has a nominal re-gasification capacity of approximately 3,900 MM Nm^3 y^{-1}. British Gas controls 40% and has a contract to supply its three customers, ENAP, Endesa and Metrogas, each one with a 20% stake in the terminal. The main market for natural gas is focused in Santiago (Metropolitan Region) and Valparaiso, and has a natural gas supply via terrestrial pipeline.

From the beginning of its operation, the delivery price of LNG was calculated using the Brent index. Nevertheless, from 2013 on and for a new supply contract, the Henry Hub index will be introduced in the indexation for the calculation of the trade price (Financial News 2012^a), instead of exclusively using the Brent index. This new way of calculating the price will positively affect the national companies and negatively affect the British since the discovery of shale gas in the US has caused a drop in prices over the last years; the Henry Hub index was supposed to be high but has dropped to 2.65 US$ $MMBUT^{-1}$ in 2012. However, a negotiation has taken place between the parties and they are expected to reach an agreement in which other aspects such as transportation and re-gasification cost as well as fees will be taken into consideration in the formula for fixed price. If this new mode of price fixing is applied, the price of LNG is expected to decrease to approximately 10 US$ MMBTU, significantly lower than the current declared price, which is in the 14-17 US$ $MMBTU^{-1}$ range[3] (Financial News 2012^a).

Mejillones terminal began operations in 2010, with a nominal gasification capacity of roughly 2,000 MM Nm^3y^{-1}. In contrast with Quintero terminal, this is an off-shore storage terminal. The terminal is owned by the Chilean state copper mines Codelco and GDZ Suez,

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[3] This value without including the cost of re-gasification of LNG.

both sharing equal stakes in participation. This LNG is mainly devoted to electricity generation for the mining industry in the north of the country.

Currently there are numerous projects underway for the expansion of existing LNG terminals, construction of new ones or the installation of electricity generation projects with LNG as a fuel. In 2014, an expansion of Quintero terminal with an estimated investment of 30 MM US$ for a new storage tank is expected. Similarly, in Mejillones a storage tank that demanded an estimated investment of 200 MM US$ is being constructed, and it is projected to be operative by 2014. Additionally, there are four projects aimed at installing re-gasification terminals using floating ships, projects with a estimated investment of approximately 3,100 MM US$, the impact of which should principally be a drop in the marginal cost of electricity (Financial News 2012[b]).

3.3.2 Pipelines

In 1990 a series of pipelines started being constructed in order to connect Chile to the supply of natural gas from Argentina. The deliver of natural gas, however, started being restricted since 2004, when Argentina began facing an internal economic crisis and decided to concentrate on its internal market. Since the period 2007-2008, the operation of the pipelines has become virtually non-existent (EIA 2012).

The most remarkable gas supply pipelines are NorAndino and GasAtacama in the north; GasAndes, which connects to Santiago; Gaseoducto del Pacífico to Concepción and other small-pipelines that connect to Magallanes (EIA 2012). In principle, the unused pipelines could be employed to store natural gas; nevertheless, there are legal issues to be resolved between the partners. It is important to point out that there are no gas sites that are solely designated for storage in Chile, principally because of the country’s geological instability, which makes the implementation of these storage stations technically unfeasible.

3.4. Pricing of Natural Gas

Being that the distribution of natural gas is segmented in the aforementioned way, the price of natural gas is layered, with a portion of the total price added by each intermediate supplier. When assuming that the base price is fixed by the wellhead price or the LNG price after re-gasification, the pipeline transportation cost is added yielding the city gate price. Finally, the local distribution companies charge additional fees for transportation and delivery to end-consumers, leading to the price paid by them. As in others energy markets, the final tariff and evolution of the prices will be significantly influenced by the role played by the state; therefore, the existing regulations as well as the possibilities of competition between different markets. For the case of Chile in particular, Fosco and Saavedra (2002) made the assertion that the distribution of natural gas, mainly because of the infrastructure and concentration of distribution, is a monopoly, and, in the best of the cases, a duopoly. Gavetovic (2007) cast doubt on the previous statement, and by using econometric models evaluated the performance of the natural gas distribution market in Chile. Excepting Magallanes region, Gavetovic (2007) concluded that the distribution of natural gas is not a natural monopoly within the relevant markets and the distribution grid is not an essential installation. According to him, the arguments normally given for the state to regulate the distribution of natural gas are not valid and inapplicable for Chile. In spite of the fact that the abovementioned studies were inconclusive, there is recognition that the Chilean market for natural gas, comparatively, has a minimal regulation. This issue was deliberately designed in this way in order to boost investment so that the country could quickly develop adequate infrastructure for the commercialisation of natural gas.

3.5. Prospect for Natural Gas

If the price of LNG is finally fixed by using a new way in which the Henry Hub index can be introduced, the price of electricity generation must decrease in the short-term. Similarly, if the LNG projects for the expansion of the existing infrastructure or construction of new ones are finally completed, the operation of the electrical market will rely more and more on LNG, with a subsequent decrease in prices of electricity for those plants which operate under combined cycle. According to preliminary calculations, the price should drop down from the 14-17 US\$ MMBTU^{-1} to approximately 5-7 US\$ MMBTU^{-1} in 2013, and this price range should stay relatively low.

4. Methodology for Potential Analysis at National Level

In the forthcoming sections the theoretical background and methodological approach developed for the assessment of renewable methane potential is described. The first part of this section will show how the limits for the potential analysis were mathematically formulated with the help of a Boolean logic, which allowed a highly structured procedure for the evaluation and the development of methods for a cross-assessment comparison between the options of using biomass for each sector and enumerate the differences between them in a consistent way. Similarly, the economic modelling for the calculation of unitary cost of secondary energy is presented; the modelling was developed with the help of a basic concept of economic engineering based on estimation of investment, cost of operation & maintenance, and cost of provision of raw material, among others. Finally, the general methodology for the calculation of the economic indicators and its interpretation for both options of biomass conversion (i.e. biogas-to-energy and biogas-to-upgrade) is laid out.

4.1 Limits for Potential Analysis

The definitions of limits of potential in the literature are not always consistent and, in numerous cases, lead to misunderstandings and misinterpretations of the results. In this respect, Thrän *et al*. (2006) defines technical potential as the *"...percentage of the theoretical potential than can be given current technical possibilities [...] takes into account available utilisation technologies, their efficiency, availability of sites also in terms of competing uses, as well as "insurmountable" structural, ecological (e.g. nature conservation areas) and other non-technical restrictions".* The economic limit is put forward as the "*percentage of the technical potential that can be used economically in the context of given basic industry conditions...[...] the economic potential for using renewable energy is affected by conventional energy systems and the prices of energy sources".* In the first definition used by Thrän *et al*. (2006) an inconsistency is observed by defining the technical limit as affected by both technical and non-technical restrictions. Secondly, for the economic limit, it is indicated that this restriction is used economically. This is incorrect because the production cost of this energy can be higher than its market price; furthermore, it is not influenced by the prices of energy sources. As will be shown later, the economic limit is not affected by market conditions. Similarly, Eisentraut *et al.* (2010) defines the technical limit as the "*amount of biomass that can be harvested from available and suitable land*", and the economic limits as "*the biomass technically acquirable and can be derived at costs competitive with alternative energy applications*". As can be noted, attention is paid to the procurement of harvestable biomass from plantations and it is excluded from the biomass obtainable from other sources, therefore. Similar to Thrän *et al*. (2006), the economic potential is understood by Eisentraut *et al.* (2010) as a competitive limit for the supply of biomass, which is erroneous.

For the methodological approach developed to conduct the potential analysis of biomass, the definitions put forward by Hoogwijk (2004) and Pakenas *et al.* (2003) will be used with slight modifications. In the forthcoming section the limits of potential are defined by using a mathematical nomenclature that will be employed across the entire dissertation.

4.1.1 Definition of Limits of Potential

- ***Physical Limit***

The physical limit (also called theoretical limit) is the upper limit of primary energy calculated without imposing any kind of restriction. It corresponds to all the available primary energy in the biomass and can be estimated by applying the following equation:

$$\Pi_f = \sum_{i=1}^{n} \pi_{f,i} \qquad \text{Equation 4.1}$$

This indicates that the aggregate potential (in capital letter) is the sum of all the single potential (in lower case) within a specific geographical zone. A graphical representation is presented in Figure 4.1.

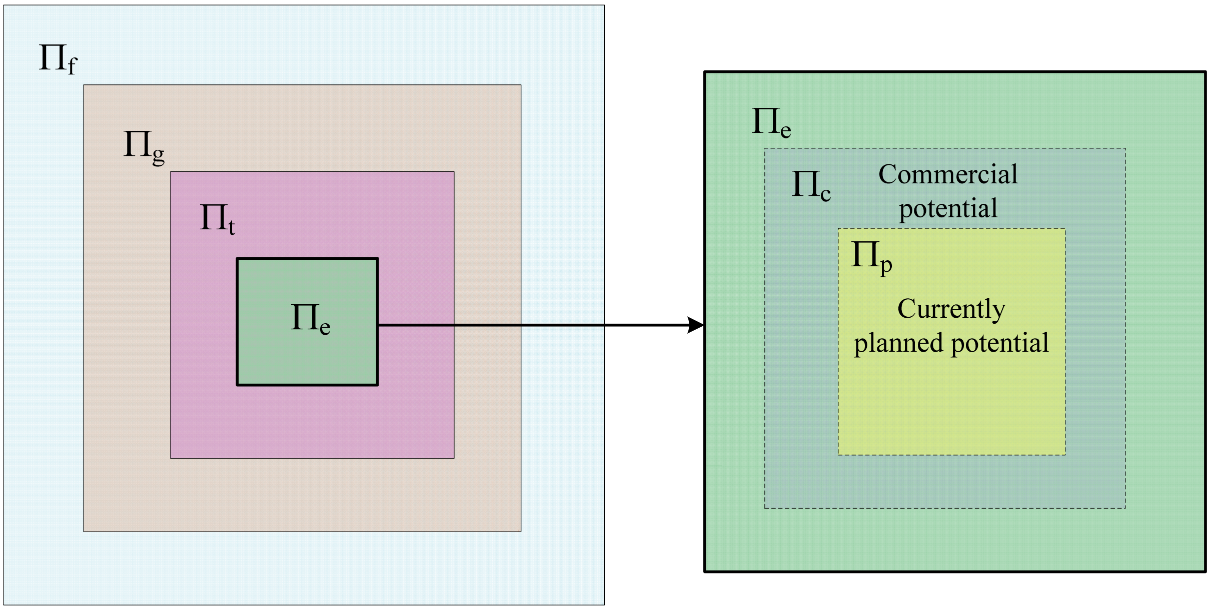

Figure 4.1. Diagrammatic representation of the hierarchy of limits for the potential analysis of renewable energy.

- ***Geographical limit***

This component constrains the potential because of legal considerations, urban regulations or limitations imposed by the geography such as when biomass is forbidden to be collected, typically for human settlements, protected areas such a parks, lakes, rivers, beaches and modes of transportation (influence areas) such as roads, airports, etc.

$$\Pi_g = \sum_{i=1}^{n} \pi_{g,i} = \sum_{i=1}^{n} \pi_{f,i} A_{g,i} \qquad \text{Equation 4.2}$$

Mathematically, the geographical limit can be expressed as a fraction of the physical limit by imposing a Boolean constraint $A_{g,i}$, an exclusion factor with the value zero or one, when there is or is not a geographical restriction, respectively. Therefore, the geographical limit is a fraction of the physical one, equal to or lower than it.

- ***Technical Limit***

This limit takes into account the restrictions given by the technology for the conversion from a primary to a secondary form of energy such as electricity and gaseous, solid or liquid fuel, considering the entire value chain starting at the collection of the biomass and ending with the end-product in a condition in which it is ready to be used.

This conversion process for a specific technology is normally characterised by means of the conversion efficiency (η_c). Consequently, the technical limit can be calculated from the geographic limit by applying both technical restrictions $(A_{t,i})$ for the use of biomass when biomass can or cannot be collected, comminuted or processed and the characteristic efficiency of a specific technology (η_c) as follows:

$$\Pi_t = \sum_{i=1}^{n} \pi_{t,i} = \sum_{i=1}^{n} \pi_{g,i} A_{t,i} \eta_c = \sum_{i=1}^{n} \pi_{f,i} A_{g,i} A_{t,i} \eta_c \qquad \text{Equation 4.3}$$

It is important to emphasise that this represents the theoretical outer limit of secondary energy available, *without any regard for cost or market acceptability, so it is not indicative of economic feasibility*. Therefore, *the technical limit must be used only as the basis for further analysis*.

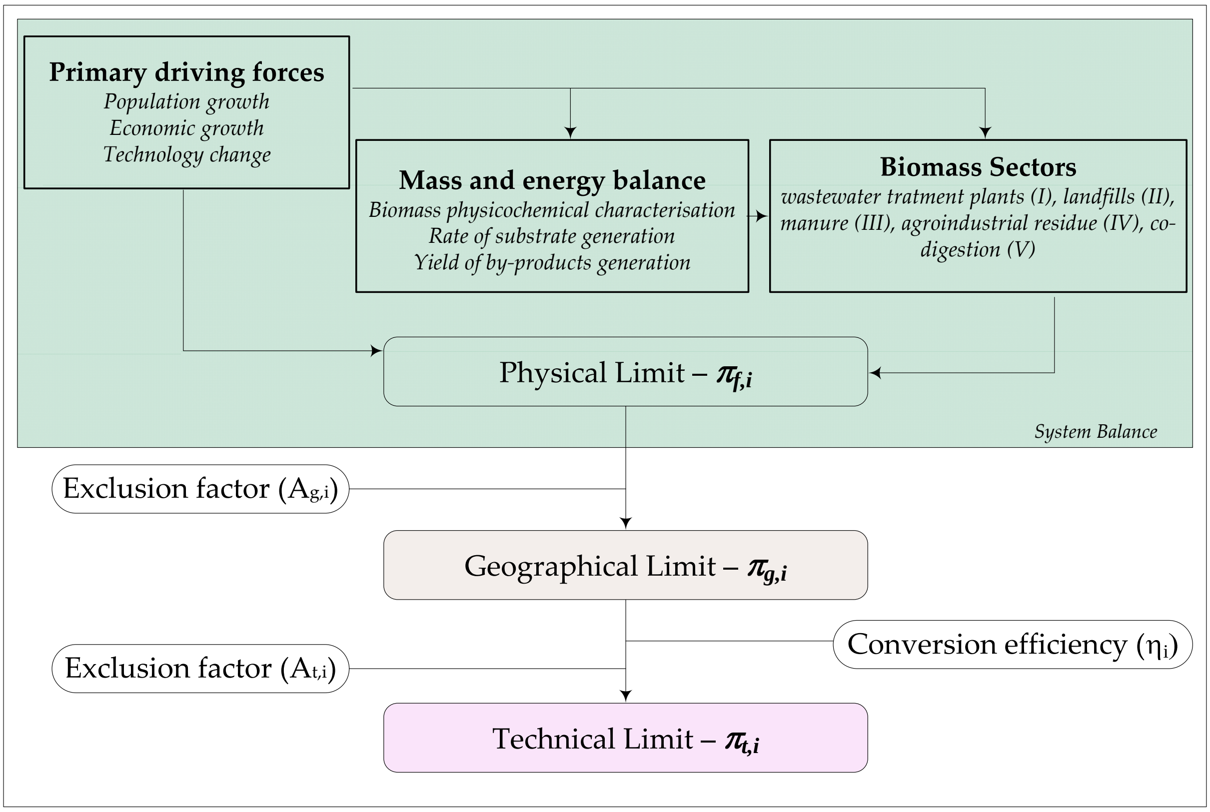

Figure 4.2. Relationship between limits and the exclusion factor for their calculation. Adapted from Hoogwijk (2004).

Figure 4.2 sets out, in a diagrammatic form, the sequence of limits for the potential analysis and how the exclusion factors $(A_{x,i})$ and the conversion efficiency (η_c) penalise each aggregate level of energy. As illustrated, the physical limit for each sector of biomass to be assessed, i.e. (i) municipal solid waste; (ii) wastewater treatment plants; (iii) livestock farming; (iv) agricultural residue; and (v) co-digestion of agro-industrial residue, will basically depend on aspects such as rate of substrate generation, physicochemistry of the biomass and yield of biomethane generation. Another group of variables, labelled in Figure 4.2 as primary driving forces, are population growth, economic growth and technology change, all which may also directly or indirectly affect the generation of biomass, and, consequently, the biomethane potential in a time-horizon. In this sense, each sector has distinguishing characteristics that can not be easily generalised. Nevertheless, it is possible to calculate the potential flow of methane that can be generated by each sector from the energy and mass balances previously described, thus obtaining a conservative estimate on a temporal and geographical basis.

The hierarchy of limits mentioned above allows a highly structured way of organising the potential analysis, which is particularly advantageous when there is a significant amount of data to be processed. More importantly, it makes clear how each aggregate level of energy leads to the following one, avoiding misleading definitions and misinterpretations of the results, which are commonly found in the scientific literature as initially discussed.

For its importance and relevance in further analysis, the issue of economic potential will be addressed separately in the next section. Aspects related to the commercial potential and currently planned potential are beyond the scope of this work. They could be considered in further research.

4.2 Economic Limit and Its Definition

The economic limit is directly related to the analysis of generation cost and, for this reason, supply-cost curves are frequently used to conduct economic analysis and develop energy policies. Supply-cost curves are utilised in numerous assessments of technologies, and in a range of potential analyses for both non-renewable and renewable resources at different geographical levels. In this sense, Radov *et al.* (2009) used supply-cost curves for the estimation of the availability of renewable heat, whereas Hare & Ladbrook (2007) employed them for the calculation of cost of carbon capture and storage in the UK. In a thorough research, Hoogwijk (2004) used supply-cost curves for the assessment the global and regional potential of renewables (i.e. biomass, on shore wind-energy and photovoltaic). Daniels & Uyterlinde (2005) modelled the European electricity market for renewable energy by combining the use of supply-cost curves and policy-based demand curves so that the pertinence of public policies could be evaluated, and the most adequate use of electricity, trade or internal consumption for the producers, could be assessed.

The supply-cost curves are constructed by estimating the specific cost of production of each technical supply $c_i(\pi_{t,i})$, and then adding up the potential in the order of decreasing cost[1]. The unitary cost of production of each single potential $(\pi_{t,i})$ can be calculated through an economic model that considers annualised investment, operation and maintenance cost and procurement cost of substrates, as Equation 4.4 indicates:

$$c_i \pi_{t,i} = \alpha I_i + C_{o\&m,i} + C_{p,i} - R_i \qquad \text{Equation 4.4}$$

In Equation 4.4 c_i is the unitary cost of secondary energy; $\pi_{t,i}$ is the single technical potential of the *i*th-source of energy; I_i is the total investment of the conversion technology for the whole supply-chain; α is the capital recovery factor; $C_{o\&m,i}$ is the operation and maintenance cost; and $C_{p,i}$ is the feedstock supply cost for conveyance at the gate of plant (when applicable). In addition, R_i are the revenues from by-products sales, which may exist depending on particular circumstances. To depict the distribution of cost of secondary energy (technical potential) an assumed-shape distribution is employed as shows Figure 4.3. The aggregate function is defined as Equation 4.5 indicates.

$$\Pi(c) = \int_0^c \pi(t)dt \qquad \text{Equation 4.5}$$

Therefore, in Equation 4.5 Π is the *aggregate function* of the potential, whereas π is *marginal function* of the potential. The variable c is the unitary cost and t the variable of integration. The solid line in Figure 4.3 represents the distribution function of the potential, while the dotted-line represents the aggregate function of that. Equation 4.5 can be also written for a discrete function as follows:

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[1] More details on this matter will be given in further section.

$$\Pi(c_i) = \sum_{i=1}^{n} \pi_i(c_i) \qquad \text{Equation 4.6}$$

In which Π is the *aggregate function* of the potential, π_i is *marginal function* of the potential and n the totality of single potential within the framework of evaluation. It is worth underlining that this definition coincides with the limit of potential (i.e. physical limit, geographical limit and technical limit) previously defined by Equations 4.1-3.

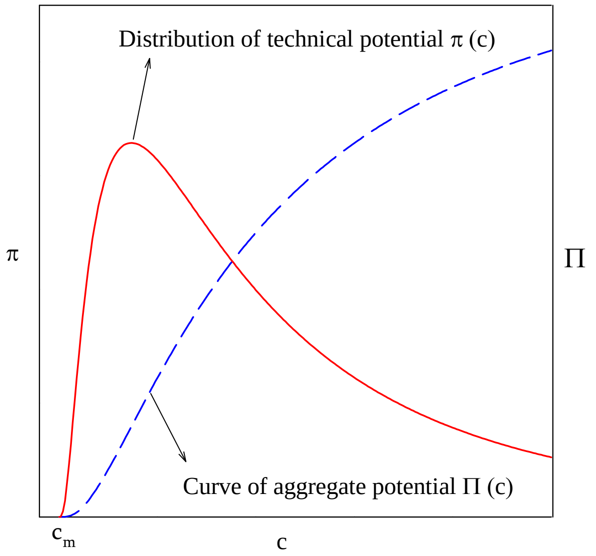

Figure 4.3. Relationship between the marginal function and aggregate function of potential. Adapted from Izquiero *et al.* (2010).

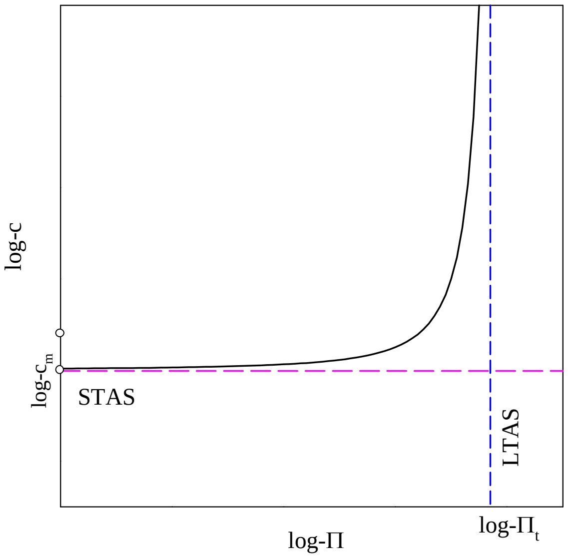

Figure 4.4. Typical supply-cost for renewables. Adapted from Izquiero *et al.* (2010) in logarithmic variables.

Figure 4.4 shows schematically the basic structure of a logarithmic supply-cost curve. This structure and share of a general supply-cost curve is characteristic of a variety of renewables (Izquiero, *et al*. 2010; Hoogwijk 2004), as will be discussed later on. There are two tendencies in the supply-cost curve worth pointing out. On the one hand, an asymptotic tendency of the curve is observed when reaching the technical limit. This value receives the name *Long-term Aggregate Potential Supply* (LTAS), and, by definition, it is the maximum amount of energy that can be produced by means of a specific technology. Mathematically, it can be then written as follows:

$$\lim_{\Pi \to \Pi_t} LTAS = \infty \qquad \text{Equation 4.7}$$

On the other hand, a straight line is observed, which is horizontal in the limit case and defines the minimal cost of production. This limit receives the name *Short-term Aggregate Potential Supply* (STAS) and can be mathematically expressed as the minimum cost at the limit production condition:

$$\lim_{\Pi \to 0} STAS = c_m$$ Equation 4.8

Although an important fraction of the aggregate potential exhibits a *plateau cost* roughly the same as STAS, the remaining fraction substantially increases with proximity to LTAS, as Figure 4.4 shows. This tendency is highly relevant and applicable for a distribution of resources as well as for a distribution of cost; consequently, it may be necessary to devise a way of calculating a *representative generation cost* (c_r) for a particular technology under assessment. This characteristic parameter, as its name indicates, must represent and combine the tendencies defined by the STAS and LTAS simultaneously. Furthermore, this characteristic cost must be applicable for different technologies in order to make possible a comparison of cost under dissimilar conversion processes.

As a consequence of the aforementioned statement, the aggregate economic potential (Π_e) becomes the characteristic of a technology for a specific framework under evaluation; it can be formulated as follows:

$$\Pi_e = \Pi(c_r) = \int_o^{c_r} \pi(t)dt$$ Equation 4.9

Therefore, the economic potential (Π_e) can be defined as *the total amount of secondary energy that can be produced at a cost lower than the representative generation cost* (c_r).

4.3 Representative Generation Cost

A log-normal distribution of variables is observed in a variety of fields of natural science such as geology, mining, human medicine, environment, ecology and economics, among others (Limpert, *et al.* 2001). More remarkably, an approximate log-normal distribution is observed in datasets of spatial environmental variables (Bossew 2010). Izquierdo *et al.* (2010) observed a log-normal distribution for the cost of renewables in Spain, discerning variables for fitting geo-referenced data by collating geographically-spaced information of four renewables technologies, i.e. concentrated solar thermal with parabolic trough (CST), centralised photovoltaic with fixed modules (PV), on-shore wind energy (wind) and combustion of biomass from energy crops (biomass), as Figure 5 shows.

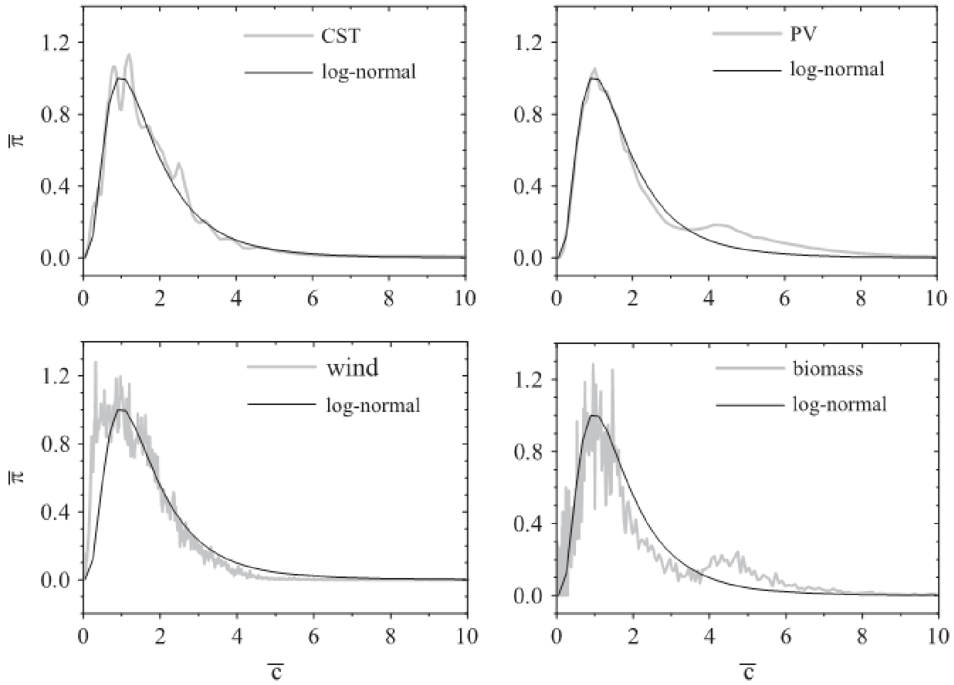

Figure 4.5. Log-normal fitting of normalised supply-cost curves in Spain from Izquierdo *et al.* (2010). Cost and potential are presented as the normalised variables (dimensionless) $\overline{c}$ and $\overline{\pi}$, respectively.

The hypothesis of a log-normal distribution put forward by Izquierdo *et al.* (2010) was tested by them through a statistical analysis of empirical data for the four technologies previously above mentioned, reaching the conclusion that the *log-normal distribution describes the cost distribution problem for renewables satisfactory*. As can be seen, Figure 4.5 gives the log-normal fitting of normalised supply-cost curves of the four renewables previously mentioned. As can be observed, PV and CST exhibit the best fit, whereas the worst is observed for biomass, with significant variations in the range of low costs. This fluctuation can be explained by the permanent interaction between the potential limits, and thus between the geographical constraints and the technical restrictions.

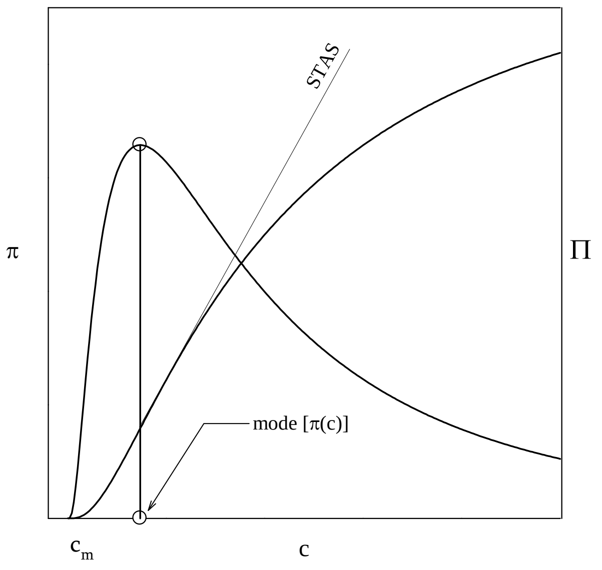

Figure 4.6. Relationship between mode of the distribution cost and the STAS.

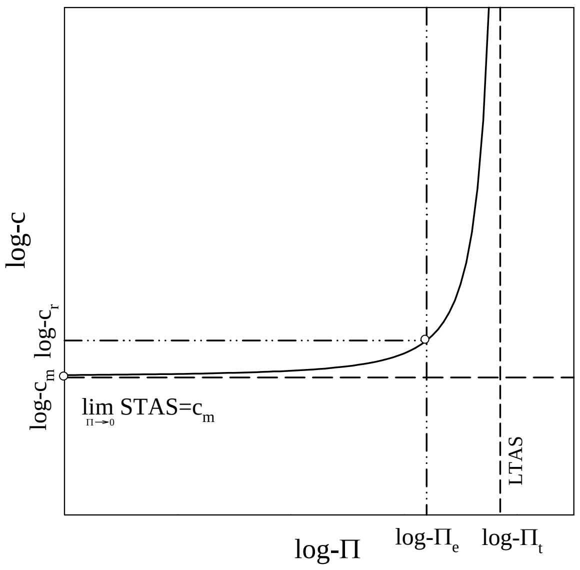

Figure 4.7. Relationship between representative generation cost (c_r) and economic potential.

Considering the empirical facts laid out by Izquierdo *et al.* (2010) for renewables, the statistical mode of a log-normal distribution of cost will be considered as the *representative generation cost* of the technology to be assessed, and can be calculated through the following expression (Ross 2009).

$$c_r = \text{mode}[c_i(\pi_{t,i})] = e^{\mu-\sigma^2} \qquad i = \overline{1,n} \qquad \text{Equation 4.10}$$

In which c_r is the representative generation cost; $c_i(\pi_{t,i})$ is the unitary cost of production for the i*th*-technical potential; and μ and σ^2 are the mean and variance of the production cost of the totality of single potential (n) within the framework of evaluation. The economic limit can be alternatively calculated using the representative generation cost as a cut-off criterion, setting the exclusion factor $(A_{e,i})$ equal to zero for all the single potential (π_i) with a cost of production higher than it. Mathematically, it can be written as follows:

$$\Pi_e = \sum_{i=1}^{n} \pi_{t,i} A_{e,i} \qquad \begin{array}{l} A_{e,i} = 0;\ \forall\, \mathrm{c_i} \le \mathrm{c_r} \\ A_{e,i} = 1;\ \forall\, \mathrm{c_i} > \mathrm{c_r} \end{array} \qquad \text{Equation 4.11}$$

4.4 Economic Modelling and Cost Assessment Methodology

A conceptual representation for the biochemical conversion of biomass by digestion is shown in Figure 4.8. The two main pathways to assess are the generation of electricity via direct combustion, also called *biogas-to-energy*, and the production of substitute natural gas (Bio-SNG) through a pathway denominated *biogas-to-upgrade*.

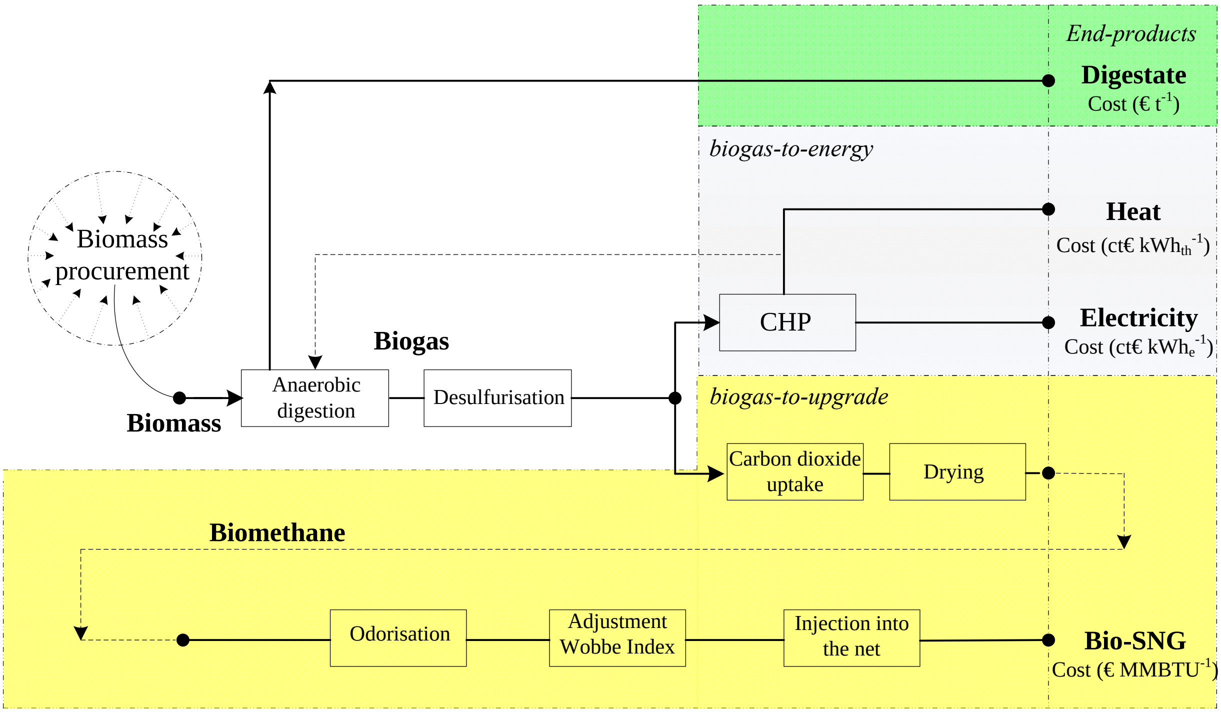

Figure 4.8. Layout of a conventional biogas plant and the potential products from biomass conversion.

The process starts with the supply of biomass. This operation may demand hauling, comminution, transportation and finally storage. When the biomass is received for processing, the feedstock is normally pre-treated to accelerate the digestion process and sterilised if there are requirements. Technologies for storage, preparation and pre-treatment have been adapted from the waste-processing industry (Poeschel, *et al.* 2010). On the other hand, a direct utilisation of biomass generated in situ is also possible, without necessitating a supply chain for procurement. For biomass already stored and pre-treated, conversion starts with the anaerobic digestion process whereby organic biomass is broken down by microorganisms in low-oxygen media. The main products are biogas, a gaseous mixture made principally of methane (40-70%), carbon dioxide (60-30%) and trace compounds. The composition of biogas is highly dependent on the sort of substrate to be treated, operation conditions and type of reactor.

For the energetic use of biogas, its desulphurisation is practically compulsory and can be done in situ (during anaerobic digestion, within the reactor) or afterwards by a variety of techniques. The removal of compounds containing sulphur is desirable because they are corrosive, unhealthy and environmentally hazardous; and their removal is mandatory for any eventual application. The desulphurised biogas can then be used either for the production of electricity (*biogas-to-energy* route) or for the production of a gaseous fuel such as Bio-SNG (*biogas-to-upgrade* route), as Figure 4.8 indicates.

The conversion route for *biogas-to-energy* involves the direct combustion of biogas for the production of electricity, normally by a combined heat and power (CHP) scheme, a decentralised and state-of-the art technology encouraged as a means to reduce CO_2 emissions (Jiri 2008). By this means, electricity and heat are simultaneously generated, and the latter can be used internally for warming-up the digester or commercialised as a by-product for local heating (Jiri 2008). When considering the *biogas-to-upgrade* pathway, the processing can be seen (downstream raw biogas) as a series of unitary operations of cleaning, upgrading, odorisation, adjustment of Wobbe Index and finally feed-in. There are numerous technologies for biogas treatment considered mature enough to carry out this process, with the generation of Bio-SNG from anaerobic digestion of biomass considered as a state-of-the art technique. As mentioned in previous chapters, the raw biogas is cleaned to remove trace compounds such as hydrogen sulphide (100-1,000 ppm), mercaptanes (0-100 ppm) and traces of COS, siloxanes and ammonia. Afterwards, the carbon dioxide uptake takes place by using technologies with dissimilar processing principles (i.e., adsorption, chemical absorption, or physical absorption). Finally, the process chain is closed with monitoring and injection, and, if necessary, a recompression step is incorporated to reach the network pressure and conditioning. Propane can also be added to achieve the local natural gas standards (Wobbe Index adjustment).

The specific cost of secondary energy (*c*) through either *biogas-to-energy* or *biogas-to-upgrade* pathway can be calculated by applying Equation 4.12.

$$c\pi_t = \alpha I + C_{o\&m} + C_p - R \qquad \text{Equation 4.12}$$

In this equation, π_t stands for the technical potential of secondary energy of any of the two routes to assess; I_i is the total capital investment of the entire processing chain for energy generation, which starts with biomass procurement and finishes with the end-product generation ready for commercialisation; α is the capital recovery factor; $C_{o\&m}$ is the operation and maintenance cost; and R is the revenue obtained from selling by-products or any other kind of income (e.g. from heat or bio-fertiliser sale, subsidies for green-electricity or waste management). C_p corresponds to the cost of processing biomass supply when it arrives at the gate of the plant. This value can be zero when the biomass is generated in situ, or may have to be calculated according to the sort of biomass and the particular physical or chemical characteristics associated with it.

For the estimation of investments, it was assumed that the total capital investment of each conversion unit that constitutes the process can be correlated through a power function such as Equation 4.13 indicates:

$$I = \gamma \pi_t^{\delta} \qquad \text{Equation 4.13}$$

In which γ and δ are parameters to fit from statistical data. Furthermore, it was considered that the annual operation and maintenance cost can be estimated as a fraction of the capital investment (Crundwell 2008), which is represented by the parameter β. When taking into consideration these premises, by manipulating Equation 4.12 and Equation 4.13 algebraically and making them time-consistent, it can be demonstrated that the specific cost of secondary energy obtained through processing biomass can be estimated by applying the following linear equation:

$$c = \frac{\gamma}{p}(\alpha + \beta)\pi_t^{\delta-1} + \frac{1}{p}\frac{C_p}{\pi_t} - \frac{1}{p}\frac{R}{\pi_t} \qquad \text{Equation 4.14}$$

In which p represents the operating hours per year (h y^{-1}) of the process. The capital recovery factor α is calculated through the well-known expression (4.15), which is based on the capital cost i (%) and the amortisation period n (y) (Newman, *et al.* 2004).

$$\alpha = (A/P, i, n) = \frac{i(i+1)^n}{(1+i)^n - 1}$$ Equation 4.15

4.5 Cost of Biomass Provision

The residue left after harvesting biomass are normally highly spread, and in principle are difficult and costly to recover. Furthermore, due to their low energy value and physicochemical variability, they are expensive to transport and store. Nevertheless, agricultural residue may be located in zones with a deficit of fossil fuels or difficulty accessing an energy supply; these circumstances may make biomass an appealing alternative and offer conditions that could outweigh the drawbacks previously mentioned. Moreover, crop residue has low sulphur content, is generated regularly in large amounts as well as it is renewable and valuable in energy applications.

For a macro-economic evaluation of the cost of biomass recovery and transportation and its influence on the cost of energy generation via anaerobic digestion throughout the country, a simplified model will be put forward in the next section. This method will allow conservative cost-estimation to be conducted by using the best available information on a yearly temporal basis. Nonetheless, when considering the simplifications and the assumptions made to develop it, it is worth underlining that the results obtained via this approach must be worked out as a macro estimation that might differ to some extent when comparing with case-to-case assessments.

4.5.1 Cost of Biomass Transportation

In general terms, there is a lack of information on the geographic distribution of residue after harvesting, the time of processing and the way in which the biomass is employed afterwards. In Chile in particular, the only existing information, and tentatively useful for the purposes of this research, is at county level for a reference year (data from 2007), and it corresponds specifically to data related to productivity per crop species and exploited agricultural surface. Taking into consideration these basic facts, it can then be assumed that it is possible to estimate the amount of agricultural residue at county level on an annual basis as the following information is known: i) county surface; ii) types of crops; and iii) productivity per species.

With this information, a superficial density of residual biomass after annual harvesting ρ_s (t km^{-2}) can be calculated, when assuming it is constant at county level.

On the basis of the aforementioned assumptions and the data restrictions previously indicated, it is necessary to develop a model to estimate the cost of supply for a macro economic assessment of the impact of biomass provision for energy utilisation at large scale. In this model, it is assumed that each county can be approximated by regular geometry such as a circle or square *of equivalent area*, hence the characteristic geometric parameter (i.e. radius or side) can be calculated directly.

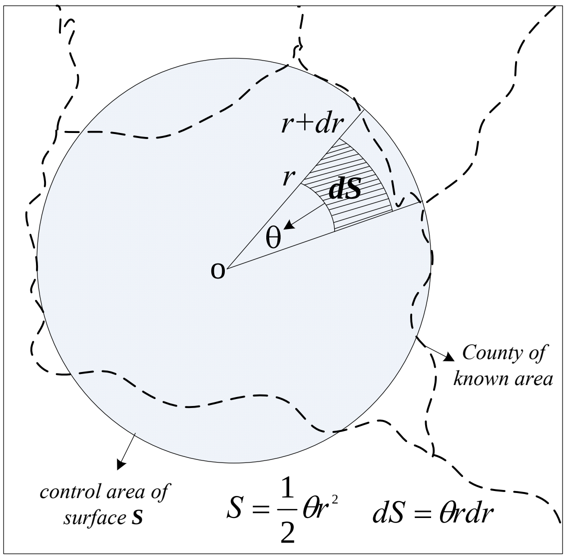

Figure 4.9. Modelling a county with a circle shape that has radius *r*.

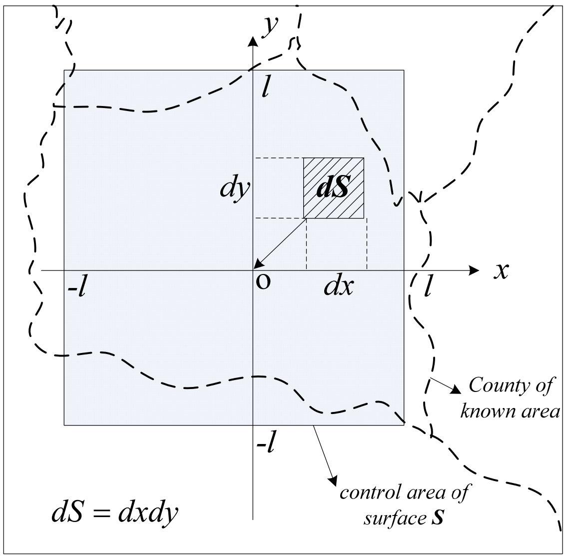

Figure 4.10. Modelling a county with a square shape that has side *l*.

Secondly, it is assumed that a single biomass processing facility is located at the geometric centre of each county already approximated as a square or circle, and finally, that all the biomass available within the county is transported to this point for processing.

Taking into account these groups of assumptions for a county approximated as a circle, a differential cost of transportation dC_t of a differential amount of biomass dm available in a differential area dS can be expressed as a function of the differential surface dS and the superficial density ρ_s as follows:

$$dC_t = c_e^t \rho_s \, \tau \, r \, dS \qquad \text{Equation 4.16}$$

In which c_e^t is the specific o n-road transportation cost (normally expressed as € t^{-1} km^{-1}); ρ_s is the superficial density of residual biomass at county level (normally expressed as t km^{-2}); τ is the tortuosity of the on-road transport (a dimensionless parameter estimated empirically); r is the radius of the circle-approximated county. Making a change of variables, the differential area *dS* can be expressed as a function of the radius of the circular sector so that it is possible to rewrite the Equation 4.16 as follows:

$$dC_t = \tau\, c_e^t \rho \theta r^2\, dr \qquad \text{Equation 4.17}$$

By integrating Equation 4.17 in the domain $[0, r]$, equivalent to the distance that differential mass dm has travelled to the centre of the county, the final expression for the total cost of transportation results in:

$$C_t = \int_0^r \tau\, c_e^t \rho \theta r^2\, dr = \frac{2}{3} \pi\, c_e^t \rho_s\, r^3 \qquad \text{Equation 4.18}$$

The total cost for the conveyance of biomass C_t can be expressed as a linear relationship between the specific cost of transportation c_e^t, the total mass m that has to be transported to the centre of the county and the average distance to traverse the county, $\overline{d}$. Thus this expression has the mathematical form indicated by Equation 4.19:

$$C_t = \overline{d}_c\, m\, c_e^t \qquad \text{Equation 4.19}$$

By direct comparison of Equation 4.18 and Equation 4.19, it is possible to demonstrate, after some algebra, that the average distance to traverse the county can be expressed as Equation 4.20 indicates:

$$\overline{d}_c = \frac{2}{3} r \tau \qquad \text{Equation 4.20}$$

Equation 4.20 is a linear relationship that allows for the estimation of an average distance of displacement within a county, which is representative of the distance to cover for the provision of biomass to a processing facility located in the centre of a county *when its shape is approximated as a circle*.

For the approximation of the county as a square and with the equivalent geometric parameters as Figure 4.10 illustrates, the mathematical procedure for the calculation of the cost of transportation is based on the same basic assumptions, thus the differential equation that represents the cost of conveyance of a differential amount of biomass to the centre of the county can be expressed as Equation 4.21 indicates.

$$dC_t = c_e^t \, \rho_s \, \tau \, (\mathrm{x}^2 + \mathrm{y}^2)^{\frac{1}{2}} dxdy \qquad \text{Equation 4.21}$$

Solving the above-listed equation by integral calculus, it is possible to demonstrate that the total cost of transportation can be calculated as follows:

$$C_t = \frac{1}{6} l^3 c_e^t \, \rho_s \, \tau(\sqrt{2} + \ln(1+\sqrt{2})) \qquad \text{Equation 4.22}$$

By comparing Equation 4.19 and Equation 4.22, analogously as done before, the average distance of displacement across the county for a square-shaped approximation of the county is indicated in Equation 4.23:

$$\overline{d_s} = \frac{1}{6} l \tau \, (\sqrt{2} + \ln(1+\sqrt{2})) \qquad \text{Equation 4.23}$$

The average distance for biomass conveyance through a circular-shaped approximation of the geographic control area (county) is lower in the entire distance domain in comparison to approximating it by a circular-shaped geometry, as can be seen in Figure 4.11. These results suggest that the use of a square-shaped approximation offers a more conservative estimation of the average displacement distance. Additionally, for the county’s average surface at national level, roughly 2,100 km^2 (PACD 2007) excluding the Antarctic Region, the estimated average distances are lower than the recommended displacement for biogas projects in which biomass provision is necessary (Deublein & Steinhauser 2011).

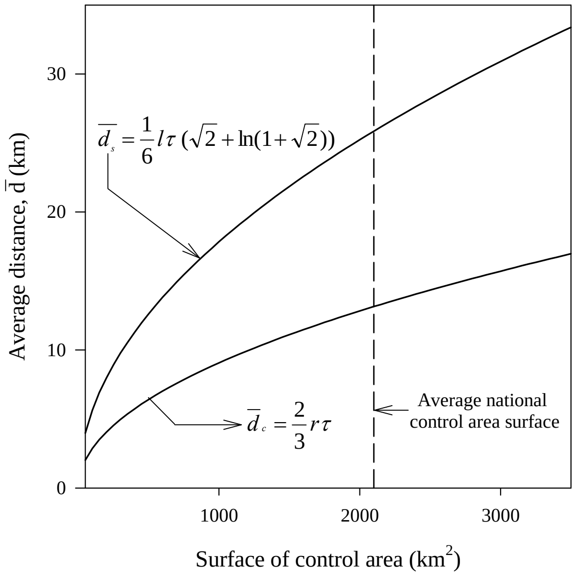

Figure 4.11. Average distance as a function of the surface of control area.

4.5.2 Cost of Biomass Recovery

Crop residue has different characteristics which influence the selection of the technology to be used for hauling, recovering or storing. These aspects, consequently, have an impact on the final cost of provision, and finally on the cost of production of biogas or any of its end-products (Dauve & Flaim 1979).

The majority of information available on the cost of recovery for biomass at an international level is focused on corn stover and wheat straw, basically because they are the dominant crops in a substantial number of countries (Marchert 2011; Scarlat, *et al.* 2010). Considering these two agricultural species, there are a variety of techniques and technologies for the process of recovery, among them big rectangular bales, stackwagons and loose chop. The total cost of collection is informed normally per hectare (€ ha^{-1}) or per dry mass recovered (€ t^{-1}). Being more convenient for the proposed methodology, the latter form will be used and addressed as *specific cost of biomass recovery* c_r^e.

Taking into consideration the above-mentioned information, the cost of recovery of residual biomass from annual crops can be calculated by a linear relationship between the mass to be recovered and the specific cost of recovery c_r^e, as Equation 4.24 indicates:

$$C_r = c_e^r \, m \qquad \text{Equation 4.24}$$

This cost is representative of the harvesting, hauling, staking, packaging and loading of the recovered biomass[2].

4.5.3 Total Cost of Biomass Provision

The total cost of biomass provision, which contemplates the whole chain of supply from the field where the biomass is available and recovered up to the gate of the processing plan, can be calculated by summing up the total cost of recovery and transportation as Equation 4.25 shows:

$$C_p = C_r + C_t = c_e^r m + \bar{d} m c_e^t \qquad \text{Equation 4.25}$$

Economic information on specific cost of transportation, recovery, and other financial parameters will be provided and discussed in Section 6, *Economics of Biogenic Gas Generation*.

4.6 Construction of Supply-cost Curves

As defined in the introduction of this section, both the physical and geographical limits are primary forms of energy since there is no use of a particular technology for its conversion. The technical limit, in contrast, offers the potential of secondary energy such as electricity, heat or fuels and involves the selection of a specific conversion technology. As represented in Figures 4.12 and 4.13, the calculation of the physical and geographical limit is the input data for the subsequent computation of the technical limit. In this way, both physical and geographical limits have no meaning by themselves, so they are only intermediate steps of a further calculation.

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[2] The unloading cost was charged at the transport step.

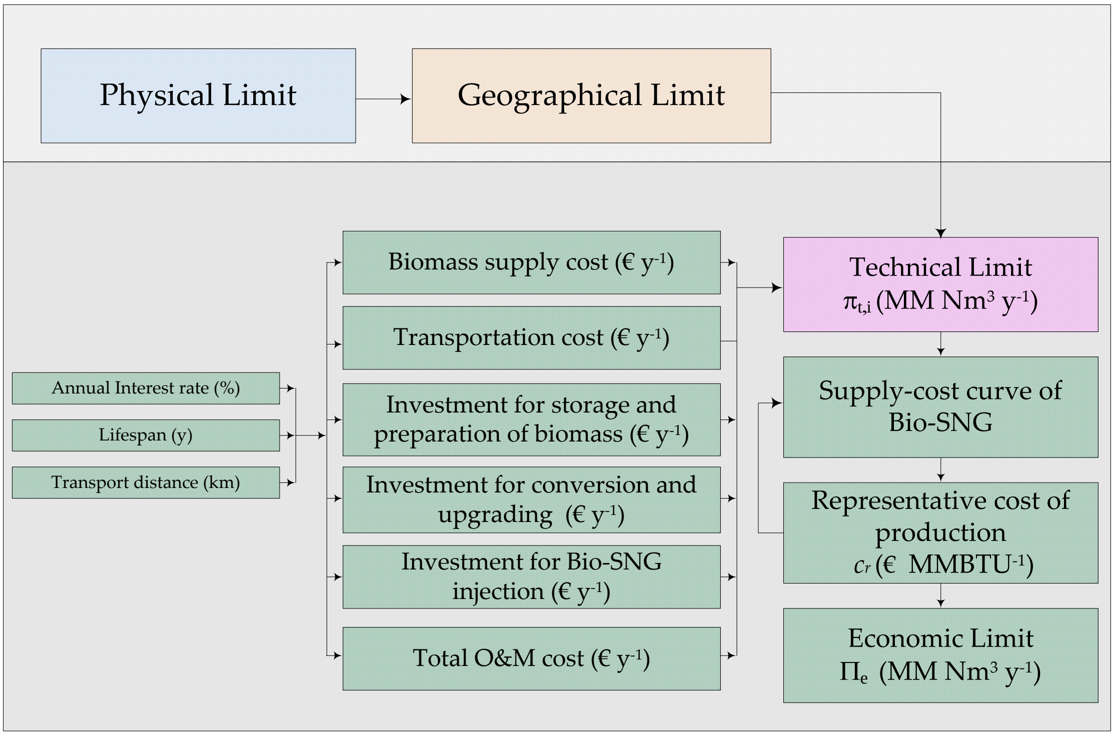


Figure 4.12. Schematic representation of the procedure for the construction of the supply-cost curve and the calculation of the representative generation cost and the economic limit for the *biogas-to-upgrade* pathway. Adapted from Hoogwijk (2004).

The estimation of the economic limit involves setting up parameters such as interest rate, lifetime of conversion units, distance of conveyance, investment for equipment of the operation that constitutes the chain process of each conversion route to be assessed and estimation of operation and maintenance cost (O&M). As far as the technical limit is concerned, it is the input data for the estimation of the unitary cost of production and its estimation procedure that enables the calculation of the distribution of the cost of production for the entire framework of analysis.

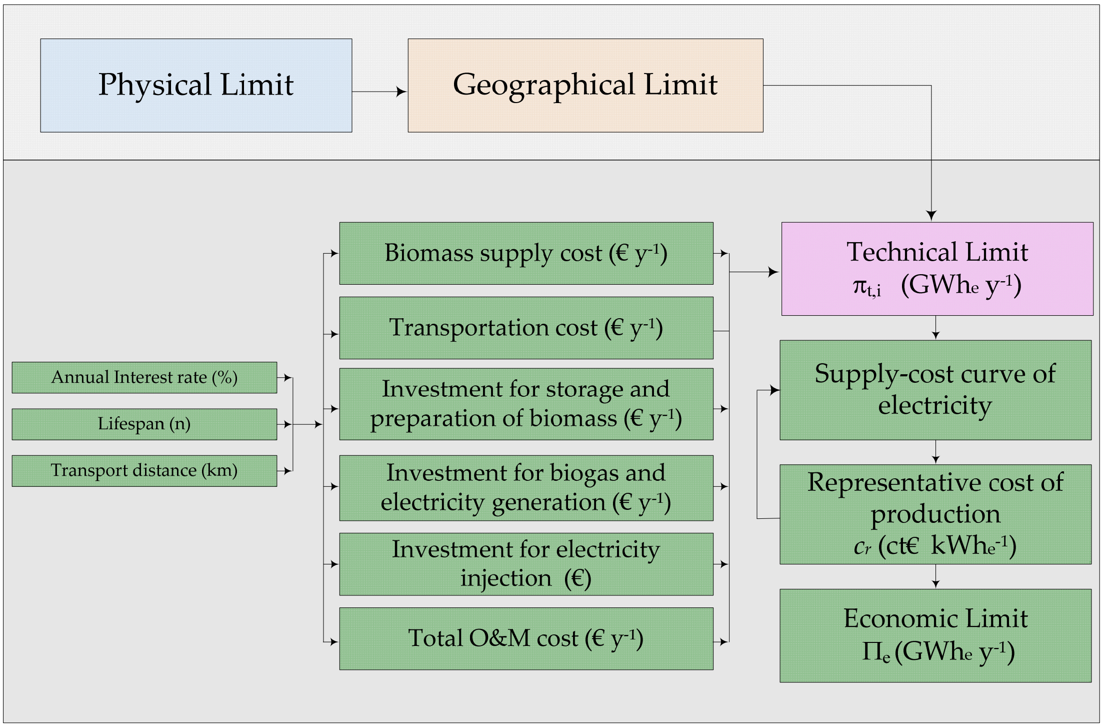


Figure 4.13. Schematic representation of the procedure for the construction of the supply-cost curve and the calculation of the representative generation cost and the economic limit for the *biogas-to-energy* pathway. Adapted from Hoogwijk (2004).

The representative generation cost, as defined in Equation 4.10, can be used for the interpolation of the economic limit directly within the curve constructed by summing up the energy potential in a decreasing order, and then representing it on a Cartesian system, as schematically presented in Figure 4.14. The x-axis represents the added-supply-energy Π; *therefore, it is an aggregate variable* of the technical potential, in contraposition to the single potential π which is a *marginal variable*. The y-axis is the unitary cost of production at levelised energy potential.

4.7 Data Integration into Geographical Information Systems (GIS)

Geographical Information Systems (GIS) have been used to some extent for showing the energy potential of biogas either at a different energy (technical potential, geographical potential, economic potential, etc.) or geographical level (regional, national, etc.). Moreover, a number of authors have presented different approaches in which discernible differences can be observed. In a leading investigation, Batzias *et al.* (2005) developed a GIS-based assessment informatics application for the evaluation of biogas potential from the digestion of livestock manure in Greece. In this study, the possibility of biogas upgrading and subsequent injection into the natural gas distribution grid was discussed although economic assessments were not conducted. More recently, Zubaryeva *et al.* (2012) established an analysis on the co-digestion of cattle slurry with fruit and vegetable waste and the organic fraction of municipal solid waste in Levece (a province of Apulia, Italy). They applied a multi-criteria evaluation methodology and integrated it into a GIS system by using the county as the smallest political-administrative control area. The analysis allowed the selection of promising areas for the development biogas clusters although no economic analyses were included for the decision-making. In connection with this, Sliz-Szkliniarz *et al.* (2012) conducted an extensive economic and technical analysis for the detection of optimal sites for biogas plants through a centralised concept of biogas generation. The method was applied in the region of Kujawsko-Pomorskie, Poland, as a case of study to evaluate the biogas potential via co-digestion of livestock manure (swine and cattle) and crop-silage as co-substrate, and subsequently both the generation of biomethane for injection into the grid and cogeneration. Similarly, Yabe (2013) considered the study area Hokkaido, a 83,000 km^2 island of Japan. This study aimed at selecting a location for biogas plants in each county and evaluating the cost of production of electricity. Through a GIS-based method that incorporated the network function of ArcGIS Ver.10, the required number and location of centralised biogas plants was estimated. Most recently, a study by Höhn *et al.* (2014) attempted to determine energy potential and location sites feasible for biogas plants in southern Finland by using a GIS-based method. The methodology focused on minimising the transportation distance for feedstock so that an optimal allocation could be found whilst no economic assessment was conducted.

Due to the characteristics of biomass, in most of cases widely distributed and having both a spatial and temporal component in its availability, GIS tools are ideal for showing energy potentials, analysing, assembling or rearranging energy-related data, which would be highly laborious or even impossible to manipulate with other methods.

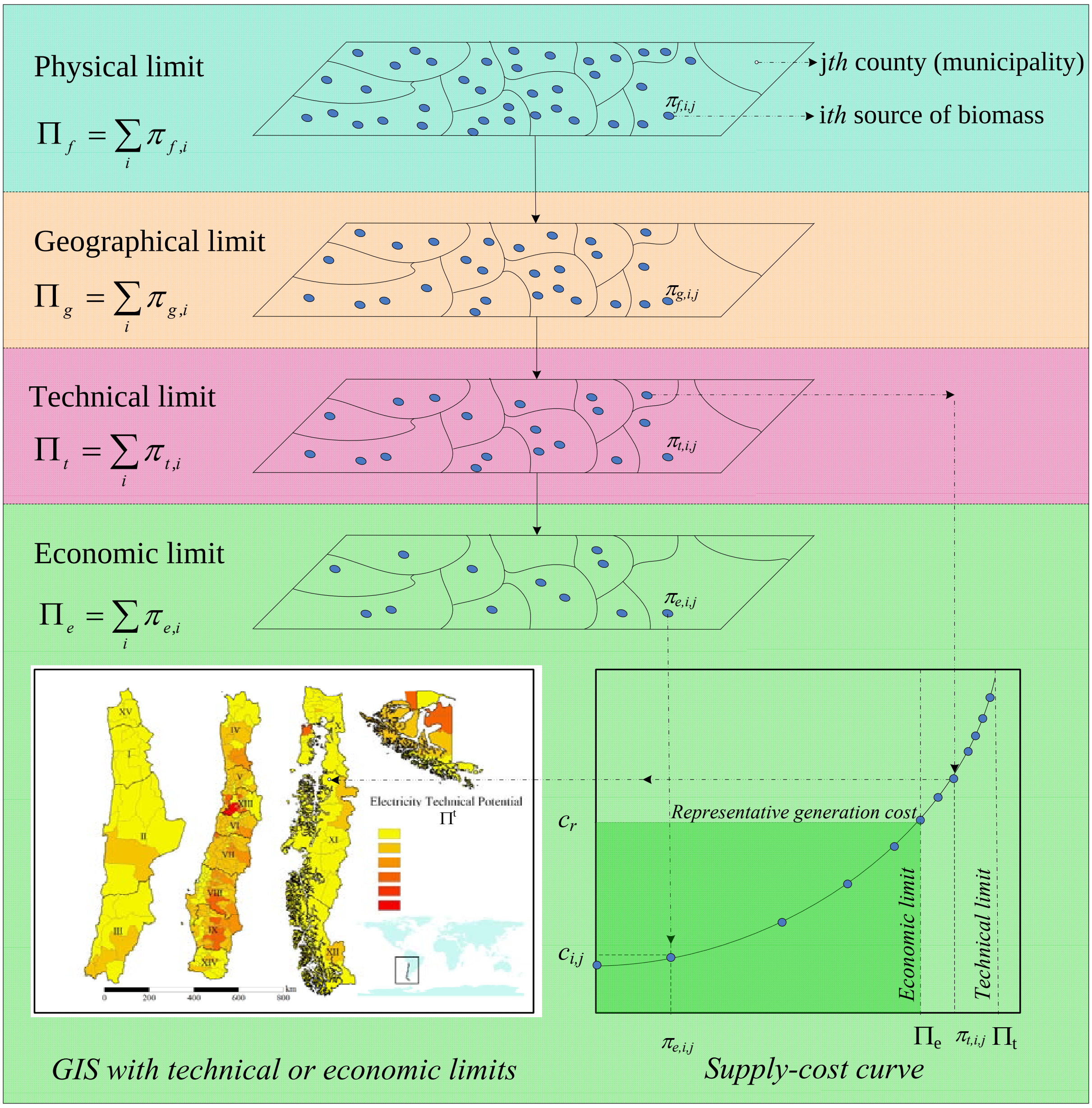


Figure 4.14. Schematic representation of the limits of potential and its integration onto a Geographical Information System (GIS).

To construct the maps of secondary energy of the technical potential, the software ArcGIS 10.1, module ArcMap, and GIS Desktop 1.8.0 were used. The source data was taken from a free source development (Albers 2012), being this information available per region and with different shapefiles and cartographic layers (region, provinces, counties, populated places, etc.). By using the module Quantum GIS and then exporting the data files to ArcMap to generate colour scales, the maps were built to present the technical potential of the whole country at a county level, for each sector under analysis and both for electricity and Bio-SNG options. Figure 4.14 displays a schematic representation of the four levels of potential analysis to be conducted and how the GIS is eventually integrated to visualise the geographical distribution of the technical potential across the country.

5. Technology for Bio-SNG and Electricity Generation

In this chapter the technologies used either for the generation of a gaseous fuel via upgrading of biogas or electricity by direct burning are characterised. The primary focus was on state-of-the-art techniques because the goal of the research focused on the potential analysis of energy rather than on the assessment of cutting-edge technologies. Besides, a discussion of the main findings outlined by other authors which relevant assumptions for the economic assessment to be presented in further sections were based on are also included.

5.1. Reactor Technology for Biogas Generation

Anaerobic digestion is considered the most efficient way of generating energy from organic matter with dry matter below 30 % (w/w) (OECD 2010). The basic technology of anaerobic digestion permits converting organic biomass into methane and carbon dioxide in a variable composition normally ranging from 50% to 65% (methane). The anaerobic digestion process can be carried out by using either wet-fermentation or dry-fermentation technologies (Deublein & Steinhauser 2011). The former operates with a concentration (measured as dry solid) lower than 20%, whereas the latter is adequate for a substrate with water content lower than 85% (Karellas, *et al.* 2010).

The anaerobic digestion process occurs in a reactor, the digester, where biomass undergoes a reaction with bacteria in an anoxic media. These microorganisms break biodegradable solids and soluble matter down, thus producing biogas. This biochemical chain reaction is constituted of four sequential phases. The first stage is called hydrolysis, in which complex molecules are decomposed by the action of cellulases, amylases, proteases and other such fermentative bacteria (Borja 2011). In the following phase, acidogenesis, the simple monomers previously produced are converted into volatile fatty acids (e.g. acetic acids, propanoic acid, butyric acid and traces of alcohol, ketones, ammonia and hydrogen sulphide). Afterwards, the acid and alcohols produced in the acidogenesis phase are converted into carbon dioxide, acetic acid and hydrogen, while the hydrogen and carbon dioxide are converted into acetic acid by the homoacetogenic enzyme. Finally, the methanogenesis phase takes place, and as its name indicates, acetic acid and all one-carbon compounds (alternatively also called C_1) are transformed into methane (Liu, *et al.* 2011). In addition to methane and carbon dioxide, oxygen (lower 2% v/v), nitrogen (lower than 2%), ammonia (lower than 1%)

and hydrogen sulphide (ppm range), traces of compounds such as halogenated and organic silicon can be found (Rasi, e*t al.* 2010).

The temperature, along with acidity and other operating parameters, plays a pivotal role in the kinetic of biogas generation. For biogas production, Yenigün and Demirel (2013) distinguished two temperature ranges for anaerobic digestion: mesophilic (30-40°C) and thermophilic (45-60°C). Similarly, Liu *et al.* (2011) classified the digestion process into psychrotropic digestion (below 25°C), mesophilic digestion (25-45°C) and thermophilic digestion (45-60°C). The bulk of reactors operate either under mesophilic or thermophilic conditions, with an optimal thermal condition between 35°C and 55°C (Borja 2011).

Anaerobic digesters can be classified according to the relation between their hydraulic and sludge retention time. For reactors with the same retention time of sludge and hydraulic flow, batch reactors, plug flow and continuous tank reactor (CSTR) can be distinguished. CSTR is one of the most commonly used anaerobic reactors in which stirrers are installed to ensure efficient mixing between the substrates and microorganisms. As expected, they offer higher conversion efficiency than batch reactors. The main advantages of CSTR reactors lie in the high concentration of total solid that it can be fed and the ease of implementation for automatic control systems (Liu 2010). Plug flow digesters are normally used for the processing of viscose feedstock, usually waste from ruminant animals. These reactors operate by horizontally displacing reacting biomass, which is usually pumped, hence displacing an equivalent portion of matter that has already reacted and which is then pushed out to the other end of the reactor (Krich, *et al.* 2005).

Reactors with dissimilar sludge and hydraulic retention time are normally operated at high sludge retention times and relatively low hydraulic ones; upflow anaerobic sludge blanket (UASB) and upflow solids reactor (USR) are two representatives types. The former (UASB) is based on the conformation of small dense granules formed by the self-immobilisation of microorganisms, which can normally take 40-50 days to form a common inoculum. USR is another model and more adequate for the treatment of waste with a high concentration of solids. The inflow is fed from the bottom by using a distribution system and passed across the bed. Due to this configuration, the organic matter can be rapidly converted into biogas. The supernatant is discharged by overflow, therefore leading to higher hydraulic and sludge retention time than UASB reactors (Liu 2010).

For the subsequent use of biogas, the removal of hydrogen sulphide and other sulphur-containing compounds is practically compulsory. The simplest method to deal with this issue is the direct addition of air or pure oxygen into the anaerobic reactor with which the concentration of hydrogen sulphide can drop down to levels lower than 50 ppm. In spite of being a practical and effective way of controlling sulphur based-compounds, the addition of oxygen might make the methane-oxygen mixture explosive when overdosing. An alternative method for hydrogen sulphide control is by using bio-filter filled with packing material in which desulfurising microorganisms are fixed (Arnold 2009). Another alternative is the use of scrubbing with caustic soda or sodium hydroxide (Tippayawong & Thanompongchart 2010) to induce the formation of insoluble salts like sodium sulphide or sodium hydrosulfide (Abatzoglou & Boivin 2009).

5.2 Upgrading Technologies for Bio-SNG Generation

Nowadays, there are more than 220 biogas upgrading plants running in the world (Peterson & Wellinger 2011), most of which are operated in Germany (96 units) and Sweden (55), followed by the installations located in The Netherlands (14 units) and USA (14 units) (Bauer, *et al.* 2012). Although the available technologies for upgrading biogas are in principle six, i.e. cryogenic separation, membrane, organic physical scrubbing, chemical scrubbing, pressure swing absorption (PSA), and pressurised water scrubbing (PWS), PSA and PWS are the dominant ones and the only ones for which there is robust cost data and extensive experience (Altaus & Urban 2005). Lately, membrane and chemical absorption solution upgrading technologies have increased their share in the market although technical and cost data is still lacking or incomplete (Bauer, *et al.* 2012).

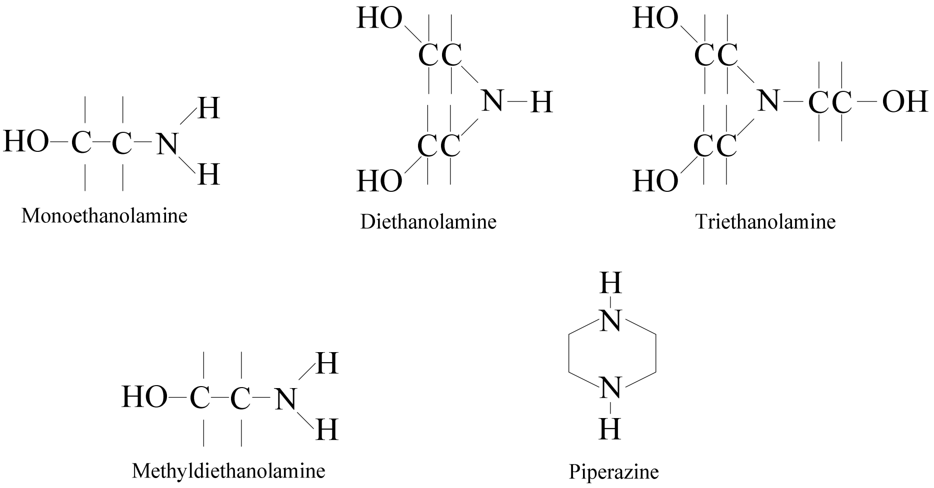
In the forthcoming section the biogas upgrading technologies are described, presenting their principles of operation, main technical features as well as their main advantages and disadvantages. The majority of attention will be paid to pressure swing adsorption, pressurised water scrubbing and the organic physical scrubbing process since they are proven technologies and there is enough technical and economic data to conduct an assessment for potential analysis.

5.2.1 Absorptive Processes

Absorption is a process in which a gaseous substance in contact with a liquid phase is transferred into its bulk, thus being absorbed. Normally, there is a distinction made between chemical and physical absorption; the difference between them is related to the possibility of either undergoing a chemical reaction or the interaction of physical forces, with or without the participation of a chemical bond. The classification of whether the absorption is physical or chemical is based on the Henry’s constant (Yokozeki, *et al*. 2008); a low Henry’s constant is indicative of chemical absorption (lower than 10^{-3} MPa), while high values of it suggest physical absorption (higher than 2 MPa). Nevertheless, in many cases this constant takes an intermediate value, and the absorption is therefore denominated physicochemical.

5.2.1.1 Chemical Absorption

Chemical absorption, also known as chemisorption, has been used extensively in the gas industry for sweating natural and refinery gases since 1930, when the first patent was presented for covering this application; this process is used for making triethanolamine (TEA), the first solvent to become commercially available and used in the early gas treatment plants (Kohl & Riesenfeld 1979).


Monoethanolamine

Diethanolamine

Triethanolamine

Methyldiethanolamine

Piperazine

Figure 5.1. Structural formulas of some alkanolamines used for biogas upgrading (Kohl & Riesenfeld 1979).

Alkanolamines have at least one hydroxyl group and one amino group, and in these terms, the hydroxyl groups help decrease the vapour pressure and increase the solubility of water, whereas the amino groups provide the necessary basicity to the medium, which allows the absorption of acid gases. Alkanolamines are normally classified into *primary*, *secondary* and *tertiary* (Allinger, *et al.* 1973; Cekanova, *et al.* 2011), depending on the number of alky groups attached to the nitrogen atom in the molecule.

Equations 5.1-5.5 show the main reactions when the aqueous solution of a primary amine is used as an absorbent of carbon dioxide in the presence of hydrogen sulphide (Kohl & Riesenfeld 1979):

$$2RNH_2 + H_2S \leftrightarrow (RNH_3)_2S$$ Equation 5.1

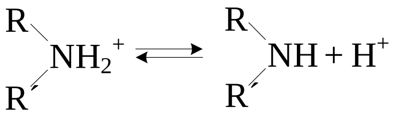
$$(RNH_3)_2S + H_2S \leftrightarrow 2RNH_3HS$$ Equation 5.2

$$2RNH_2 + CO_2 + H_2O \leftrightarrow (RNH_3)_2CO_3$$ Equation 5.3

$$(RNH_3)_2CO_3 + CO_2 + H_2O \leftrightarrow 2RNH_3HCO_3$$ Equation 5.4

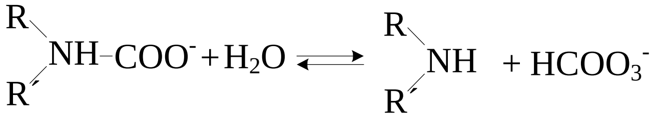
$$2RNH_2 + CO_2 \leftrightarrow RNHCOONH_3R$$ Equation 5.5

In strict terms, the majority of the products of Equations 5.1-5.5 are chemical products, so they can be isolated. However, these chemicals exhibit high vapour pressure under normal conditions, hence the equilibrium of the solution can be modified by changing the pressure of the gases to be treated. Furthermore, the vapour pressures of the acid gases vary significantly with temperature, and, consequently, the absorbed gases can be deabsorbed (stripped) by the application of heat. Primary and secondary alkanolamines normally exhibit a low CO_2-loading, although with a high absorption rate. In contrast, tertiary alkanolamines react slower but have a higher CO_2-loading. However, an additional step, the formation of a carbamete ion which limits the maximum CO_2-loading to 0.5, has been proposed for reaction with primary and secondary amines.



$$\mathrm{R_2NH_2^+ \rightleftarrows R_2NH + H^+}$$

Equation 5.6



$$\mathrm{R_2NH{-}COO^- + H_2O \rightleftarrows R_2NH + HCOO_3^-}$$

Equation 5.7

$$\mathrm{CO_2 + H_2O \rightleftarrows HCOO_3^- + H^+}$$

Equation 5.8

$$\mathrm{HCOO_3^- \rightleftarrows CO_3^{2-} + H^+}$$

Equation 5.9

$$\mathrm{H_2O \rightleftarrows OH^- + H^+}$$

Equation 5.10

The accepted mechanism for the formation of the carbamate (Benamor & Aroua 2005; Haji-Sulaiman, *et al.* 1998) is represented by a series of equilibrium reactions as indicated above. Equation 5.6 represents the protonation of the amine followed by the hydrolysis of the carbamate. Equations 5.7-5.10 are the ionisation reactions for the different species in the solutions.

Although the most used amines for sweating gas are monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDEA), diglycolamine (DGA), diisopropanolamine (DIPA), N-methyldiethanolamine (MDEA) and 2 amino-2-methyl-1-propanol (AMP) (Samanta & Bandyopadhyay 2011), blendings are currently used more frequently, for both carbon dioxide capture and biogas treatment, to maximise desirable characteristics of the solution (Park, *et al.* 2002; Olajire 2010). For biogas upgrading in particular, a blending of MDEA and piperazine (PZ) is normally used. The PZ acts as an activator of the reaction, so the kinetic of the absorption and the load capacity of the solution for the carbon dioxide uptake is improved (Derks, *et al.* 2010). A plausible explanation for this activation lies in the two amino groups that piperazine contains, which can attack the carbon dioxide. Additionally, piperazine can bond strongly and it is not easily released from MDEA, reducing the partial pressure of the solution (Privalova, *et al.* 2012). Other solution activators have been proposed recently, such as 2-(1-piperazinyl)ethylamine.

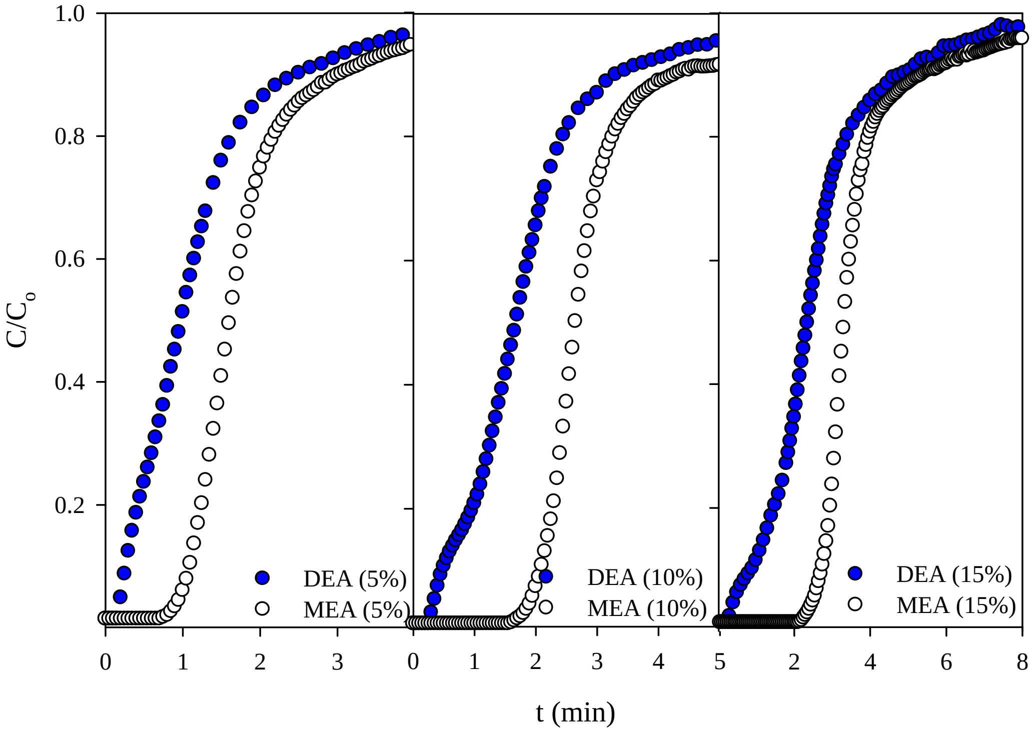


Figure 5.2. CO_2-absorption breakthrough curves of DEA and MEA for a biogas model at room temperature and 1 atm total pressure. Bidart *et al.* (2011).

Normally, amines are used as aqueous solutions because they are solid or gels at room temperature. Typical amino aqueous concentrations range from 10% to 30 % (w/w), and they are restricted by corrosiveness, viscosity of the solution, regeneration energy and cost of the solvent. For instance, MEA is corrosive and therefore cannot be used at high concentration; DEA is typified as hazardous to water. As shown in Figure 5.2, for aqueous solutions of MEA and DEA in the 5-15% (w/w) range, the higher the alkanolamine concentration, the higher the carbon dioxide uptake.

From Figure 5.3 it is observed that when reaching normal pressure (101.3 kPa), the CO_2-loading capacity of DEA and MEA changes only slightly. A similar tendency is observed for MEA at different concentrations and for 1,6-hexanedediamine, N, N´-dimethyl and 1,6-hexanediamine, B,N´-dimethyl (see Figure 5.4). These results show that at normal pressure (101 kPa approximately) the quimisortion is governed by the kinetic (and therefore indirectly by temperature) and not by pressure.

Considering the structure of the alkanolamine, a proportionality between the length of the alkaly-chain and the CO_2-loading capacity is observed; the larger the alkaly-chain the greater this is. A similar pattern is observed for the concentration; a higher concentration involves a greater CO_2-loading capacity (Singh *et al.* 2010; Singh *et al.* 2007).

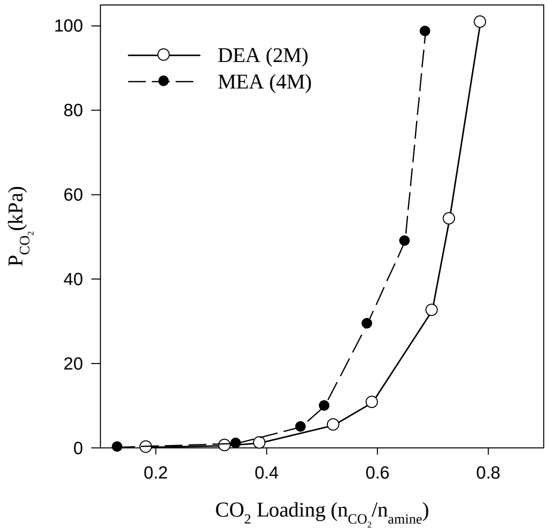


Figure 5.3. Experimental carbon dioxide loading in aqueous solutions of DEA and DEA. Haji-Sulaiman *et al.* (1998).

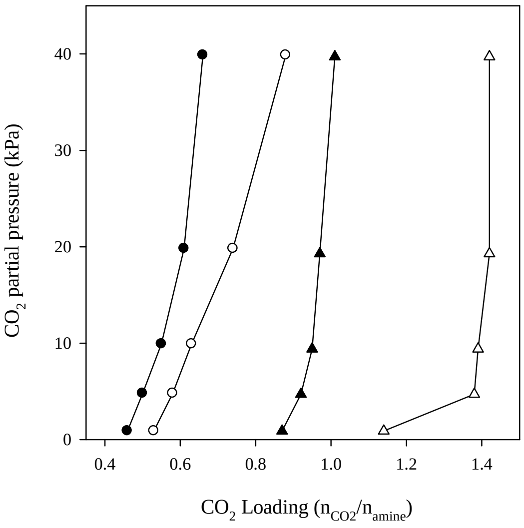


Figure 5.4. Loading capacity of CO_2 in alkanolamine solvents at 30°C. Singh *et al.* (2010).
●: MEA 0.5 M; ○: MEA 2.5 M; ▲: 0.51 M 1,6-hexanedediamine, N, N´-dimethyl; △: 2.55 M 1,6-hexanediamine, B,N´-dimethyl.

Figure 5.5 shows a schematic representation of a commercial amine scrubber upgrading process. As can be seen, the raw biogas to be absorbed enters through the bottom of the absorber (T-1) and comes into contact with the amine fed into the top in counter-flow. The reaction of carbon dioxide and hydrogen sulphide is exothermic, so the solution is heated up from 20-40°C to 45-65°C approximately. Normally, the amine is fed in excess in relation to the concentration of carbon dioxide, 4 or 7 times the theoretical (molar ration), in order to avoid any restriction imposed by the thermodynamic equilibrium. When the reaction has been completed, the gas leaving from the top of the absorber (T-1) is composed almost entirely of biomethane.

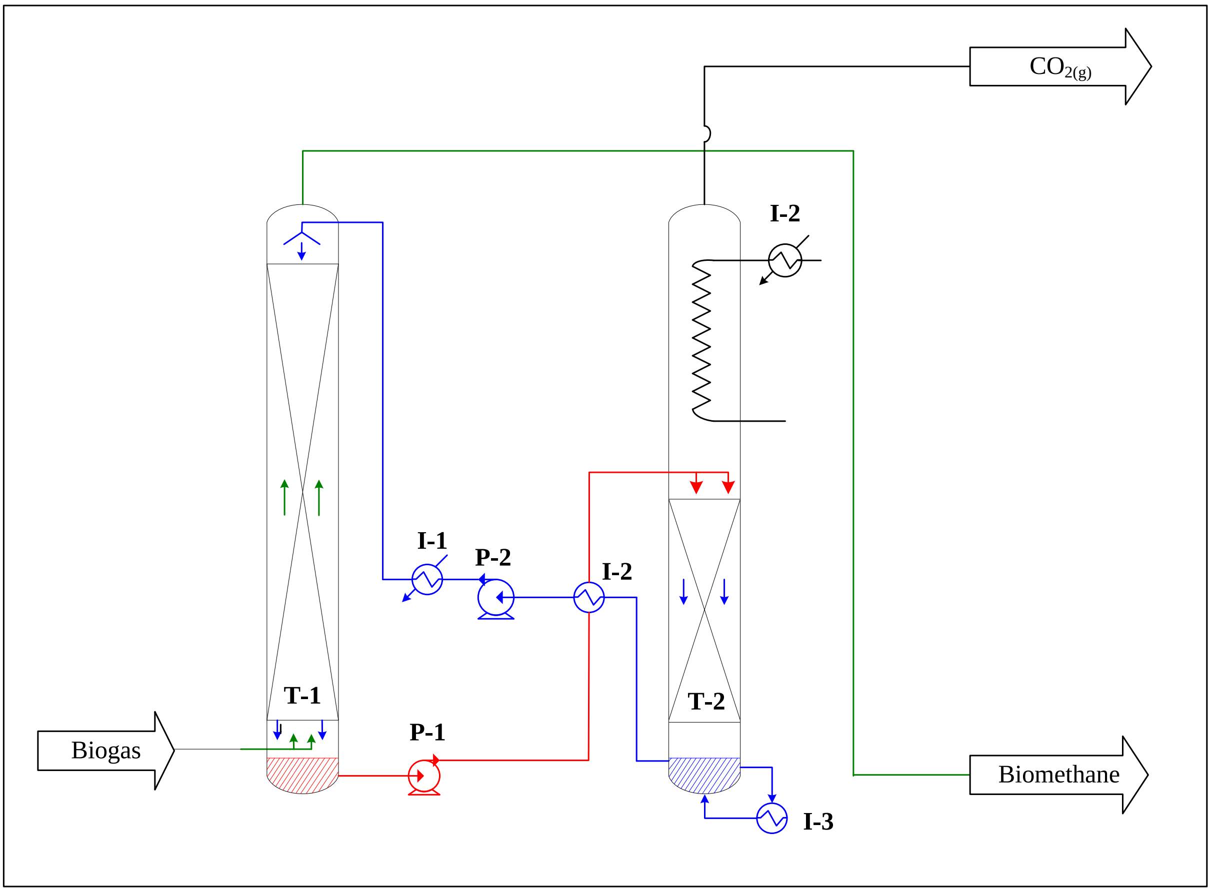


Figure 5.5. Schematic representation of a commercial amnie scrubber upgrading process.
T-1: absorber; T-2: stripper; I-1: heat exchanger; I-2: heat exchanger; I-3: reboiler; P-1: pump; P-2: pump.
Adapted from Purac (2012).

The exiting stream from the absorber (T-1) is pre-heated in a heat-exchanger (I-2) through energy integration between the carbon dioxide amino solution stream leaving the stripper (T-2) and the rich carbon dioxide solution stream leaving the absorber (T-1). When the pre-heated solution has already been warmed up, it is then fed into the top of the stripper (T-2) and normally passed through a packing material, such as Rasching rings, to improve the efficiency of separation. This process takes place when the carbon dioxide released from the bottom of the column by the action of the heat ascends, generating liquid-phase interface where the mass transfer occurs (Khan, *et al.* 2011), and, therefore, the chemical desorption of carbon dioxide. The stripper is commonly equipped with a rebolier (I-3), and it accomplishes a double function. Firstly, it provides heat that the endothermic reaction needs for the release of carbon dioxide before it can be absorbed in the first column (T-1). The typical operation temperature ranges from 120°C to 150°C. Secondly, it generates steam to reduce the vapour pressure of carbon dioxide within the column, thus improving the desorption kinetics.

5.2.1.2 Physical Absorption

High pressure water scrubbing, as its name indicates, is a process based on the increasing solubility of carbon dioxide in water when its partial pressure is raised, and the large difference in solubility between carbon dioxide and methane which leads to a significant selectivity.

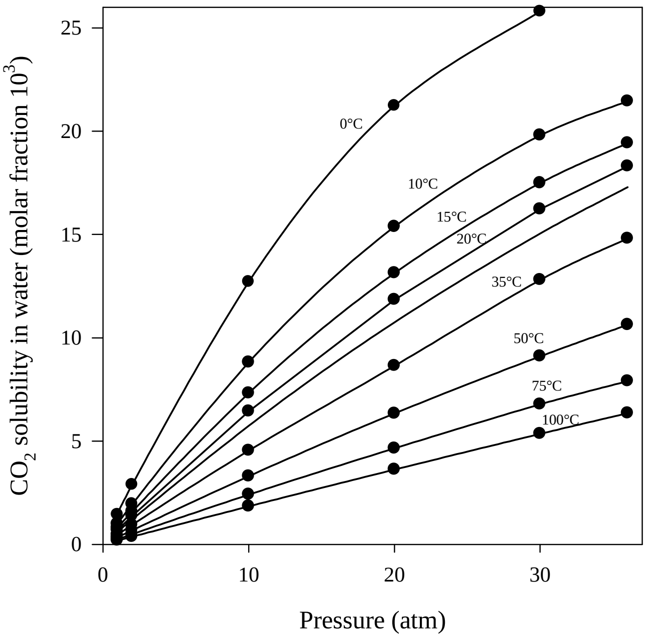


Figure 5.6. Solubility of carbon dioxide in water.
Data: Perry´s Chemical Engineering´s Handbook, 8th Edition, pg **2**-125 (2008)

As Figure 5.6 depicts, the solubility of carbon dioxide in an aqueous media is influenced by both temperature and pressure, although in a different way. As can be observed, the higher the pressure, the higher the solubility; conversely, the higher the temperature, the lower the solubility. These facts, in addition to its availability and low cost, have made it worth considering for the removal of acid gases in the gas industry in general and for biogas upgrading in particular. Furthermore, being that water is less sensitive to the presence of impurities, this characteristic makes it even more attractive for the separation of carbon dioxide.

A flow diagram of a high pressure water scrubbing (HPWS) process for biogas upgrading is shown in Figure 5.7. In its standard and modern form, the process consists of an absorption tower that operates at elevated pressure (T-1), normally 6–10 atm, a flash unit for the partial desorption of carbon dioxide (F-1), and an absorption column (T-2) for the release of the carbon dioxide. The gas treatment starts increasing the raw biogas pressure by compressing (C-1) before feeing it to top the absorption tower (T-1). Because of the gas compression, most of the water condenses and then separates from the raw gas that was previously injected into the bottom of the column. Having reached the top of the column, the gas flow is made of almost exclusively of methane, which is withdrawn for further processing. The gas-liquid contact is performed in counter-flow, so the water is fed to the top of the column. As is customary for all gas-liquid separation systems, the contact surface is increased by filling the column with random packing, which improves not only the separation efficiency, but also reduces the equipment volume and energy consumption.

In spite of having low water solubility, a non-negligible amount of methane is also taken up in the absorption column (T-1), and, to avoid its instant release after the absorption, it is fed to a flash unit within which the pressure plummets to 2-4 bar approximately. With this abrupt expansion, a fraction of the carbon dioxide and almost all the absorbed methane is released to the gaseous phase to be recirculated to the compressor (C-1).

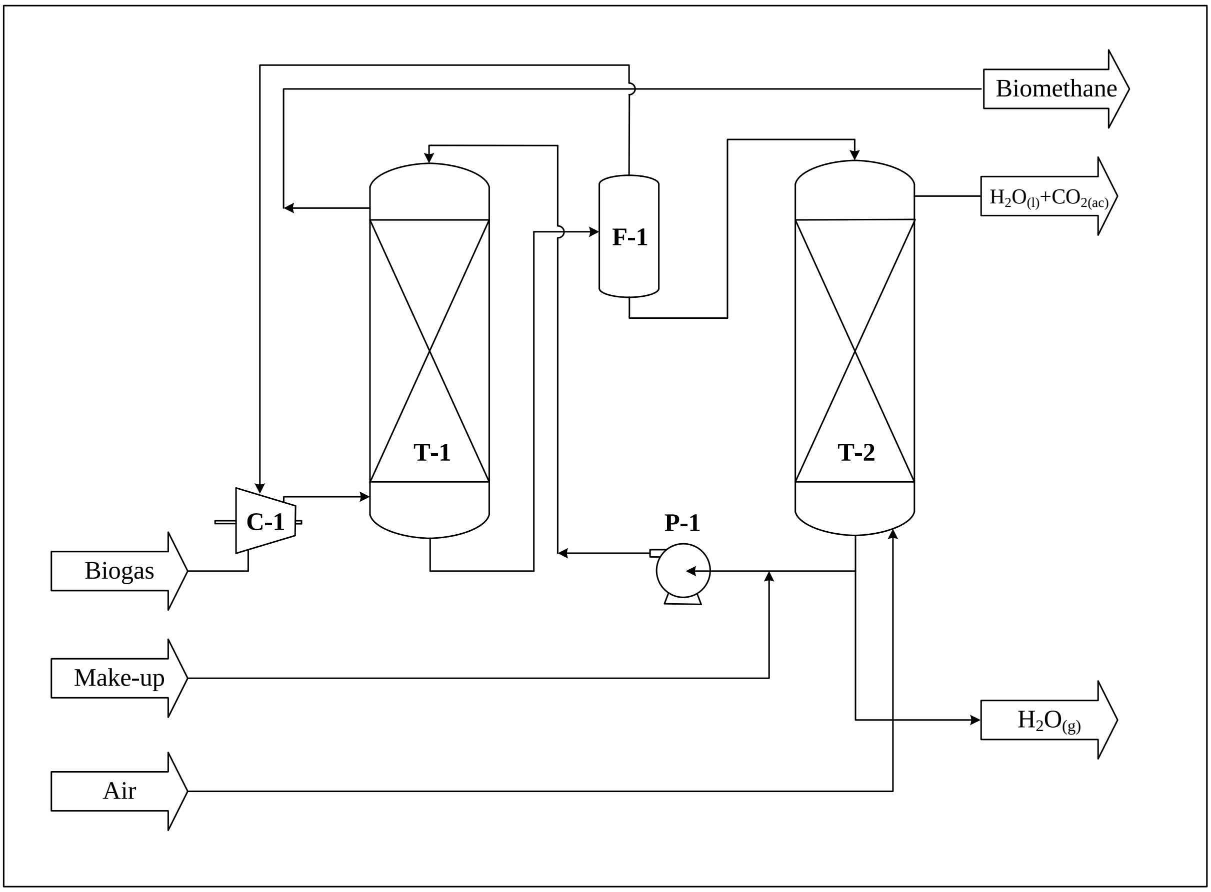


Figure 5.7. Schematic representation of a water scrubber system for biogas upgrading. C-1: compressor; T-1: absorption column; T-2: desorption column; P-1: pump; C-1: F-1: flash. Adapted from Bauer *et al.* (2012).

When most of the methane in the flash unit (F-1) is released, the carbon dioxide is afterwards released in the desorption column (T-2). Analogously, the liquid stream is fed on the top of the column while air is injected at the bottom. Because the desorption column operates at normal pressure, the solubility of carbon dioxide in water is practically insignificant, thus the water is practically pure and in a condition to be recirculated to the absorption column for reuse.

5.2.1.3 Physicochemical Absorption

By using the same principle of operation as that of water scrubbing, a contact column and subsequent regeneration of the solvent, a solution of polyethylene glycol (Selexol) can be used as physicochemical agent for the upgrading of biogas (Ryckeboch 2011). One advantage of using this solution is the simultaneous absorption of carbon dioxide, hydrogen sulphide and water that takes place when scrubbing (Persson 2003). Furthermore, polyethylene glycol has a low vapour pressure and, therefore, the losses are significantly lower. Being that carbon dioxide and hydrogen sulphide solubility are substantially higher in Selexol than in water, less absorbent is required to fulfil a specific upgrading standard, and the requirement of pumping and equipment size are lower as a consequence.

5.2.2 Adsorptive Process

This process is based on the adsorption of gases onto a solid carrier bed. Adsorption as a physicochemical phenomenon is a consequence of intermolecular forces between the gases and the surface of the solid, which is normally characterised for having large active surface areas. Zeolites (Zhao, *et al.* 2007), activated carbon (Do 1998) or metal organic frameworks (MOFs) (Gassensmith, *et al*. 2011) are among the most common adsorbents. In terms of cost-effectiveness, adsorptive processes are viewed as competitive as a consequence of the simplicity of its operation, high performance at room temperature, high regeneration rate and low energy intensity, which makes it among the most employed technique for biogas upgrading (Grande 2011).

Gas purification via adsorption is normally done in practise by using at least two adsorbent materials, usually mixed or packed in layers in a vessel. As a rule, the stream to be treated is preliminarily passed through a layer of silica gel to remove the humidity from which the water is afterwards desorbed. Silica gel typically has micro-pores in the 2-4 nm range, which additionally facilitates the removal of siloxanes and hydrocarbons of small molecular weight (Ajhar, *et al.* 2010).

Zeolites have attracted attention as an adsorbent in that they have numerous advantageous properties. Furthermore, they can be chemically modified in order to improve specific properties. Among the unmodified ones, zeolite 13 X has been reported as having the highest adsorption capacity at room temperature, reaching 3.5 mmol g^{-1} under normal conditions. Another adsorbent normally used in PSA in general is activated carbon, a highly porous and complex material with a large surface area. The surface area of commercial activated carbon has been reported in the region of 1,200 m^2 g^{-1}. Normally activated carbon has large-sized micro-pores, which are less selective for the adsorption of silicates or hydrocarbons of higher molecular weight (heavier than 300 for hydrocarbons and 225 for siloxanes).

Porous metal organic frameworks (MOFs) are a novel type of adsorbent and consist of organic and inorganic building blocks made of metal ions, their clusters or metal oxides surrounded by polymeric clusters bridged by organic ligands. The attractiveness of MOFs lies in their versatility for carbon dioxide uptake, high surface area, high porosity, low density and chemical and thermal stability. Moreover, the development of a MOFs-based process can be optimised through pore size control, introduction of immobilised functional groups or introduction of particular cations.

This process allows regeneration in situ of the bed by an adsorption-desorption cycle. It operates on an isothermal cycle, adsorbing at high pressure and desorbing at low pressure, and, for biogas upgrading, the optimal operating pressure ranges from 4 to 10 bar. The commercial processes that are based on the adsorption principle are usually called pressure swing adsorption (PSA), and they basically consist of four phases which are feed, blowdown, purge and finally pressurisation.

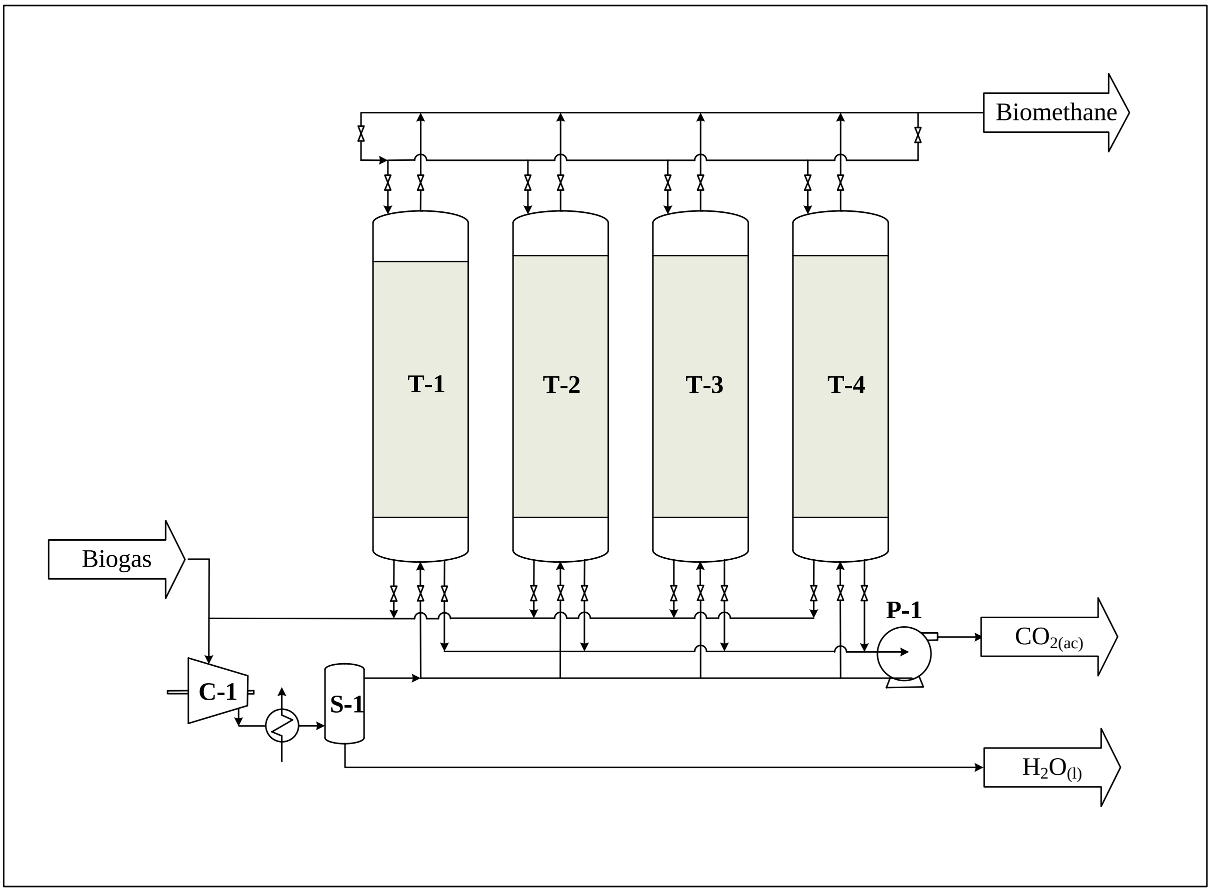


Figure 5.8. Schematic illustration of pressure swing adsorption (PSA) process. T: adsorption column; C: compressor; P: pump; S: gas conditioning. Adapted from de Hullu *et al.* (2008).

As Figure 5.8 illustrates, in the first phase of the four abovementioned phases the column is fed with raw biogas, and the carbon dioxide is adsorbed selectively on the activated bed while the methane flows up across the column and is recovered on the top of the vessel with a slight drop of pressure. When the saturation point is reached, the feed of raw biogas is ended and starts to operate in the second column. Thereafter, in the blowdown phase, before carbon dioxide breaks though, the column has to be regenerated by stopping the feed and decreasing the column pressure. With this drop in pressure, the carbon dioxide is desorbed, thus this phase is finished when the carbon dioxide exiting flow is small. Having reached this minimum pressure, a feed-in counter-flow is injected to eliminate the remaining carbon dioxide still adsorbed on the solid bed. Finally, a new phase of pressurisation is initiated when feeding with a raw gas feed-stream, or with a counter-flow of purified biomethane.

5.2.3 Other Upgrading Process

Membrane separation is another upgrading process whose functioning principle is the difference in permeability between the components of a mixture, in this case carbon dioxide and methane. Membrane-based separation units could overcome the inherent disadvantages shown by commercial upgrading systems (i.e. PSA, water scrubbing or amine scrubbing), such as high consumption of energy, biomethane (end-product) at low pressure, large equipment size and complex control systems (Scholz, *et. al.* 2013). Nowadays membranes are produced by commercial manufacturers and are continuously improving their performance (selectivity) and reducing cost, thereby becoming more competitive with other options. Nevertheless, there is still lack of solid data for economic analysis.

Cryogenic technologies, in contraposition to all the previous options of upgrading, take advantage of the different liquefaction temperature and/or pressure of gases making up biogas (i.e. methane, carbon dioxide and its impurities) (Ryckebosch, *et al.* 2011). Normally, raw biogas is compressed up to 8 MPa following sequential steps with intermediate refrigeration, or only through one direct step of cooling. Although there is some experience in operating cryogenic techniques for biogas upgrading, it is not available at large scale for it is still considered uneconomical (Bauer, *et al.* 2012).

5.2.4 Main Features of CO_2 Uptake Technologies

Table 5.1 summarises the main characteristics of the previously discussed technologies for the removal of carbon dioxide. As can be seen, each option has advantages and disadvantages, and depending on the physicochemical principle which the separation is based on, the most proper method to be selected will depend on particularities that are to be analysed case-by-case (Kabasci 2009).

Concerning the economics of the process, the operation of them demands a different sort of consumables (water, chemicals, electricity, etc.), in principle associating dissimilar cost of operation and maintenance. In a similar manner, the construction and design of each system associates diverse investments for the same treatment capacity. Nevertheless, according to Althaus and Urban (2005), and based on analysing technical information gathered from manufacturers, such as CarboTech, Malmberg, Flotech, it was concluded that for the same plant capacity, there is no significant difference in the cost of treatment and that a strong drop in cost is observed with increasing plant size. These results enable to hypothesize that the carbon dioxide uptake process is favoured by economies of scale and, more importantly, that these technologies (i.e. amino absorption, PWS, and PSA) are indistinguishable in terms of the final cost of carbon dioxide separation. These two assumptions are based on empirical facts and crucial for the subsequent economic modelling to be presented in Chapter 6 for the cost estimations of carbon dioxide uptake.

Table 5.1. Advantages and disadvantages of absorptive and adsorptive techniques for CO_2 uptake.

CO_2-Uptake Method	Advantages	Disadvantages
Absorptive Method		
Absorption with water	• Simultaneous removal of H_2S • Stable operation • Low sensitivity to impurities • Regeneration of solvent	• High investment • High cost of operation • Potential problems of foaming
Absorption with amines	• High selectivity • High performance • Low losses of CH_4	• Corrosiveness • Poisoning with impurities • Need of heating for regeneration • Low scale for upgrading • High investment
Absorption with polyethylene glycol	• Simultaneous removal of sulphured-based compounds • Regenerative • Low fugitive emissions • Tolerant to impurities	• Heat for regeneration • High investment • Corrosiveness problems • High cost of operation
Adsorptive Method *Molecular sieves* *Zeolites* *Alumina silicates*	• Tolerant to impurities • Small in size • Regenerative • High efficiency	• High losses of CH_4 • Need of complex control systems • Intensive in investment • Costly operation

5.3 Biogas Injection into the Natural Gas Grid

The injection of biomethane into the grid is the final step, and requires conditioning in order to homologate the quality of the gas with which it will be mixed. It is worth pointing out that each country has different standards for natural gas, and this is not a “universal” natural gas, as can be seen in Table 5.2. Therefore, and for the fulfilment of local standards of operation, odorising, drying, gas quality measurement, pressure regulation and gas heating adjustment are done, which are practically automatised nowadays.

Table 5.2. Specifications for supplying Bio-SNG into the grid.

Specification	Germany	Sweden	Austria	US	Chile
Wobbe index (kWh m^{-3})	12.8-15.7	n.s.	13.25-15.72		13.1 – 14.6
Heating value (kWh m^{-3})	8.4-13.1 $^{(1)}$	8.4-13.1	10.7-12.8 $^{(*)}$	9.8-11.4 $^{(2)}$	10.1-11.4
O_2 gas networks (%)	< 3	< 1	< 4	< 0.2-1	< 1
H_2S (ppm)	3	23 $^{(3)}$	4	3.7	35 $^{(3)}$
H_2O	< dewpoint		< dewpoint	< 120 ppm	< dewpoint
CO_2 (%)	n.s.	< 3	n.s.	< 2-4	1.5-4.5 $^{(4)}$

$^{(1)}$: Upper heating value. $^{(2)}$: lower heating value. $^{(3)}$: measured as total sulphur (mgSm^{-3}). $^{(4)}$: As total inert gases.

Sources: For Germany, Austria and US, see Scholz *et al.* (2013); for Sweden see Praß et al (2008); for Chile Nch 3213.Of2010.

The injection of Bio-SNG is generally possible into any type of natural gas grid (Ramesohl & Arnold 2005). Nevertheless, low-pressure and high-pressure grids work differently, so “pendulum zones” are observed when two gases are put in contact but not mixed (Klinsky 2006). This problem is observed when the gas distribution is done through a grid with numerous feed-in points, thus not being the gases mixed (Prassl 2008; Klinski 2006).

5.4 Technology for Electricity Generation by Biogas Burning

The generation of electricity through the direct combustion of biogas is often referred to as the *distributed generation concept* because biogas facilities are normally located near the end user. For these sorts of power plants there are a variety of technologies that can be utilised with characteristic capacities, performance and level of commercialisation (Randolph & Masters 2008).

5.4.1 Microturbines

Microturbines, as the name indicates, are small-scale combustion turbines which can generate electricity from approximately 2.5 kW_e, with an equally considerable amount of heat available for recovery (Pehnt, *et al.* 2006). As a scalable technology, multiple units can function together to reach higher power and can be fed with biogas as well as propane, hydrogen or diesel.

The electrical efficiency of microturbines is relatively low in comparison with that of systems that can operate at a similar power capacity, ranging from 25-30%. When electricity is generated via a CHP scheme, the overall efficiency can rise to 80%. As in most CHP systems, the economics of this technology is closely linked to the use of heat as a by-product since the refrigerant fluid normally used is water and can be used for heating in the 50-80°C range. Because of their low capacity and the necessity of recovery and use of heat to improve the economics of the whole process, microturbines might have better chances in applications with stable demands of heat such as swimming pools, hospitals, etc (Praetorius & Schneider 2006).

5.4.2 Stirling Engines

Stirling engines have a long tradition in engineering, principally in the 19th century, mainly for operating at a relatively low-pressure, thus being safer to work with. Nevertheless, the operation of the spark-ignition engine and the improvements in the steam engine virtually eliminated them from the market (Randolph & Masters 2008).

In contraposition to microturbines or reciprocating engines, the operation principle of Stirling engines is not based on the explosion of a fuel, but in the difference of temperature between a hot source and a cold sink. The ideal Stirling cycle is made of the four processes or steps which are isothermal compression, addition of heat at constant volume, isothermal expansion and finally a removal of heat at a constant volume (Wu 2004). The Stirling engine is appropriate for stationary operation, and because it involves a continuous burning of fuel rather than the intermittent explosion in an internal-combustion engine, the fuel is used more efficiently and lower emissions (i.e. NO_x and CO) are generated. Furthermore, Stirling engines have lower maintenance cost, longer lifespans, and safer operations. On the other hand, the capital investment is relatively high, most proven prototypes are been tested only in the small-scale and data regarding reliability and useful life is still lacking (Corria, *et al.* 2006).

5.4.3 Reciprocating Engines

Reciprocating engines constitute the bulk of generation technology for distributed systems (Randolph & Masters 2008). They are commercially available in ranges from 20 kW_e to 5 MW_e approximately (ASUE 2011), and along with biogas, they can be designed to run using gasoline, diesel, kerosene, propane, alcohol, hydrogen and other such fuels. Reciprocating engines can operate either under Otto or diesel cycle, hence they are based on spark-ignition (also known as sparkplug-ignition) or compression-ignition schemes, and with electrical efficiencies that can rise to 40%. When a CHP mode of functioning is used, thus recovering the heat from the cooling system and the exhaust gas, the overall efficiency can reach roughly up to 85%. Although a reciprocating engine is a reliable technology and electricity can be generated in a wide range of power, thermal and electrical efficiency are highly dependent on capacity.[1]

Because a mixture of biogas and air cannot fulfil the conditions necessary for ignition when compressing it, the spark-ignition engines demand a supplementary fuel such as diesel, biodiesel or a vegetable oil (Lantz 2012). Modern spark-ignition engines typically operate with 10% supplementary ignition fuel; however, consumption in the 3%-30% range has also been reported (FNR 2010).

As noted by Lantz (2012), the comparison between spark-ignition and compression-ignition engines is not straightforward, and as for many techno-economic assessments, the most convenient alternative depends on specific local conditions that cannot be generalised. In addition to providing demonstrations of this fact, Lantz (2012) emphasises the scarcity of technical data, which prevents comparison between the reciprocating engine and an alternative technology such as microturbines. According to Lantz (2012), the comparison of spark-ignition, compression-ignition and microturbines, using the Swedish conditions based on farm-based biogas as a framework, seems inconclusive about the superiority of one technology over the other, and no remarkable differences in terms of cost or technical performance was observed.

Table 5.3. Comparison of diesel and Otto engines (FNR 2010).

Engine	Advantages	Disadvantages
Otto engine	• High technical lifetime • Less maintenance • High total efficiency • Especially designed for gaseous fuel burning	• High electric efficiency for small engines • Relatively low investments
Diesel engine	• Requirement of ignition fuel • Low total efficiency • Short technical lifetime • Higher requirement of maintenance	• Associates a higher investment • Low efficiency at small scale

As a result of the abovementioned observation and technical analysis, further assessment for energy potential will be based on reciprocating engines as a reference technology. Furthermore, it will be assumed that there is no distinguishable difference in cost of production for either electricity or heat when using Otto-engine or diesel based-engines in spite of operating using different back-up fuels or requiring different consumables.

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[1] More antecedents about efficiencies are given in Chapter 6, section 6.8.5 *Combined Heat and Power Systems*.

6. Economics of Biomass Conversion Technologies for Biogas

The main features of technologies for the anaerobic conversion of biomass and the subsequent production of an energy carrier in the form of electricity or gaseous fuel were presented in Chapter 5. In this chapter, the main economic figures useful for the assessment of the economics or financials of a biogas project are provided and discussed.

6.1. Introduction

The estimation of capital cost is a necessary and challenging task for any financial or strategic analysis in the decision-making phase, and of paramount importance for the success of any capital project. For biogas projects in particular, capital cost information of anaerobic digestion plants is lacking, and additionally it exhibits extremely high variability attributable to the digestion technology itself as well as the various add-ons such as pre-treatment modules, abatement systems and mixing systems that may or may not be included (Karellas, *et al.* 2010). Moreover, the definitions employed to refer to "capital cost" are not always used consistently by plant owners or equipment suppliers in economic analysis.

Biegler *et al.* (1999) noted that capital cost estimates can be classified into five categories, according to their accuracy: the *order-of-magnitude*, with an associated error lower than 40%; *study estimate*, with associated error lower than 25%; *preliminary estimate*, with an associated error lower than 12%; *definitive estimate*, with an associated error lower than 6%; and finally the *detailed estimate* with an associated error lower than 3%. Similarly, the Association for the Advancement of Cost Engineering International-AACE (Amos 2007) proposed a classification for the level of accuracy of the estimate through four stages associating different preparation effort, these are: *concept stage*, with 50-100% associated confidence limit; *pre-feasibility*, with 30-50% associated confidence limit; *feasibility*, with 10-30% associated confidence limit; and *detailed engineering*, with 5-15% associated confidence limit. For the purposes of the assessment which is to be conducted in this work, the definitions proposed by AACE will be used.

In the following section of this chapter the issues of major relevance to the economic potential analysis, with the main criteria taken into consideration and the economic data in which the calculation of cost will be based on, will be discussed and set up.

6.2 Estimation of Capital Cost

The most commonly used techniques for the estimation of capital cost are the *factored estimation technique*s and the *unit cost techniques* (Crundwell 2008). While factored techniques are used in a preliminary stage of design, unit cost techniques are employed when a bill of quantities is available, normally when the design is in the phase of consolidation. Factored estimation techniques are based on the utilisation of historical data of plants, process, unitary operations or items of different sizes, and being that this information available for a specific case, the cost or investment can be updated or adjusted for the current situation. Whereas some factors account for the updating from the past to the present, others account for the amendment of size or capacity.

For the adjustment of time, cost index ratios are commonly used to estimate a current cost (in general on a yearly base) with information from the past. There is a variety of cost indices for specific groups of operations and processes published regularly in specialised literature. The most commonly used are the Chemical Engineering Plant Cost Index (CEPCI) and the Marschall and Swift equipment cost index, which are issued on a monthly basis and then expressed under a yearly average basis (Chauvel, *et al.* 2003; Mignard 2014). Normally, these dimensionless factors are applied by dividing the index for the year under evaluation (the current year, for instance) and that for which information is available, as Equation 6.1 indicates.

$$C_t = C_o \frac{CI_t}{CI_o} \qquad \text{Equation 6.1}$$

In which C_t and CI_t represent the cost and cost index for the year to be calculated, *t*, and C_o and CI_o represent the cost and index at another time, respectively.

Another approach used to estimate capital cost is based on reference items or plants of similar characteristics. In these terms, cost of civil work, investment of major equipment and structures can be calculated by the normal application of an exponential correlation as presented in Equation 6.2.

$$C = C_o\left(\frac{Q}{Q_o}\right)^n \qquad \text{Equation 6.2}$$

In which C is the cost to be estimated at capacity Q, C_o is the reference cost at a known capacity, Q_o, and n is the correlation index.

For the estimation of capital cost, a combination of these two procedures was used to obtain adequate data for the economic assessment to be conducted. For the updating of information in respect to time, principally investment, the CEPCI for the year 2011 was used, the value of which is 394.3 (Chemical Engineering 2009); thus all the financial data and cost figures will be expressed as $€_{2011}$ for the remainder of this thesis.

6.3 Estimation of Operation and Maintenance Cost

Although some authors may differ in the way they allocate and conceptualise expenses of operation and maintenance, in some cases (Chauvel, *et al.* 2003; Silla 2012), it is possible to distinguish between *variable cost* and *fixed cost*. Variable cost is proportional to the production capacity of the facility, and this expense reflects the mass and energy balance of the process. Conversely, fixed cost does not depend on the quantity produced, is directly linked to nominal processing capacity and is virtually known when this parameter is defined. Normally, personnel cost (marketing, general services, administrative, etc.) is also included in fixed cost although some companies account for it as part of variable cost when employees have to work in shifts or for longer periods to ensure a continuous operation. In common applications, variable cost is related to a processed variable or product, and as long as the plant scale does not modify the energy and mass balance significantly, the *variable cost* becomes a *constant cost*. On the other hand, when fixed cost is expressed in terms of a processed variable, it becomes variable, thus dependent on the actual annual production. For a biogas plant, variable cost is mainly grouped into: maintenance, services, utilities (principally power to run the plant auxiliary equipments, e.g. pumps, blowers, fans, feeding systems) and heat cost. Fixed cost is simply categorised as personnel and general cost (Karellas, *et al.* 2010). Van Dael *et al.* (2013) distinguished between investment[1] and operational cost, the latter of which includes maintenance, insurance, repair, energy, personnel and auxiliary products in the techno-economic assessment of biomass conversion facilities. They took

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[1] In the original publication addressed as *investment cost*.

advantage of classifying capital cost in this way to assess the profitability of biogas facilities more directly by using indicators such as the net present value (NPV) and the internal rate of return (IRR) as indicators of the economic attractiveness of the project.

For the purposes of this research, it was assumed that the annual cost of operation and maintenance ($C_{o\&m}$) includes personnel, maintenance and support services, internal consumption of electricity and heat and contingencies. Additionally, when assuming a linear proportionality between investment (I) and this operation and maintenance cost ($C_{o\&m}$), the annual operation and maintenance cost ($C_{o\&m}$) can be expressed as Equation 6.3 indicates.

$$C_{o\&m} = \beta I \qquad \text{Equation 6.3}$$

In which β is a fixed fraction of the investment and I is the total investment. This simplification has already been proposed and used by Hoogwijk (2004), Faaij (2006) and Gómez *et al.* (2010; 2011) as a conservative approach to estimate the cost of production for renewables.

6.4 Effect of the Location

Most equipment and investment data are informed by either US$ or Euros (€) since USA and Northwest Europe have historically been the centres of the chemical and process industry (Towler & Sinnott 2008). The cost of constructing a productive facility depends on local infrastructure, local labour availability and its cost, cost of shipping, currency exchange rates, import duties, materials, local standards, variation in the cost of labour and other such factors. A location factor of 1.08 was included as the investment for Chile; this factor mainly addresses the additional cost for freight, taxes and insurance of goods produced in and transported from central Europe (Chauvel, *et al.* 2003).

6.5 Local Currency

Because the economic data is expressed in literature as either US dollars (US$) or euros (€), the exchange rate for the year 2011 in Chile was used for conversion into euros and is equivalent to 0.7189 US$ €$^{-1}$ (Central Bank 2013).

6.6 Discount Rate and Lifetime

To calculate an economic indicator such as net present value, annual equivalent cost or others, the discount rate will be set in a specific time period. The selection of this parameter is basically a strategic choice of an organisation. As is known, the results obtained from aforementioned economic indicators represent the combination of financial cost of capital, economic cost of capital and the added effect of the risk level associated with the project. For the present evaluation, an annual interest rate of 10% (i) and lifetime of 15 years (n) was used.

6.7 Load Factor

For the purpose of this thesis, the load factor was defined as the duration of operation of the biogas facility over the year with allowance for programmed routine maintenance; therefore, it reflects the optimal use of the infrastructure and the best possible production capacity. This parameter is normally expressed as hours per year (h y^{-1}) or as a percentage of the total operating time of a facility that can run continuously such as a chemical plant. For all the cases, a load factor of 8,000 h y^{-1} (90% approximately) was employed as the effective time of operation for biogas processing (see Equation 4.12 in Chapter 4).

6.8 Biogas Plant Economics

As mentioned earlier, capital cost for anaerobic digestion plants is not easily obtainable and is associated with high variability (Karellas, *et al.* 2010). Furthermore, the definitions employed to refer to economics are not always used consistently in literature. Terms such as *investment cost*, *capital cost* or *total plant cost* are used indistinguishably, and authors normally avoid informing of the error associated with them; the time basis of the data provided (money in terms of a specific year, e.g. €$_{2010}$, €$_{2013}$), and the component of cost, add more uncertainties to the assessments.

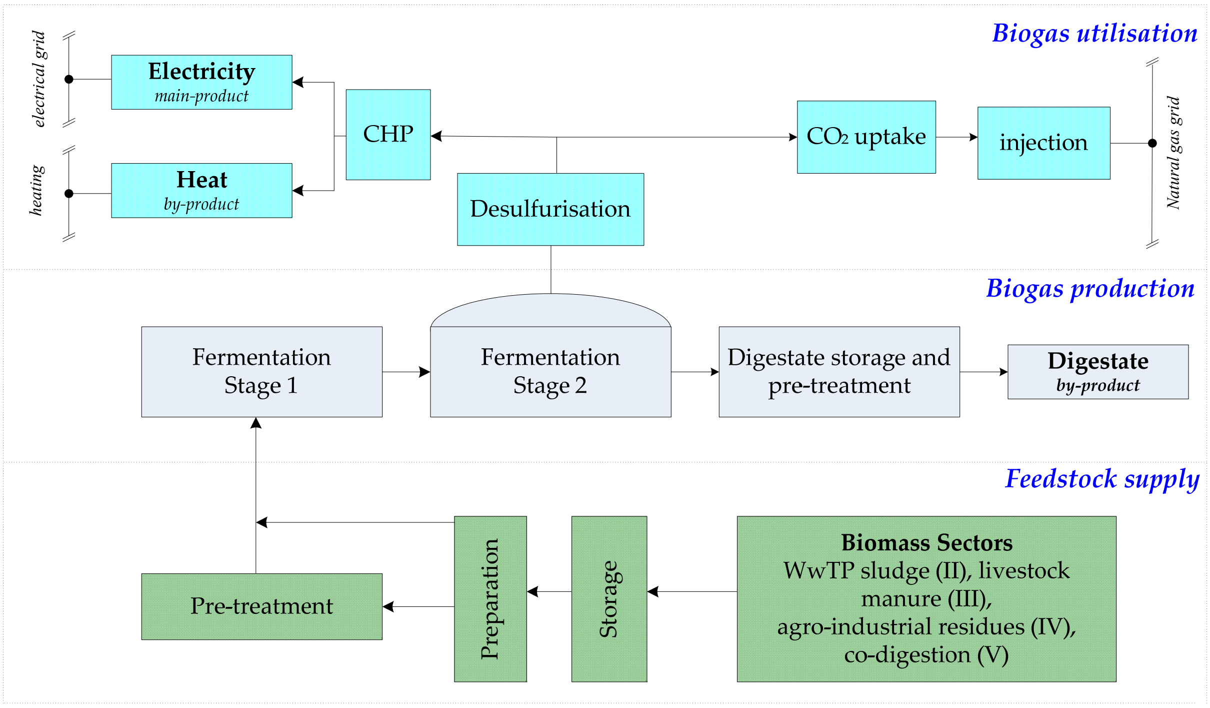

Figure 6.1. Schematic representation of a generic anaerobic digestion plant for the production of electricity of Bio-SNG based on organic feedstock. Adapted from Poeschl *et al.* (2010[a]).

For the purposes of this section, a biogas plant is conceptually organised as schematically presented in Figure 6.1. It can be observed that this facility is made of three sections (Poeschl, *et al.* 2010[a]). First, the *feedstock supply* area, where the biomass is received, then stored and pre-treated. Next, the *biogas production* area, where the digesters and digestate receiver are located. Normally during the generation of biogas a rough desulphurisation takes place within the digester, and the biogas attains the conditions necessary for subsequent utilisation. Finally, the biogas utilisation area consists of the fine desulphurisation (when needed) and the conversion units for the generation of secondary energy through a *biogas-to-energy* pathway or *biogas-to-upgrade* route (Poeschl, *et al.* 2010[b])

The information presented in the following sections correspond to the capital cost, also addressed as total investment; hence the direct cost (major equipment, bulk material, freight and transportation), construction (site facilities, site cost, civil, mechanical, electrical, instrumentation, etc.), engineering, procurement, construction and cost of studies of basic engineering are included.

6.8.1. Biogas Production

The investment to be presented is made of the *feedstock supply area* and *biogas production area*, according to Figure 6.1. It involves machinery, biogas plant (including ancillary construction), substrate storage, electrical and control equipments and dismantling cost.

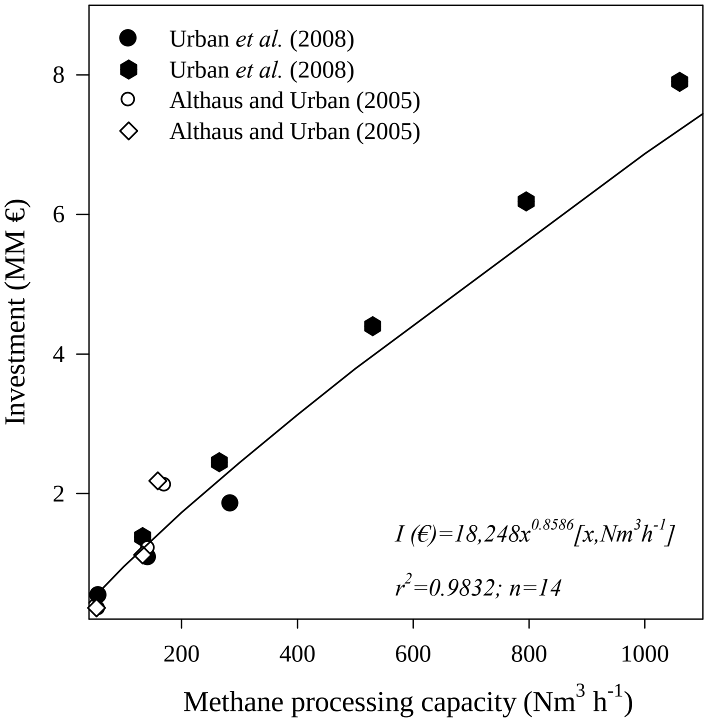

Figure 6.2. Investment of plant facility for biogas production.

The biogas investment can be correlated by an exponential equation which was discussed previously (see Equation 6.2). By fitting statistical data published by Urban *et al.* (2008) and Althaus and Urban (2005), this economic information can be correlated as follows.

$$I(€) = 18{,}248x^{0.8586}[\mathrm{x}, \mathrm{Nm}^3\mathrm{h}^{-1}] \qquad \text{Equation 6.4}$$

The annual operating cost was estimated as 12% y^{-1} of investment and is constituted by personnel, maintenance and service cost as well as electricity. This figure is in line with that published by Gómez *et al* (2010) for biogas conversion technologies.

$$C_{o\&m}(€\ y^{-1}) = 0.12I\ [I, €]$$

6.8.2 Carbon Dioxide Uptake

The carbon dioxide uptake, an operation within the *biogas utilisation area*, is the most expensive step in the biogas conditioning process. Fine desulphurisation as well as the drying of treated gas are normally included as part of this step; additionally, the treatment of exhaust gases is generally included in this step in order to fulfil the mandatory standards for methane and sulphur emissions. In general, the highest cost of operation in this step corresponds to electricity, which is used when biogas is compressed or water is pumped. Comparison to the carbon dioxide uptake process is possible when taking into consideration that the only processes with enough technological maturity are pressure swing adsorption (PSA), pressurised water scrubbing (PWS) and amino solutions (AS).

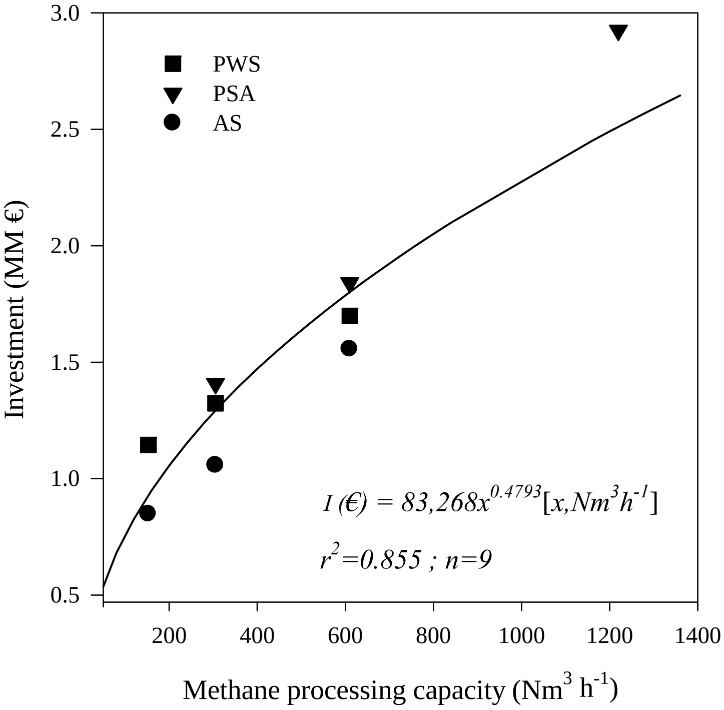

Figure 6.3. Investment of carbon dioxide removal units for biogas upgrading: pressure swing adsorption (PSA), pressurised water scrubbing (PWS) and amino solutions (AS).

The investment was correlated by fitting economic data published by Urban *et al.* (2008) and Althaus and Urban (2005). It can be demonstrated that Equation 6.5 adjusts this data properly:

$$I(€) = 83{,}268\, x^{0.4793}[\mathrm{x, Nm^3h^{-1}}] \qquad \text{Equation 6.5}$$

A total of nine points were fitted, with a correlation index of approximately 0.855, so this process exhibits economies of scale. The annual operational and maintenance cost was estimated by fitting the same data at 24.9% of total investment (% y^{-1}). This cost includes electricity, operating media (water and chemical absorbent, as applicable), exhaust gas treatment, personal and maintenance and services cost.

6.8.3 Network Connection for Bio-SNG Injection

The cost related to the injection of Bio-SNG into the natural gas distribution network depends heavily on particular local standards as well as distance to feed-in points and the quality of the natural gas that it is to be mixed with, among others. Additionally, the lack of solid data for this step makes it difficult to generalise information that would apply to a wider set of situations and circumstances. Nevertheless, from data published by Althaus and Urban (2005), it can be observed that this step only plays a marginal role in the whole cost structure. This being so, the uncertainty related to the estimates will not significantly modify the results and conclusions.

The connection cost is normally shared by the gas supplier and the natural gas distribution owner; therefore, it was assumed that 50% of the investment and cost would be charged by the Bio-SNG supplier. In addition to this and as noted above, the distance between the connection depends on the geographical conditions of the grid and the location of the biogas plant. To overcome this issue, a distance of 1 km to a grid of natural gas distribution operating at 45 bar was assumed. Concerning the operation and maintenance annual cost, an equivalent to 5% of investment (% y^{-1}), a conservative and representative value for this sort of operation, was assumed.

As shown in Figure 6.4, three points were correlated for a methane injection flow in the 250-1,200 Nm^3h^{-1} range from the data published by Althaus and Urban (2005). It includes the recompression unit, odorising, gas quality measurement equipment, pressure regulation, gas heating adjustment equipment and management station as well as the mechanical network connection and the investment for the stub line.

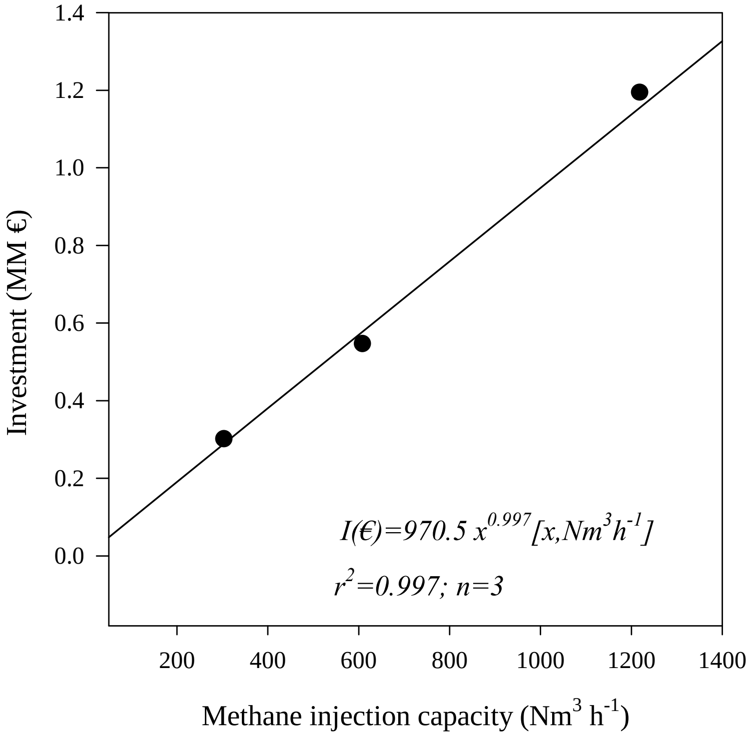

Figure 6.4. Investment of network injection system for Bio-SNG.

6.8.4 Cost of Biogas Desulphurisation

Mescia *et al.* (2011) reported a cost of desulphurisation for landfill biogas by using a fixed bed of activated carbon from 1.99 $\text{ct€ Nm}^{-3}_{\text{CH}_4}$ to 3.5 $\text{ct€ Nm}^{-3}_{\text{CH}_4}$ and 0.40 $\text{ct€ Nm}^{3}_{\text{CH}_4}$ when using scrubber technology[2]. Althaus and Urban (2005) reported a gross desulphurisation cost for vegetable matter-based biogas of 0.86 $\text{ct€ Nm}^{-3}_{\text{CH}_4}$ when using sulphide precipitation and indicated that it ranges from 0.34 $\text{ct€ Nm}^{-3}_{\text{CH}_4}$ to 0.64 $\text{ct€ Nm}^{-3}_{\text{CH}_4}$ when using scrubbers. For gross desulphurisation when processing manure-based biogas, the same authors indicated that the cost of desulphurisation is approximately 3.89 $\text{ct€ Nm}^{-3}_{\text{CH}_4}$ when using sulphide precipitation, whereas it ranges from 1.24 $\text{ct€ Nm}^{-3}_{\text{CH}_4}$ to 2.3 $\text{ct€ Nm}^{-3}_{\text{CH}_4}$ when using scrubbers. The data provided by Althaus and Urban (2005) corresponds to the treatment of raw biogas in commercial scale biogas plant, i.e 100 – 2,000 Nm^3h^{-1}. Conversely, data given

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[2] Assuming a biogas composition of 55% methane and 45% carbon dioxide.

by Mescia *et al.* (2011) are based in lab-scale experiments. As can be observed, variability is high and depends on which technology is used, flow of biogas to be treated and the sort of feedstock used. Depending on the type of substrate to be processed, a specific cost of desulphurisation will be employed from the aforementioned data. For the purposes of this research only one step of gross desulphurisation will be included, assuming that this is enough to fulfil the local environmental standards.

6.8.5 Combined Heat and Power Systems

Figure 6.5 and Figure 6.6 show the electrical and thermal efficiency of reciprocating engine-based CHP modules (ASUE 2011). As observed, the electrical efficiency decrease is significant in the 10-2,000 kW_e range, whereas it tends towards a maximum limit value of 45% from 5,000 kW_e approximately. Conversely, the thermal efficiency tends to decrease drastically in the 10-2,000 kW_{th} range, and it stabilises from 5,000 kW_{th} to 40% approximately.

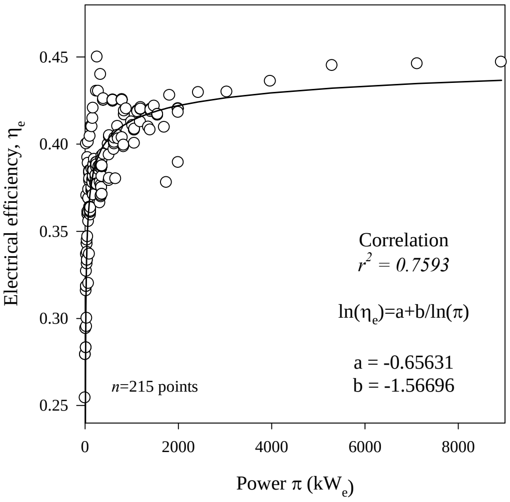

Figure 6.5. Electrical efficiency of reciprocating engine-based CHP (ASUE 2011).

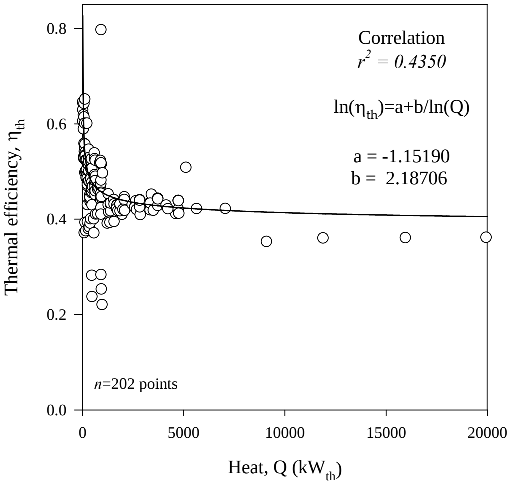

Figure 6.6. Thermal efficiency of reciprocating engine-based CHP (ASUE 2011).

Statistical information on electrical efficiency (η_e) and thermal efficiency (η_{th}) as a function of electrical power (π) and heat (Q) published by ASUE (2011) was correlated for biogas reciprocating engines in the 10–8,500 kW_e range, and then fitted with a logarithmic function as indicated in Equation 6.6 and Equation 6.7.

$$\ln(\eta_e) = -0.6563 - 1.5670\ln(\pi)^{-1}$$ Equation 6.6

$$\ln(\eta_{th}) = -1.15190 + 2.18706\ln(Q)^{-1}$$ Equation 6.7

In which (η_e) is the electrical efficiency, (π) is the electrical power, (η_{th}) is thermal efficiency and (Q) is the heat from the CHP. To estimate the specific capital investment of CHP modules and operation & maintenance cost, technical information already correlated and published by ASUE (2011) was used. Re-organising Equation 4.14 (see Chapter 4), the generation cost can be written as:

$$c_i = \frac{\alpha}{p}\left(\frac{I}{\pi_{t,i}}\right) + \left(\frac{1}{p}\frac{C_{o\&m}}{\pi_{t,i}}\right) - \frac{1}{p}\frac{(R_i + C_p)}{\pi_{t,i}}$$ Equation 6.11

In which c_i is the unitary cost of secondary energy; $\pi_{t,i}$ is the single technical potential of the *i*th-source of energy; I is the total investment of the conversion technology for the whole supply-chain; α is the capital recovery factor; $C_{o\&m}$ is the operation and maintenance cost; and C_p is the feedstock supply cost for conveyance at the gate of plant (when applicable) and R_i are the revenues from by-products sales. The expressions in round brackets in Equation 6.11 correspond to specific capital investment and specific operation & maintenance cost, according to ASUE definitions, respectively. With the proposed designation, the following equivalences can be established with ASUE data.

$$\left(\frac{I}{\pi_t}\right) = 15{,}648\,\pi_t^{-0.536}\,(\text{€}\,kW_e^{-1})$$ Equation 6.12

$$\left(\frac{1}{p}\frac{C_{o\&m}}{\pi_t}\right) = 17.053\,\pi_t^{-0.478}\,(ct\text{€}\,kWh_e^{-1})$$ Equation 6.13

Equation 6.12 and Equation 6.13 can be used to estimate the unitary cost of electricity through the *biogas-to-energy* pathway

6.8.6 Investment for Landfill Gas Recovery Systems

Landfill gas extraction is the first step of the recovery (Rubio-Romero, *et al.* 2013). The collection system contains a set of extraction wells that are normally located at selected depth intervals and share a common collection point by means of a pipe network. Afterwards, the gas is normally desulphurised by a conventional activated carbon system and then burned to produce electricity (Barros, *et. al.* 2014; Bolan, *et al.* 2013).

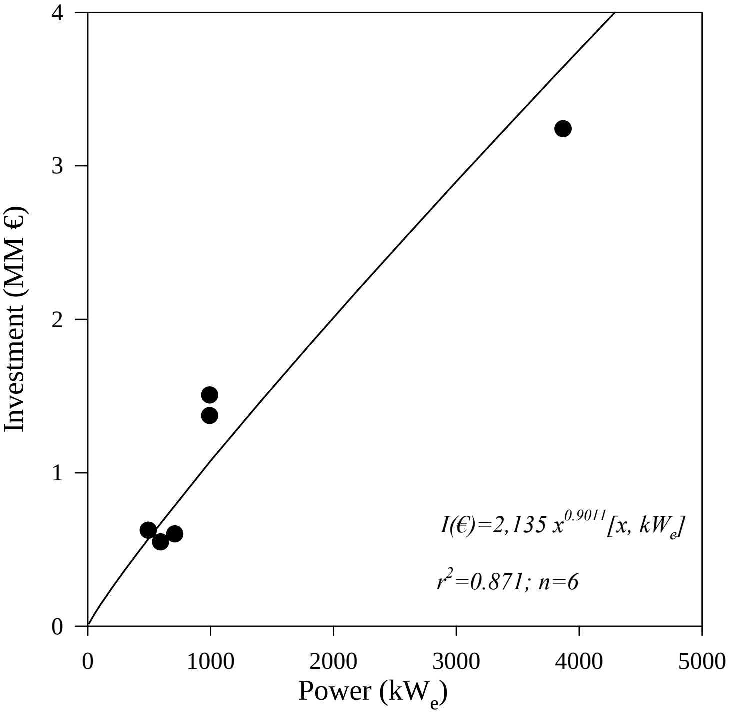

Figure 6.7. Investment of landfill biogas recovery system.

The investment of this recovery system was correlated through an exponential equation. A total of six points, gathered from data published by Caresana *et al.* (2011), Willumsen (2012) and available in the technical reports LGTE (2012) and COGEN (1994), were fitted with a correlation index of approximately 0.871. This equation correlates the investment with the nominal electrical power capacity as Equation 6.14 indicates.

$$I(€) = 2{,}135\, x^{0.9011}[\mathrm{x}, \mathrm{kW_e}] \qquad \text{Equation 6.14}$$

It can be demonstrated that the equivalence between the investment expressed in electricity power (P_e) and thermal gaseous power are as follows:

$$I = aP_e^b \qquad \text{Equation 6.15}$$

$$I = \frac{a}{f^b}\eta_e^b P_{th}^b \qquad \text{Equation 6.16}$$

In which *a* and *b* are the correlation factors; η_e is the average electrical efficiency assumed as 35%; and *f* is the thermal equivalent of methane (9.45 kW_{th} Nm^{-3}). When these values are used in the equations, the following is obtained.

$$I(€) = 7{,}304\ x^{0.8755}[x, Nm^3h^{-1}] \qquad \text{Equation 6.17}$$

6.9 Waste-to-energy System Economics

Gómez *et al.* (2010) proposed a correlation for *waste-to-energy* (WTE) technologies based on gathering data published elsewhere. The correlation is as indicated by Equation 6.18.

$$I(€) = 15{,}797\ x^{0.82}[x, kW_e] \qquad \text{Equation 6.18}$$

Furthermore, an annual operation and maintenance cost of 4% y^{-1} of the investment was estimated by these authors. Electrical efficiencies in the 21-28% range are reported by Burnley *et al.* (2011) for WTE technology, based on the BRET by the European Commission (2006). Taking into consideration that the use of corrosion-resistant materials allows higher operating temperatures, efficiencies of up to 30% might be present in the new generation of WTE conversion units, according to the authors. However, many of these techniques are still unproven, and the authors recommend a 21% net electrical efficiency. This being so, the calculation was made by using a net electrical efficiency of 21% for the WTE option.

Gómez *et al.* (2010) did not make clear if the BAT investment for gas abatement was included in Equation 6.18. Comparing this data with that reported by Zabaniotou and Giannoulidis (2002), who offer segregated economic information of WTE investment with and without BAT gas abatement, the additional investment due to the BAT inclusion was calculated. Zabaniotou and Giannoulidis (2002) reported an emission abatement system investment to total investment ratio from 13.3% to 24.4%. The latter value was used as a conservative approximation in the calculations.

6.10 Natural Market Price

The economic attractiveness of electricity or Bio-SNG can be evaluated by comparing the corresponding representative generation cost with the market price of natural gas at the corresponding level of commercialisation. A city gate price of natural gas in the 15-22 € MMBTU^{-1} range was estimated to compare the Bio-SNG pathway with fossil natural gas in the same period (National Commission of Energy 2011; Pirog 2004). For the purpose of this study, these values can be considered as representative at the national level.

6.11 Electricity Market Price

Similarly, the nodal price of the main electricity system of the country, SIC (central interconnected system) (National Commission of Energy 2011), can be used as a reference for the electricity pathway comparison. Considering a trade price of electricity 60% higher than the annual average nodal price as a representative value for the evaluation of projects of electricity generation at low scale, an electricity price of 12 ct€ kWh$_e^{-1}$ for the year 2011 is estimated. This value is based on a comparative analysis of the price paid by an electrical distribution company in a reference small-scale renewable electrical project which supplies energy to a consumption centre close to the electricity generation point. The price was calculated as a percentage over the nodal price and took into account the saving of money for the distribution company as a consequence of lower cost for transmission (lower cost of operation and maintenance and lower losses because of long transmission, lower voltage transmission, etc.), which should be reflected in a better price for the electrical supplier. This value is to be considered only as a reference price useful for macro-assessments, which has an empirical basis that has arisen from discussions with businessmen and electrical practitioners with enough experience in the field.

6.12 Summary of Economic Information

In table 6.1 the main techno-economic information, systematised and mathematically correlated for the use of economic assessment in the further sections, is summarised. It is worth pointing out that this data can be used for the preliminary or pre-feasibility cost estimate level, and, for the purposes of this research, can provide a reasonable order of magnitude in the economics and financials useful for the development of macro-policies or in decision-making.

Table 6.1. Parameters employed for the techno-economic assessment. Correlation index (r^2), number of data and limits of validity below each correlation were added.

Option to assess	*Item*	*Correlation*	Source
Landfill gas collection	*Landfill gas collector system investment (I)*	$I(€) = 2{,}135\, x^{0.9011} [x, kW_e]$ $r^2=0.871;\ n=6;\ [500\ kW_e;\ 3.9\ MW_e]$	Caresana *et al.* (2011) Willumsen (2012) LGTE (2008) CONEG (1994)
Direct raw gas burning for electricity	*Energy generator investment (I)*	$I(€\, kW_e^{-1}) = 15{,}648\, x^{-0.536} \left[x, kW_e\right]$ $r^2=n.a.;\ n=127;\ [10\ kW_e;\ 2\ MW_e]$	(ASUE 2011)
	Operation and maintenance cost (o&m)	$C_{o\&m}(ct€\, kWh_e^{-1}) = 17.053\, x^{-0.478} \left[x, kW_e\right]$ $r^2=n.a.;\ n=127;\ [10\ kW_e;\ 2\ MW_e]$	(ASUE 2011)
	Average electrical efficiency (η_e)	$\ln(\eta_e) = -0.6563 - 1.5670 \ln(\pi_e)^{-1}$ $r^2=0.7953;\ n=215;\ [7.5\ kW_e;\ 8.92\ MW_e]$	(ASUE 2011)
Waste-to-energy (WTE)	*Investment (I)*	$I(€) = 15{,}797\, x^{0.82} [x, kW_e]$	Gómez *et al.* (2010)
	Annual operation and maintenance cost (o&m)	*4% y^{-1} of investment (I)*	Gómez *et al.* (2010)
	Emission cleaning system investment for BAT	*24% of investment (I)*	Zabaniotou and Giannoulidis (2002)
	Average electrical efficiency (η_e)	*21%*	Burnley et al. (2011)
Biogas-to-BioSNG	*Digester (I)*	$I(€) = 18{,}248 x^{0.8586} [x, Nm^3 h^{-1}]$ $r^2=0.9832;\ n=14;\ [53\ Nm^3_{CH_4} h^{-1},\ 1{,}060\ Nm^3_{CH_4} h^{-1}]$	Urban et al. (2008). Althaus and Urban (2005)
	Annual operation and maintenance cost (o&m) digester	*13% y^{-1} of Investment (I)*	
	Upgrading unit (I)	$I(€) = 83{,}268\, x^{0.4793} [x, Nm^3_{CH_4} h^{-1}]$ $r^2=0.855;\ n=9;\ [152\ Nm^3_{CH_4} h^{-1};\ 1{,}220\ Nm^3_{CH_4} h^{-1}]$	Urban et al. (2008). Althaus and Urban (2005)
	Annual operation and maintenance cost (o&m)	*25% y^{-1} of investment (I)*	Urban et al. (2008). Althaus and Urban (2005)
	Injection into the net (I). 45 bar max. network pressure and 1 km length	$I(€) = 970.5\, x^{0.997} [x, Nm^3_{CH_4} h^{-1}]$ $r^2=0.997;\ n=3;\ [305\ Nm^3_{CH_4} h^{-1};\ 1{,}192\ Nm^3_{CH_4} h^{-1}]$	Urban et al. (2008). Althaus and Urban (2005)
	Annual operation and maintenance cost (o&m) injection	*3% y^{-1} of investment (I)*	Assumed

7. Results

7.1 Municipal Solid Waste Sector

The potential energy that could be derived from municipal solid waste (MSW) in Chile was analysed using the proposed methodological approach based on a techno-economic assessment described in Section 4. Supply-cost curves were used to present and compare the aggregated data for the energy potential and the cost of energy generation. The electricity generation alternatives assessed were landfill gas-to-energy (LGTE) and direct waste-to-energy (WTE) as well as gas collection and upgrading to feed into the grid (LGU). These options were evaluated and subsequently compared using such criteria as the production cost, the technical and economic potential and the challenges for the country in the near future.

7.1.1 Introduction

Municipal solid waste (MSW) generation is a major topic in the management and planning of modern societies. MSW applies pressures to both the environment and the health of the population, steadily accumulating cost for management and potentially detracting from the population's standard of living. Furthermore, the public's greater awareness of environmental matters leads to additional motivation via environmental issues, resulting in demands on authorities for stricter control and environmentally sound strategies for addressing this problem.

Although the hierarchy of landfilling versus incineration as the most effective method to treat MSW is unclear because it depends on local particularities (Dijkgraaf & Vollebergh 2004, 2008; Themelis 2008), there is consensus that recycling offers substantial benefits and must be considered as the starting point of any national MSW policy; this consideration would facilitate the decoupling of the MSW generation rate from economic growth (an aspect particularly relevant for developing countries), the reduction of biodegradable matter deposition and the subsequent uncontrolled emission of such greenhouse gases (GHG) as methane, carbon dioxide, ammonia and other trace compounds. Nonetheless, recycling demands relevant modifications to the habits of a population; for instance, the introduction of well-distributed curb-side services throughout the country (for collection of plastic bottles, glass, paper, etc.), the existence of a formal industry able to recover and process the recycled material and actively coordinated actions among the public entities responsible for household waste.

In Chile, approximately 6.5 millions of tons of MSW were generated in 2008 (Pérez 2010), and, since the System of Environmental Evaluation (SEE) came into force in 1997, the country has made considerable progress in matters of collection, recycling, minimisation and landfilling of MSW. Approximately 60% of the total MSW generated was collected in the municipalities (data from 2008), with a rate of approximately 80% collection in municipalities with populations upwards of 50,000 inhabitants (Machado & Malarín 2007). Furthermore, the country contains an internal market for recycled plastic, cardboard, glass, aluminium and scrap, accounting for 11% in the Metropolitan Region (Bräutigam & González 2012).

Beyond the progress accomplished thus far, significant challenges remain to improving the management of a growing amount of MSW associated with the rising income levels observed in recent decades as well as demographic growth. Modifications of recent sanitary regulations should improve the conditions of final MSW deposition sites.

7.1.2. MSW Management

According to the new laws and regulations in Chile (Willumsen 2005; Decree 189), final deposition sites are classified under three categories: a *sanitary landfill* is defined by such requirements as impermeable liners, leachate collection and lixiviation treatment systems. The second category is a *landfill dump*, which consists of dumps where the MSW is deposited without major technical requirements; these dumps are only allowed to operate under exceptional conditions; this type of deposition site is being eliminated and should be completely gone within the current year. The final category is *illegal dumps,* which, as their name suggests, do not fulfil the established sanitary conditions, and consequently, are illegal to operate.

Methane is continuously released mainly during landfill operation, but it can also extend long after landfill closure; methane generation is uncontrollable because it is produced by the anaerobic microbiological activity within the landfill material. Worldwide methane emissions from landfills are estimated at 35-73 Tg of the total 598 Tg per year (IPPC 2001). Because methane is a greenhouse gas (GHG) with commercial value, a permanent effort has been made to capture and use it as a source of energy (Methane to Markets 2004). Until recently, it has been primarily used for electricity generation and direct heating, and to a lesser degree, as a pipeline gas for injection into distribution networks (Themelis & Ulloa 2007).

An alternative to direct landfilling is the waste-to-energy option (WTE), which was previously known as incineration. This method uses the MSW (with or without sorting) as a fuel to generate energy via a (normally) combined heat and power scheme. The WTE technology has exhibited a noteworthy improvement in performance in recent years, with the integration of enhanced abatement control of pollutants. The U.S. Environmental Protection Agency (EPA) named WTE technology as *one of the cleanest sources of energy* (Psomopoulos, *et al.* 2009) due to the steadily diminishing levels of dioxin, furan, mercury and other heavy metal emissions over the last twenty years. From an international perspective, Taiwan constitutes a unique experience in the field (Kuo, *et al.* 2008) incinerating 53% of its MSW (data from 2008). Close on the heels of Taiwan are Denmark, which incinerates 48% of MSW, Switzerland and Sweden with 49%, the Netherlands at 39% and Germany at 34% (data from 2009) (Eurostat News Release 2011).

Today, there are approximately 39 landfills operating in Chile (data from 2011) (National Service of Environmental Assessment 2012), with an approximate average population of 420,000 inhabitants served per landfill. Fourteen of these landfills have incorporated clean development mechanisms (CDMs) (CGF-MDL 2011) in which collection systems were implemented primarily to flare the released gas. Only one landfill has implemented gas capture to produce electricity, attaining a current generation capacity of 14 MW_e that is projected to reach 28 MW_e by 2024. No application of landfill gas recovery for injection into the country’s natural gas grid exists yet, nor are there any incineration facilities.

The aim of this section is to explore the uses of MSW generated in Chile for energy recovery at the national level via an economic assessment of three energy alternatives based on state-of-the-art technologies and without proposing substantial modifications to MSW collection. The energy options considered in this research, and schematically presented in Figure 7.1.1, are: i) burning of spontaneously generated landfill gas that is captured to produce electricity (LGTE); ii) direct use of unsorted MSW via incineration (WTE); and iii) landfill gas recovery and upgrade for injection into the natural gas grid (LGU).

At a regional level, Amini & Reinhart (2011) evaluated the recovery of landfill gas in Florida (USA) by applying selected modification to the LandGEM model. The modified assessment considered the generation of electricity via direct combustion and an equivalent gaseous fuel, although an economic evaluation of the end-product cost was not incorporated. An alternative approach was discussed by Schneider *et al.* (2012), who proposed an evaluation of the use of landfill gas for electricity production (LGTE), MSW use for refuse-derived fuel (RDF) in the cement industry, landfill gas flaring, waste-to-energy (WTE) (also known as incineration and thermal treatment) and mechanical-biological treatment (MBT). The assessment was conducted by comparing the specific cost reduction for the above-mentioned alternatives. Each conversion route was evaluated for a typical plant size.

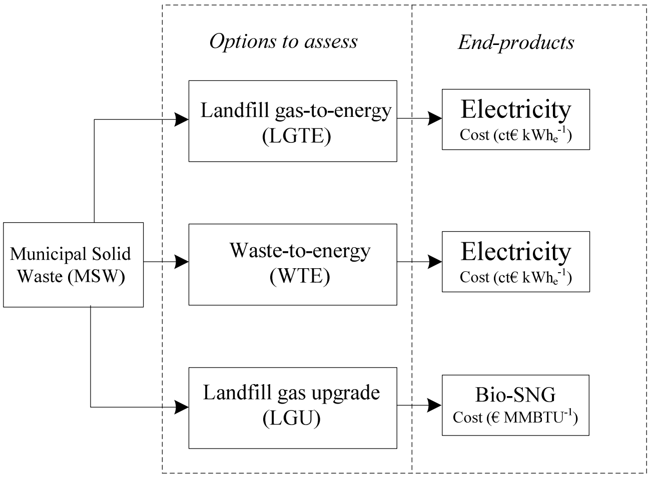

Figure 7.1.1 Energy options for assessment for MSW utilisation.

Although the mechanical-biological treatment (MBT) seemed promising, it was not considered within the scope of the evaluation because this approach requires sorting and other intermediate pre-treatments. Furthermore, from preliminary experience, the MBT performance is highly dependent on the involved mechanical treatment steps and the quality of the raw material, as discussed by Bayard *et al.* (2010). A specific study is needed for assessment of the MBT option at a regional or national level, which can be carried out in follow-up research.

7.1.3. Methodology

The following sub-sections present the methodology applicable to the previously indicated three conversion routes in MSW analysis. It structures the specific economic and technical framework under analysis and allows for the comparison of conversion routes, their potential and the cost of their end products, with a particular focus on the conditions of the conversion option within a market framework.

7.1.3.1 Methodology for the Technical Potential

The estimation of the MSW was carried out for each landfill in operation using technical information published by official government entities and the approximate serviced population, in addition to the composition and characteristics of the MSW (National Service of Environmental Assessment 2012). In the calculation, a specific MSW generation rate per inhabitant (R) was applied to each administrative region. The value of this indicator, shown in Table 7.1.1, is in agreement with the country's economic development. For instance, the U.S. produced 0.733 t $hab^{-1}y^{-1}$ (data from 2008) (EPA 2011); in the European Union this value reaches 0.542 t hab^{-1} y^{-1} (data from 2008) (Waste Oportunities 2011), whereas in urban India this value ranges from 0.50 to 0.70 t $hab^{-1}y^{-1}$ (data from 2008) (Jha, *et al.* 2008).

Table 7.1.1 Specific MSW generation rate in Chile per inhabitant per administrative region (Pérez 2010).

Country region's name	R_j (t $hab^{-1}y^{-1}$)	Country region's name	R_j (t $hab^{-1}y^{-1}$)
Región Arica y Parinacota (XV)	0.59	Región Libertador B. O'Higgins (VI)	0.24
Región de Tarapacá (I)	0.59	Región del Maule (VII)	0.30
Región de Antofagasta (II)	0.34	Región del Biobío (VIII)	0.29
Región de Atacama (III)	0.37	Región de la Araucanía (IX)	0.34
Región de Coquimbo (IV)	0.22	Región de los Lagos (X)	0.32
Región de Valparaíso (V)	0.34	Región de Aysén (XI)	0.39
Región Metropolitana (XIII)	0.42	Región de Magallanes (XII)	0.39
		Región de los Ríos (XIV)	0.36

Although the specific MSW generation rate depends on the socioeconomic level of the population as well as its consumption habits, this rate was assumed as constant for each administrative region and simply adjusted to the year of evaluation (2011) by assuming a linear proportionality with an expected annual economic growth rate of 6.3% for 2011 (Financial News 2012[c]).

The main components of landfill gas are methane (40%-60%), carbon dioxide (35%-50%), nitrogen (0%-20%), oxygen (0%-1%), hydrogen sulphide (50-200 ppm) and ammonia (5 ppm, typically) (Rasi, *et al.* 2011). The organic silicon compound concentration in landfill gas is particularly high (Dewil, *et al.* 2006), ranging from 3 to 24 mg Nm^{-3} (Ajhar, *et al.* 2010). Numerous volatile organics (VOC), aromatics and halogenated compounds are present, and in certain cases, more than one hundred trace compounds have been reported. This complexity is a consequence of the heterogeneity of the residues and the uncontrolled conditions under which a landfill operates. The generation rate of landfill gas additionally depends on local conditions and seasonal variations (i.e. humidity, temperature, rainfall) as well as the type of landfill operation and how the MSW is deposited. Furthermore, the gas release is intrinsically related to the opening and closing times. There are numerous models available to estimate the landfill gas emitted on a temporal basis although significant differences between cases are generally observed in the predictions (Thompson, *et al.* 2009; Ritzkowski & Stegmann 2007; Meraz, *et al.* 2004; EPA 2005).

According to Themis *et al.* (2007), the capture of landfill gas (M), expressed as pure methane, is in the 100-150 $\mathrm{Nm}^3_{\mathrm{CH_4}}\mathrm{t}^{-1}$ range and depends on the way in which the gas is collected (i.e. whether it uses a passive venting or active collection system, vertical wells or horizontal gas collection trenches, etc.). Thus, a conservative estimate of 50 $\mathrm{Nm}^3_{\mathrm{CH_4}}\mathrm{t}^{-1}$ from placed MSW was employed for the methane generation rate from a landfill, following the recommendations given by the same author. Therefore, the gas flow, expressed as pure methane that can be technically recovered and upgraded is calculated as indicated in Equation 7.1.1.

$$\pi_{t,i}^{LGU} = M\ R_j\ P_i \qquad \text{Equation 7.1.1}$$

In which $\pi_{t,i}^{LGU}$ is the methane technically recovered from the *i*th-landfill, *P* is the population serviced (hab) at the *i*th-landfill, R_j is the MSW generation rate per capita (t $\mathrm{hab}^{-1}\mathrm{y}^{-1}$) of the *j*th-administrative region and *M* is the methane-landfill gas recovered per unit of landfilled MSW ($\mathrm{Nm}^3_{\mathrm{CH_4}}\mathrm{t}^{-1}$). The technical potential of the electricity generated by burning the landfill gas can be calculated as indicated in Equation 7.1.2.

$$\pi_{t,i}^{LGTE} = M\ R_j\ P_i\ \Delta\tilde{H}_{LHV}^{CH_4}\ \eta_e \qquad \text{Equation 7.1.2}$$

In which η_e corresponds to the electrical efficiency of the conversion units, $\Delta H_{LHV}^{CH_4}$ is the lower heating value of methane estimated as 50,000 kJ kg^{-1} (Avallone, *et al.* 2007), and equivalent to approximately $31.59\ \mathrm{Nm}^3_{\mathrm{CH_4}}\ \mathrm{MMBTU}^{-1}$. If reciprocating engines are sufficient for the power range of the landfills under analysis, this equipment will be used as a reference technology in the assessment for the conversion of the landfill gas to electricity presented in the forthcoming section.

Regarding the composition and the corresponding humidity for the sorted components, Table 7.1.2 shows the MSW characteristics in the XIII Region (also called the Metropolitan Region) (Bräutigam & González 2012), which was taken as representative for the entire country due to the lack of more specific information.

Table 7.1.2. Composition, humidity and lower heating value (dry) of MSW components.

MSW Component	MSW composition as received (%)	Estimated humidity (%) (wet basis)	LHV (kJ kg^{-1})
Paper and cardboard	10.7	0.5	10,000
Fabrics	3.5	1.0	12,500
Plastics	10.8	1.5	28,000
Glass	6.3	0	0
Metals	3.2	0	0
Organic matter	49.4	29.5	3,300
Miscellaneous components	16.1	0	14,300
Dust-ash	1.2	0	0

Considering the lower heating value of each component (Finet 1987) and its humidity (Bräutigam & González 2012), an average heat of combustion (LHV) of 7,930 MJ t^{-1} for a homogenous fuel is estimated for this MSW; this value is then used for the estimation of the technical potential on a thermal basis, as Equation 7.1.3 indicates. The electrical potential of burning the MSW without sorting (WTE) is then calculated by considering an electrical efficiency (η_e) of 21% (Burnley, *et al.* 2011).

$$\pi_{t,i}^{WTE} = \Delta\tilde{H}_{LHV}^{MSW} \; R_j \; P_i \; \eta_e \qquad \text{Equation 7.1.3}$$

The technical potential of the entire country, either for the electricity or gas evaluation route, can be calculated as the sum of all single technical potentials on the *nth*-landfills and for each conversion pathway, as shown in Equation 7.1.4.

$$\Pi_t^{LGTE} = \sum_{i=1}^{n} \pi_{t,i}^{LGTE} \qquad \Pi_t^{WTE} = \sum_{i=1}^{n} \pi_{t,i}^{WTE} \qquad \Pi_t^{LGU} = \sum_{i=1}^{n} \pi_{t,i}^{LGU} \qquad \text{Equation 7.1.4}$$

7.1.3.2 Methodology for the Economic Modelling

The unitary cost of electricity or upgraded gas generated from each landfill is calculated according to Equation 7.1.5.

$$c_i \pi_{t,i} = \alpha I_i + C_{o\&m,i} - R_i \qquad \text{Equation 7.1.5}$$

In which c_i is the unitary cost of secondary energy, either for the landfill gas-to-energy (LGTE), waste-to-energy (WTE) option, or landfill gas upgrade (LGU) alternative. The parameter α is the capital recovery factor, calculated with an annual interest rate of 10% and a fifteen-year lifetime for all cases. The annual operation and maintenance cost, $C_{o\&m}$, was estimated as a fraction of the investment, a methodology based on mathematical regressions of economic data published elsewhere and an approach used in pre-feasibility studies and economic analysis (Chauvel, *et al.* 2003; Couper 2003). A location factor of 1.08 was included as the investment for the country; this factor mainly addresses the additional cost for freight, taxes and insurance (Chauvel, *et al.* 2003). The value of R_i corresponds to revenues, which may be incorporated as heat generated for sale or re-use of any by-product. Because Chile does not have a district heating market, revenues were not incorporated (OECD-B 2012). Detailed information of the methodology and technical and economic information is given in Chapter 4 and Chapter 6.

Landfill gas extraction is the first step of the recovery. The collection system contains a set of extraction wells that are normally located at selected depth intervals and share a common collection point by means of a pipe network. Afterwards, the gas is normally desulphurised by a conventional activated carbon system and then burned to produce electricity, as previously mentioned. On the other hand, in the WTE option, the MSW is combusted at high temperature (above 800°C), and the heat generated is then used in a steam power generation cycle to produce electricity. The current development status of WTE technologies may allow its use without creation of dioxin pollution (Cheng & Hu 2010; Zhiqiang, *et al.*; 2006; Montejo, *et al.* 2011). WTE is an advanced technology characterised by a heavy investment and high operating cost and is appropriate in most cases when landfilling is unfeasible (Rand, *et al*. 1999; Rand, *et al*. 2000) The main solid residue is ash, and its generation rate depends on the MSW composition. This residue could be used as a by-product in construction applications but a large fraction must be landfilled. The final ash deposition cost (transportation included) for this assessment was estimated at 16 € t^{-1} (Willumsen 2005).

The third energy alternative for evaluation corresponds to the generation of a gaseous fuel by treatment of the landfill gas. The product was defined as a bio-substitute natural gas (Bio-SNG) because it fulfils the definition of originating from biomass digestion and has the capacity for subsequent improvement and adjustment of properties for injection into the net distribution or for use as a fuel for vehicles (Steifer 2009).

In a simplified representation, the treatment of landfill gas to produce high-quality pipeline gaseous fuel can be split into the steps of collection, cleaning, upgrading and feed-in, as analogously described in Chapter 5. Normally, in the cleaning step, hydrogen sulphide and other sulphur compounds are removed through a conventional active carbon adsorption, alone or in combination with chilling systems (Urban, *et al.* 2009). The next step contains the most expensive unit in this chain in which carbon dioxide is uptaken by a technology such as pressure swing absorption (PSA), pressure water wash (PWW) (Läntela, *et al.* 2012), or amino-chemical absorption (Gaur, *et al.* 2012). In addition to carbon dioxide removal, the simultaneous elimination of ammonia take places as well as sulphur, halogenated and silicon compounds; in most cases, these two steps are sufficient to satisfy the most relevant gas injection requirements. Although there are differences in the cost of carbon dioxide uptake between the previously mentioned technologies, these differences intrinsically depend on utility prices (i.e. electricity, cooling water, labour, etc.) and landfill gas flow to be treated. Nevertheless, for this study, no differences in the upgrade technology investments and operating cost are assumed, such that a unique mathematical relation can correlate them, as discussed in previous chapters.

Economic information from the literature and other technical reports was gathered for the estimation of the investment and total the operation cost for landfill gas collection systems (see Chapter 4), waste-to-energy facilities (Gómez, *et al.* 2010; Zabaniotou & Giannoulidis 2002), upgrade units and gas injection systems for feeding into the natural gas grid (Althaus & Urban 2005; Urban, *et al.* 2005) as well as for reciprocating engines for electricity generation (ASUE 2011). The value of 0.22 $\text{ct€}\,\text{Nm}^{-3}_{\text{CH}_4}$ was used for the desulphurisation cost, according to Mescia *et al.* (2011). Table 6.1 summarises the economic information related to the investment and to operation and maintenance cost as well as key technical figures such as the conversion efficiency of each technological pathway to be assessed, i.e., collection of landfill gas and its posterior direct burning in a reciprocating engine (LGTE), waste-to-energy (WTE) and the collection of landfill gas and follow-up upgrade to feed-in (LGU). This information was subsequently incorporated into the economic model defined in Equation 7.1.5. In each case, the representative generation cost and the economic potential were calculated as described in the following section.

7.1.3.3 Methodology for the Economic Potential

For the three energy alternatives proposed, supply-cost curves were used to conduct the potential analysis with selected adaptations made for the purposes of this study as previously mentioned in chapter 4 *Methodology for the Potential Analysis at National Level*. The supply-cost curve was built for each conversion route, i.e. LGTE, WTE and LGU, by assessing the unitary cost for each single potential $\pi_{t,i}$. The representative generation cost is then expressed as the most frequent cost and mathematically calculated in the statistical mode as follows:

$$c_r = \text{mode}[c_i(\pi_{t,i})] \qquad \text{Equation 7.1.6}$$

After calculating the representative generation cost, the economic potential of the technology can be estimated by interpolation with the supply axes. Therefore, the economic potential can be interpreted as the total amount of energy that can be generated at a cost lower than the representative generation cost. The comparison between the representative generation cost (c_r) for each secondary energy, either gaseous fuel or electricity, with its average market price is performed to discuss the economic cost effectiveness of each assessed option and to identify the need for subsidies if the process is not economically competitive.

Finally, the information is integrated into a geographical information system (GIS), in which the energy potential map can be visualised with the *county* as the smallest geo-administrative control area for each of the regions composing the country.

7.1.4. Results

Figures 7.1.2 and 7.1.3 display the supply-cost curves for electricity generation through the collection and burning of landfill gas (LGTE) and by waste-to-energy (WTE) without sorting. The former option exhibits a technical potential of approximately 1.1 $TWh_e\ y^{-1}$ with a representative generation cost of 11.0 ct€ kWh_e^{-1}, whereas the latter offers a technical electrical potential of approximately 2.2 $TWh_e\ y^{-1}$ and a representative generation cost of electricity of 10.6 ct€ kWh_e^{-1}.

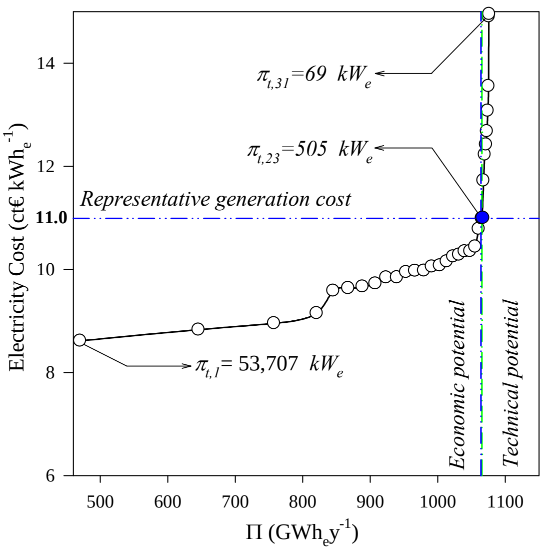

Figure 7.1.2. Supply-cost curve for landfill gas-to-energy option (LGTE).

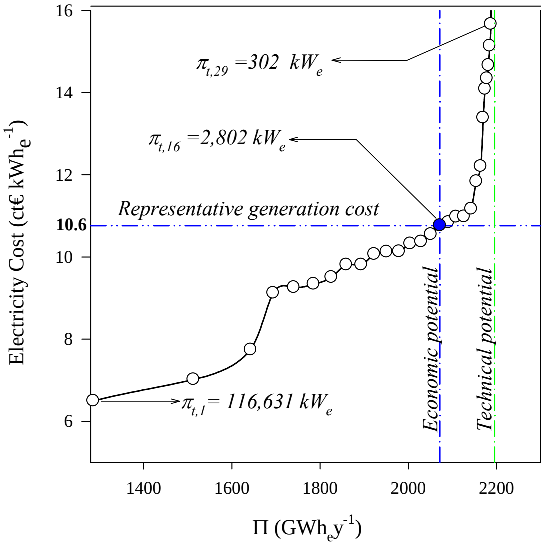

Figure 7.1.3 Supply-cost curve for waste-to-energy option (WTE).

The technical and economic potential of the LGTE option are practically identical (see Figure 7.1.2); therefore, it is made of the 23 largest landfills in operation. On the other hand, as Figures 7.1.3 shows, the economic potential of the WTE option is approximately 95% of the technical potential and can be supplied by the MSW currently disposed of in the 16 largest landfills.

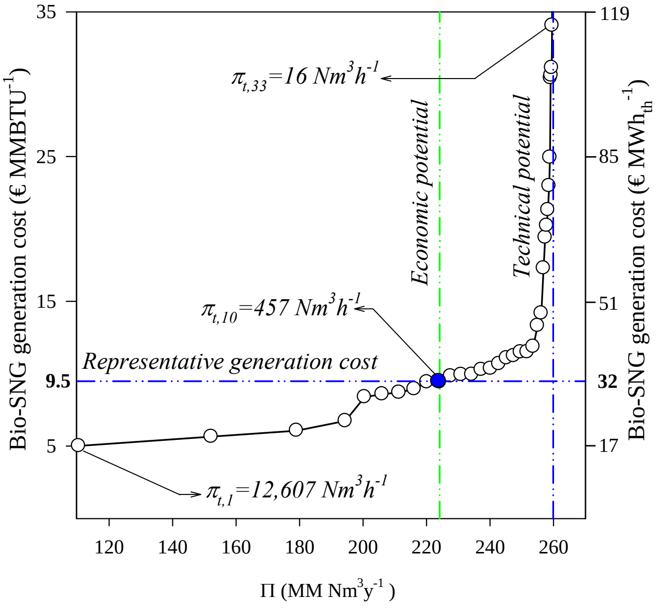

Figure 7.1.4. Supply-cost curve for landfill gas upgrade option (LGU).

The third energy alternative involves the collection of landfill gas released under uncontrolled conditions and the subsequent upgrades required for injection into the natural gas grid. Due to the difference between the forms of secondary energy generated in the two previous alternatives, the figure was also expressed in millions of British Thermal Units (MMBTU), the unit commonly used in official energy statistics of LNG and natural gas prices (BP 2013). For the totality of landfill gas under evaluation, the representative cost of the upgraded gas is 9.5 € $MMBTU^{-1}$ with a technical potential of 260 MM $Nm^3\ y^{-1}$. The economic potential is approximately 86% of the technical potential and can be supplied by the 10 largest landfills in operation.

Table 7.1.3. Energy potential of the three assessed options for MSW utilisation.

	Alternative of energy generation from MSW		
Economic Indicator	Landfill gas-to-energy (LGTE)	Waste-to-energy (WTE)	Landfill gas-to-upgrade (LGU)
Technical potential	1.1 $TWh_e\ y^{-1}$	2.2 $TWh_e\ y^{-1}$	260 MM $Nm^3\ y^{-1}$
Economic potential	1.1 $TWh_e\ y^{-1}$	2.1 $TWh_e\ y^{-1}$	224 MM $Nm^3\ y^{-1}$
Minimum cost of production	5.4 ct€ kWh_e^{-1}	8.6 ct€ kWh_e^{-1}	5.0 € $MMBTU^{-1}$
Representative cost	11.0 ct€ kWh_e^{-1}	10.6 ct€ kWh_e^{-1}	9.5 € $MMBTU^{-1}$

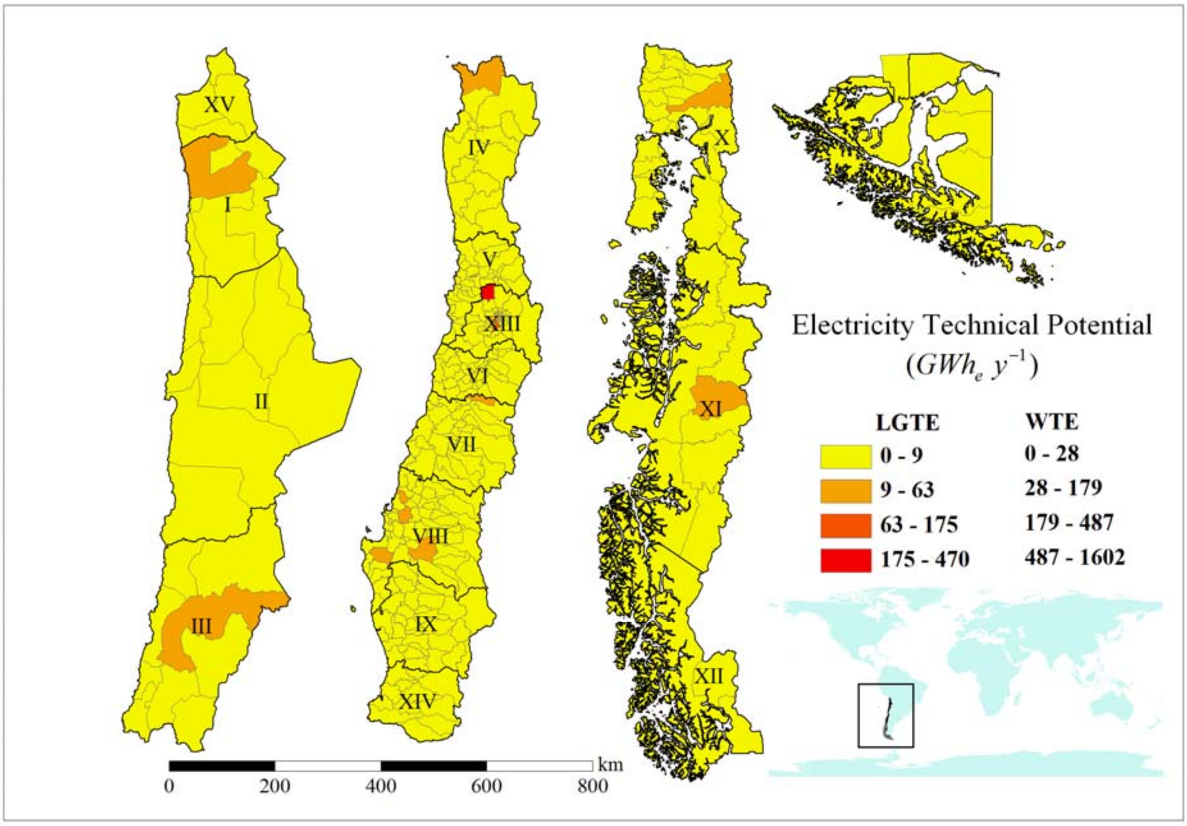

Figure 7.1.5. Electricity technical potential from landfill gas-to-energy (LGTE) and waste-to-energy (WTE) options.

As shown in Figures 7.1.5 and 7.1.6, the technical potential for the three assessed options are concentrated in certain municipalities in the XIII Region (Metropolitan Region), accounting for 67% of the total energy potentially available from the MSW in the most populated area of Chile. On the other hand, a significantly lower energy potential is observed in the rest of the country, which is explained not only by the lower population density but also by the construction of small-scale landfills.

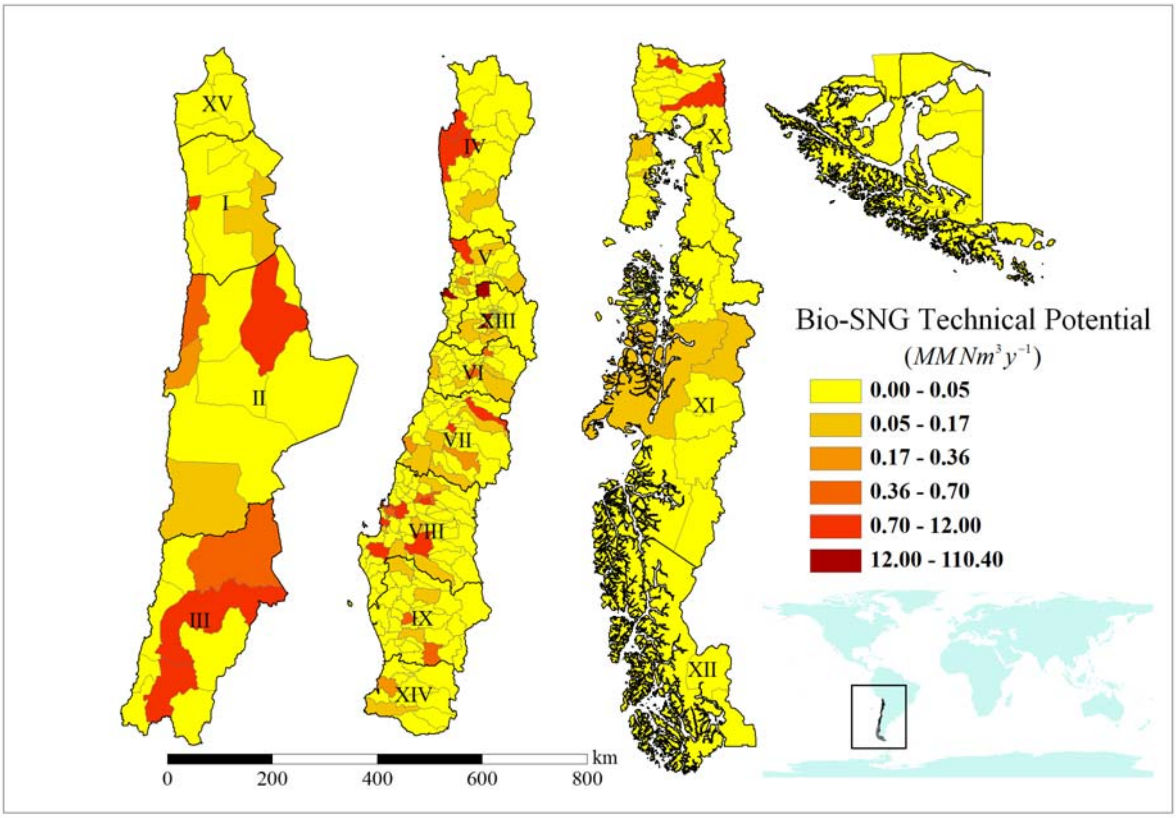

Figure 7.1.6. Bio-SNG technical potential from landfill gas upgrade option (LGU).

7.1.5. Discussions

During 2010, the average industrial and commercial electricity prices for the country reached 10.4 ct€ kWh_e^{-1} and 16.8 ct€ kWh_e^{-1}, respectively (OLADE 2011), and these prices have experienced a steady increase in recent years. In this context, considering the electricity generation cost for the LGTE and WTE options mentioned previously, both options are nearly economically profitable, at least on a pre-feasibility level, if only the cost of production is considered as the most relevant economic indicator.

Despite the fact that the end products from both the LGTE and WTE options are electricity, the difference in the cost and potential can be explained as a consequence of the different technologies used in the conversion process, which implies a substantial difference in investment and operating cost as well as in the efficiencies and environmental implications.

All of these factors have an impact on the economic potential, which have a ratio of approximately 1:2 for this case.

Similarly, the natural gas price has been increasing in recent years and reached a distribution price of approximately 15-22 € $MMBTU^{-1}$ (data from 2011); thus, the cost of production for Bio-SNG would be competitive at 9.5 € $MMBTU^{-1}$, and this option would not require subsidies to become economically attractive for the 10 landfills that comprise the economic potential. The injection of Bio-SNG is an alternative that takes advantage of the benefits of transportation across the natural grid; however, its use as a vehicle fuel may have a significant chance at commercial implementation when it is considered for particular applications e.g., compressed methane as a fuel for garbage and cleaning trucks, with filling stations located near the landfill and upgrading plant where it is compulsory for the trucks to arrive and depart. This option offers a realistic starting point for a commercial application without coming up against fuel distribution for private transportation in which fuel supply plays a highly relevant role.

Although the largest energy potential lies in the WTE option, which represents approximately 3.7% of the total national electricity consumption[1] (National Commission of Energy 2010), according to international experience the major inconvenience of this technology rests on its social acceptance. Furthermore, a national effort focusing on MSW recycling should be implemented before the introduction of WTE technologies despite the favourable current market condition of electricity prices in the long-term. Although there have been notable achievements in recycling and MSW landfilling in Chile, these efforts remain modest when compared with countries where WTE has been successfully introduced as a part of a national MSW strategy in which recycling plays a pivotal role.

7.1.6. Preliminary Conclusions

Using a comparative analysis, the main differences in the cost and potential uses of MSW for energy generation were assessed at a national level. For the LGTE and WTE alternatives, the difference between the economic potential is a factor of two, with a slightly lower cost of electricity generation in the former case. For landfill gas upgrade to feed-in (LGU), the economic potential of the entire country reaches a scale that may allow for the implementation of recovery systems with upgrade to a commercial size.

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[1] 56.05 TWh_e of electricity consumption for 2009 (National Commission of Energy 2010).

The results suggest that a combined implementation of the production of high quality pipe-gas and electricity would be the most satisfactory practice because the Bio-SNG option is only competitive for the largest 10 landfills, accounting for 25% of the total landfills in operation and exhibiting a high sensitivity to the cost of generation. A significant number of landfills are inadequately suited for the implementation of any of the three energy recovery systems evaluated because of their scale. The results support the fact that the main difficulty lies in the existence of landfills that cannot profit from economies of scale at the range in which energy recovery systems operate economically, most significantly affecting those landfills that serve regions with lower population densities. This difficulty could be overcome if waste transfer stations were set up for regions with low populations, such that fewer but larger landfills could operate at a higher capacity, and, consequently, under conditions that are more advantageous for energy recovery. However, this option entails coordinated and cooperative actions between municipalities that have historically faced the problem of waste management independently instead of looking for cooperative solutions.

These results must be considered as a basic framework that can orient the decision-making process or the implementation of environmental policies either in the short or long term. Other aspects that will become more important in the long-term must be taken into consideration in further research such as environmental impacts or public acceptance of MSW processing technologies as well as the incorporation of incentives for recycling and the sorting of organic fractions of the MSW, tax-cuts for recovered methane for use as a transportation fuel and the impact of these efforts in the strategy of using MSW as an alternative source of energy.

7.2. Wastewater Treatment Sector

In this section, the energy that can potentially be obtained from the digestion of sludge generated from wastewater treatment processing (WwT) was calculated using the proposed methodology. The different pathways of electricity generation via the direct combustion of biogas and upgraded biogas produced as bio-substitute natural gas (Bio-SNG) for injection into the gas grid were assessed and compared. Information such as the population served, WwT technology employed and geographical distribution of the sludge sources was gathered to estimate energy potential.

In contrast with the previously assessed sector, municipal solid waste (MSW), either electricity or Bio-SNG from WwTP sludge processing would necessitate subsidisation to become economically attractive. To illustrate the procedure for the calculation, this chapter will act as a test case for the other sectors to be evaluated in this thesis (i.e. livestock farming, agricultural and co-digestion).

7.2.1 Introduction

The supply of water and sanitation services constitutes an indispensable requirement for the protection of public health, maintenance of basic living conditions, and the protection of biota and natural resources. Although the advances made in wastewater treatment technologies over last decades have been outstanding, the universalisation of water and sanitation services remains a major challenge for the 21st century (Castro, *et al.* 2009).

Under a modern perspective, a centralised municipal wastewater treatment (WwT) programme was set up in Chile thanks to a large-scale water reform policy started in the late 1990s, leading to the privatisation of this service sector which was previously managed integrally by the state. In parallel to this restructuring, the development of emissions standards for municipal sewage discharge was introduced when the General Environmental Law (1997) came into effect with the consequent obligation for water supply companies to treat polluted water after discharging it into the surface-water environment for the purposes of preserving biota, avoiding the detrimental effects, improving the value of touristic sites and protecting human health. According to the World’s Water Report (2008), Chile has 922 billion cubic meters of total renewable freshwater. Furthermore, 87% of the urban population was connected to wastewater treatment plants (WwTPs) by 2010 (Water Supply Superintendence

2012), a share that is in line with OECD countries (European Environment Agency 2011 2011); this figure is expected to reach 98% and then 99% by the present year (2013) and 2015, respectively (see Figure 7.2.1).

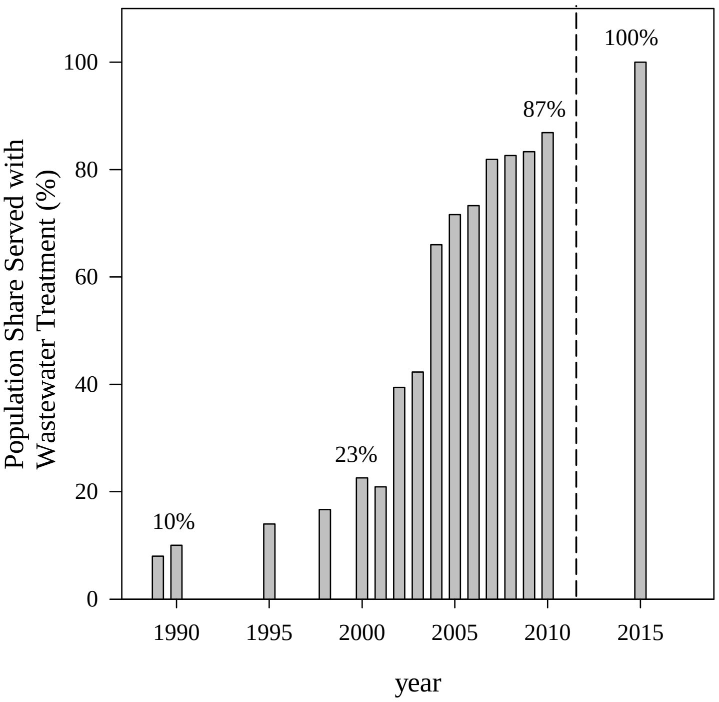

Figure 7.2.1. Share of population served by public wastewater treatment facilities in Chile 1990-2010 and projection for 2015. Water Supply Superintendence (2012).

WwT is a set of physicochemical processes employed to remove pollutants, which can be physical, chemical or biological substances. WwT is normally divided into primary, secondary and tertiary treatment and selected according to the environmental regulations that the treated water must comply with. Whereas primary systems (also know as mechanical treatments) entail the removal of suspended solids, floating materials and scum from raw sewage, commonly by sedimentation or flotation, secondary treatments (also known as biological treatments) aim to remove dissolved organic matter by anaerobic or aerobic biochemical processes. In tertiary systems (also called advanced treatments), the organic matter remaining after secondary treatment is removed, along with phosphorous and nitrogen, to control nutrient levels. Finally, disinfection may be conducted to meet the standards of effluent regulations.

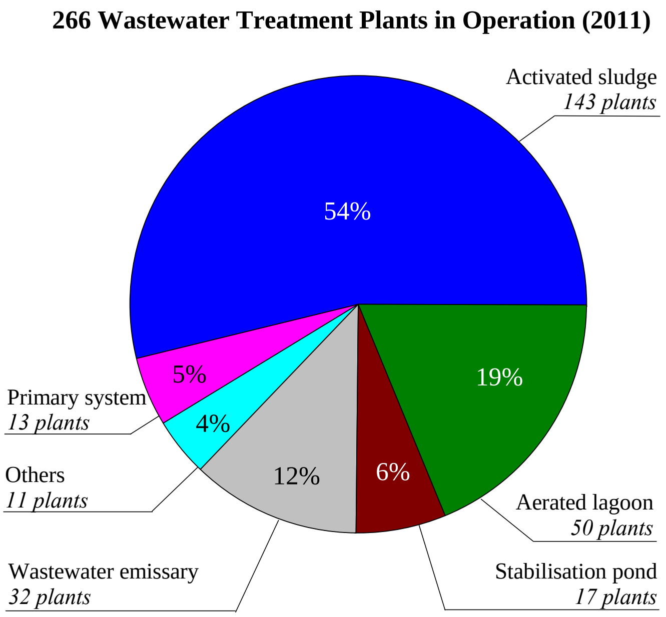

Figure 7.2.2. Wastewater treatment technologies used in Chile.
Water Supply Superintendence (2012).

As Figure 7.2.2 shows, the most common primary treatment technology employed in the country is sedimentation, which comprises 5% of the total. In particular cases, it is followed by disinfection, and this two-step treatment is sufficient to meet the environmental regulations. The most heavily employed system of secondary treatment is activated sludge, which includes conventional activated sludge (CAS), extended aeration, oxidation ditch or sequential batch reactors and makes up 54% of the total technology employed. The stabilisation pond is the second most commonly used technology in secondary treatment at 6% of the total and entails wastewater treatment of large surfaces, with or without aeration. Of the total number of WwTPs, the remaining 12% are wastewater emissary, which collect wastewater and then dispose of it in the ocean. The introduction of a tertiary system is practically nonexistent, mainly as a consequence of current environmental observances.

7.2.2. WwTP Sludge Management

In spite of the advantages in WwT, processing inevitability generates sludge at a significant rate, creating a new environmental problem to deal with (Athanasoulia, *et al.* 2012). Although sludge has been traditionally handled as a waste management problem (WMP) in most EU countries, sludge landfilling has gradually decreased as the trend of reusing it as fuel has gained value (Kalderis, *et al.* 2010). The same tendency can be observed in Chile, where sludge landfilling has faced increasingly strict regulations with which to comply (Decree 4;

Decree 189). In addition, prior to transportation and final disposal, which involve total cost of $60\ €\ t^{-1}_{FM}$ roughly, the sludge necessarily requires pre-treatment. This pre-treatment typically include mechanical dewatering and thickening, operations that demand energy as well as consumable chemicals, and, consequently, increases the cost of wastewater treatment (Coffey 2009). These new conditions are indirectly forcing WwTP operators to seek new cost-competitive options. Additionally, the environmental framework previously discussed coupled with an increase in the cost of energy could become an additional driving force for sludge “residues” to become “by-products”, useful as a raw material for energy generation, with a trade price that might reflect market competition.

In this new environmental and economic scenario, anaerobic digestion could significantly contribute to solving the situation previously described. The main product from the anaerobic digestion of WwTP sludge is biogas composed mainly of methane (40-75%) and carbon dioxide (15-60%). As previously described, biogas can be used either to generate electricity through combustion or to produce an upgraded gas with the option to use it as vehicle fuel, or for injection into the existing natural gas network. Besides, biogas generation via anaerobic digestion offers the chance to stabilise and considerably reduce the volume of WwTP sludge by generating a by-product that may be sold as a bio-fertiliser, consequently improving the economics of the entire process. The body of evidence indicates that biogas generation as a *waste-to-energy* strategy to deal with the sludge generation problem can be considered an economic, environmentally friendly and decentralised solution. Concerning the biogas for electricity or gaseous biofuel generation option, it has particularities that must be analysed on a case-by-case basis in order to identify the most attractive option from an economic, environmental and socio-political standpoint.

In the biogas-to-energy pathway, the direct production of electricity from the biogas combustion, a CHP scheme seems to be the most suitable option (Jiri 2010). A decentralised gas-engine CHP is a robust, state-of-the-art technology encouraged as a means to reduce CO_2 emissions. Alternatively, raw biogas can be treated to produce a gaseous energy carrier, the so-called bio-substitute natural gas (Bio-SNG), with the same standards as commercial natural gas (Seifert 2009). The main advantages of this option are associated with a high transportation efficiency and the possibility of using the existing distribution infrastructure without the need to adapt or substantially modify it. To attain this, biogas conditioning can be carried out via a subsequent set of unitary operations such as desulphurisation, drying, siloxane removal, carbon dioxide uptake and the adjustment of calorimetric properties and injection, as previously described.

With an orientation towards a *waste-to-energy* strategy, Chile has already started producing biogas at large scale from WwTPs. In a pioneer project performed by the gas distribution company Metrogás, sludge generated in La Farfana WwTP is used as a substrate for anaerobic digestion. This is one of the world's largest WwTPs (Halcrow 2013), processing the municipal wastewater of approximately 3.6 million inhabitants via a CAS. An estimated biogas generation rate of 24 MM Nm^3 y^{-1} with 63% methane is transported through a 16 km pipeline to a town gas facility after it has been upgraded through cleaning and carbon dioxide removal. Afterwards, it is treated catalytically to increase its hydrogen content. This new town gas is then injected into the gas grid and distributed for residential consumption (Nelson 2010). This waste-to-energy system is a prime example of how integrating processes produce a gaseous energy carrier with commercial value, and, simultaneously, solve an environmental problem without relying on subsidies.

Despite the example mentioned above, there is still a lack of reliable information on biogas potential in regard to WwTPs. Furthermore, the increase in the price of both electricity and natural gas, and the WwTP scale opens the discussion as to which alternative is the most appropriate, biogas-to-energy or the biogas-to-upgrade pathway. Although in principle both options offer well-known advantages, at the moment there is no assessment that provides sufficient evidence through cross-assessment comparison to make a well-educated decision.

Although on an international level, Poeschl *et al.* (2010) indicated that the annual useful biogas energy potential in Germany is 18PJ from WwTPs, and highlights that only 10% of the global potential for biogas is utilised, the theoretical and technical potential are not explicitly identified nor is the economic potential assessed at the regional level. Rao *et al.* (2010) estimated the biogas generation potential in India based on statistical data, putting special attention on residue. According to the authors, sludge from WwTPs is available in large quantities, however, it is not included in the assessment. Lantz *et al.* (2007) indicated that 60% (3PJ y^{-1}) of Swedish biogas production takes place in WwTPs with a total potential of 3.6 PJ y^{-1}. Gómez *et al.* (2010) evaluated the potential and electricity generation cost in Spain by burning biogas generated via wastewater sludge digestion, assuming the capacity for WwTPs and wastewater treatment technology. The assessment was then incorporated into a

GIS to detect areas with a high electricity potential. An analysis of upgraded biogas for injection was not included in the study.

7.2.3 Methodology

The analysis of the potential for biogas generation was conducted by applying the sequential limits as defined in chapter 4. These boundaries were delineated as physical limit, geographical limit, technical limit and economic limit, according to the definition propounded by Hoogwijk (2004, 2005) and Izquierdo *et al.* (2010). Each limit implied restrictions used to estimate the economic use of biogas.

Supply-cost curves (Izquierdo, *et al.* 2010) were built for the two assessed alternatives. In each case, the whole process chain was considered, starting with the generation of sludge in situ and ending with the production of secondary energy under conditions to be utilised. In both cases, electricity and Bio-SNG, the representative generation cost for secondary energy was estimated and then employed as a simple cut-off criterion to interpolate the economic potential.

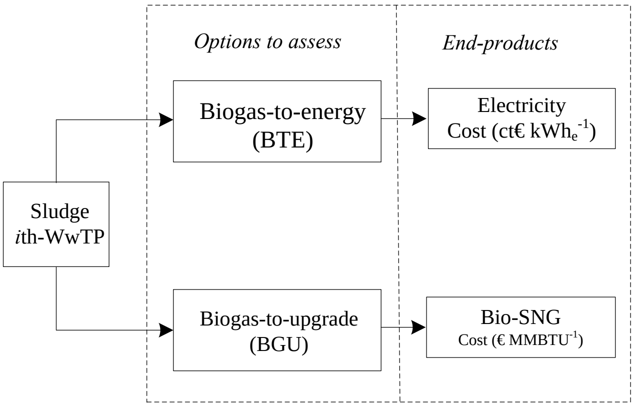

Figure 7.2.3. Conversion pathways to assess for the utilisation of wastewater treatment sludge for the production of either electricity or Bio-SNG through mono digestion.

Economic and technical information such as investment and operational and maintenance cost (O&M) were drawn on from technical reports available elsewhere (see Chapter 6). Moreover, the cost-generation curve for electricity generation was constructed by considering electricity produced via a CHP module with a reciprocating engine because this technology is more suitable for electricity in the low power generation range, which the electrical potential in WwTPs is expected to be. A closing discussion about the implementation of a feed-in tariff system was considered to assess its relevance in the enhancement of this bio-energy option.

7.2.3.1 Methodology for the Technical Potential

- ***Physical Limit***

Also know as theoretical potential, the physical limit is the upper limit of the primary energy calculated without imposing any kind of restriction, thus corresponding to all available primary energy in the biomass (i.e. total sludge) and can be estimated by applying the following equation:

$$\pi_{f,i} = P_i \, R \, S_j \, M_j \qquad \text{Equation 7.2.1}$$

In which P_i represents the population served by the ith-WwTP (hab); $R\,(\mathrm{kg_{ts}\ hab^{-1}\ y^{-1}})$ corresponds to the sludge generation rate per inhabitant; $S_j\ (\mathrm{kg_{vs}\ kg_{ts}^{-1}})$ is the volatile-to-total solid ratio of primary or secondary sludge $(j = 1, 2)$; $M_j\ (\mathrm{Nm^3_{CH_4}\ kg^{-1}_{vs}})$ is the yield of methane generation from the mono-digestion of sludge. The parameters used to make the calculation correspond with average data obtained from literature, as Table 7.2.1 indicates.

Table 7.2.1. Parameters employed for the calculation of biogas potentials from WwTPs.

Parameter	Symbol	Unit	Value	References
Population served by *i*-WwTP	P_i	hab	National statistics	(a)
Average sludge production rate	R	$\mathrm{kg_{ts}\ hab^{-1}y^{-1}}$	22.20	(b)-(f)
Volatile-to-total solid ratio in primary sludge	S_1	$\mathrm{kg_{vs}\ kg_{ts}^{-1}}$	0.571	(g)
Volatile-to-total solid ratio in secondary sludge	S_2	$\mathrm{kg_{vs}\ kg_{ts}^{-1}}$	0.642	(h)-(j)
Methane yield from primary sludge	M_1	$\mathrm{Nm^3_{CH_4}\ kg^{-1}_{vs}}$	0.271	(g), (k)
Methane yield from secondary sludge	M_2	$\mathrm{Nm^3_{CH_4}\ kg^{-1}_{vs}}$	0.220	(h), (j)-(l)
Influent organic matter-to-sludge ratio in primary system	τ_1	$\mathrm{kg_{ts}\ kg_{ts}^{-1}}$	0.750	(m)
Influent organic matter-to-sludge ratio in secondary system	τ_2	$\mathrm{kg_{ts}\ kg_{ts}^{-1}}$	1.00	(n)-(o)
Conversion efficiency of Bio-SNG generation	η_c	%	98.0	(p)

(a) (WSS 2012), (b) Osorio & Torres (2009), (c) Marxsen (2001), (d) Lundin *et al.* (2004), (e) Jensen & Jepsen (2005), (f) Fytili & Zabaniotou (2008), (g) Kepp & Solheim (2012), (h) Luostarinen *et al.* (2009), (i) Bougrier *et al.* (2006), (j) Davidsson (2008), (k) Gavala *et al.* (2003), (l) Qiao *et al.* (2011), (m) Zaror (2000), (n) Lin (2007), (o) Uggetti *et al.* (2011), (p) Pettersson & Wellinger (2009).

- ***Geographical Limit***

Also known as geographical potential, geographical limit constrains the potential because of legal considerations, urban regulations or limitations imposed by the geography, such as the inability to collect biomass due to geographical features. As previously indicated, 266 plants are under operation and use conventional activated sludge (CAS) technology, primary systems and sequential bioreactors, and they generate sludge that may be used for biogas generation as well as aerated lagoon, lagooning, and oxidation ditch. On the other hand, a wastewater emissary does not generate sludge, so the wastewater stream empties directly into the sea at a safe distance from the coastline. Thus, the geographic restriction is defined as follows, with a new constraint applied to the physical limit:

$$\pi_{g,i} = P_i \; R \; S_j M_j A_{g,i} = \pi_{t,i} A_{g,i} \qquad \text{Equation 7.2.2}$$

The geographical restriction $A_{g,i}$ is equal to one for all cases, except for wastewater emissary where it takes the value of zero.

- ***Technical Limit***

The technical limit represents the theoretical outer limit of secondary energy available, without any regard for cost or market acceptability. To calculate the technical limit, the sludge generated must be estimated as a consequence of the treatment. In primary systems, in which only mechanical removal of suspended matter occurs, sedimenters remove approximately 75% of total solid suspended (TS), and approximately 30 to 40% of BOD (Zaror 2000). Therefore, a 0.75 $(\mathrm{kg}_{ts}\ \mathrm{kg}_{ts}^{-1})$ mass generation is considered since this definition coincides with the removal efficiency. The majority of WwTPs running have either a primary system or secondary treatment system (see Figure 7.2.4), thus this configuration is assumed throughout the evaluation.

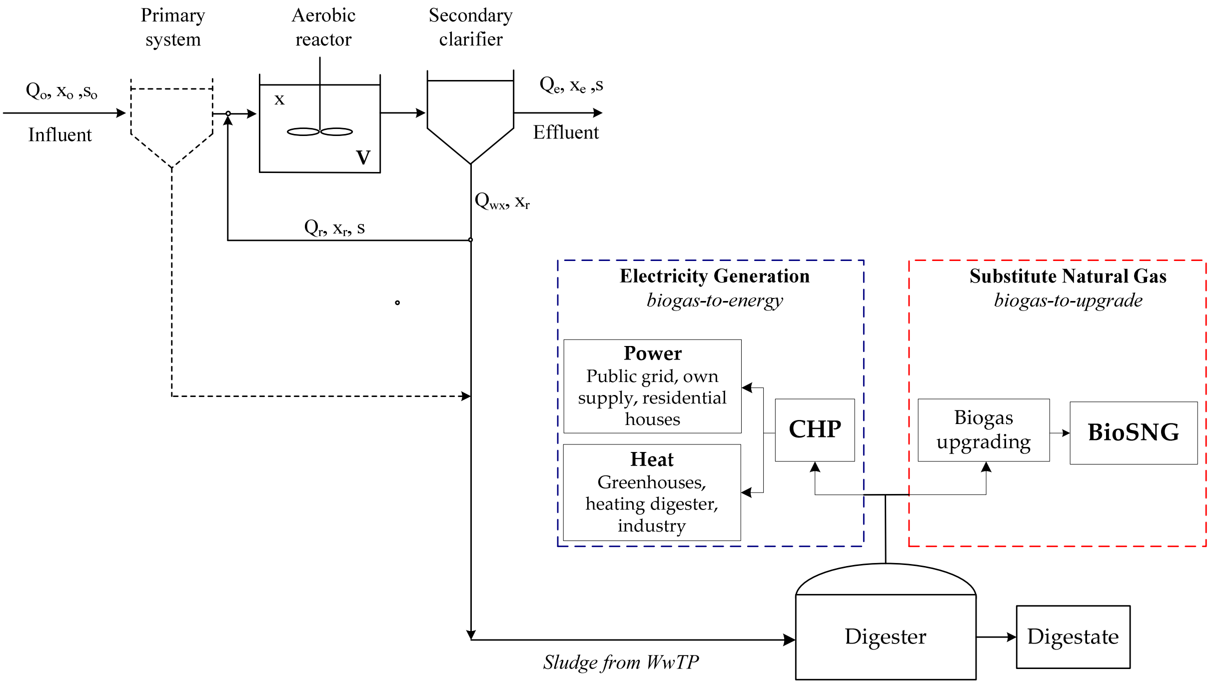

Figure 7.2.4. Schematic representation of a conventional activated sludge system (CAS) and sludge processing options to assess.

In complete-mix systems that recycle, as Figure 7.2.4 shows schematically, the mean hydraulic retention time (θ) can be calculated as indicated in the following Equation 7.2.3.

$$\theta_H = \frac{V}{Q_o} \qquad \text{Equation 7.2.3}$$

In which V is the volume of the aerobic reactor and Q_o is the influent volumetric flow. Furthermore, in this configuration the sludge can be continuously withdrawn from the recycling line. If the volatile suspended solid (VSS) content (x_e) in the exit line is negligible, the mean cell residence time θ_c can be estimated as Equation 7.2.4 indicates (Lin, 2008).

$$\theta_c = \frac{V\,x}{Q_{wx}\;\,x_r} \qquad \text{Equation 7.2.4}$$

Dividing Equation 7.2.3 by Equation 7.2.4 and reorganising the results yields Equation 7.2.5 as follows.

$$\tau_2 = \frac{Q_{wa} x_r}{Q_o x_o} = \frac{\theta_H}{\theta_c} \frac{x}{x_o}$$ Equation 7.2.5

The term τ_2 of Equation 7.2.5 corresponds to the influent organic matter-to-sludge generation ratio. For a typical and representative operation condition of a WwTP (Lin 2007), with parameters θ_H = 4 day; θ_c = 10 day; x(MLVSS) = 2,000 mg L^{-1}; and x_o(TS) = 800 mg L^{-1}, the sludge generation rate is approximately 1.0 kg^{ts} kg^{ts}. Therefore, the technical limit can be estimated by applying Equation 7.2.6, in which the conversion efficiency and the corresponding restrictions are included:

$$\pi_{t,i} = P_i \, R \, M_j \, \tau_j \, S_j \, \eta_c A_{g,i} \;\; A_{t,i} = \pi_{g,i} \, \eta_c \, A_{t,i}$$ Equation 7.2.6

In the biogas-to-upgrade (BTU) pathway, a conversion efficiency (η^{BTU}) of 98% was assumed to represent the amount of methane recovered in all the processing, from digestion to injection (Pettersson & Welliger 2009). Because the electrical efficiency (η^{BTE}) is highly dependent on the plant capacity in the biogas-to-energy pathway, its calculation was proposed as a function of electrical power. In this evaluation, the assessment considered biogas burning through a CHP module by a reciprocating gas-engine because its typical capacity is in the expected power range for the expected electric power.

7.2.3.2 Methodology for the Economic Modelling

The specific cost of secondary energy (c_i) can be calculated through Equation 7.2.7.

$$c_i \pi_{t,i} = \alpha I_i + C_{o\&m,i} - R_i$$ Equation 7.2.7

In which $\pi_{t,i}$ is the technical potential of secondary energy from the *i*th-WwTP, either electricity or Bio-SNG; I_i is the total capital investment; α is the capital recovery factor; $C_{o\&m,i}$ is the operation & maintenance cost; and R_i the revenue obtained from selling by-products or any other kind of income (e.g. from heat or the sale of bio-fertiliser, subsidies for green-electricity or waste management).

7.2.3.3 Methodology for Economic Potential

The representative generation cost (c_r) is then calculated as the mode of the log-normal cost distribution, and the economic potential interpolated as a fraction of the technical potential composed by all the plants with a specific generation cost lower than the representative one. This can be mathematically expressed as Equations 7.2.8 indicates.

$$c_r = Mode[c(\pi_{t,i})] \qquad \text{Equation 7.2.8}$$

The economic limit can be calculated as the summing-up of the total number of WwTP within the country as Equation 7.2.9 indicates.

$$\Pi_e = \sum_{i=1}^{n} P_i \; R \, M_j \; \tau_j \; S_j \; \eta_c \; A_{g,i} \; A_{t,i} \; A_{e,i} = \sum_{i=1}^{n} \pi_{t,i} A_{e,i} \qquad \begin{array}{l} A_i^e = 0;\ \forall\, \mathrm{c_i} \le \mathrm{c_r} \\ A_i^e = 1;\ \forall\, \mathrm{c_i} > \mathrm{c_r} \end{array} \qquad \text{Equation 7.2.9}$$

The data was finally integrated into a geographical information system (GIS) to visualise the technical potential by using the county (also called municipality) as the control area. This is the smallest geopolitical administrative division for each of the fifteen regions that make up the country, with a total of 346 units and an average area of 2,100 km^2.

7.2.4 Results

The theoretical potential of electricity generation, however irrelevant in practical terms, reached 359 GWh$_{th}$ y^{-1}, whereas the geographical potential bordered 253 GWh$_{th}$ y^{-1}. The technical limit was estimated at 83 GWh$_e$ y^{-1}, significantly lower than the two previous limits. In the biogas-to-upgrade pathway, the theoretical potential reached 38 MMNm^{3}y^{-1}, whereas the geographical potential reached 27 MMNm^{3}y^{-1}, or nearly 71% of the maximum theoretical limit. The technical potential reached 24 MMNm^{3}y^{-1}, corresponding to 62% of the theoretical one.

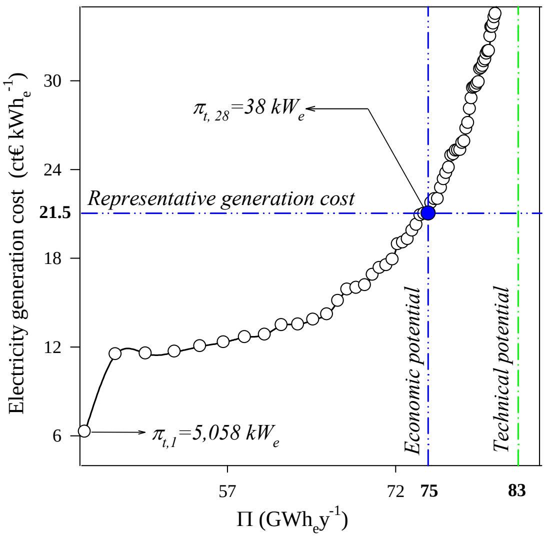

Figure 7.2.5. Supply-cost curve for biogas-to-energy option.

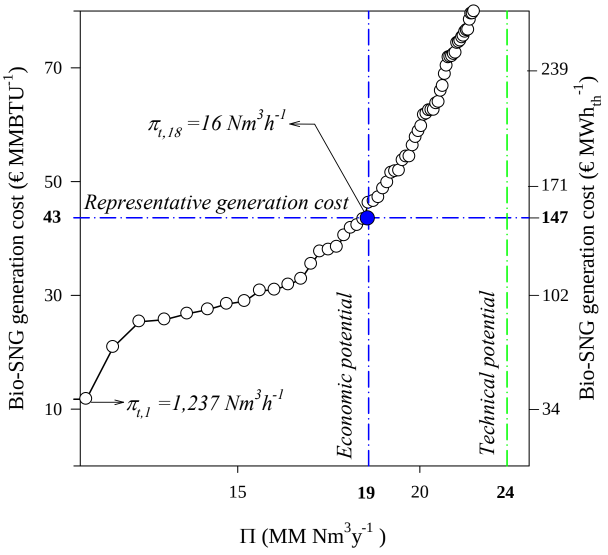

Figure 7.2.6 Supply-cost curve for biogas-to-upgrade option.

Figures 7.2.5 and Figure 7.2.6 are supply-cost curves of the biogas-to-energy and biogas-to-upgrade pathways. Each point of the curve represents an amount of secondary energy supplied by a WwTP at a specific levelised cost. In the former, the representative generation cost of electricity was estimated at 21.5 ct€ kWh$_e^{-1}$, with a minimum generation cost of 6.3 ct€ kWh$_e^{-1}$ for the largest WwTP in operation. The economic potential is approximately 75 GWh$_e$ y^{-1}, and consists of the 28 WwTPs.

For the biogas-to-upgrade route, the representative generation cost was estimated at 43 € MMBTU^{-1}, with 11.2 € MMBTU^{-1} as the lowest cost of generation at the national level for a plant with nominal Bio-SNG capacity of 1,237 Nm^3 hr^{-1}. The economic potential reached approximately 19 MMNm^3 y^{-1}, and was made up of the Bio-SNG potentially available from 18 of the largest WwTPs in operation.

Figure 7.2.7 and Figure 7.2.8 show the technical potentials distributed throughout the country. For both options under analysis, there are direct correlations between highly populated areas and higher electricity and Bio-SNG potential at the lowest cost of production. This is an expected result, and supported by the proportionality between population served by a WwTP and sludge generation. Both electricity and the largest Bio-SNG potential are concentrated in the XIII Region, or Metropolitan Region, (approximately 49%) and the VIII Region (approximately 15%).

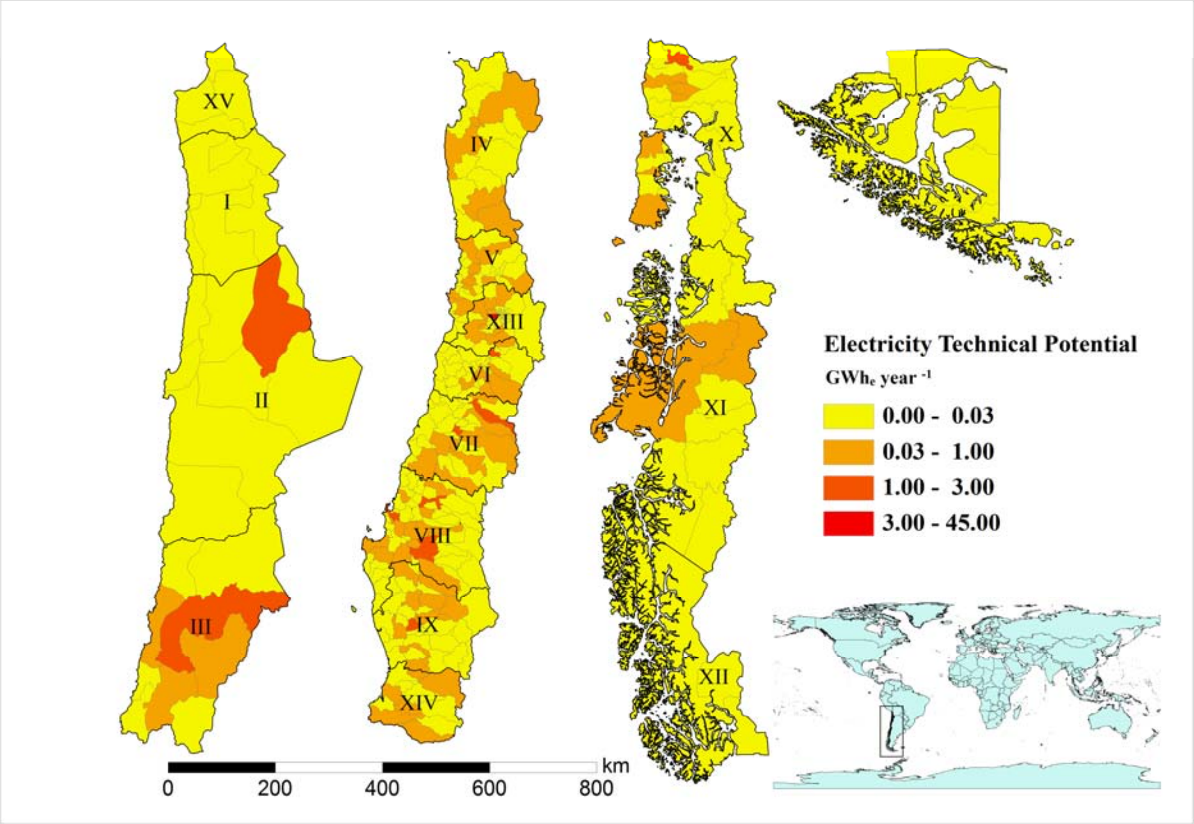

Figure 7.2.7. Geographical distribution of the technical potential for electricity generation from WwTP sludge digestion.

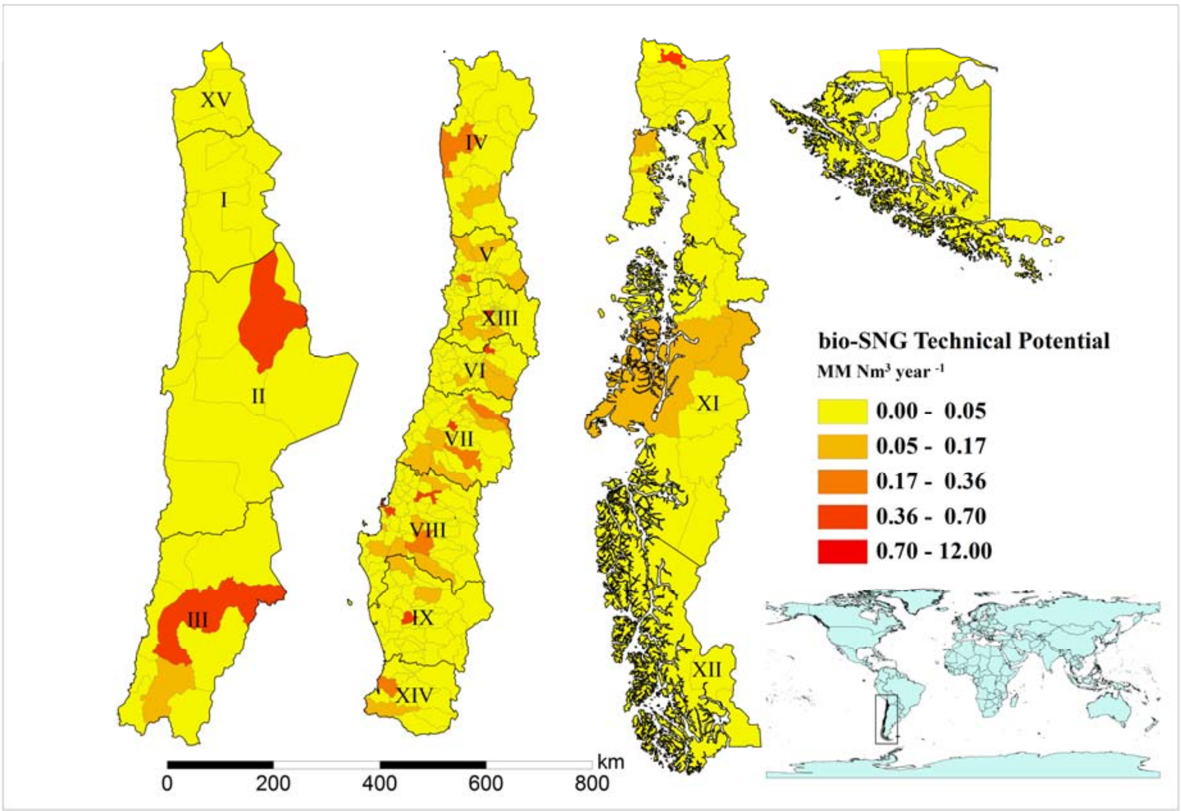

Figure 7.2.8. Geographical distribution of technical potential for Bio-SNG production from WwTP sludge digestion.

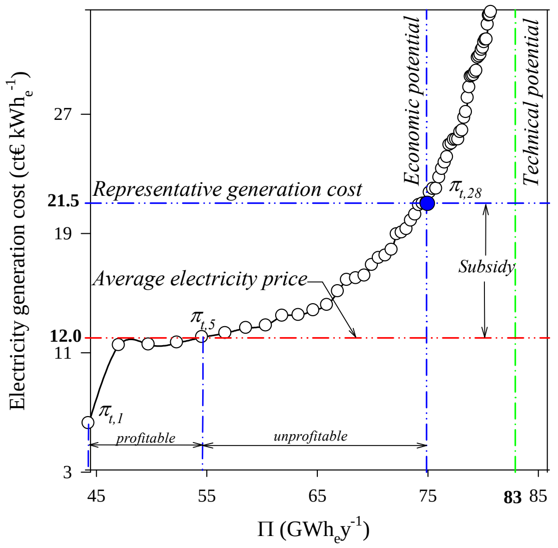

Figure 7.2.9. Comparison between representative generation cost and market price for electricity option.

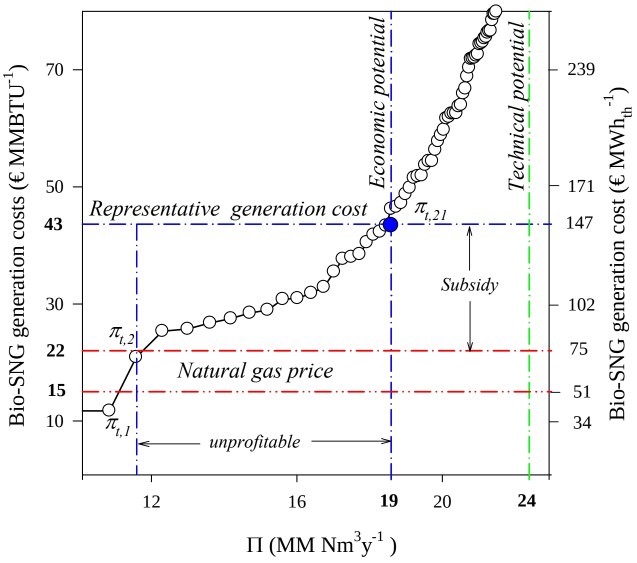

Figure 7.2.10. Comparison between representative generation cost and market price for Bio-SNG option.

Figure 7.2.9 shows that the representative generation cost of electricity is higher than its market price. In the same way, Figure 7.2.10 presents the representative generation cost of Bio-SNG as higher than the price of natural gas. For the biogas-to-energy pathway, the first five WwTPs have electricity generation that may be profitable, offering an achievable potential of roughly 55 GWh$_e$y^{-1}. To make the unprofitable fraction economically appealing (the remaining 23 WwTPs), would necessitate the introduction of a feed-in tariff subsidy of approximately 9.5 ct€ kWh$_e^{-1}$, the difference between the representative generation cost and the market price.

Table 7.2.2. Energy potential of the biogas-to-electricity and biogas-to-BioSNG.

	Alternative of energy generation	
Economic indicator	biogas-to-energy	biogas-to-BioSNG
Technical potential	85 GWh$_e$y^{-1}	24 MM Nm^3 y^{-1}
Economic potential	83 GWh$_e$y^{-1}	19 MM Nm^3 y^{-1}
Minimum cost of production	6.3 ct€ kWh$_e$	11.2 € MMBTU^{-1}
Representative cost of production	21.5 ct€ kWh$_e$	43 € MMBTU^{-1}
Needed feed-in tariff	9.5 ct€ kWh$_e$	21-28 € MMBTU^{-1}
Needed subsidy	1 MM €	4 - 6 MM €

For the biogas-to-upgrade route, there are one or two WwTPs in which the generation of Bio-SNG makes sense in economic terms, thus its generation cost is lower than natural market price and has an achievable potential for injection into the grid at roughly 12 MMNm^3 y^{-1}. A subsidy in the 21-28 € MMBTU^{-1} range for generated Bio-SNG would be necessary to make 7

MMNm^3 y^{-1} of Bio-SNG economically competitive. In both cases, the feed-in tariff scheme would associate a direct subsidy, which would mean approximately 1 MM € y^{-1} for the biogas-to-energy option, whereas the biogas-to-upgrade would reach 4-6 MM € y^{-1}. Table 7.2.2 summarises the main economic outcomes from the assessment.

7.2.5. Discussions

Tsagariks (2007) reported an electricity cost of 8.76 ct€ kWh$_e^{-1}$ for a set of generators installed at a municipal WwTP located in Iraklio, Greece. Gómez *et al.* (2010) estimated a minimum electricity generation cost of 11.0 ct€ kWh$_e^{-1}$ at WwTPs facilities in Spain. Morin *et al.* (2011) found an electricity cost of 7 ct€ kWh$_e^{-1}$ via biogas co-generation through the mono-digestion of 150,000 inhabitants' municipal WwTP sludge in Quebec, Canada. These figures are in the line with the calculated representative generation cost of electricity. For the Bio-SNG option, no assessments of large areas were found in that most of the available information is based on case studies and oriented to estimate generation cost at a typical plant.

In spite of the inherent difficulty in generalising the market's prices for secondary energy at a national level for a specific time-frame, the above-mentioned values can be employed as a reference in the short-term for the development of a national strategy that addresses the sludge generation problem via a waste-to-energy approach. This strategy should be based on a macro-policy for the handling of wastes with similar characteristics, offering consistent incentives than can lead to a sustainable way of achieving environmental and economic benefits.

7.2.6. Preliminary Conclusions

This section has shown how the introduction of a technology to control an environmental issue, wastewater treatment specifically, resulted in the appearance of a new environmental problem (i.e. sludge). In this way, anaerobic digestion may offer a solution through a waste-to-energy approach. For the two state-of-the-art options to the treat WwTP sludge, biogas-to-energy and biogas-to-upgrade, it was found that the economic limit heavily penalised the energy potentially available based on the technical limit. Furthermore, it was found that at national scale 63% of the electricity's technical potential would be competitive with conventional generation, whereas this share would reach approximately 58% for Bio-SNG; all of these percentages consider the average energy prices for 2011. As far as Bio-SNG generation is concerned, its injection only makes sense in large scale production, so it is heavily dependent on the amount of residual substrate available for processing.

It is observed that there is a high concentration of energy potential in only two regions of the country, which is attributed to the high population density present in only a few areas. This implies that there are numerous small-scale WwTPs in which either electricity or Bio-SNG is not adequate to be produced at a commercial scale, being in this way landfilling the immediate possibility of handling.

Both assessed options are hardly competitive without the introduction of incentives such as feed-in tariffs for energy generation or another indirect mechanism of subsidisation. Nevertheless, in comparison with the Bio-SNG option, a greater number of electricity projects may run profitably, and a significantly larger number might become profitable once the steady increase in electricity prices is considered. Consequently, the biogas-to-energy route is more effective and larger environmental externalities are present when no-subsidies from the state are considered.

Under a hypothetical scenario in which subsidisation was contemplated for the promotion of a waste-to-energy policy, the generation of electricity seems to be the most advantageous because a similar number of WwTPs (24 for biogas-to-energy and 21 for biogas-to-upgrade) would be profitable, but the annual cost for the state would be significantly lower. Taking into account these results, evidence suggests that a policy towards the electricity pathway should be promoted under the current economic context of the country.

7.3 Livestock Farming Sector

The production of biogas through anaerobic digestion has recently garnered considerable attention as an option for the generation of energy with significant environmental, social and political benefits, especially in the rural sector. However, and in contraposition with other alternatives, it is associated with a series of uncertainties that make it difficult to generalise either technical or economic assessments at a large-scale. This is principally due to the diversity and amount of substrates potentially suitable as raw material, the geographical distribution of the resource, scale of generation and environmental and energy policies.

As previously done for municipal solid waste and wastewater treatment, the potential analysis is carried out for the livestock farming sector, which involves the assessment of energy from the anaerobic processing of manure by mono-digestion. The same structured methodological approach put forward in chapter 4 and already applied is once again employed, providing the same economic indicators to allow a cross-assessment comparison between the conversion routes (i.e. electricity or Bio-SNG) as well as among sectors.

7.3.1. Introduction

Anaerobic digestion is particularly attractive when searching for an environmentally friendly solution for the manure generated by farms (Hom-Nielsen, *et al*. 2009; Berglund &. Borjesson 2006). On the one hand, the intensification of farming industries has enabled the inherent benefits of the economies of scale for edible goods production, and on the other hand the increased production of edible goods has been accompanied by significant volumes of manure during processing, involving higher cost and posing a risk to the environment. Although manure has historically been employed as a natural fertiliser to increase the quality of farmland and return nutrients to the soil, its use can be responsible for the eutrophication of waterways and losses of nitrate or phosphate when it is applied at non-optimal rates (Randall, *et al*. 2000).

In recent years, Chile's livestock industry has experienced considerable development; the country was an importer of dairy products up until 2001, and then became a net exporter due to a surplus in production. For instance, the poultry industry supplies most of the internal demand with 594,000 t y^{-1} (data from 2010), accounting for 45% of the total demand of meat.

Pork follows with 498,000 t y^{-1} (expressed as dressed meat) and has exhibited steady growth during the last decade (6.7% annually). Both are attributable to a higher demand from export markets like South Korea and Japan and the internal increase in consumption (ODEPA 2012). The dairy industry is made of approximately one hundred medium and large milk supplying plants principally located in the central and southern zones (ODEPA 2012). In the context of this expansion in the feedstock industry, the country ought to confront this new environmental issue in accordance with the new challenges to reach long-term economic competitiveness in a sustainable fashion. In these terms and based on scientific evidence, the introduction of anaerobic technologies as an approach to overcoming this environmental issue is seen as a promising solution.

In Chile, the introduction of on-farm anaerobic technology has taken place slowly and only in last few years. Total biogas generation only reached 0.4 PJ y^{-1} in 2011 (Ministry of Energy 2011), but, nonetheless, preliminary evaluations have shown that the theoretical potential of biogas from the digestion of manure is roughly 15 PJ y^{-1} (Chamy, *et al.* 2007), indicating that less than 3% of the potential from these sectors is being realised so far.

7.3.2. Livestock Characterisation

Table 7.3.1. Livestock (per 1,000 heads) by category and region in Chile (Ministry of Agriculture 2007).

	Bovine	**Sheep**	**Swine**	**Equine**			**Goat**	**Camelid**		**Wildboar**	**Deer**	**Rabbit**	**Total**
Country region´s name				*Horse*	*Mule*	*Donkey*		*Alpaca*	*Llama*				
Región de Tarapacá (I)	0.1	10.0	1.4	0.0	0.1	0.6	2.3	3.5	23.7	0.0	0.0	6.7	**48.5**
Región de Antofagasta (II)	0.3	10.5	1.9	0.5	0.0	0.8	6.2	0.2	5.6	0.0	0.0	8.6	**34.6**
Región de Atacama (III)	7.1	5.2	1.4	3.9	0.7	3.4	39.2	0.0	0.0	0.0	0.0	2.5	**63.6**
Región de Coquimbo (IV)	41.3	84.2	3.8	25.7	3.9	8.8	404.6	0.1	0.2	0.0	0.0	2.9	**575.4**
Región de Valparaíso (V)	102.7	30.3	173.8	26.7	0.7	1.0	45.5	0.2	0.2	0.0	0.0	2.9	**384.0**
Región de O'Higgins (VI)	83.4	157.6	860.0	26.8	0.2	0.0	18.5	0.5	0.1	0.0	0.0	5.1	**1,152.3**
Región del Maule (VII)	258.2	155.1	93.4	54.0	0.5	0.1	40.1	0.4	0.0	0.2	0.5	1.5	**604.1**
Región del Bío-Bío (VIII)	449.4	173.7	179.8	51.3	0.1	0.0	47.3	0.1	0.2	0.9	0.2	3.1	**905.9**
Región de la Araucanía (IX)	668.1	277.9	199.6	30.9	0.1	0.0	50.8	0.5	0.7	1.0	0.7	2.2	**1,232.6**
Región de los Lagos (X)	1,047.2	315.2	79.8	22.8	0.0	0.0	11.1	0.5	0.3	0.9	4.4	0.9	**1,483.1**
Región de Aysen (XI)	193.8	304.9	2.7	12.2	0.1	0.0	12.1	0.2	0.0	0.0	0.0	0.1	**526.2**
Región de Magallanes (XII)	141.8	2,205.3	1.7	10.2	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.1	**2,359.6**
Región Metropolitana de Santiago	101.3	24.0	1,292.7	24.5	0.2	0.1	12.3	0.0	0.1	0.2	0.0	5.7	**1,461.1**
Región de los Ríos (XIV)	621.6	116.1	34.3	14.3	0.0	0.0	9.3	0.5	0.4	0.7	0.1	0.3	**797.7**
Región de Arica y Parinacota (XV)	2.3	18.2	2.3	0.3	0.1	0.1	6.0	19.1	17.4	0.0	0.0	1.0	**66.9**
Total country	***3,719***	***3,888***	***2,929***	***304***	***7***	***15***	***706***	***26***	***49***	***4***	***6***	***44***	***11,696***

The total area of Chile is 756,102 km^2, and the country is divided into fifteen administrative regions. The climatological diversity of the country enables the production of various kinds of livestock products. The total livestock is composed of an estimated 11.7 million heads (Ministry of Agriculture 2007) and is comprised of 32% bovine, 33% sheep and 25% swine. Table 7.3.1 lists the data organised by administrative region. As can be observed, the livestock is mainly concentrated in Región de Magallanes (XII) (20%), Región de los Lagos (X) (13%) and Región Metropolitana (XIII) (12%).

7.3.3. Methodology

The methodology for the potential analysis of this sector follows the same procedures that were used in the previous sectors, providing the same technical and economic indicators. Besides, a similar analysis can be carried out by using the supply-cost curves to evaluate the necessity of subsidies, the most adequate conversion route and the fraction of the economic potential that can run profitably under the current economic conditions.

7.3.3.1 Methodology for the Technical Potential

The primary information on the existing farms in Chile used for the assessment was provided directly by the Department of Studies and Agrarian Policies (ODEPA), branch of the Ministry of Agriculture. This electronic database includes the totality of existing heads of livestock within the country (data from 2007) and is segregated by the type of livestock (bovine, sheep, swine, etc.) for each farm at a county level, which is made of approximately 87,000 farms distributed all across the country. With this data, the technical potential (π_t) of the *biogas-to-energy* (BTE) and *biogas-to-upgrade* (BTU) pathways can be calculated for each *j*th-farm by applying Equation 7.3.1 and Equation 7.3.2.

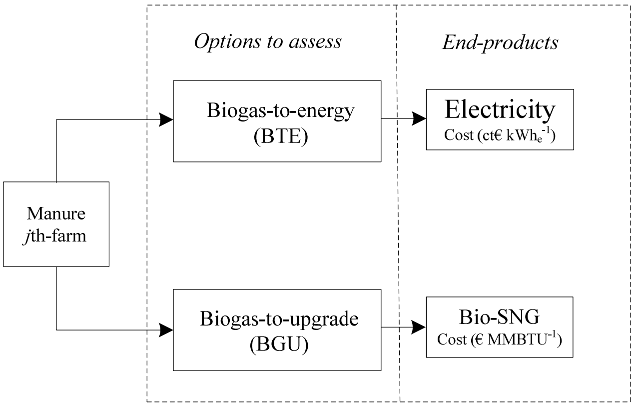

Figure 7.3.1. Conversion pathways to assess for the utilisation of manure for the production of either electricity or Bio-SNG through mono-digestion.

$$\pi_{t,j}^{BTE} = \sum_k N_{j,k}\, M_k\, S_k\, R_k\, \Delta\widetilde{H}_{\mathrm{LHV}}^{\mathrm{CH4}}\, \eta_a\, \eta_e\, A_e \qquad \begin{cases} A_e = 1; \forall\, \pi_{t,j}^{BTE} > 8kW_e \\ A_e = 0; \forall\, \pi_{t,j}^{BTE} \le 8kW_e \end{cases} \qquad \text{Equation 7.3.1}$$

$$\pi_{t,j}^{BGU} = \sum_k N_{j,k}\, M_k\, S_k\, R_k\, \eta_a\, A_u \qquad \begin{cases} A_u = 1; \forall\, \pi_{t,j}^{BGU} > 5Nm_{CH_4}^3\, h^{-1} \\ A_u = 0; \forall\, \pi_{t,j}^{BGU} \le 5Nm_{CH_4}^3\, h^{-1} \end{cases} \qquad \text{Equation 7.3.2}$$

In which $(N_{j,k})$ represents the number of livestock heads in the *j*th-farm of the *k*th-species; $\Delta\widetilde{H}_{LHV}^{CH_4}$ is the lower heating value of methane and estimated as 50,000 kJ kg^{-1} (Avallone, *et al.* 2007); and (η_e) is the electrical efficiency. Table 7.3.2 lists the employed parameters, estimated from the literature and used for the estimation of the technical potential, which are for the *k*th-species: M_k is the amount of manure produced per head of livestock yearly; S_k is the volatile-to-total solid ratio; R_k is the yield of biomethane per volatile solid; LSU_k is the livestock unit; and the manure availability factor is (η_a), the fraction of manure that is recoverable. By using the values shown in Table 7.3.2, the biogas yield reaches 0.37 Nm^3 LSU^{-1} d^{-1} for dairy and 0.59 LSU^{-1} d^{-1} for swine. These values are conservative when compared with data reported in the literature (Deublein & Steinhauser 2011).

Table 7.3.2. Parameters employed for the calculation of biogas potential of liquid manure. M: average animal weight; S: volatile sold and total solid ratio; R: biogas yield; and η_a: manure availability factor.

Livestock $(k = \overline{1,n})$	Manure per head M (kg$_m$head^{-1}y^{-1}) $^{(a)}$	Volatile-to-total solid ratio S (kg$_{vs}$ kg$_m$$^{-1}$) $^{(a)}$	Specific methane yield R (Nm^3 kg$_{vs}$$^{-1}$)	Livestock unit (LSU) $^{(h)}$	Availability factor $^{(i)}$ η_a
1. Dairy	20,090	0.12	0.230 $^{(b)}$	1.2	0.45
2. Beef	7,261	0.12	0.230 $^{(b)}$	0.6	0.45
3. Veal	2,059	0.04	0.230 $^{(b)}$	0.6	0.45.
4. Other (Ox, butt, etc.)	15,695	0.12	0.230 $^{(b)}$	0.7	0.45
5. Sheep–Ovine	394	0.23	0.248 $^{(b)}$	0.05	0.35
6. Swine	6,132	0.10	0.265 $^{(b)}$	0.5	0.8
7. Equine (Horse, mule, and donkey)	8,377	0.20	0.165 $^{(b)}$	1.1	0.1
8. Goat	958	0.22	0.248 $^{(b)}$	0.05	0.1
9. Camelid (Alpaca and llama)	958	0.22	0.165 $^{(c)}$	1 $^{(g)}$	0.1
10. Wild boar	6,132	0.10	0.265 $^{(c)(d)}$	0.5 $^{(g)}$	0.1
11. Deer	958	0.22	0.165 $^{(e)}$	0.1 $^{(g)}$	0.1
12. Rabbit	58	0.18	0.174 $^{(f)}$	0.01 $^{(g)}$	0.1

(a) ASAE (2003), (b) Pascual (2012), (c) estimated as equine, (d) estimated as swine, (e) estimated as equine, (f) Li *et al.* (2011), (g) assumed, (h) Deublein and Steinhauser (2011), (i) Batzias *et al.* (2005).

A Boolean restriction was included to set up the minimal output-capacity for the conversion units, defined as A_e and A_u for the *biogas-to-energy* and *biogas-to-upgrade* routes as indicated in Equation 7.3.1 and Equation 7.3.2[2]. Thus $8\,kW_e$ was considered as the minimum output- capacity for reciprocating engines, while $5\,Nm^3_{CH_4}h^{-1}$ was the value for upgrading units. These values correspond to the smallest nominal capacities of commercial units according to technical information (Petersson & Wellinger 2009; ASUE 2011).

7.3.3.2 Methodology for the Economic Modelling

The unitary cost of production of secondary energy c_j from the *j*th-farm was estimated by applying the economic model showed in Equation 7.3.3.

$$c_j \pi_{t,j} = \alpha I_j + C_{o\&m,j} + C_{p,j} - R_j \qquad \text{Equation 7.3. 3}$$

In which, for each *j*th-farm, $\pi_{t,j}$ corresponds to the technical potential; α is the capital recovery factor; $C_{o\&m,j}$ is the operation and maintenance cost; $C_{p,j}$ is the procurement cost of biomass at the processing point; and R_j represents the revenues potentially obtainable from selling by-products such as heat or digestate. Afterwards, the gathered information and biomass supply model was integrated into the economic modelling previously presented for the calculation of the distribution of the unitary cost of production for all the sources of biomass under investigation.

Due to the conditions of farms in the country, no commercialisation either for surplus heat from the cogeneration units or digestate from the anaerobic treatment of manure was assumed. Additionally, it was assumed that the manure was processed in situ, hence without associating any cost of transportation.

7.3.3.3 Methodology for the Economic Potential

The mathematical procedure for the calculation of the representative generation cost, worked out as the log-normal mode of the distribution of unitary cost of energy generation, and the associated economic limit, can be found in detail in Chapter 4 or as illustrated in the sectors already assessed.

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[2] This Boolean operator was not used for the potential analysis of the previous sectors because no technical potential was lower that 8 kW_e or 5 Nm^3h^{-1} for biogas-to-energy or biogas-to-upgrade, respectively.

7.3.4 Results

Figure 7.3.2 and Figure 7.3.3 display the supply-cost curves for the biogas-to-energy and biogas-to-upgrade pathways assessed for the mono-digestion of manure. The technical potential for the former option reached 887 $\mathrm{GWh_e y^{-1}}$, whereas its economic potential bordered 780 $\mathrm{GWh_e y^{-1}}$ at a representative generation cost of 25 ct€ $\mathrm{kWh_e^{-1}}$. For the biogas-to-upgrade route the technical limit reached 225 $\mathrm{MMNm^3 y^{-1}}$, with economic potential reaching 182 $\mathrm{MMNm^3 y^{-1}}$ at a representative generation cost of 98 € $\mathrm{MMBTU^{-1}}$.

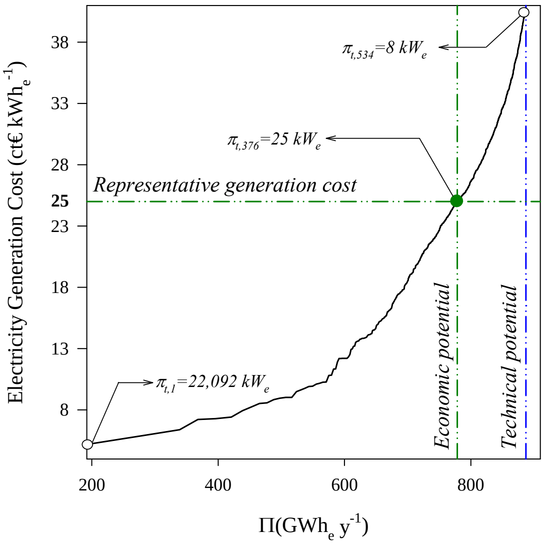

Figure 7.3.2. Supply-cost curve for the biogas-to-energy pathway by mono-digestion of manure.

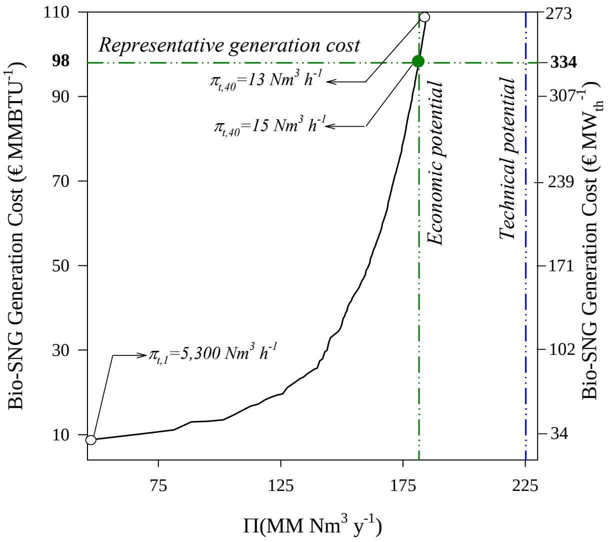

Figure 7.3.3. Supply-cost curve for biogas-to-upgrade pathway by mono-digestion of manure.

Figure 7.3.4 and Figure 7.3.5 reveal that the technical potential from manure processing is highly concentrated in Región Metroplitana (XIII) and estimated to account for approximately 62% and 64% for electricity and Bio-SNG production, respectively. The second highest concentration is found in Región de la Araucanía (IX), which has 11% and 10% of the electricity and Bio-SNG technical potential. Additionally, it was found that on the national level the technical potential of electrical power was primarily on the small-scale, in the 20-250 $\mathrm{kW_e}$ range, and accounted for 71% of the country's total. A similar tendency was observed in the technical potential of Bio-SNG, in which approximately 80% of the potential was concentrated on a scale lower than 1 MM $\mathrm{Nm^3 y^{-1}}$.

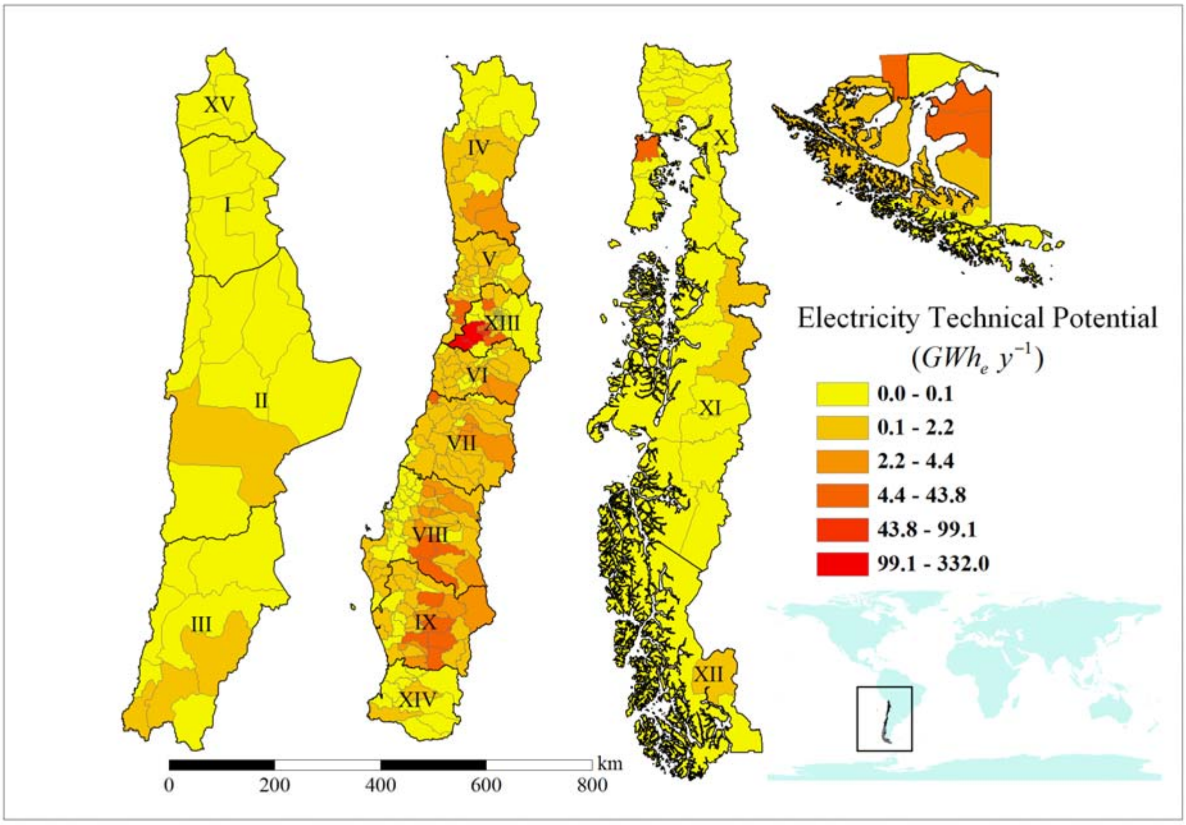

Figure 7.3.4. Technical potential of electricity from mono-digestion of manure.

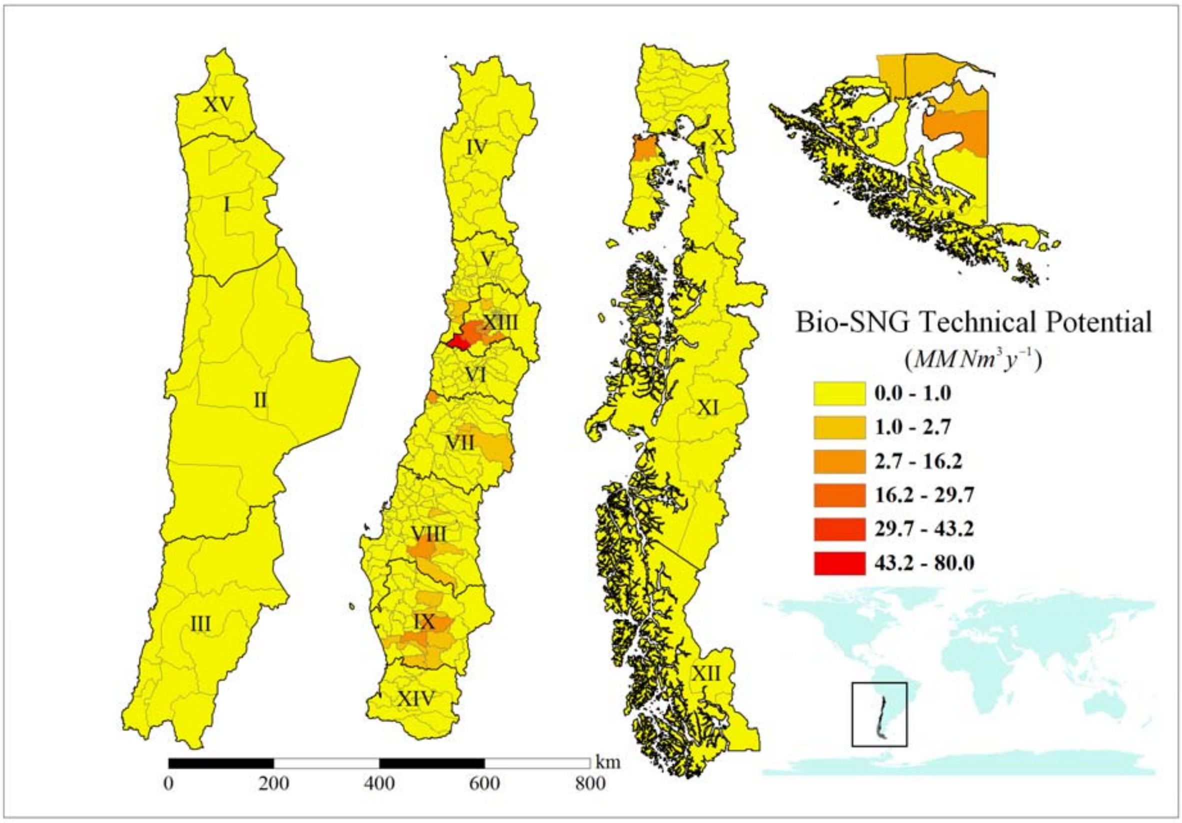

Figure 7.3.5. Technical potential of Bio-SNG from mono-digestion of manure.

7.3.5 Discussions

Only a modest fraction of the total number of farms in the country (approximately 370 from 87,000, or less than 1%) was found to offer adequate conditions to develop biogas projects. This is because the majority of them were constituted of a limited number of livestock, which severely restricted the amount of biogas units technically feasible. Additionally, a large amount of the technical potential of electricity for mono-digestion of manure could be found in the low scale, the 10-250 kW_e range, and is strongly concentrated in only some geographical areas. A similar tendency was also observed for the possibility of producing Bio-SNG, for which the scale rarely surpassed 1 $MM\ Nm^3 y^{-1}$ and was concentrated in a few regions.

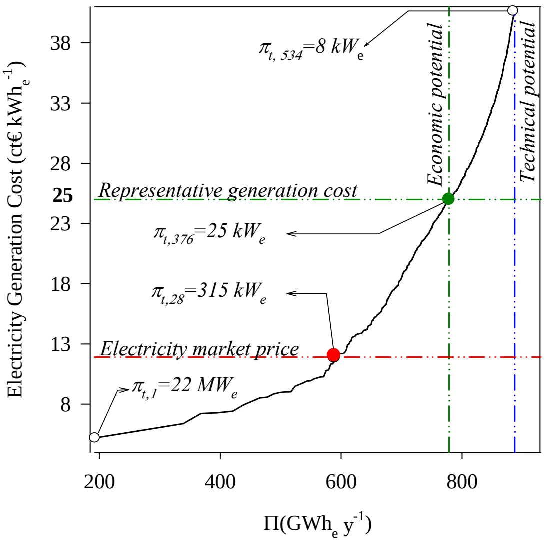

Figure 7.3.6. Supply-cost curve for the biogas-to-energy pathway by mono-digestion of manure.

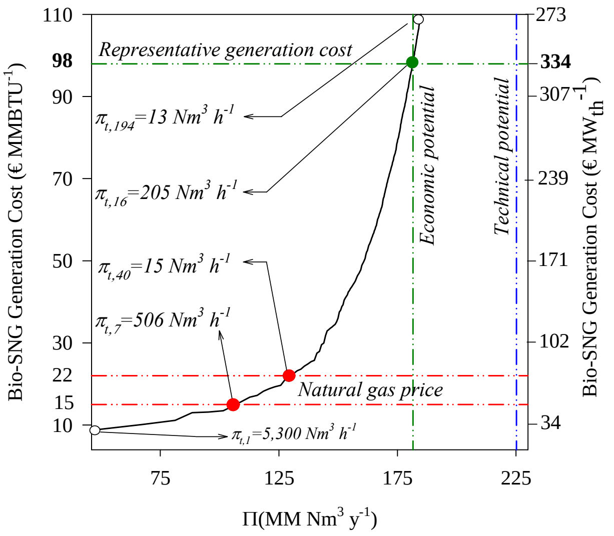

Figure 7.3.7. Supply-cost curve for biogas-to-upgrade pathway by mono-digestion of manure.

For the electricity alternative, as seen in Figure 7.3.6, it was observed that there is an important fraction of the economic potential that could be profitable when a referential market price of electricity of 12 $ct€\ kWh_e^{-1}$ is considered, representative for projects at the low scale. In these terms, this is the most attractive part of the potential made of 28 plants, and it should be targeted for enhancing biogas production.

With the market price of natural gas (see Figure 7.3.7) currently ranging from 15 to 22 $€\ MMBTU^{-1}$ roughly, most of the cost associated with the economic potential of the gas-to-upgrade route, the Bio-SNG option, hardly seems competitive without heavy subsidies. More importantly, approximately 80% of the Bio-SNG technical potential is in a range lower than 1 $\mathrm{MM\ Nm^3 y^{-1}}$, a scale that is not commercially attractive for these sorts of projects, at least in practical terms.

Table 7.3. 3. Energy potential of the biogas-to-energy and biogas-to-upgrade of manure utilisation.

	Route of conversion	
Economic indicator	Biogas-to-energy (BTE)	Biogas-to-upgrade (BTU)
Technical potential	1,067 $\mathrm{GWh_e y^{-1}}$	225 MM $\mathrm{Nm^3\ y^{-1}}$
Economic potential	779 $\mathrm{GWh_e y^{-1}}$	182 MM $\mathrm{Nm^3\ y^{-1}}$
Minimum cost of production	5.2 ct€ $\mathrm{kWh_e}$	8.7 € $\mathrm{MMBTU^{-1}}$
Representative cost of production	25.0 ct€ $\mathrm{kWh_e}$	98 € $\mathrm{MMBTU^{-1}}$
Needed feed-in tariff	13.0 ct€ $\mathrm{kWh_e}$	83-76 € $\mathrm{MMBTU^{-1}}$
Needed subsidy	23 MM €	198-124 MM €

The potential analysis was conducted for the decentralised generation of biogas when manure was used as substrate. Another option to assess is the centralised use of manure as substrate, which may improve the economics of the whole process. However, this option implies a location analysis for a centralised-processing plant, normally associated with an optimisation problem under geospatial restrictions. Furthermore, centralised manure usage involves the additional cost of slurry transportation with low solid content, and a potential instability in the substrate supply because it involves dependency on third-parties, contracts and the creation of business models and mechanisms of partnership affiliation.

The great variability of biomethane yield from manure digestion is a well-known fact principally linked with the sort of substrate and operating conditions of the reactor. Thus, the presented results should be considered referentially, as an order of magnitude taking into consideration the limitations intrinsically related to the technologies considered for the evaluation and their economic implications.

7.3.6 Preliminary Conclusions

For the farm sector, two principle tendencies are observed. Firstly, the electricity generation option seems to be more advantageous than the possibility of producing a gaseous biofuel. This is because the greatest fraction of the technical potential is concentrated in a low power range for both electricity or Bio-SNG. Under this condition, the Bio-SNG option exhibits a considerable increase in cost, much more significant than for electricity when the representative generation cost and the number of plants that account for the economic potential of each option is compared. Secondly, and when the electricity option is considered, there are only two regions, Región Metropolitana (XIII) and Región de la Araucanía (IX), accounting for more than 73% of the technical potential, which are not necessarily the regions (except the Metropolitan) that concentrate the largest number of livestock heads.

7.4 Agricultural Sector

The anaerobic digestion of crop residue may provide a significant amount of energy in the context of biogenic residues currently available in the country. Nonetheless, the uses are wider ranging than those of the biomass from the previously evaluated sectors, and with an associated competition due to other uses that can significantly reduce its availability. In addition, the procurement of crop residue involves collection, conveyance, storage and pre-treatment before the digestion takes place, hence involving extra cost that are absent when the biomass is generated and used in situ. On the other hand, the possibility of collecting larger amounts of biomass may enable the implementation of biogas projects of larger capacity, associating lower specific investment and likely taking advantages of economies of scale which may in turn lower the cost of energy production.

7.4.1 Introduction

The continental surface of Chile accounts for 75.6 millions of hectares (ha). From this, 34.8 millions ha are unproductive, which makes up 46.1% of the national continental surface. The land used for agro-pecuarian exploitation constitutes less than 10% of the national surface, from which 1.1% corresponds to land without any sort of restriction. The remainder exhibits limitations because of topography, desertification, increasing of salinity, lack of irrigation, the presence of heavy metals, etc. (Saa-Vidal, *et al*. 2010).

Table 7.4.1. Use of land in Chile (Saa-Vidal, *et al*. 2010).

Use type	**Use**	**Land capability(*)**	**Surface (ha)**	**Percentage (%)**
Agricultural arable lands	Without restrictions	I	111,346	0.15
		II	652,818	0.86
	With restrictions	III	1,762,559	2.33
		IV	2,106,619	2.79
Subtotal			**4,633,342**	**6.13**
Non-arable agricultural lands	Cattle	V	2,271,444	3.00
	Cattle-forestry	VI	6,219,736	3.22
	Forest	VII	13,430,602	17.76
Subtotal			**21,921,462**	**28,99**
Non-agricultural lands		VIII	14,200,000	18.78
Unproductive land			34,869,936	46.11
Total			**75,624,760**	**100**

(*) Land capability has been defined according to standards of U.S. Department of Agricultural (Gilo 2010).

Chilean agriculture and horticulture are mainly focused on five sectors, they are: i) major fruits and vine; ii) vegetables; iii) annual crops; iv) industrial crops; and v) livestock farming, secribed as follows (Saa-Vidal, *et al*. 2010):

- **Major Fruits and Vine:** Due to its exceptional climatological conditions, Chile has significant competitive advantages for the production of these sorts of crops in the central zone, which in general terms have land that is in high demand and of high quality, climate, technology, capital and workforce. These requirements have created conditions so that mainly large private companies control this business. The land usage tends to be intensive both in the planting stage and the subsequent stages of harvesting, using technical irrigation systems, great amounts of fertilisers and agrochemicals.

- **Vegetables:** The production of vegetables tends to be concentrated in the proximity of large consumer centres (i.e. medium and large cities). The management of the land is intensive in that the species have a short vegetative growing time, allowing more than one annual harvesting, although with a thorough handling of the land. The production of vegetables is carried out preferentially in land with capability I and II.

- **Annual Crops:** Annual cultivations are performed with a wide range of technologies and by using both irrigated and rainfed land across the country. Generally, it is associated with a high demand of workers and takes place in land with capability II, III and IV.

- **Industrial Crops:** The production of industrial crops such as raps, sugar beet, tobacco or sunflower depends on the demand of large buying companies, which normally provide technical assistance to the producers. Most of the cultivation of these crops takes place in land with capacity II, III and IV.

- **Livestock:** This activity is associated with a land demand of crops intended for fodder production and/or pasture use. It can be intensive in terms of land demand or highly concentrated if animals are stabled, for instance dairy, swine farming, etc.

Because preliminary rough estimations indicate that the main amount of biomass adequate for anaerobic digestion may be provided by annual crops (Chamy, *et al.* 2007), the potential analysis to be carried out in this chapter was focused on residues procured after harvesting them. Besides this, most of the available information on the agricultural sector is devoted to these crops due to their economic prominence.

The use of residue appears to be the most reasonable starting point for the development of a strategy focused on biogas as a source of energy because it brings direct environmental externalities. The use of energy crops, still a heated discussion at the political level, does not seem to be appropriate for implementation, at least in a first stage; it would be counterproductive for Chile to change the land currently used for food production in that it would force the country to revert to exports in order to address the internal consumption for biofuel production (Ramírez 2012). Although the biofuel alternative has not been thoroughly assessed at a national level yet, either technically or economically, preliminary evaluations indicate that the main constraints arise due to the limited potential available surface for the most promising crops both for liquid and gaseous biofuels (García, *et al.* 2012).

7.4.2 Annual Crops Characterisation

As can be observed in Table 7.4.2, the predominant species in terms of surface are wheat (40%), corn (19%), oats (15%) and potatoes (10%). At the regional level, 69% of wheat and 85% of oat crops are concentrated in Región del Bio-Bio (VIII) and Región de la Araucanía (IX), whereas corn is cultivated mainly in Región de O´Higgins (IX) and Región del Maule (VI), comprising 75% of the total area. Finally, potato plantations are dispersed across the country although more significantly concentrated in the south.

Table 7.4.2. Surface of annual crops (ha) (Ministry of Agriculture 2007).

								Regions								**Total**
Species	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	RM	XIV	XV	
Beer barley		0				226	626	1,363	7,509	431			53	977	24	**11,208**
Barley			3	507		125	155	1,449	1,631	752	90		4	9	4	**4,730**
Beans (a)				2	5	14	426	607	48							**1,102**
Beans(b)			5	280	253	691	4,717	2,802	616							**9,362**
Bread wheat		2	4	596	174	2,067	1,264	2,726	659							**7,493**
Chickpeas					246	869	896	925	2				778	3,957		**7,672**
Corn	1	153		659	1,127	46,705	29,407	12,019	685				264	14,418		**105,435**
Lentils			186			22	210	501	128				5,189	7		**6,243**
Mandioca			33		5								51	321		**410**
Oats (c)				25	170	830	1,255	20,033	48,290	6,272	334		22	1,180	3	**78,412**
Other cereals		4	66	137	720	902	533	696	1,039	405	3	15	1,705			**6,225**
Others	22	0		27	134	161	129	155	246	24	0	4	1,240			**2,144**
Peas				9	402	126	238	477	288	18	3		138	3,902	0	**5,601**
Grass peas				2	9	37	126	66	17				143	865		**1,263**
Potatoes	94	4	249	3,233	2,163	1,687	3,342	8,293	14,029	11,154	185	130				**44,562**
Quinoa	1,357	8		1		58			1							**1,424**
Rice (d)					48	101	17,333	4,146	0				24	28	5	**21,683**
Rye		1					353	278	291	6			12,010	3		**12,942**
Tricale						77	13	2,588	15,882	362						**18,922**
White wheat		18	1	1,133	1,595	5,176	22,781	67,742	93,623	11,379	21					**203,468**
Total	**1,472**	**190**	**548**	**6,610**	**7,050**	**59,874**	**83,803**	**126,864**	**184,984**	**30,802**	**637**	**148**	**21,618**	**25,667**	**36**	**550,303**

(a) for export, (b) internal consumption, (c) dray grain, (d) with peal.

Annual crop plantations have declined during the last decades. For the 2010-2011 period, for example, a decrease of roughly 18% can be observed in the planted area in comparison with that a decade ago. This decrease has not been uniform, with more substantial decreases occurring in wheat, vegetables, sugar beets, rape and potatoes. This fall has been partly counterbalanced by the growth of corn, oats, barley and lupine crops. On the contrary, a rise in the average productivity is observed in virtually all crops, reaching high values when compared at the international level (ODEPA 2012).

Table 7.4.3. Productivity of crops and total exploited surface at national level (Ministry of Agriculture 2007).

Species $(l=\overline{1,n})$	Average productivity p_l (qqm ha^{-1} y^{-1})	Total surface (ha)
1. Beer barley	50.62	11,108
2. Barley	41.52	5,983
3. Beans (for export)	20.81	1,153
4. Beans (for internal consumption)	17.02	9,633
5. Bread wheat	52.36	9,198
6. Chickpeas	8.94	2,940
7. Corn	108.32	102,955
8. Grass peas	8.34	255
9. Lentils	8.43	861
10. Oats	41.80	81,480
11. Others	n.a.	1,061
12. Others cereals	n.a.	6,187
13. Peas	14.10	1,258
14. Potatoes	154.54	53,731
15. Quinoa	6.08	1,427
16. Rice (with peel)	50.77	21,579
17. Rye	44.97	1,115
18. Tapicoa	1.35	5.18
19. Tricale	48.18	19,243
20. White wheat	47.77	219,126
Total country	-	**550,303**

7.4.3 Methodology

The methodology for the potential analysis of the mono-digestion of agro-industrial residue follows the same principles as those applied for all the previously assessed sectors, hence providing the same technical and economic indicators.

7.4.3.1 Methodology for the Potential Analysis

The annual amount of residue from seasonal crops was calculated using residue-to-crop production ratios, productivity per crop and planted area in a county. Because of the lack of more specific information, some parameters were assumed by applying a conservative criterion. The technical potential of *biogas-to-energy* and *biogas-to-upgrade* routes can be calculated through Equation 7.4.1 and Equation 7.4.2 as follows:

$$\pi_{t,i}^{BTE} = \sum_{l} M_l \; S_l \; f_l \; (1 - H_l \,) \, \Theta_l \; p_l \; a_i \; \Delta\widetilde{H}_{\mathrm{LHV}}^{\mathrm{CH_4}} \;\; A_e \, \eta_e \qquad \begin{cases} A_e = 1; \forall \, \pi_{t,i}^{BTE} > 8kW_e \\ A_e = 0; \forall \, \pi_{t,i}^{BTE} \leq 8kW_e \end{cases} \qquad \text{Equation 7.4.1}$$

$$\pi_{t,i}^{BTU} = \sum_{l} M_l \; S_l \; f_l \; (1 - H_l \,) \, \Theta_l \; p_l \; a_l \; A_u \qquad \begin{cases} A_u = 1; \; \forall \, \pi_{t,i}^{BGU} > 5Nm_{CH_4}^{3} h^{-1} \\ A_u = 0; \; \forall \, \pi_{t,i}^{BGU} \leq 5Nm_{CH_4}^{3} h^{-1} \end{cases} \qquad \text{Equation 7.4.2}$$

In which $\pi_{t,i}$ is the technical potential from the *i*th-county, either electricity or Bio-SNG. For the *l*th-crop species within the *i*th-county, M_l corresponds to the methane yield; S_l is the volatile-to-total solid ratio; f_l is the residue-to-crop production ratio; H_l is the humidity assumed at 15% (wet basis); p_l is the crop average productivity (see Table 7.4.3); Θ_l is the sustainable rate removal; and a_i is the area of the *i*th-county. The remaining parameters correspond as defined in Equations 7.3.1 and 7.3.2 in Section 7.3 *Livestock Farming Sector*. In this calculation, it is implicitly assumed that the total amount of biomass to convert into biogas within each county is done at a single centralised biogas plant. This assumption is put forward since there is no further information on the geographical distribution of crop residue after harvesting to conduct an assessment in greater detail. This point and its implications will be discussed more broadly in the section on economic modelling for cost estimation.

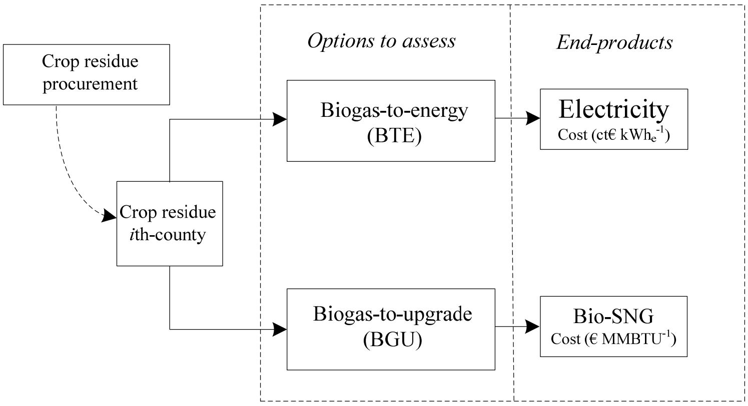

Figure 7.4.1. Conversion pathways to assess for the utilisation of crop residue for the production of either electricity or Bio-SNG through mono-digestion.

Table 7.4.4. Agricultural crops and parameters for the calculation of potential of biogas generation.

Agricultural crops $(l = \overline{1,n})$	Reside-to-crop production ratio f (kg kg^{-1})	Sustainable rate removal Θ (kg kg^{-1}) (a)	Volatile-to-total solid ratio S (kg$_{vs}$ kg$_{ts}$$^{-1}$)	Biomethane yield M ($\mathrm{Nm^3_{CH_4}\,kg^{-1}_{vs}}$)
1. Beer barley	1.4 (a)	0.40 (a)	0.94 (d)	0.229 (d)
2. Barley	1.4 (a)	0.40 (**)	0.90(d)	0.229 (d)
3. Beans (for export)	2.1 (b)	0.40 (**)	0.90(**)	0.174 (e)
4. Beans (for internal consumption)	2.1 (b)	0.40 (**)	0.90(**)	0.174 (e)
5. Bread wheat	1.3 (a)	0.40 (**)	0.92 (**)	0.087 (g)
6. Chickpeas	2.1 (*)	0.40 (**)	0.90 (**)	0.200 (e)
7. Corn	1.4 (a)	0.50 (a)	0.98 (d)	0.317 (d)
8. Grass peas	2.1 (*)	0.40 (**)	0.90 (**)	0.200 (**)
9. Lentils	2.1 (*)	0.40 (**)	0.90(**)	0.200 (**)
10. Oats	1.5 (a)	0.40 (a)	0.58(g)	0.203 (g)
11. Others	1.0 (**)	0.40 (**)	0.90 (**)	0.200 (**)
12. Others cereals	1.0 (*)	0.40 (**)	0.70(**)	0.200 (**)
13. Peas	2.1 (*)	0.40 (**)	0.90(**)	0.200 (**)
14. Potatoes	0.4 (b)	0.40 (**)	0.90(**)	0.366 (h)
15. Quinoa	1.0 (*)	0.40 (**)	0.192(j)	0.241 (j)
16. Rice (with peel)	1.6 (a)	0.50 (a)	0.92(d)	0.195 (d)
17. Rye	1.8 (a)	0.40 (a)	0.92(j)	0.360 (i)
18. Tapicoa	1.0 (*)	0.40 (**)	0.90(**)	0.100 (**)
19. Tricale	1.3 (c)	0.40 (**)	0.93(j)	0.100 (**)
20. White wheat	1.3 (a)	0.40 (a)	0.92(**)	0.087 (g)

(a) Scarlat *et al*. (2010), (b) IPCC (1996), (c) Wikström and Adolfsson (2006), (d) Dinuccio *et al.* (2010), (e) Deublein and Steinhauser (2011), (f) Somayaji and Khanna (1994), (g) Lehtomäki *et al*. (2008), (h) Parawira *et al.* (2008), (i) Petersson *et al.* (2007), (j) Cropgen Database, (k) López-Dávila *et al.* (2012), (*) assumed as beans, (**) assumed.

The technical potential of the entire country, either for the *biogas-to-energy* or *biogas-to-upgrade route*, can be evaluated as the sum of all single technical potential on the totality of counties (n) as equation 7.4.3 shows:

$$\Pi^{BTE} = \sum_{i}^{n} \pi_{t,i}^{BTE} \qquad \Pi^{BTU} = \sum_{i}^{n} \pi_{t,i}^{BTU} \qquad \text{Equation 7.4.3}$$

7.4.3.2 Methodology for the Economic Modelling

The mono and co-digestion of crop residue implies intermediate steps (depending on the harvesting system) of collecting, hauling, packing, on-farm transporting and on-road conveyance of biomass to a processing facility since it is irregularly widespread across large areas, incurring an additional cost for the biogas production. Under these circumstances, it is necessary to estimate the cost of crop residue procurement by proposing a simplified model for the operations associated to its recovery, from the field after the annual harvesting to its supply at the gate of plant, as discussed in Chapter 4. Based on this, it was assumed that the shape of each county can be approximated through a square with side l and surface equivalent to the county's. Moreover, it was assumed that all the available biomass after harvesting had a homogeneous superficial density (measured for instance as $t\,m^{-2}$) and was conveyed to the geometric centre of the county; therefore, the geometric centre of the square. Assuming a tortuosity for on-road transportation, it is possible to demonstrate, after applying some integral calculus, that the average displacement distance for the transportation of biomass $\overline{d_s}$ at county-level can be calculated by Equation 7.4.4 (see Chapter 4, section 4.5).

$$\overline{d_{s,i}} = \frac{1}{6} l_i \tau (\sqrt{2} + \ln(1 + \sqrt{2})) \qquad \text{Equation 7.4.4}$$

For the specific on-road transportation cost (c_e^{t}), 1.8 € t^{-1} km $^{-1}$ was considered as representative according to Hetz *et al.* (2010). This value, when multiplied by the average displacement distance (Equation 7.4.4), leads to the total on-road transportation cost of biomass.

The majority of information available on the cost of collecting biomass from the field is focused on wheat straw and corn stover, basically because they are the dominant crops in a substantial number of countries (Marckert 2011; Scarlat, *et al.* 2010). Although crop residue has diverse characteristics affecting the cost of recovery, transportation and processing, the cost of collecting all crop residue from the field (which includes preparing, packing and on-farm transportation) was approximated without distinguishing their differences to wheat straw because of the lack of more specific data. Hetz *et al.* (2010) reported that the cost of collecting wheat straw after harvesting was in the 6-10 € t^{-1} range, hence a value of 8 € t^{-1} was approximated for the assessment.

Therefore, the total procurement cost of crop residue, which includes collecting and on-road conveyance, can be estimated by applying Equation 7.4.5.

$$C_{p,i} = (c_e^t \overline{d}_{s,i} + c_e^c)m_i \qquad \text{Equation 7.4.5}$$

In which $C_{p,i}$ is the procurement cost of biomass at the gate of plant in the *i*th-county; c_e^t is the specific on-road transportation cost; $\overline{d}_{s,i}$ is the average displacement distance for the transportation of biomass within the *i*th square-approximated county; c_e^c is the specific biomass collecting cost; and m_i is the total crop residue available yearly within the *i*th-county.

The unitary cost of production, either for the *biogas-to-energy* or *biogas-to-upgrade* pathway, was calculated following the same procedure applied in previous chapters, and according to Equation 7.4.6.

$$c_i \pi_{t,i} = \alpha I_i + C_{o\&m,i} + C_{p,i} - R_i \qquad \text{Equation 7.4.6}$$

In which $\pi_{t,i}$ is the technical potential of secondary energy from the *i*th-county, either electricity or Bio-SNG; I_i is the total capital investment; α is the capital recovery factor; $C_{o\&m,i}$ is the operation & maintenance cost for the biogas plant located in the *i*th-county; and R_i the revenue obtained from selling by-products such as digestate or heat.

Revenues from heat and digestate by-products were not considered in the cost estimation. Firstly, because there is no established market for the commercialisation of surplus heat in the country (i.e. district heating), and, secondly, due to the fact that the sale of digestate plays only a marginal role in terms of the economics of the process (Lantz 2012), and moreover its use is not regulated in the country.

7.4.3.3 Methodology for the Economic Potential

The mathematical method for working out the representative generation cost and the corresponding economic limit can be found in detail in Chapter 4, or as already illustrated in previous sectors. Following the same methodology, the estimation of the needed feed-in tariff and the total yearly needed subsidisation was calculated.

7.4.4 Results

For the mono-digestion of agricultural residue, the technical potential of electricity reached 1,360 $\mathrm{GWh_e y^{-1}}$ and the economic potential 1,112 $\mathrm{GWh_e y^{-1}}$ at a representative generation cost of 15.4 ct€ $\mathrm{kWh_e^{-1}}$ (see Figure 7.4.2). On the other hand, the generation of Bio-SNG from this substrate offered a technical potential of 351 $\mathrm{MMNm^3 y^{-1}}$ and an economic potential of 280 $\mathrm{MMNm^3 y^{-1}}$ at a representative generation cost of 40 € $\mathrm{MMBTU^{-1}}$ (see Figure 7.4.3).

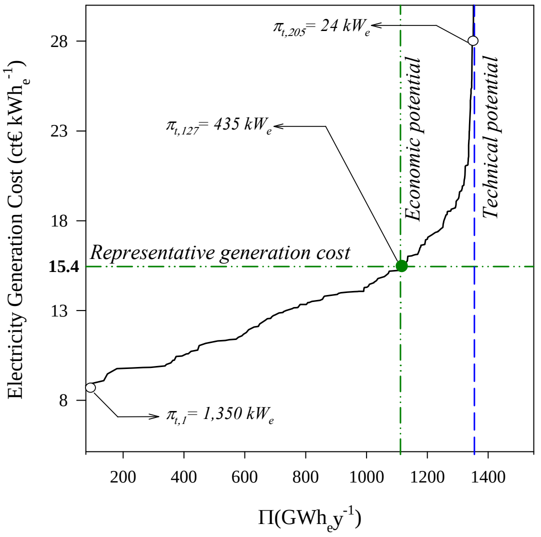

Figure 7.4.2. Supply-cost curve for biogas-to-electricity pathway by mono-digestion of agriculture residue.

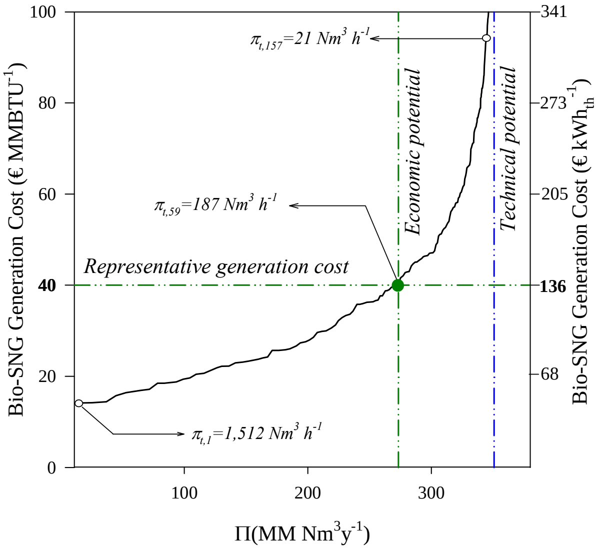

Figure 7.4.3. Supply-cost curve for the biogas-to-upgrade pathway by mono-digestion of agricultural residue.

A high concentration of this technical potential was observed in the low-power range (10-250 $\mathrm{kW_e}$) and accounted for 46% of the total. However, the 500 $\mathrm{kW_e}$-5 $\mathrm{MW_e}$ range had 33% of the total technical potential. For the Bio-SNG option, more than 57% of the potential was concentrated in a range lower than 1 $\mathrm{MM\,Nm^3 y^{-1}}$, followed by 22% at the 1.0-2.7 $\mathrm{MMN\,m^3 y^{-1}}$ scale. Geographically, the technical potential of electricity and Bio-SNG was concentrated in the Región de O´Higgins (VI) (32%), Región del Maule (VII) (19%) and Región de la Araucanía (IX) (18%) which represented almost 70% of the total, as seen in Figure7.4.4 and Figure 7.4.5.

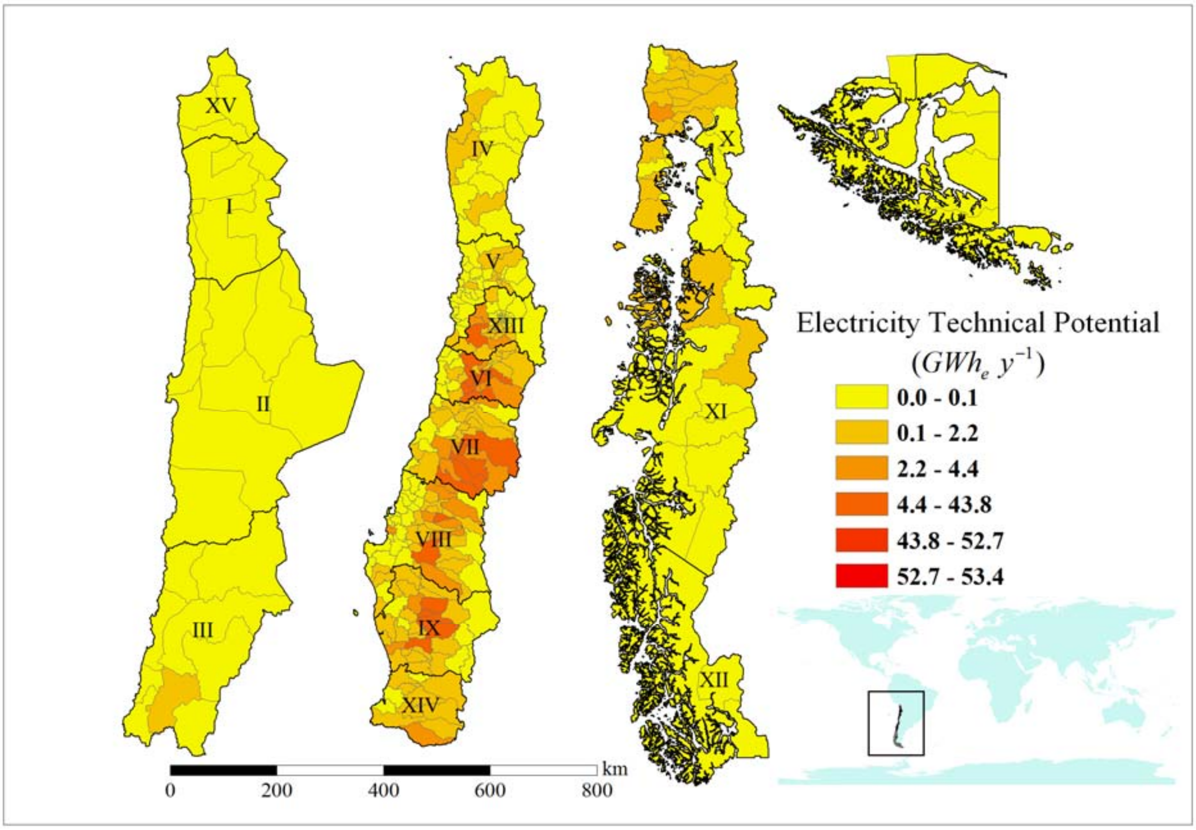

Figure 7.4.4. Technical potential of electricity from mono-digestion of agricultural residue.

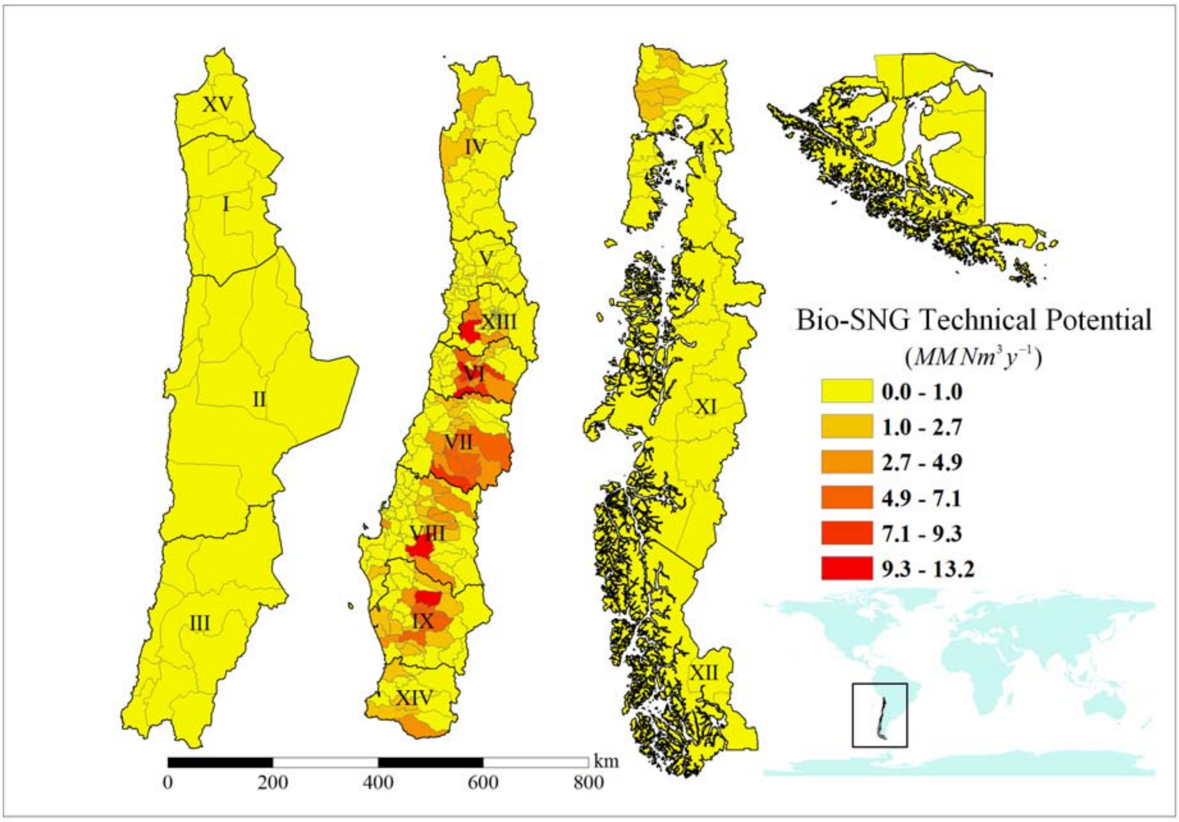

Figure 7.4.5. Technical potential of Bio-SNG from mono-digestion of agricultural residue.

7.4.5 Discussions

For the electricity alternative, as observed in Figure 7.4.6, there is a fraction of approximately 600 $GWh_e y^{-1}$ that may run profitably, when 12 $ct€kWh_e^{-1}$ is considered as the electricity market price. This realisable potential is made of 31 biogas plants with power capacity from 1.4 MW_e MWe to 94 kW_e . To achieve the economic potential, a generation subsidy of roughly 3.4 $ct€kWh_e^{-1}$ would be necessary.

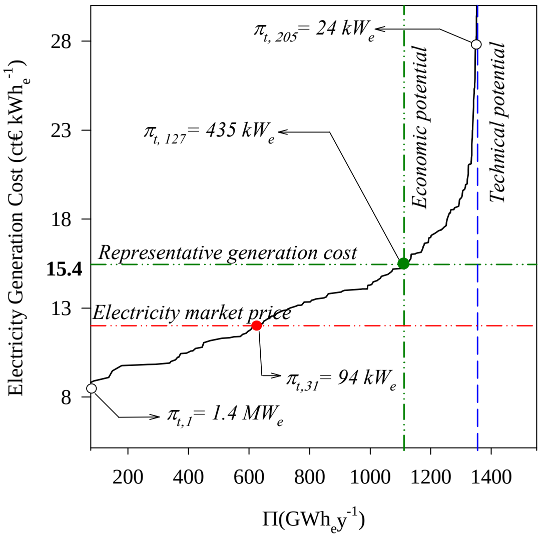

Figure 7.4.6. Supply-cost curve for biogas-to-energy pathway by mono-digestion of agricultural residue.

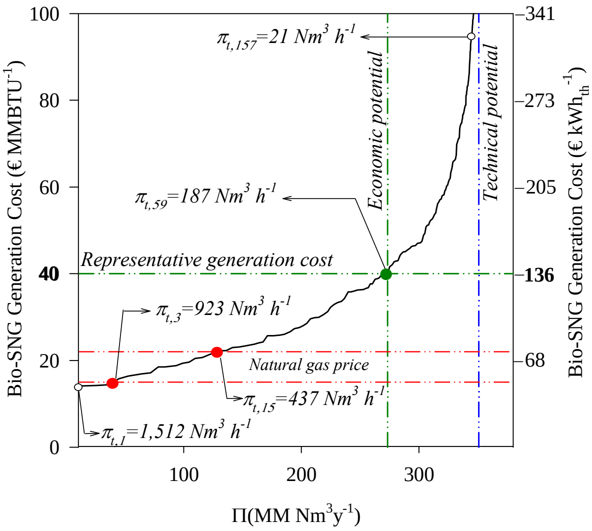

Figure 7.4.7. Supply-cost curve for biogas-to-upgrade pathway by mono-digestion of agricultural residue.

As shown in Figure 7.4.7, the biogas-to-upgrade route has only three units offering a cost of production lower than the market price of natural gas, although with capacities in the commercial scale. In spite of this advantageous condition, this high cost linked with relatively high capacity (in the context of biogas plants) is explained by the additional cost of production associated with the procurement of biomass (crop residue), which raises it somewhat, an aspect not present in the previously assessed sectors. This fact can be observed in the high associated generation subsidy (25-18 € $MMBTU^{-1}$) if this alternative were wanted to become profitable. Besides, the total annual subsidisation for Bio-SNG is approximately 82 MM€, almost five orders of magnitude greater than that of electricity, and with a considerably lower number of plants, 59 versus 127 (see Figure 7.4.6 and Figure 7.4.7).

Table 7.4.4 summarises the main economic indicators characterising the crop residue sector for the two possibilities of biogas processing, biogas-to-energy and biogas-to-upgrade.

Table 7.4.5. Energy potential of the biogas-to-energy and biogas-to-upgrade routes for crop residue utilisation.

	Route of conversion	
Economic indicator	Biogas-to-energy (BTE)	Biogas-to-upgrade (BTU)
Technical potential	1,355 $GWh_e y^{-1}$	351 MM Nm^3 y^{-1}
Economic potential	1,112 $GWh_e y^{-1}$	280 MM Nm^3 y^{-1}
Minimum cost of production	8.3 ct€kWh_e^{-1}	14.1 € $MMBTU^{-1}$
Representative generation cost	15.4 ct€kWh_e^{-1}	40 € $MMBTU^{-1}$
Needed feed-in tariff	3.4 ct€kWh_e^{-1}	25-18 € $MMBTU^{-1}$
Needed subsidy	17 MM€	82 MM€

7.4.6 Preliminary Conclusions

As observed for the previous sectors, the biogas-to-energy pathway implies a larger number of plants that can run without relying on subsidisation for energy generation (31 plants – see Figure 7.4.6). On the other hand, the biogas-to-upgrade exhibited a minimum cost of production (STAS) only slightly lower than the market price of natural gas, which makes the mono-digestion of this substrate hardly competitive.

As mentioned earlier, a significant geographic concentration of the technical potential, either electricity or BioSNG, was observed in three administrative areas, which correspond to Región de O´Higgins (VI), Región del Maule (VII) (19%) and Región de la Araucanía (IX) (18%). This being so, the implementation of bioenergy policy to boost biogas production should be considered as a priority to target.

7.5 Co-Digestion of Agro-Industrial Residue

Although crop residue, as previously described, can be converted anaerobically as if they were a single substrate, the option of mixing them with other feedstock such as manure offers significant advantages, among them an increase in biogas yield, operation of the reactor at higher solid concentration thus offering a larger gas flow at the same capacity, and more stable operation. The co-digestion is, however, limited both to the availability of feedstock, when the manure slurry is used as a substrate to increase solid concentration, and the total concentration of solids in the reactor, when a wet-technology is being used. These aspects will basically determine the possibility of implementation.

7.5.1 Introduction

The production of biogas from manure can be stepped up when co-substrates are added to make the biogas yield and the content of methane in the gas rise (Deublein & Steinhauser 2011), thus improving reactor efficiency and the economics of the plant. This enhancement can be explained because of the synergism in the reacting medium and the addition of some missing nutrients (Mata-Alvarez, *et al.* 2000).

The possibility of carrying out co-digestion is plausible, as livestock industries are normally located near the agricultural complex where residue might be available. However, the supply of biomass is restricted by logistical issues and the cost related to the procurement of substrates; the availability of manure is not necessarily associated with that of crop residue, and, conversely, the availability of manure at adequate scale is not necessarily associated with crop residues supplied at a proper rate. Nonetheless, considerable attention has been paid to the assessment of biogas by co-digestion in large areas (Szkliniarz & Vogt 2012; Zubaryera, *et al.* 2012), mainly as a consequence of the environmental gains as previously mentioned, but also because of the opportunities for rural development and the contribution this could make to reach the goal of renewable energy generation.

7.5.2 Methodology

The methodology for the potential analysis of co-digestion by mixing agro-industrial residue (i.e. manure and the material left on the field after the annual harvest) follows the same procedure applied for all the previously assessed sectors. Because this assessment only considers the possibility of mixing the substrates at a proper rate and concentration under the restrictions imposed by the geographical distribution of the feedstock, the specific parameters such as biomethane yield, rate of manure generation, crop productivity, etc. are the same here as those presented in sections 7.3 and 7.4.

7.5.2.1 Methodology for the Potential Analysis

As depicted in Figure 7.5.1, the co-digestion involves mixing a co-substrate (crop residue in this case) with manure for the purpose of improving the biogas generation. Nevertheless, the supplementary solid that can be added to the manure slurry is limited by the operating conditions of the anaerobic technology being employed. In general terms, anaerobic digestion technologies are classified into wet-fermentation and dry-fermentation. The former operates with a total solid concentration lower than 10-15% (dry basis), whereas the latter is adequate for a total solid concentration higher than 20% (Karthikeyan & Visvanathan 2013; Abbassi-Guendouz, *et al.* 2012). The dominant technology for the treatment of agricultural residues is wet fermentation (Karellas, *et al.* 2010), and, for the national potential analysis, it was used as the reference in this assessment. Thus, a total solid concentration in the digestor (x^m) of 15% as maximum limit was set up.

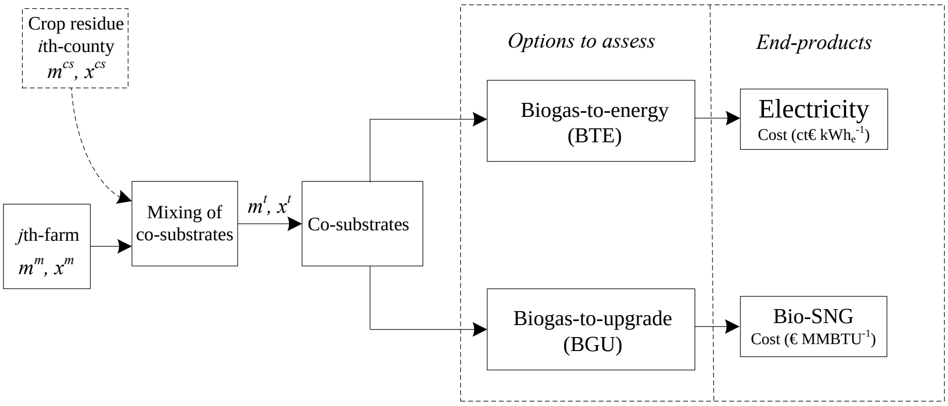

Figure 7.5.1. Conversion pathway for co-digestion of manure and crop residue.

The information provided in Table 7.3.1 can be used to calculate the solid concentration of the manure for each type of livestock. For instance, the concentration of total solid for dairy manure is 14%, while swine is 13%. For the assumed humidity of agricultural residue, 15% wet basis, its total solid concentration is 85%.

It can be demonstrated, by applying a mass balance (see Figure 7.5.1), that the maximum amount of co-substrate tolerable for a wet-fermentation mixing manure and crop residue, and the total mixed substrate to digest can be calculated with the following equations:

$$m_{\max}^{cs} = m^m \frac{(x^m - x_{\max})}{(x_{\max} - x^{cs})} \qquad \text{Equation 7.5.1}$$

$$m^t = m^m \frac{(x^m - x^{cs})}{(x_{\max} - x^{cs})} \qquad \text{Equation 7.5.2}$$

In which $m_{\max}^{cs}$ is the maximum amount of co-substrate to add for a wet-fermentation with manure; m^m is the total available manure per farm; x^m is the total solid manure concentration; x^{cs} is the total solid concentration of the co-substrate, in this case crop residue; and $x^{\max}$ is the maximum total solid concentration within the reactor for a wet co-fermentation, set up at 15% as previously indicated.

The availability of both substrates for co-digestion (i.e. manure and crop residue) depends on both the spatial distribution of farms and location of annual crops, which cannot necessarily be proportional or supplied because of the distance, in practical terms. Due to the fact that the assessment was conducted using the county as the smallest geo-administrative control area, a necessary condition for the co-digestion was that the totality of biomass (crop residue in this case) in each county (m_i) must be at least equal to the maximal amount of co-substrate to be added $(m_{\max}^{cs})$ to the totality of the farm-based units within that county. The latter can be expressed by a Boolean operator (A_c) to differentiate when the co-digestion can be performed or not, as indicated by Equation 7.5.3 and Equation 7.5.4.

$$\pi_{t,j}^{BTE} = \sum_j m_j^t \; S_c \; R_c \; \Delta\tilde{H}_{LHV}^{CH_4} \; \eta_a \; \eta_e \; A_e \; A_c \qquad \begin{cases} A_e = 1; \forall\, \pi_{t,j}^{BTE} \geq 8kW_e \\ A_e = 0; \forall\, \pi_{t,j}^{BTE} < 8kW_e \\ A_c = 1; \forall\, m_i \geq \sum_{i,j} m_{\max,j}^{cs} \\ A_c = 0; \forall\, m_i < \sum_{i,j} m_{\max,j}^{cs} \end{cases} \qquad \text{Equation 7.5.3}$$

$$\pi^{BGU}_{t,j} = \sum_i m^t_j \, S_c \, R_c \, \eta_a \; A_u A_c \qquad \begin{cases} A_u = 1; \; \forall \; \pi^{BGU}_{t,j} > 5 Nm^3_{CH_4} h^{-1} \\ A_u = 0; \; \forall \; \pi^{BGU}_{t,j} \leq 5 Nm^3_{CH_4} h^{-1} \\ A_c = 1; \; \forall \; m_i \geq \sum_{i,j} m^{cs}_{\max,j} \\ A_c = 0; \; \forall \; m_i < \sum_{i,j} m^{cs}_{\max,j} \end{cases} \qquad \text{Equation 7.5.4}$$

In which R_c corresponds to the yield of biomethane for co-digestion estimated in 250 $Nm^3_{CH_4} kg_{vs}$ as a representative value (Lehtomäki, *et al.* 2007), and S_c is the volatile-to-total solid ratio calculated for the mixing of manure and crop residue.

The technical energy potential of the entire country derived from the co-digestion of crop residue and manure either via the *biogas-to-energy* or *biogas-to-upgrade* route can be calculated by adding up the technical potential for all the *i*th-counties as Equation 7.5.6 indicates.

$$\Pi^{BTE}_t = \sum_j \pi^{BTE}_j \qquad \Pi^{BTU}_t = \sum_j \pi^{BTU}_j \qquad \text{Equation 7.5.6}$$

7.5.3.2 Methodology for the Economic Modelling

The economic modelling was conducted according the same procedure already applied for the evaluation of livestock farm and agricultural sectors (sections 7.3 and 7.4, respectively), and consequently by using identical economic and technical parameters. In these terms, the cost of feedstock supply was estimated by using the square-shape approximation of the county where the biomass is available. Moreover, no use or commercialisation of the by-products heat and fertiliser were considered on account of the same reason above given.

7.5.3.3 Methodology for the Economic Potential

The mathematical method for computing the representative generation cost and the corresponding economic limit can be found in detail in Chapter 4 or as already illustrated in previous sectors. Following the same methodology, the estimation of the needed feed-in tariff and the total yearly needed subsidisation was calculated.

7.5.3 Results

The possibility of co-digesting manure with agricultural residue offered an increase in the economic limit for the electricity generation option and provided the same representative generation cost as the mono-digestion of manure. As observed in Figure 7.5.2, the co-digestion raised the economic potential from 780 $GWh_e y^{-1}$ to 1,140 $GWh_e y^{-1}$ at a representative generation cost of 25 $ct€\,kWh_e^{-1}$. This greatly increased the number of biogas plants that could achieve the minimal technical conditions to operate. As seen in Figure 7.5.2, whereas the economic limit of biogas-to-energy from mono-digestion of manure was made up of 367 plants, with nominal capacities from 22 MW_e to 25 kW_e, the economic limit of biogas-to-energy via co-digestion accounts for 1,108 plants with nominal capacity in a similar power range.

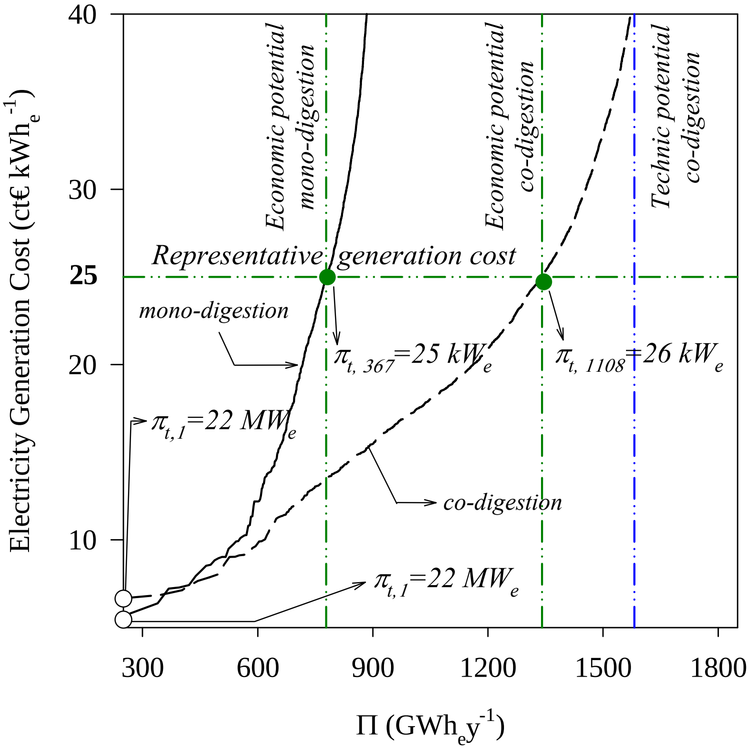

Figure 7.5.2. Supply-cost curve for the electricity generation of co-digestion of manure and crop residue.

Although the increase in electrical potential by the co-digestion was significant at 46%, the power capacity was still concentrated in the low scale and accounted for 39% in the range from 10 to 250 kW_e, and 31% were lower than that of 10 kW_e. Potentials exceeding 5 MW_e were exceptional, and constituted less than 3% of the technical potential.

The assessment of the biogas-to-upgrade route was conducted following the same methodological approach applied to the biogas-to-energy pathway by considering co-digestion; however, the results led to an increase in the Bio-SNG potential predominantly in the low range, with the consequence that the representative generation cost reached extremely high and empirically unprecedented levels. Nevertheless, counties were found where it would be possible to develop Bio-SNG exploitation projects at commercial scale, although they represented no more than 15% of the total technical potential. Similar to the mono-digestion option, only two regions concentrated more than 61% of the technical potential, Región Metropolitana (XIII) and Región de la Araucanía (IX).

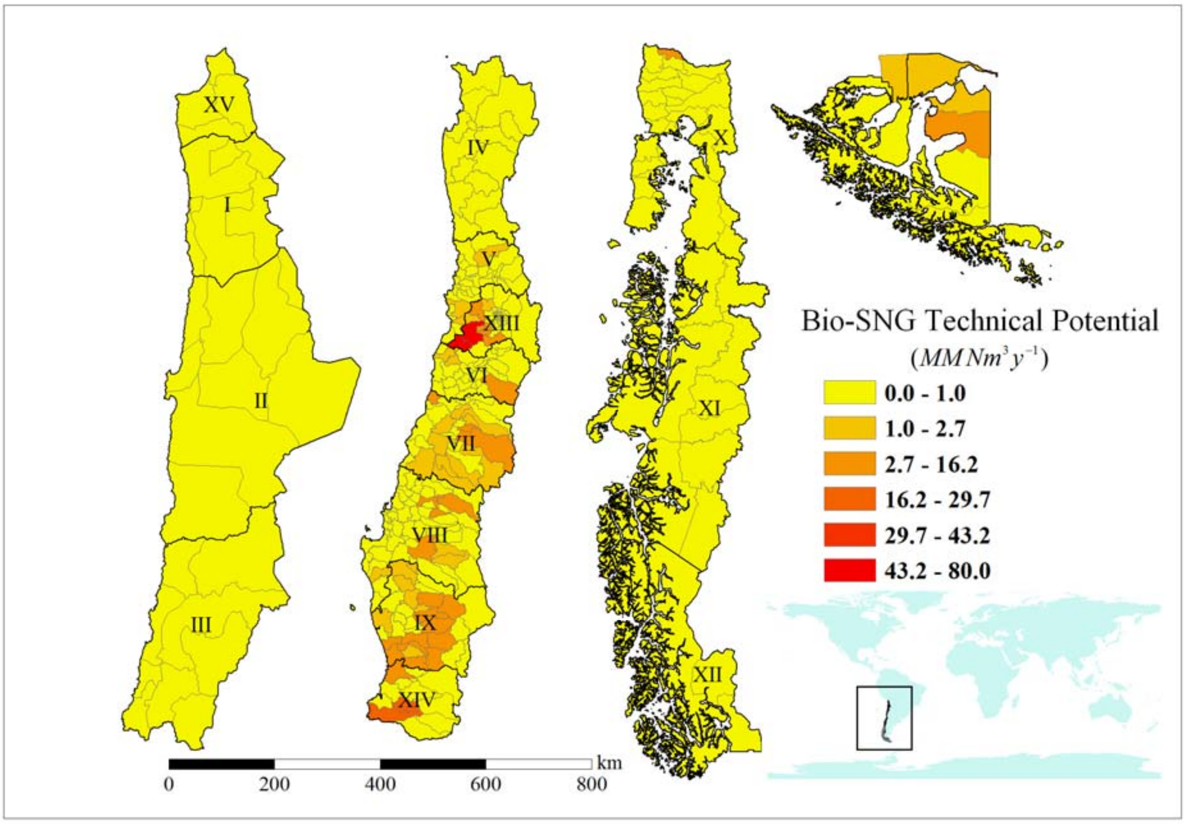

Figure 7.5.3. Technical potential of Bio-SNG from co-digestion of manure and agricultural residue.

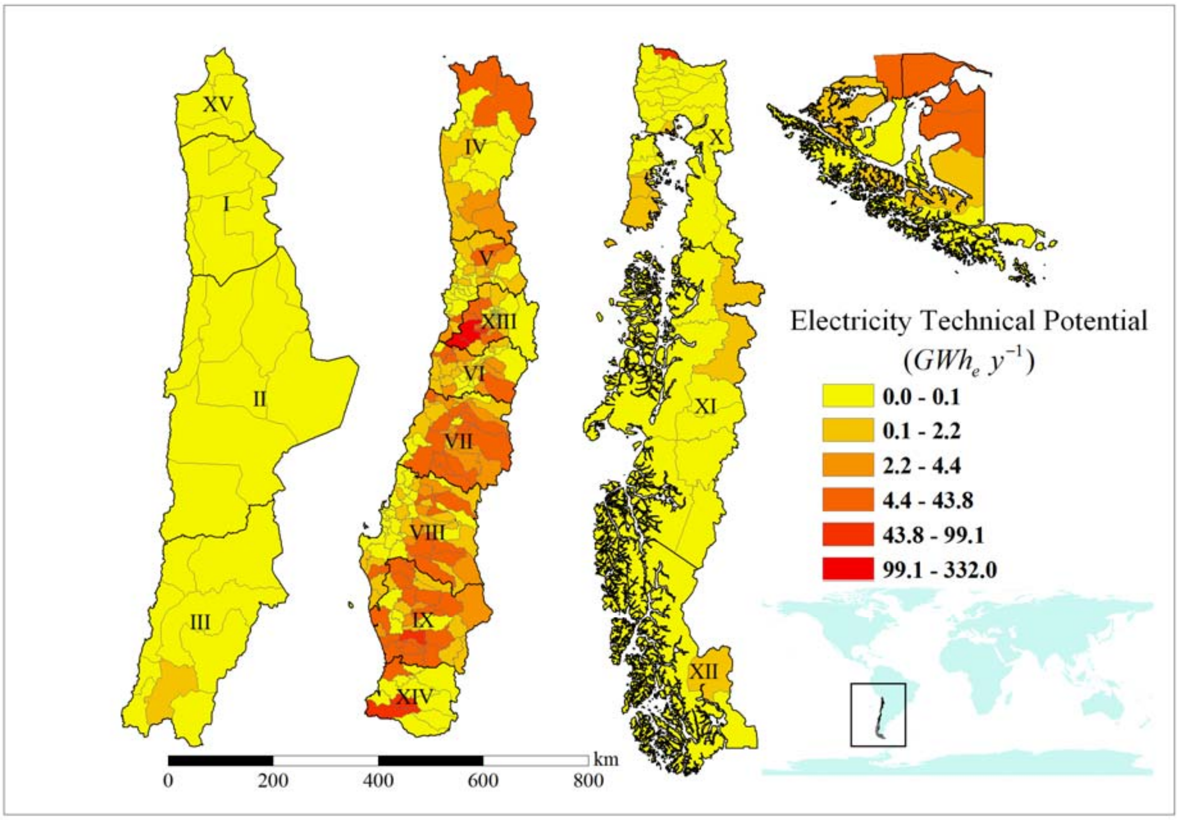

Figure 7.5.4. Technical potential of electricity from co-digestion of manure and agricultural residue.

Additionally, it was found that the technical potential of electrical power on the national level was heavily concentrated on the small-scale, in the 10-250 kW_e range, and accounted for 71% of the country's total. A similar tendency was observed in the technical potential of Bio-SNG, in which approximately 80% of the potential was concentrated on a scale lower than 1 $MMNm^3y^{-1}$, with only 12% in the 1.0 - 2.7 $MMNm^3y^{-1}$ range.

7.5.4 Discussions

As previously indicated, the representative generation cost for electricity generation was not modified as a consequence of the co-digestion in spite of being increased substantially the technical and the economic potential, the later from 779 GWh_ey^{-1} to 1,338 GWh_ey^{-1}. Consequently, the co-digestion gave rise to the number of biogas plants making up the economic potential, from 376 to 1,108, almost three times the order of magnitude.

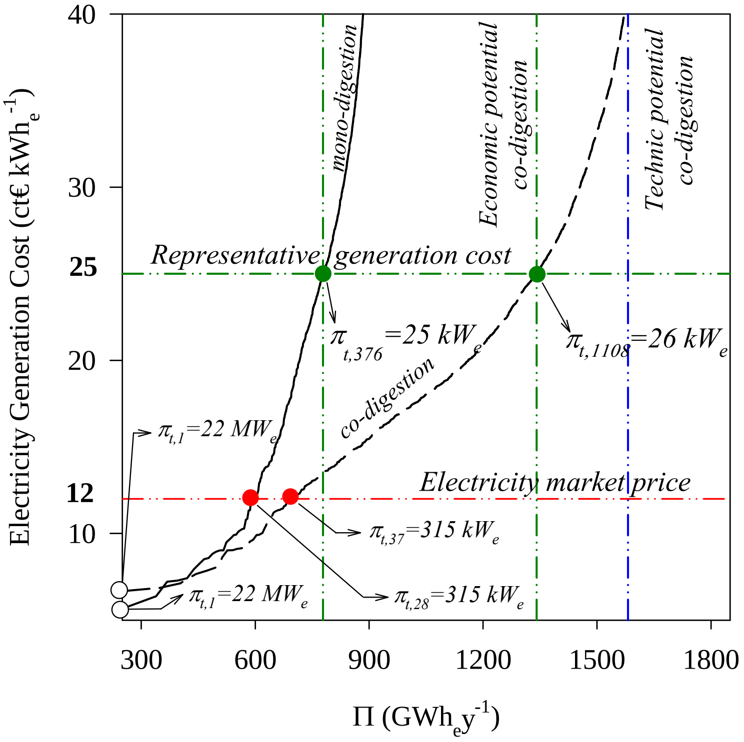

Figure 7.5.5. Supply-cost curve for the electricity generation of co-digestion of manure and agricultural residue.

Although the same methodological approach used for the assessment of the biogas-to-energy route was applied, the results led principally to an increase in the Bio-SNG potential in the very low range, with the consequence that the representative generation cost rose to high levels; however, this should not be used as a means of evaluation because it is only relevant in a theoretical context and has no practical meaning; therefore, it was not included in Table 7.5.1. Nevertheless, counties were found where it would be possible to develop Bio-SNG exploitation projects at commercial scale.

Table 7.5.1. Energy potential of biogas-to-energy and biogas-to-upgrade for co-digestion of agro-industrial residue.

Economic indicator	Route of conversion	
	Biogas-to-energy (BTE)	Biogas-to-upgrade (BTU)
Technical potential	1,582 GWh$_e$y^{-1}	429 MM Nm^{3}y^{-1}
Economic potential	1,338 GWh$_e$y^{-1}	-
Minimum cost of production	5.2 ct kWh$_e^{-1}$	-
Representative generation cost	25.0 ct kWh$_e^{-1}$	-
Needed feed-in tariff	13.0 ct kWh$_e^{-1}$	-
Needed subsidisation	84 MM € y^{-1}	-

7.5.5 Preliminary Conclusions

On the basis of the assessment presented above, co-digestion is possible to be carried out in economic terms and its implementation may provide a significant increase in the economic potential of the electricity option. As observed systematically for the four sectors previously assessed, a high concentration of the potential is observed, and for this option (i.e. co-digestion of agro-industrial residues) in only two regions located in the south of the country. On the contrary, the biogas-to-upgrade route as the main option does not seem advantageous since the potential is concentrated mainly in the low scale, in which the Bio-SNG option exhibits a highly sensitive cost of production. In these terms, the biogas-to-energy pathway offers greater flexibility in terms of the potential and distribution of biomass available in the country.

7. Results

7.1 Municipal Solid Waste Sector

The potential energy that could be derived from municipal solid waste (MSW) in Chile was analysed using the proposed methodological approach based on a techno-economic assessment described in Section 4. Supply-cost curves were used to present and compare the aggregated data for the energy potential and the cost of energy generation. The electricity generation alternatives assessed were landfill gas-to-energy (LGTE) and direct waste-to-energy (WTE) as well as gas collection and upgrading to feed into the grid (LGU). These options were evaluated and subsequently compared using such criteria as the production cost, the technical and economic potential and the challenges for the country in the near future.

7.1.1 Introduction

Municipal solid waste (MSW) generation is a major topic in the management and planning of modern societies. MSW applies pressures to both the environment and the health of the population, steadily accumulating cost for management and potentially detracting from the population's standard of living. Furthermore, the public's greater awareness of environmental matters leads to additional motivation via environmental issues, resulting in demands on authorities for stricter control and environmentally sound strategies for addressing this problem.

Although the hierarchy of landfilling versus incineration as the most effective method to treat MSW is unclear because it depends on local particularities (Dijkgraaf & Vollebergh 2004, 2008; Themelis 2008), there is consensus that recycling offers substantial benefits and must be considered as the starting point of any national MSW policy; this consideration would facilitate the decoupling of the MSW generation rate from economic growth (an aspect particularly relevant for developing countries), the reduction of biodegradable matter deposition and the subsequent uncontrolled emission of such greenhouse gases (GHG) as methane, carbon dioxide, ammonia and other trace compounds. Nonetheless, recycling demands relevant modifications to the habits of a population; for instance, the introduction of well-distributed curb-side services throughout the country (for collection of plastic bottles, glass, paper, etc.), the existence of a formal industry able to recover and process the recycled material and actively coordinated actions among the public entities responsible for household waste.

In Chile, approximately 6.5 millions of tons of MSW were generated in 2008 (Pérez 2010), and, since the System of Environmental Evaluation (SEE) came into force in 1997, the country has made considerable progress in matters of collection, recycling, minimisation and landfilling of MSW. Approximately 60% of the total MSW generated was collected in the municipalities (data from 2008), with a rate of approximately 80% collection in municipalities with populations upwards of 50,000 inhabitants (Machado & Malarín 2007). Furthermore, the country contains an internal market for recycled plastic, cardboard, glass, aluminium and scrap, accounting for 11% in the Metropolitan Region (Bräutigam & González 2012).

Beyond the progress accomplished thus far, significant challenges remain to improving the management of a growing amount of MSW associated with the rising income levels observed in recent decades as well as demographic growth. Modifications of recent sanitary regulations should improve the conditions of final MSW deposition sites.

7.1.2. MSW Management

According to the new laws and regulations in Chile (Willumsen 2005; Decree 189), final deposition sites are classified under three categories: a *sanitary landfill* is defined by such requirements as impermeable liners, leachate collection and lixiviation treatment systems. The second category is a *landfill dump*, which consists of dumps where the MSW is deposited without major technical requirements; these dumps are only allowed to operate under exceptional conditions; this type of deposition site is being eliminated and should be completely gone within the current year. The final category is *illegal dumps,* which, as their name suggests, do not fulfil the established sanitary conditions, and consequently, are illegal to operate.

Methane is continuously released mainly during landfill operation, but it can also extend long after landfill closure; methane generation is uncontrollable because it is produced by the anaerobic microbiological activity within the landfill material. Worldwide methane emissions from landfills are estimated at 35-73 Tg of the total 598 Tg per year (IPPC 2001). Because methane is a greenhouse gas (GHG) with commercial value, a permanent effort has been made to capture and use it as a source of energy (Methane to Markets 2004). Until recently, it has been primarily used for electricity generation and direct heating, and to a lesser degree, as a pipeline gas for injection into distribution networks (Themelis & Ulloa 2007).

An alternative to direct landfilling is the waste-to-energy option (WTE), which was previously known as incineration. This method uses the MSW (with or without sorting) as a fuel to generate energy via a (normally) combined heat and power scheme. The WTE technology has exhibited a noteworthy improvement in performance in recent years, with the integration of enhanced abatement control of pollutants. The U.S. Environmental Protection Agency (EPA) named WTE technology as *one of the cleanest sources of energy* (Psomopoulos, *et al.* 2009) due to the steadily diminishing levels of dioxin, furan, mercury and other heavy metal emissions over the last twenty years. From an international perspective, Taiwan constitutes a unique experience in the field (Kuo, *et al.* 2008) incinerating 53% of its MSW (data from 2008). Close on the heels of Taiwan are Denmark, which incinerates 48% of MSW, Switzerland and Sweden with 49%, the Netherlands at 39% and Germany at 34% (data from 2009) (Eurostat News Release 2011).

Today, there are approximately 39 landfills operating in Chile (data from 2011) (National Service of Environmental Assessment 2012), with an approximate average population of 420,000 inhabitants served per landfill. Fourteen of these landfills have incorporated clean development mechanisms (CDMs) (CGF-MDL 2011) in which collection systems were implemented primarily to flare the released gas. Only one landfill has implemented gas capture to produce electricity, attaining a current generation capacity of 14 MW_e that is projected to reach 28 MW_e by 2024. No application of landfill gas recovery for injection into the country's natural gas grid exists yet, nor are there any incineration facilities.

The aim of this section is to explore the uses of MSW generated in Chile for energy recovery at the national level via an economic assessment of three energy alternatives based on state-of-the-art technologies and without proposing substantial modifications to MSW collection. The energy options considered in this research, and schematically presented in Figure 7.1.1, are: i) burning of spontaneously generated landfill gas that is captured to produce electricity (LGTE); ii) direct use of unsorted MSW via incineration (WTE); and iii) landfill gas recovery and upgrade for injection into the natural gas grid (LGU).

At a regional level, Amini & Reinhart (2011) evaluated the recovery of landfill gas in Florida (USA) by applying selected modification to the LandGEM model. The modified assessment considered the generation of electricity via direct combustion and an equivalent gaseous fuel, although an economic evaluation of the end-product cost was not incorporated. An alternative approach was discussed by Schneider *et al.* (2012), who proposed an evaluation of the use of landfill gas for electricity production (LGTE), MSW use for refuse-derived fuel (RDF) in the cement industry, landfill gas flaring, waste-to-energy (WTE) (also known as incineration and thermal treatment) and mechanical-biological treatment (MBT). The assessment was conducted by comparing the specific cost reduction for the above-mentioned alternatives. Each conversion route was evaluated for a typical plant size.

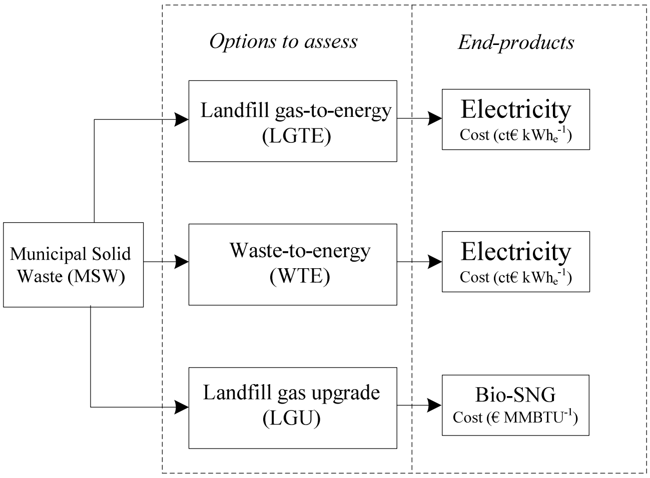

Figure 7.1.1 Energy options for assessment for MSW utilisation.

Although the mechanical-biological treatment (MBT) seemed promising, it was not considered within the scope of the evaluation because this approach requires sorting and other intermediate pre-treatments. Furthermore, from preliminary experience, the MBT performance is highly dependent on the involved mechanical treatment steps and the quality of the raw material, as discussed by Bayard *et al.* (2010). A specific study is needed for assessment of the MBT option at a regional or national level, which can be carried out in follow-up research.

7.1.3. Methodology

The following sub-sections present the methodology applicable to the previously indicated three conversion routes in MSW analysis. It structures the specific economic and technical framework under analysis and allows for the comparison of conversion routes, their potential and the cost of their end products, with a particular focus on the conditions of the conversion option within a market framework.

7.1.3.1 Methodology for the Technical Potential

The estimation of the MSW was carried out for each landfill in operation using technical information published by official government entities and the approximate serviced population, in addition to the composition and characteristics of the MSW (National Service of Environmental Assessment 2012). In the calculation, a specific MSW generation rate per inhabitant (R) was applied to each administrative region. The value of this indicator, shown in Table 7.1.1, is in agreement with the country's economic development. For instance, the U.S. produced 0.733 t $hab^{-1}y^{-1}$ (data from 2008) (EPA 2011); in the European Union this value reaches 0.542 t hab^{-1} y^{-1} (data from 2008) (Waste Oportunities 2011), whereas in urban India this value ranges from 0.50 to 0.70 t $hab^{-1}y^{-1}$ (data from 2008) (Jha, *et al.* 2008).

Table 7.1.1 Specific MSW generation rate in Chile per inhabitant per administrative region (Pérez 2010).

Country region's name	R_j (t $hab^{-1}y^{-1}$)	Country region's name	R_j (t $hab^{-1}y^{-1}$)
Región Arica y Parinacota (XV)	0.59	Región Libertador B. O'Higgins (VI)	0.24
Región de Tarapacá (I)	0.59	Región del Maule (VII)	0.30
Región de Antofagasta (II)	0.34	Región del Biobío (VIII)	0.29
Región de Atacama (III)	0.37	Región de la Araucanía (IX)	0.34
Región de Coquimbo (IV)	0.22	Región de los Lagos (X)	0.32
Región de Valparaíso (V)	0.34	Región de Aysén (XI)	0.39
Región Metropolitana (XIII)	0.42	Región de Magallanes (XII)	0.39
		Región de los Ríos (XIV)	0.36

Although the specific MSW generation rate depends on the socioeconomic level of the population as well as its consumption habits, this rate was assumed as constant for each administrative region and simply adjusted to the year of evaluation (2011) by assuming a linear proportionality with an expected annual economic growth rate of 6.3% for 2011 (Financial News 2012[c]).

The main components of landfill gas are methane (40%-60%), carbon dioxide (35%-50%), nitrogen (0%-20%), oxygen (0%-1%), hydrogen sulphide (50-200 ppm) and ammonia (5 ppm, typically) (Rasi, *et al.* 2011). The organic silicon compound concentration in landfill gas is particularly high (Dewil, *et al.* 2006), ranging from 3 to 24 mg Nm^{-3} (Ajhar, *et al.* 2010). Numerous volatile organics (VOC), aromatics and halogenated compounds are present, and in certain cases, more than one hundred trace compounds have been reported. This complexity is a consequence of the heterogeneity of the residues and the uncontrolled conditions under which a landfill operates. The generation rate of landfill gas additionally depends on local conditions and seasonal variations (i.e. humidity, temperature, rainfall) as well as the type of landfill operation and how the MSW is deposited. Furthermore, the gas release is intrinsically related to the opening and closing times. There are numerous models available to estimate the landfill gas emitted on a temporal basis although significant differences between cases are generally observed in the predictions (Thompson, *et al.* 2009; Ritzkowski & Stegmann 2007; Meraz, *et al.* 2004; EPA 2005).

According to Themis *et al.* (2007), the capture of landfill gas (M), expressed as pure methane, is in the 100-150 $\mathrm{Nm}^3_{\mathrm{CH_4}}\mathrm{t}^{-1}$ range and depends on the way in which the gas is collected (i.e. whether it uses a passive venting or active collection system, vertical wells or horizontal gas collection trenches, etc.). Thus, a conservative estimate of 50 $\mathrm{Nm}^3_{\mathrm{CH_4}}\mathrm{t}^{-1}$ from placed MSW was employed for the methane generation rate from a landfill, following the recommendations given by the same author. Therefore, the gas flow, expressed as pure methane that can be technically recovered and upgraded is calculated as indicated in Equation 7.1.1.

$$\pi_{t,i}^{LGU} = M\ R_j\ P_i \qquad \text{Equation 7.1.1}$$

In which $\pi_{t,i}^{LGU}$ is the methane technically recovered from the *i*th-landfill, *P* is the population serviced (hab) at the *i*th-landfill, R_j is the MSW generation rate per capita (t hab^{-1}y^{-1}) of the *j*th-administrative region and *M* is the methane-landfill gas recovered per unit of landfilled MSW ($\mathrm{Nm}^3_{\mathrm{CH_4}}\mathrm{t}^{-1}$). The technical potential of the electricity generated by burning the landfill gas can be calculated as indicated in Equation 7.1.2.

$$\pi_{t,i}^{LGTE} = M\ R_j\ P_i\ \Delta\tilde{H}_{LHV}^{CH_4}\ \eta_e \qquad \text{Equation 7.1.2}$$

In which η_e corresponds to the electrical efficiency of the conversion units, $\Delta H_{LHV}^{CH_4}$ is the lower heating value of methane estimated as 50,000 kJ kg^{-1} (Avallone, *et al.* 2007), and equivalent to approximately $31.59\ \mathrm{Nm}^3_{\mathrm{CH_4}}\ \mathrm{MMBTU}^{-1}$. If reciprocating engines are sufficient for the power range of the landfills under analysis, this equipment will be used as a reference technology in the assessment for the conversion of the landfill gas to electricity presented in the forthcoming section.

Regarding the composition and the corresponding humidity for the sorted components, Table 7.1.2 shows the MSW characteristics in the XIII Region (also called the Metropolitan Region) (Bräutigam & González 2012), which was taken as representative for the entire country due to the lack of more specific information.

Table 7.1.2. Composition, humidity and lower heating value (dry) of MSW components.

MSW Component	MSW composition as received (%)	Estimated humidity (%) (wet basis)	LHV (kJ kg^{-1})
Paper and cardboard	10.7	0.5	10,000
Fabrics	3.5	1.0	12,500
Plastics	10.8	1.5	28,000
Glass	6.3	0	0
Metals	3.2	0	0
Organic matter	49.4	29.5	3,300
Miscellaneous components	16.1	0	14,300
Dust-ash	1.2	0	0

Considering the lower heating value of each component (Finet 1987) and its humidity (Bräutigam & González 2012), an average heat of combustion (LHV) of 7,930 MJ t^{-1} for a homogenous fuel is estimated for this MSW; this value is then used for the estimation of the technical potential on a thermal basis, as Equation 7.1.3 indicates. The electrical potential of burning the MSW without sorting (WTE) is then calculated by considering an electrical efficiency (η_e) of 21% (Burnley, *et al.* 2011).

$$\pi_{t,i}^{WTE} = \Delta\tilde{H}_{LHV}^{MSW}\ R_j\ P_i\ \eta_e \qquad \text{Equation 7.1.3}$$

The technical potential of the entire country, either for the electricity or gas evaluation route, can be calculated as the sum of all single technical potentials on the *nth*-landfills and for each conversion pathway, as shown in Equation 7.1.4.

$$\Pi_t^{LGTE} = \sum_{i=1}^{n}\pi_{t,i}^{LGTE} \qquad \Pi_t^{WTE} = \sum_{i=1}^{n}\pi_{t,i}^{WTE} \qquad \Pi_t^{LGU} = \sum_{i=1}^{n}\pi_{t,i}^{LGU} \qquad \text{Equation 7.1.4}$$

7.1.3.2 Methodology for the Economic Modelling

The unitary cost of electricity or upgraded gas generated from each landfill is calculated according to Equation 7.1.5.

$$c_i\pi_{t,i} = \alpha I_i + C_{o\&m,i} - R_i \qquad \text{Equation 7.1.5}$$

In which c_i is the unitary cost of secondary energy, either for the landfill gas-to-energy (LGTE), waste-to-energy (WTE) option, or landfill gas upgrade (LGU) alternative. The parameter α is the capital recovery factor, calculated with an annual interest rate of 10% and a fifteen-year lifetime for all cases. The annual operation and maintenance cost, $C_{o\&m}$, was estimated as a fraction of the investment, a methodology based on mathematical regressions of economic data published elsewhere and an approach used in pre-feasibility studies and economic analysis (Chauvel, *et al.* 2003; Couper 2003). A location factor of 1.08 was included as the investment for the country; this factor mainly addresses the additional cost for freight, taxes and insurance (Chauvel, *et al.* 2003). The value of R_i corresponds to revenues, which may be incorporated as heat generated for sale or re-use of any by-product. Because Chile does not have a district heating market, revenues were not incorporated (OECD-B 2012). Detailed information of the methodology and technical and economic information is given in Chapter 4 and Chapter 6.

Landfill gas extraction is the first step of the recovery. The collection system contains a set of extraction wells that are normally located at selected depth intervals and share a common collection point by means of a pipe network. Afterwards, the gas is normally desulphurised by a conventional activated carbon system and then burned to produce electricity, as previously mentioned. On the other hand, in the WTE option, the MSW is combusted at high temperature (above 800°C), and the heat generated is then used in a steam power generation cycle to produce electricity. The current development status of WTE technologies may allow its use without creation of dioxin pollution (Cheng & Hu 2010; Zhiqiang, *et al.*; 2006; Montejo, *et al.* 2011). WTE is an advanced technology characterised by a heavy investment and high operating cost and is appropriate in most cases when landfilling is unfeasible (Rand, *et al*. 1999; Rand, *et al*. 2000) The main solid residue is ash, and its generation rate depends on the MSW composition. This residue could be used as a by-product in construction applications but a large fraction must be landfilled. The final ash deposition cost (transportation included) for this assessment was estimated at 16 € t^{-1} (Willumsen 2005).

The third energy alternative for evaluation corresponds to the generation of a gaseous fuel by treatment of the landfill gas. The product was defined as a bio-substitute natural gas (Bio-SNG) because it fulfils the definition of originating from biomass digestion and has the capacity for subsequent improvement and adjustment of properties for injection into the net distribution or for use as a fuel for vehicles (Steifer 2009).

In a simplified representation, the treatment of landfill gas to produce high-quality pipeline gaseous fuel can be split into the steps of collection, cleaning, upgrading and feed-in, as analogously described in Chapter 5. Normally, in the cleaning step, hydrogen sulphide and other sulphur compounds are removed through a conventional active carbon adsorption, alone or in combination with chilling systems (Urban, *et al.* 2009). The next step contains the most expensive unit in this chain in which carbon dioxide is uptaken by a technology such as pressure swing absorption (PSA), pressure water wash (PWW) (Läntela, *et al.* 2012), or amino-chemical absorption (Gaur, *et al.* 2012). In addition to carbon dioxide removal, the simultaneous elimination of ammonia take places as well as sulphur, halogenated and silicon compounds; in most cases, these two steps are sufficient to satisfy the most relevant gas injection requirements. Although there are differences in the cost of carbon dioxide uptake between the previously mentioned technologies, these differences intrinsically depend on utility prices (i.e. electricity, cooling water, labour, etc.) and landfill gas flow to be treated. Nevertheless, for this study, no differences in the upgrade technology investments and operating cost are assumed, such that a unique mathematical relation can correlate them, as discussed in previous chapters.

Economic information from the literature and other technical reports was gathered for the estimation of the investment and total the operation cost for landfill gas collection systems (see Chapter 4), waste-to-energy facilities (Gómez, *et al.* 2010; Zabaniotou & Giannoulidis 2002), upgrade units and gas injection systems for feeding into the natural gas grid (Althaus & Urban 2005; Urban, *et al.* 2005) as well as for reciprocating engines for electricity generation (ASUE 2011). The value of 0.22 $\mathrm{ct€\,Nm^{-3}_{CH_4}}$ was used for the desulphurisation cost, according to Mescia *et al.* (2011). Table 6.1 summarises the economic information related to the investment and to operation and maintenance cost as well as key technical figures such as the conversion efficiency of each technological pathway to be assessed, i.e., collection of landfill gas and its posterior direct burning in a reciprocating engine (LGTE), waste-to-energy (WTE) and the collection of landfill gas and follow-up upgrade to feed-in (LGU). This information was subsequently incorporated into the economic model defined in Equation 7.1.5. In each case, the representative generation cost and the economic potential were calculated as described in the following section.

7.1.3.3 Methodology for the Economic Potential

For the three energy alternatives proposed, supply-cost curves were used to conduct the potential analysis with selected adaptations made for the purposes of this study as previously mentioned in chapter 4 *Methodology for the Potential Analysis at National Level*. The supply-cost curve was built for each conversion route, i.e. LGTE, WTE and LGU, by assessing the unitary cost for each single potential $\pi_{t,i}$. The representative generation cost is then expressed as the most frequent cost and mathematically calculated in the statistical mode as follows:

$$c_r = \text{mode}[c_i(\pi_{t,i})] \qquad \text{Equation 7.1.6}$$

After calculating the representative generation cost, the economic potential of the technology can be estimated by interpolation with the supply axes. Therefore, the economic potential can be interpreted as the total amount of energy that can be generated at a cost lower than the representative generation cost. The comparison between the representative generation cost (c_r) for each secondary energy, either gaseous fuel or electricity, with its average market price is performed to discuss the economic cost effectiveness of each assessed option and to identify the need for subsidies if the process is not economically competitive.

Finally, the information is integrated into a geographical information system (GIS), in which the energy potential map can be visualised with the *county* as the smallest geo-administrative control area for each of the regions composing the country.

7.1.4. Results

Figures 7.1.2 and 7.1.3 display the supply-cost curves for electricity generation through the collection and burning of landfill gas (LGTE) and by waste-to-energy (WTE) without sorting. The former option exhibits a technical potential of approximately 1.1 $\text{TWh}_e\ y^{-1}$ with a representative generation cost of 11.0 ct€ kWh_e^{-1}, whereas the latter offers a technical electrical potential of approximately 2.2 $\text{TWh}_e\ y^{-1}$ and a representative generation cost of electricity of 10.6 ct€ kWh_e^{-1}.

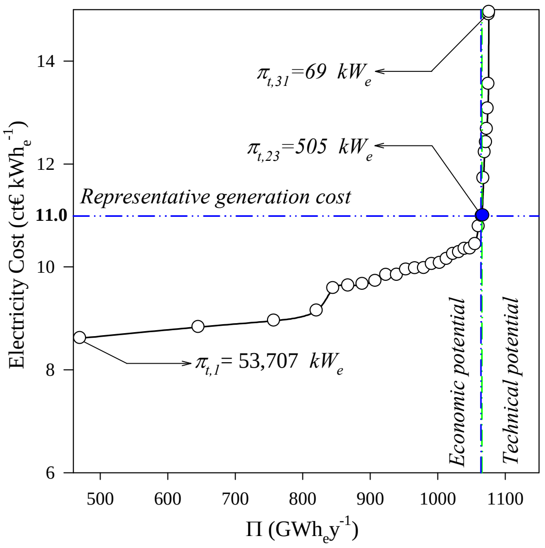

Figure 7.1.2. Supply-cost curve for landfill gas-to-energy option (LGTE).

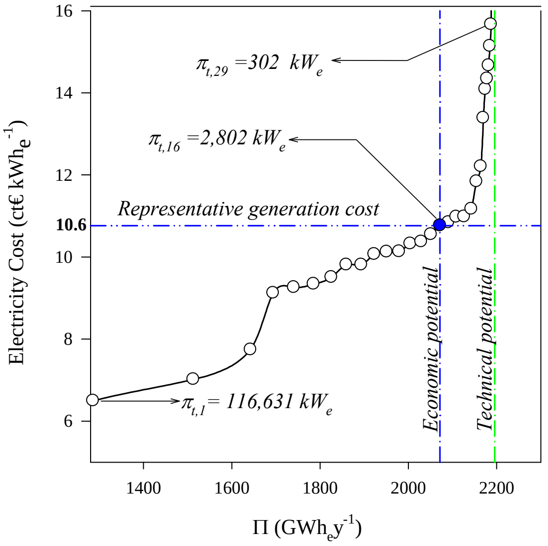

Figure 7.1.3 Supply-cost curve for waste-to-energy option (WTE).

The technical and economic potential of the LGTE option are practically identical (see Figure 7.1.2); therefore, it is made of the 23 largest landfills in operation. On the other hand, as Figures 7.1.3 shows, the economic potential of the WTE option is approximately 95% of the technical potential and can be supplied by the MSW currently disposed of in the 16 largest landfills.

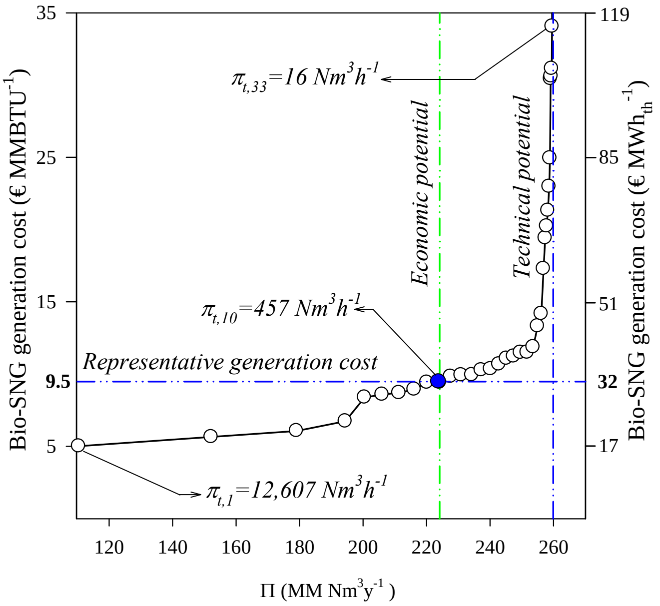

Figure 7.1.4. Supply-cost curve for landfill gas upgrade option (LGU).

The third energy alternative involves the collection of landfill gas released under uncontrolled conditions and the subsequent upgrades required for injection into the natural gas grid. Due to the difference between the forms of secondary energy generated in the two previous alternatives, the figure was also expressed in millions of British Thermal Units (MMBTU), the unit commonly used in official energy statistics of LNG and natural gas prices (BP 2013). For the totality of landfill gas under evaluation, the representative cost of the upgraded gas is 9.5 € $MMBTU^{-1}$ with a technical potential of 260 MM Nm^3 y^{-1}. The economic potential is approximately 86% of the technical potential and can be supplied by the 10 largest landfills in operation.

Table 7.1.3. Energy potential of the three assessed options for MSW utilisation.

	Alternative of energy generation from MSW		
Economic Indicator	Landfill gas-to-energy (LGTE)	Waste-to-energy (WTE)	Landfill gas-to-upgrade (LGU)
Technical potential	1.1 TWh_e y^{-1}	2.2 TWh_e y^{-1}	260 MM Nm^3 y^{-1}
Economic potential	1.1 TWh_e y^{-1}	2.1 TWh_e y^{-1}	224 MM Nm^3 y^{-1}
Minimum cost of production	5.4 ct€ kWh_e^{-1}	8.6 ct€ kWh_e^{-1}	5.0 € $MMBTU^{-1}$
Representative cost	11.0 ct€ kWh_e^{-1}	10.6 ct€ kWh_e^{-1}	9.5 € $MMBTU^{-1}$

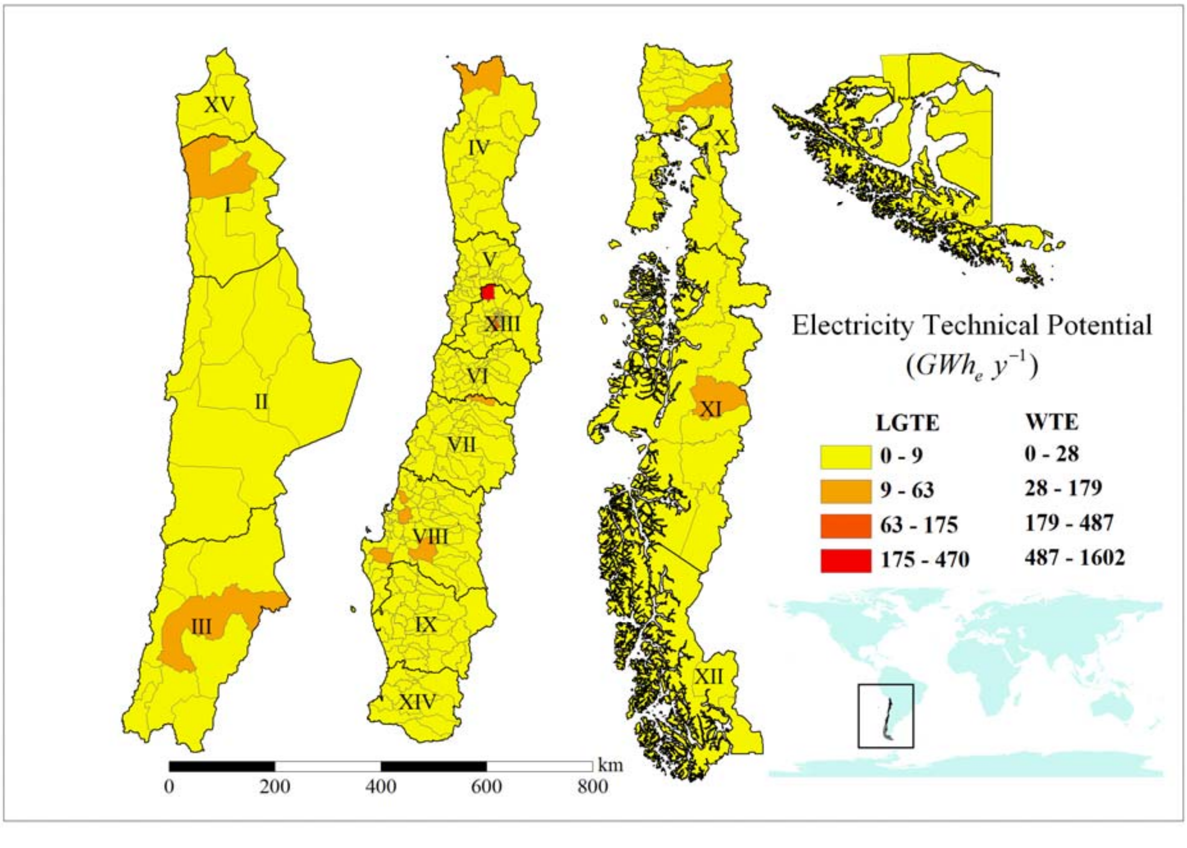

Figure 7.1.5. Electricity technical potential from landfill gas-to-energy (LGTE) and waste-to-energy (WTE) options.

As shown in Figures 7.1.5 and 7.1.6, the technical potential for the three assessed options are concentrated in certain municipalities in the XIII Region (Metropolitan Region), accounting for 67% of the total energy potentially available from the MSW in the most populated area of Chile. On the other hand, a significantly lower energy potential is observed in the rest of the country, which is explained not only by the lower population density but also by the construction of small-scale landfills.

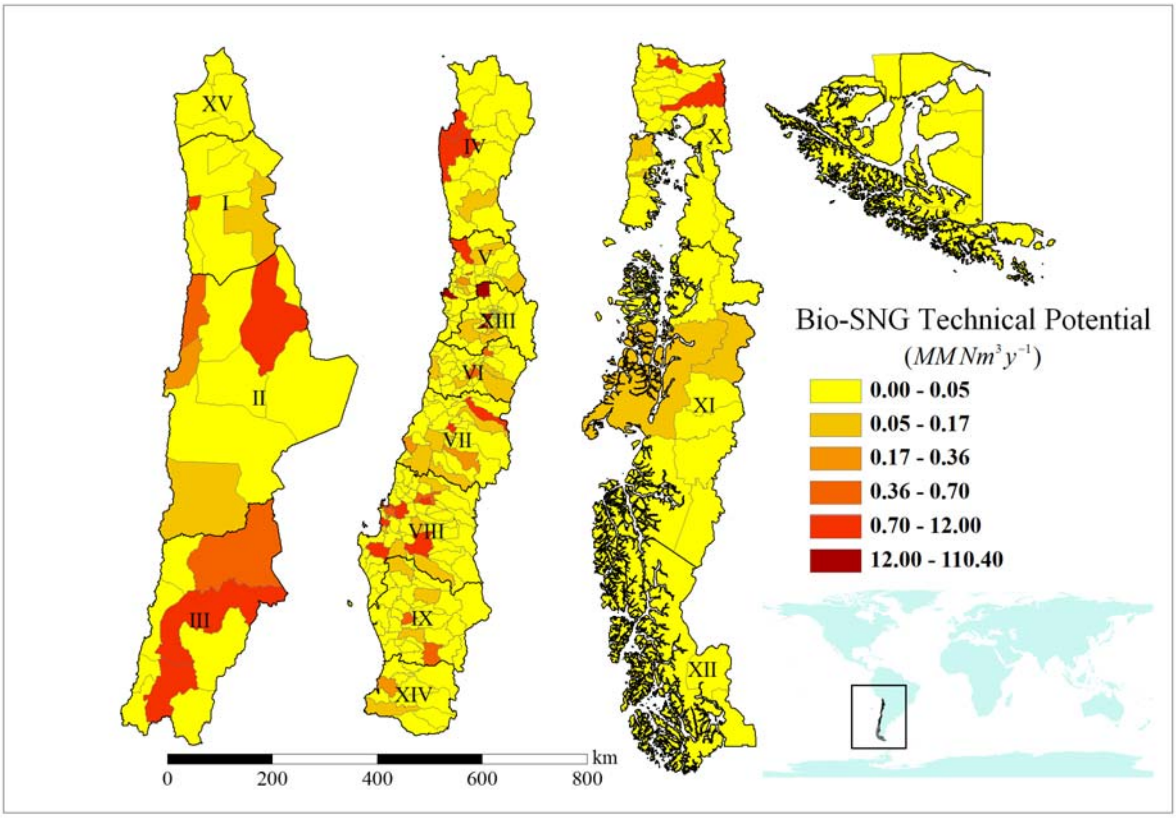

Figure 7.1.6. Bio-SNG technical potential from landfill gas upgrade option (LGU).

7.1.5. Discussions

During 2010, the average industrial and commercial electricity prices for the country reached 10.4 ct€ kWh_e^{-1} and 16.8 ct€ kWh_e^{-1}, respectively (OLADE 2011), and these prices have experienced a steady increase in recent years. In this context, considering the electricity generation cost for the LGTE and WTE options mentioned previously, both options are nearly economically profitable, at least on a pre-feasibility level, if only the cost of production is considered as the most relevant economic indicator.

Despite the fact that the end products from both the LGTE and WTE options are electricity, the difference in the cost and potential can be explained as a consequence of the different technologies used in the conversion process, which implies a substantial difference in investment and operating cost as well as in the efficiencies and environmental implications.

All of these factors have an impact on the economic potential, which have a ratio of approximately 1:2 for this case.

Similarly, the natural gas price has been increasing in recent years and reached a distribution price of approximately 15-22 € $MMBTU^{-1}$ (data from 2011); thus, the cost of production for Bio-SNG would be competitive at 9.5 € $MMBTU^{-1}$, and this option would not require subsidies to become economically attractive for the 10 landfills that comprise the economic potential. The injection of Bio-SNG is an alternative that takes advantage of the benefits of transportation across the natural grid; however, its use as a vehicle fuel may have a significant chance at commercial implementation when it is considered for particular applications e.g., compressed methane as a fuel for garbage and cleaning trucks, with filling stations located near the landfill and upgrading plant where it is compulsory for the trucks to arrive and depart. This option offers a realistic starting point for a commercial application without coming up against fuel distribution for private transportation in which fuel supply plays a highly relevant role.

Although the largest energy potential lies in the WTE option, which represents approximately 3.7% of the total national electricity consumption[1] (National Commission of Energy 2010), according to international experience the major inconvenience of this technology rests on its social acceptance. Furthermore, a national effort focusing on MSW recycling should be implemented before the introduction of WTE technologies despite the favourable current market condition of electricity prices in the long-term. Although there have been notable achievements in recycling and MSW landfilling in Chile, these efforts remain modest when compared with countries where WTE has been successfully introduced as a part of a national MSW strategy in which recycling plays a pivotal role.

7.1.6. Preliminary Conclusions

Using a comparative analysis, the main differences in the cost and potential uses of MSW for energy generation were assessed at a national level. For the LGTE and WTE alternatives, the difference between the economic potential is a factor of two, with a slightly lower cost of electricity generation in the former case. For landfill gas upgrade to feed-in (LGU), the economic potential of the entire country reaches a scale that may allow for the implementation of recovery systems with upgrade to a commercial size.

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[1] 56.05 TWh_e of electricity consumption for 2009 (National Commission of Energy 2010).

The results suggest that a combined implementation of the production of high quality pipe-gas and electricity would be the most satisfactory practice because the Bio-SNG option is only competitive for the largest 10 landfills, accounting for 25% of the total landfills in operation and exhibiting a high sensitivity to the cost of generation. A significant number of landfills are inadequately suited for the implementation of any of the three energy recovery systems evaluated because of their scale. The results support the fact that the main difficulty lies in the existence of landfills that cannot profit from economies of scale at the range in which energy recovery systems operate economically, most significantly affecting those landfills that serve regions with lower population densities. This difficulty could be overcome if waste transfer stations were set up for regions with low populations, such that fewer but larger landfills could operate at a higher capacity, and, consequently, under conditions that are more advantageous for energy recovery. However, this option entails coordinated and cooperative actions between municipalities that have historically faced the problem of waste management independently instead of looking for cooperative solutions.

These results must be considered as a basic framework that can orient the decision-making process or the implementation of environmental policies either in the short or long term. Other aspects that will become more important in the long-term must be taken into consideration in further research such as environmental impacts or public acceptance of MSW processing technologies as well as the incorporation of incentives for recycling and the sorting of organic fractions of the MSW, tax-cuts for recovered methane for use as a transportation fuel and the impact of these efforts in the strategy of using MSW as an alternative source of energy.

7.2. Wastewater Treatment Sector

In this section, the energy that can potentially be obtained from the digestion of sludge generated from wastewater treatment processing (WwT) was calculated using the proposed methodology. The different pathways of electricity generation via the direct combustion of biogas and upgraded biogas produced as bio-substitute natural gas (Bio-SNG) for injection into the gas grid were assessed and compared. Information such as the population served, WwT technology employed and geographical distribution of the sludge sources was gathered to estimate energy potential.

In contrast with the previously assessed sector, municipal solid waste (MSW), either electricity or Bio-SNG from WwTP sludge processing would necessitate subsidisation to become economically attractive. To illustrate the procedure for the calculation, this chapter will act as a test case for the other sectors to be evaluated in this thesis (i.e. livestock farming, agricultural and co-digestion).

7.2.1 Introduction

The supply of water and sanitation services constitutes an indispensable requirement for the protection of public health, maintenance of basic living conditions, and the protection of biota and natural resources. Although the advances made in wastewater treatment technologies over last decades have been outstanding, the universalisation of water and sanitation services remains a major challenge for the 21st century (Castro, *et al.* 2009).

Under a modern perspective, a centralised municipal wastewater treatment (WwT) programme was set up in Chile thanks to a large-scale water reform policy started in the late 1990s, leading to the privatisation of this service sector which was previously managed integrally by the state. In parallel to this restructuring, the development of emissions standards for municipal sewage discharge was introduced when the General Environmental Law (1997) came into effect with the consequent obligation for water supply companies to treat polluted water after discharging it into the surface-water environment for the purposes of preserving biota, avoiding the detrimental effects, improving the value of touristic sites and protecting human health. According to the World’s Water Report (2008), Chile has 922 billion cubic meters of total renewable freshwater. Furthermore, 87% of the urban population was connected to wastewater treatment plants (WwTPs) by 2010 (Water Supply Superintendence

2012), a share that is in line with OECD countries (European Environment Agency 2011 2011); this figure is expected to reach 98% and then 99% by the present year (2013) and 2015, respectively (see Figure 7.2.1).

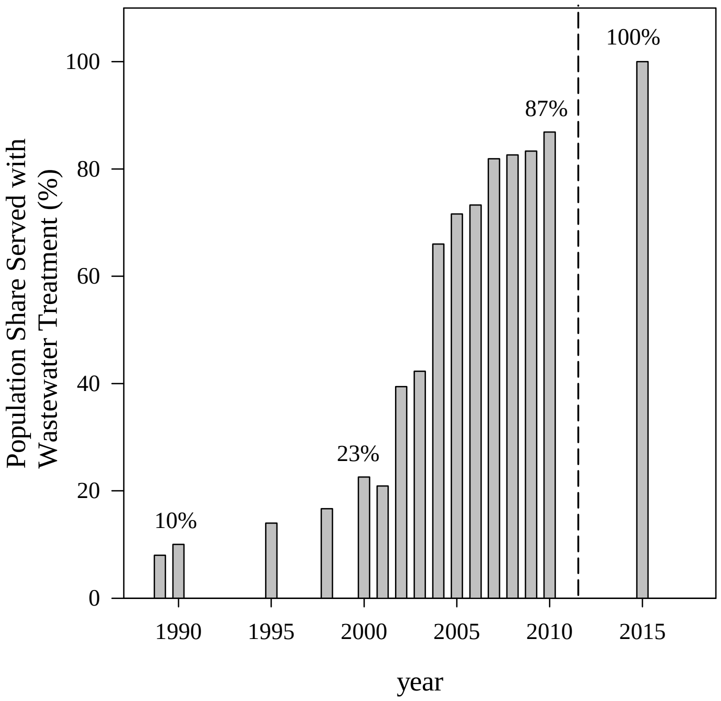

Figure 7.2.1. Share of population served by public wastewater treatment facilities in Chile 1990-2010 and projection for 2015. Water Supply Superintendence (2012).

WwT is a set of physicochemical processes employed to remove pollutants, which can be physical, chemical or biological substances. WwT is normally divided into primary, secondary and tertiary treatment and selected according to the environmental regulations that the treated water must comply with. Whereas primary systems (also know as mechanical treatments) entail the removal of suspended solids, floating materials and scum from raw sewage, commonly by sedimentation or flotation, secondary treatments (also known as biological treatments) aim to remove dissolved organic matter by anaerobic or aerobic biochemical processes. In tertiary systems (also called advanced treatments), the organic matter remaining after secondary treatment is removed, along with phosphorous and nitrogen, to control nutrient levels. Finally, disinfection may be conducted to meet the standards of effluent regulations.

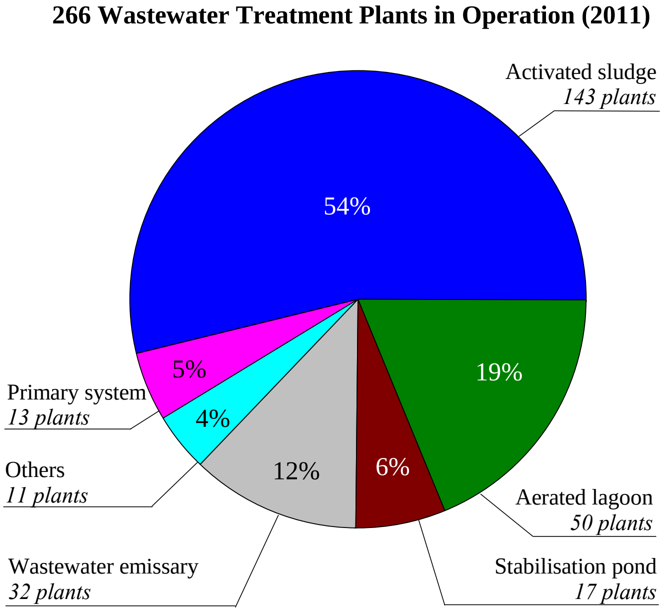

Figure 7.2.2. Wastewater treatment technologies used in Chile. Water Supply Superintendence (2012).

As Figure 7.2.2 shows, the most common primary treatment technology employed in the country is sedimentation, which comprises 5% of the total. In particular cases, it is followed by disinfection, and this two-step treatment is sufficient to meet the environmental regulations. The most heavily employed system of secondary treatment is activated sludge, which includes conventional activated sludge (CAS), extended aeration, oxidation ditch or sequential batch reactors and makes up 54% of the total technology employed. The stabilisation pond is the second most commonly used technology in secondary treatment at 6% of the total and entails wastewater treatment of large surfaces, with or without aeration. Of the total number of WwTPs, the remaining 12% are wastewater emissary, which collect wastewater and then dispose of it in the ocean. The introduction of a tertiary system is practically nonexistent, mainly as a consequence of current environmental observances.

7.2.2. WwTP Sludge Management

In spite of the advantages in WwT, processing inevitability generates sludge at a significant rate, creating a new environmental problem to deal with (Athanasoulia, *et al.* 2012). Although sludge has been traditionally handled as a waste management problem (WMP) in most EU countries, sludge landfilling has gradually decreased as the trend of reusing it as fuel has gained value (Kalderis, *et al.* 2010). The same tendency can be observed in Chile, where sludge landfilling has faced increasingly strict regulations with which to comply (Decree 4;

Decree 189). In addition, prior to transportation and final disposal, which involve total cost of $60\ €\ t^{-1}_{FM}$ roughly, the sludge necessarily requires pre-treatment. This pre-treatment typically include mechanical dewatering and thickening, operations that demand energy as well as consumable chemicals, and, consequently, increases the cost of wastewater treatment (Coffey 2009). These new conditions are indirectly forcing WwTP operators to seek new cost-competitive options. Additionally, the environmental framework previously discussed coupled with an increase in the cost of energy could become an additional driving force for sludge “residues” to become “by-products”, useful as a raw material for energy generation, with a trade price that might reflect market competition.

In this new environmental and economic scenario, anaerobic digestion could significantly contribute to solving the situation previously described. The main product from the anaerobic digestion of WwTP sludge is biogas composed mainly of methane (40-75%) and carbon dioxide (15-60%). As previously described, biogas can be used either to generate electricity through combustion or to produce an upgraded gas with the option to use it as vehicle fuel, or for injection into the existing natural gas network. Besides, biogas generation via anaerobic digestion offers the chance to stabilise and considerably reduce the volume of WwTP sludge by generating a by-product that may be sold as a bio-fertiliser, consequently improving the economics of the entire process. The body of evidence indicates that biogas generation as a *waste-to-energy* strategy to deal with the sludge generation problem can be considered an economic, environmentally friendly and decentralised solution. Concerning the biogas for electricity or gaseous biofuel generation option, it has particularities that must be analysed on a case-by-case basis in order to identify the most attractive option from an economic, environmental and socio-political standpoint.

In the biogas-to-energy pathway, the direct production of electricity from the biogas combustion, a CHP scheme seems to be the most suitable option (Jiri 2010). A decentralised gas-engine CHP is a robust, state-of-the-art technology encouraged as a means to reduce CO_2 emissions. Alternatively, raw biogas can be treated to produce a gaseous energy carrier, the so-called bio-substitute natural gas (Bio-SNG), with the same standards as commercial natural gas (Seifert 2009). The main advantages of this option are associated with a high transportation efficiency and the possibility of using the existing distribution infrastructure without the need to adapt or substantially modify it. To attain this, biogas conditioning can be carried out via a subsequent set of unitary operations such as desulphurisation, drying, siloxane removal, carbon dioxide uptake and the adjustment of calorimetric properties and injection, as previously described.

With an orientation towards a *waste-to-energy* strategy, Chile has already started producing biogas at large scale from WwTPs. In a pioneer project performed by the gas distribution company Metrogás, sludge generated in La Farfana WwTP is used as a substrate for anaerobic digestion. This is one of the world’s largest WwTPs (Halcrow 2013), processing the municipal wastewater of approximately 3.6 million inhabitants via a CAS. An estimated biogas generation rate of 24 MM Nm^3 y^{-1} with 63% methane is transported through a 16 km pipeline to a town gas facility after it has been upgraded through cleaning and carbon dioxide removal. Afterwards, it is treated catalytically to increase its hydrogen content. This new town gas is then injected into the gas grid and distributed for residential consumption (Nelson 2010). This waste-to-energy system is a prime example of how integrating processes produce a gaseous energy carrier with commercial value, and, simultaneously, solve an environmental problem without relying on subsidies.

Despite the example mentioned above, there is still a lack of reliable information on biogas potential in regard to WwTPs. Furthermore, the increase in the price of both electricity and natural gas, and the WwTP scale opens the discussion as to which alternative is the most appropriate, biogas-to-energy or the biogas-to-upgrade pathway. Although in principle both options offer well-known advantages, at the moment there is no assessment that provides sufficient evidence through cross-assessment comparison to make a well-educated decision.

Although on an international level, Poeschl *et al.* (2010) indicated that the annual useful biogas energy potential in Germany is 18PJ from WwTPs, and highlights that only 10% of the global potential for biogas is utilised, the theoretical and technical potential are not explicitly identified nor is the economic potential assessed at the regional level. Rao *et al.* (2010) estimated the biogas generation potential in India based on statistical data, putting special attention on residue. According to the authors, sludge from WwTPs is available in large quantities, however, it is not included in the assessment. Lantz *et al.* (2007) indicated that 60% (3PJ y^{-1}) of Swedish biogas production takes place in WwTPs with a total potential of 3.6 PJ y^{-1}. Gómez *et al.* (2010) evaluated the potential and electricity generation cost in Spain by burning biogas generated via wastewater sludge digestion, assuming the capacity for WwTPs and wastewater treatment technology. The assessment was then incorporated into a

GIS to detect areas with a high electricity potential. An analysis of upgraded biogas for injection was not included in the study.

7.2.3 Methodology

The analysis of the potential for biogas generation was conducted by applying the sequential limits as defined in chapter 4. These boundaries were delineated as physical limit, geographical limit, technical limit and economic limit, according to the definition propounded by Hoogwijk (2004, 2005) and Izquierdo *et al.* (2010). Each limit implied restrictions used to estimate the economic use of biogas.

Supply-cost curves (Izquierdo, *et al.* 2010) were built for the two assessed alternatives. In each case, the whole process chain was considered, starting with the generation of sludge in situ and ending with the production of secondary energy under conditions to be utilised. In both cases, electricity and Bio-SNG, the representative generation cost for secondary energy was estimated and then employed as a simple cut-off criterion to interpolate the economic potential.

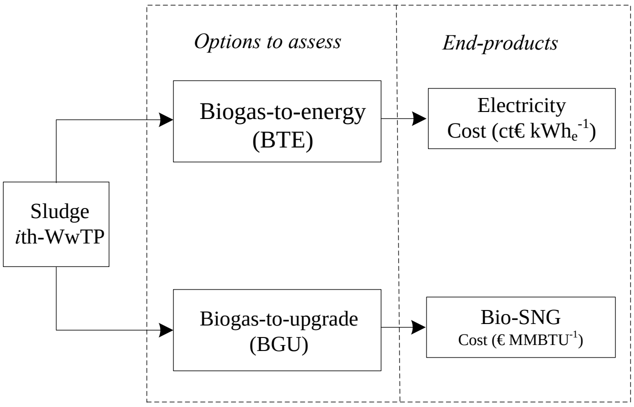

Figure 7.2.3. Conversion pathways to assess for the utilisation of wastewater treatment sludge for the production of either electricity or Bio-SNG through mono digestion.

Economic and technical information such as investment and operational and maintenance cost (O&M) were drawn on from technical reports available elsewhere (see Chapter 6). Moreover, the cost-generation curve for electricity generation was constructed by considering electricity produced via a CHP module with a reciprocating engine because this technology is more suitable for electricity in the low power generation range, which the electrical potential in WwTPs is expected to be. A closing discussion about the implementation of a feed-in tariff system was considered to assess its relevance in the enhancement of this bio-energy option.

7.2.3.1 Methodology for the Technical Potential

- ***Physical Limit***

Also know as theoretical potential, the physical limit is the upper limit of the primary energy calculated without imposing any kind of restriction, thus corresponding to all available primary energy in the biomass (i.e. total sludge) and can be estimated by applying the following equation:

$$\pi_{f,i} = P_i \, R \, S_j \, M_j \qquad \text{Equation 7.2.1}$$

In which P_i represents the population served by the *i*th-WwTP (hab); R ($\mathrm{kg_{ts}\ hab^{-1}\ y^{-1}}$) corresponds to the sludge generation rate per inhabitant; S_j ($\mathrm{kg_{vs}\ kg_{ts}^{-1}}$) is the volatile-to-total solid ratio of primary or secondary sludge $(j = 1, 2)$; M_j ($\mathrm{Nm^3_{CH_4}\ kg^{-1}_{vs}}$) is the yield of methane generation from the mono-digestion of sludge. The parameters used to make the calculation correspond with average data obtained from literature, as Table 7.2.1 indicates.

Table 7.2.1. Parameters employed for the calculation of biogas potentials from WwTPs.

Parameter	Symbol	Unit	Value	References
Population served by *i*-WwTP	P_i	hab	National statistics	(a)
Average sludge production rate	R	$\mathrm{kg_{ts}\ hab^{-1} y^{-1}}$	22.20	(b)-(f)
Volatile-to-total solid ratio in primary sludge	S_1	$\mathrm{kg_{vs}\ kg_{ts}^{-1}}$	0.571	(g)
Volatile-to-total solid ratio in secondary sludge	S_2	$\mathrm{kg_{vs}\ kg_{ts}^{-1}}$	0.642	(h)-(j)
Methane yield from primary sludge	M_1	$\mathrm{Nm^3_{CH_4}\ kg^{-1}_{vs}}$	0.271	(g), (k)
Methane yield from secondary sludge	M_2	$\mathrm{Nm^3_{CH_4}\ kg^{-1}_{vs}}$	0.220	(h), (j)-(l)
Influent organic matter-to-sludge ratio in primary system	τ_1	$\mathrm{kg_{ts}\ kg_{ts}^{-1}}$	0.750	(m)
Influent organic matter-to-sludge ratio in secondary system	τ_2	$\mathrm{kg_{ts}\ kg_{ts}^{-1}}$	1.00	(n)-(o)
Conversion efficiency of Bio-SNG generation	η_c	%	98.0	(p)

(a) (WSS 2012), (b) Osorio & Torres (2009), (c) Marxsen (2001), (d) Lundin *et al.* (2004), (e) Jensen & Jepsen (2005), (f) Fytili & Zabaniotou (2008), (g) Kepp & Solheim (2012), (h) Luostarinen *et al.* (2009), (i) Bougrier *et al.* (2006), (j) Davidsson (2008), (k) Gavala *et al.* (2003), (l) Qiao *et al.* (2011), (m) Zaror (2000), (n) Lin (2007), (o) Uggetti *et al.* (2011), (p) Pettersson & Wellinger (2009).

- ***Geographical Limit***

Also known as geographical potential, geographical limit constrains the potential because of legal considerations, urban regulations or limitations imposed by the geography, such as the inability to collect biomass due to geographical features. As previously indicated, 266 plants are under operation and use conventional activated sludge (CAS) technology, primary systems and sequential bioreactors, and they generate sludge that may be used for biogas generation as well as aerated lagoon, lagooning, and oxidation ditch. On the other hand, a wastewater emissary does not generate sludge, so the wastewater stream empties directly into the sea at a safe distance from the coastline. Thus, the geographic restriction is defined as follows, with a new constraint applied to the physical limit:

$$\pi_{g,i} = P_i \, R \, S_j M_j A_{g,i} = \pi_{t,i} A_{g,i} \qquad \text{Equation 7.2.2}$$

The geographical restriction $A_{g,i}$ is equal to one for all cases, except for wastewater emissary where it takes the value of zero.

- ***Technical Limit***

The technical limit represents the theoretical outer limit of secondary energy available, without any regard for cost or market acceptability. To calculate the technical limit, the sludge generated must be estimated as a consequence of the treatment. In primary systems, in which only mechanical removal of suspended matter occurs, sedimenters remove approximately 75% of total solid suspended (TS), and approximately 30 to 40% of BOD (Zaror 2000). Therefore, a 0.75 $(\mathrm{kg}_{ts}\ \mathrm{kg}^{-1}_{ts})$ mass generation is considered since this definition coincides with the removal efficiency. The majority of WwTPs running have either a primary system or secondary treatment system (see Figure 7.2.4), thus this configuration is assumed throughout the evaluation.

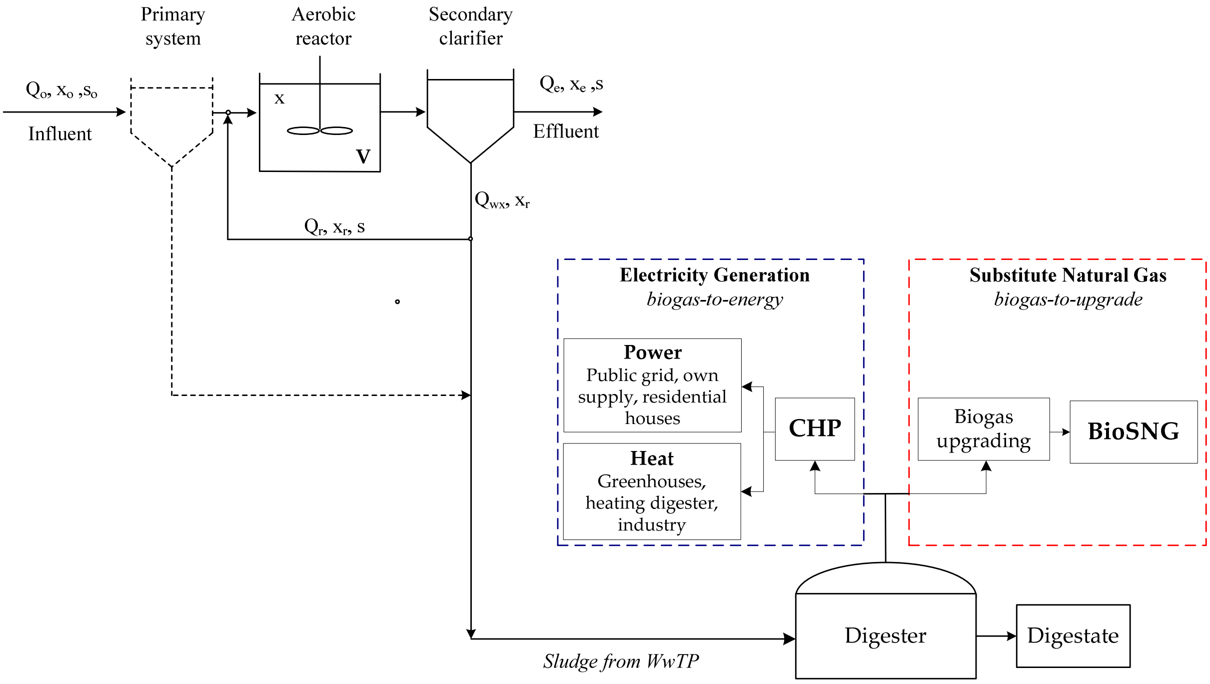

Figure 7.2.4. Schematic representation of a conventional activated sludge system (CAS) and sludge processing options to assess.

In complete-mix systems that recycle, as Figure 7.2.4 shows schematically, the mean hydraulic retention time (θ) can be calculated as indicated in the following Equation 7.2.3.

$$\theta_H = \frac{V}{Q_o} \qquad \text{Equation 7.2.3}$$

In which V is the volume of the aerobic reactor and Q_o is the influent volumetric flow. Furthermore, in this configuration the sludge can be continuously withdrawn from the recycling line. If the volatile suspended solid (VSS) content (x_e) in the exit line is negligible, the mean cell residence time θ_c can be estimated as Equation 7.2.4 indicates (Lin, 2008).

$$\theta_c = \frac{V\ x}{Q_{wx}\ \ x_r} \qquad \text{Equation 7.2.4}$$

Dividing Equation 7.2.3 by Equation 7.2.4 and reorganising the results yields Equation 7.2.5 as follows.

$$\tau_2 = \frac{Q_{wa} x_r}{Q_o x_o} = \frac{\theta_H}{\theta_c} \frac{x}{x_o}$$ Equation 7.2.5

The term τ_2 of Equation 7.2.5 corresponds to the influent organic matter-to-sludge generation ratio. For a typical and representative operation condition of a WwTP (Lin 2007), with parameters θ_H = 4 day; θ_c = 10 day; x(MLVSS) = 2,000 mg L^{-1}; and x_o(TS) = 800 mg L^{-1}, the sludge generation rate is approximately 1.0 kg^{ts} kg^{ts}. Therefore, the technical limit can be estimated by applying Equation 7.2.6, in which the conversion efficiency and the corresponding restrictions are included:

$$\pi_{t,i} = P_i\, R\, M_j\, \tau_j\, S_j\, \eta_c A_{g,i}\ A_{t,i} = \pi_{g,i}\, \eta_c\, A_{t,i}$$ 7.2.6

In the biogas-to-upgrade (BTU) pathway, a conversion efficiency (η^{BTU}) of 98% was assumed to represent the amount of methane recovered in all the processing, from digestion to injection (Pettersson & Welliger 2009). Because the electrical efficiency (η^{BTE}) is highly dependent on the plant capacity in the biogas-to-energy pathway, its calculation was proposed as a function of electrical power. In this evaluation, the assessment considered biogas burning through a CHP module by a reciprocating gas-engine because its typical capacity is in the expected power range for the expected electric power.

7.2.3.2 Methodology for the Economic Modelling

The specific cost of secondary energy (c_i) can be calculated through Equation 7.2.7.

$$c_i \pi_{t,i} = \alpha I_i + C_{o\&m,i} - R_i$$ Equation 7.2.7

In which $\pi_{t,i}$ is the technical potential of secondary energy from the ith-WwTP, either electricity or Bio-SNG; I_i is the total capital investment; α is the capital recovery factor; $C_{o\&m,i}$ is the operation & maintenance cost; and R_i the revenue obtained from selling by-products or any other kind of income (e.g. from heat or the sale of bio-fertiliser, subsidies for green-electricity or waste management).

7.2.3.3 Methodology for Economic Potential

The representative generation cost (c_r) is then calculated as the mode of the log-normal cost distribution, and the economic potential interpolated as a fraction of the technical potential composed by all the plants with a specific generation cost lower than the representative one. This can be mathematically expressed as Equations 7.2.8 indicates.

$$c_r = Mode[c(\pi_{t,i})] \qquad \text{Equation 7.2.8}$$

The economic limit can be calculated as the summing-up of the total number of WwTP within the country as Equation 7.2.9 indicates.

$$\Pi_e = \sum_{i=1}^{n} P_i \, R \, M_j \, \tau_j \, S_j \, \eta_c \, A_{g,i} \, A_{t,i} \, A_{e,i} = \sum_{i=1}^{n} \pi_{t,i} A_{e,i} \qquad \begin{array}{l} A_i^e = 0; \ \forall \, \mathrm{c_i} \le \mathrm{c_r} \\ A_i^e = 1; \ \forall \, \mathrm{c_i} > \mathrm{c_r} \end{array} \qquad \text{Equation 7.2.9}$$

The data was finally integrated into a geographical information system (GIS) to visualise the technical potential by using the county (also called municipality) as the control area. This is the smallest geopolitical administrative division for each of the fifteen regions that make up the country, with a total of 346 units and an average area of 2,100 km^2.

7.2.4 Results

The theoretical potential of electricity generation, however irrelevant in practical terms, reached 359 GWh$_{th}$ y^{-1}, whereas the geographical potential bordered 253 GWh$_{th}$ y^{-1}. The technical limit was estimated at 83 GWh$_e$ y^{-1}, significantly lower than the two previous limits. In the biogas-to-upgrade pathway, the theoretical potential reached 38 MMNm^{3}y^{-1}, whereas the geographical potential reached 27 MMNm^{3}y^{-1}, or nearly 71% of the maximum theoretical limit. The technical potential reached 24 MMNm^{3}y^{-1}, corresponding to 62% of the theoretical one.

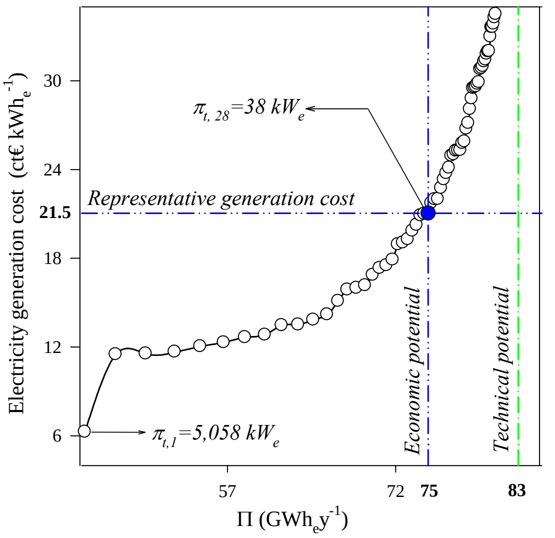

Figure 7.2.5. Supply-cost curve for biogas-to-energy option.

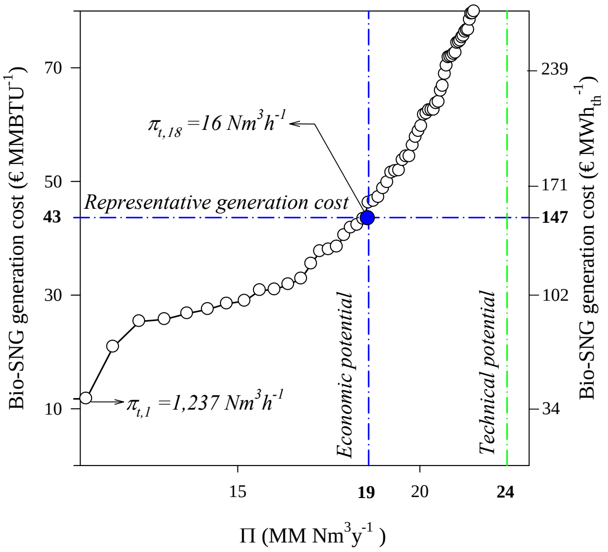

Figure 7.2.6 Supply-cost curve for biogas-to-upgrade option.

Figures 7.2.5 and Figure 7.2.6 are supply-cost curves of the biogas-to-energy and biogas-to-upgrade pathways. Each point of the curve represents an amount of secondary energy supplied by a WwTP at a specific levelised cost. In the former, the representative generation cost of electricity was estimated at 21.5 ct€ kWh$_e^{-1}$, with a minimum generation cost of 6.3 ct€ kWh$_e^{-1}$ for the largest WwTP in operation. The economic potential is approximately 75 GWh$_e$ y^{-1}, and consists of the 28 WwTPs.

For the biogas-to-upgrade route, the representative generation cost was estimated at 43 € MMBTU^{-1}, with 11.2 € MMBTU^{-1} as the lowest cost of generation at the national level for a plant with nominal Bio-SNG capacity of 1,237 Nm^3 hr^{-1}. The economic potential reached approximately 19 MMNm^3 y^{-1}, and was made up of the Bio-SNG potentially available from 18 of the largest WwTPs in operation.

Figure 7.2.7 and Figure 7.2.8 show the technical potentials distributed throughout the country. For both options under analysis, there are direct correlations between highly populated areas and higher electricity and Bio-SNG potential at the lowest cost of production. This is an expected result, and supported by the proportionality between population served by a WwTP and sludge generation. Both electricity and the largest Bio-SNG potential are concentrated in the XIII Region, or Metropolitan Region, (approximately 49%) and the VIII Region (approximately 15%).

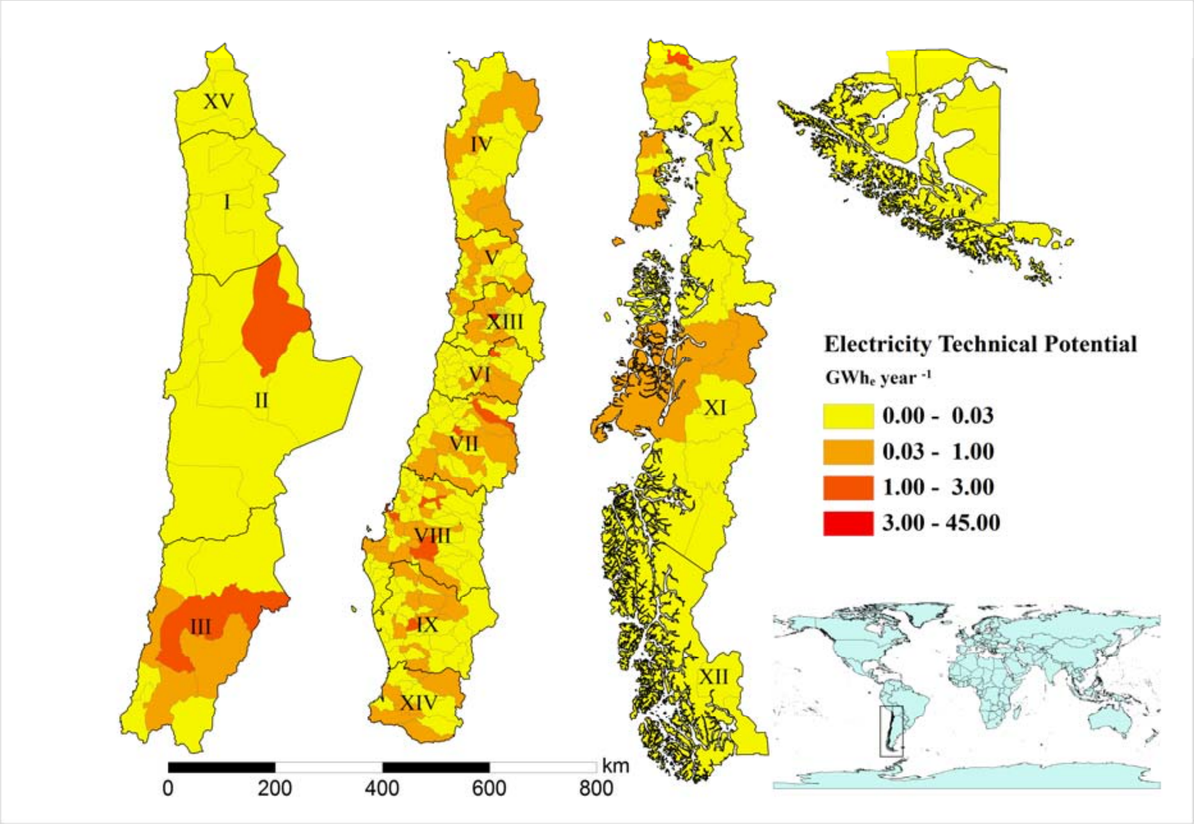

Figure 7.2.7. Geographical distribution of the technical potential for electricity generation from WwTP sludge digestion.

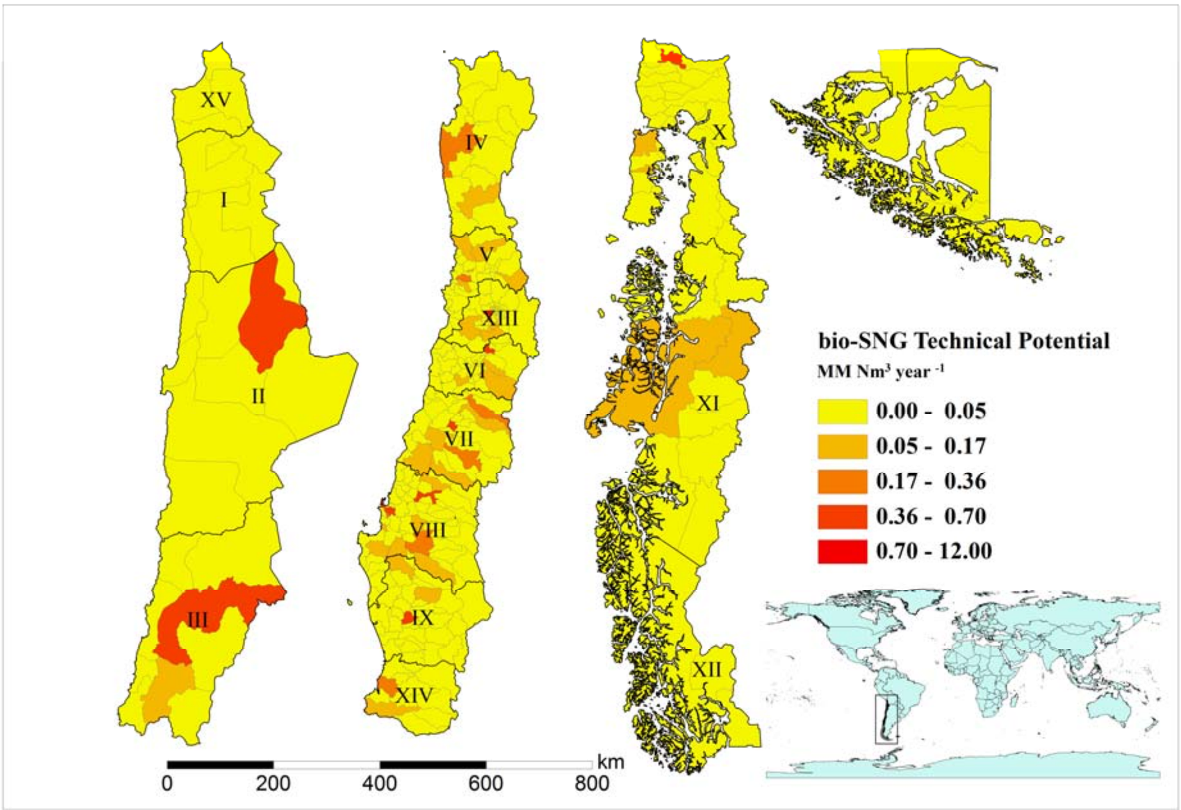

Figure 7.2.8. Geographical distribution of technical potential for Bio-SNG production from WwTP sludge digestion.

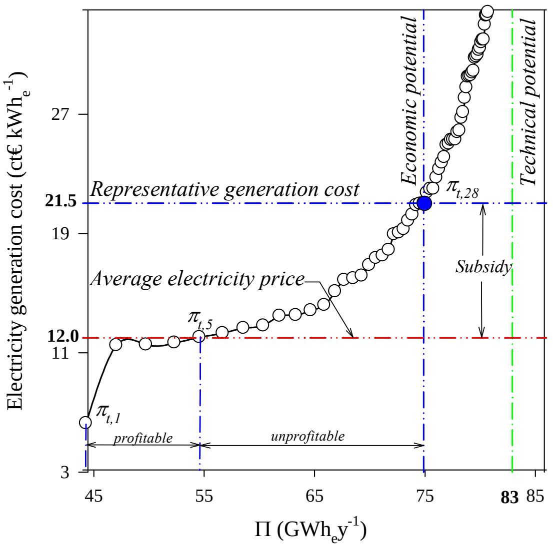

Figure 7.2.9. Comparison between representative generation cost and market price for electricity option.

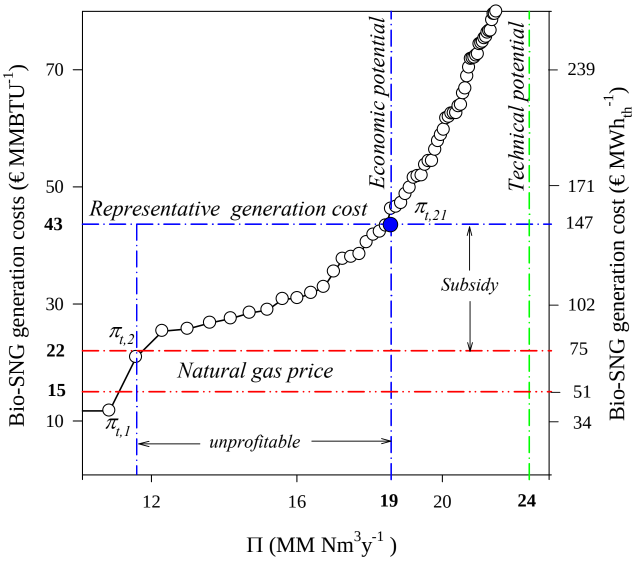

Figure 7.2.10. Comparison between representative generation cost and market price for Bio-SNG option.

Figure 7.2.9 shows that the representative generation cost of electricity is higher than its market price. In the same way, Figure 7.2.10 presents the representative generation cost of Bio-SNG as higher than the price of natural gas. For the biogas-to-energy pathway, the first five WwTPs have electricity generation that may be profitable, offering an achievable potential of roughly 55 GWh$_e$y^{-1}. To make the unprofitable fraction economically appealing (the remaining 23 WwTPs), would necessitate the introduction of a feed-in tariff subsidy of approximately 9.5 ct€ kWh$_e^{-1}$, the difference between the representative generation cost and the market price.

Table 7.2.2. Energy potential of the biogas-to-electricity and biogas-to-BioSNG.

	Alternative of energy generation	
Economic indicator	biogas-to-energy	biogas-to-BioSNG
Technical potential	85 GWh$_e$y^{-1}	24 MM Nm^3 y^{-1}
Economic potential	83 GWh$_e$y^{-1}	19 MM Nm^3 y^{-1}
Minimum cost of production	6.3 ct€ kWh$_e$	11.2 € MMBTU^{-1}
Representative cost of production	21.5 ct€ kWh$_e$	43 € MMBTU^{-1}
Needed feed-in tariff	9.5 ct€ kWh$_e$	21-28 € MMBTU^{-1}
Needed subsidy	1 MM €	4 - 6 MM €

For the biogas-to-upgrade route, there are one or two WwTPs in which the generation of Bio-SNG makes sense in economic terms, thus its generation cost is lower than natural market price and has an achievable potential for injection into the grid at roughly 12 MMNm^3 y^{-1}. A subsidy in the 21-28 € MMBTU^{-1} range for generated Bio-SNG would be necessary to make 7

MMNm^3 y^{-1} of Bio-SNG economically competitive. In both cases, the feed-in tariff scheme would associate a direct subsidy, which would mean approximately 1 MM € y^{-1} for the biogas-to-energy option, whereas the biogas-to-upgrade would reach 4-6 MM € y^{-1}. Table 7.2.2 summarises the main economic outcomes from the assessment.

7.2.5. Discussions

Tsagariks (2007) reported an electricity cost of 8.76 ct€ kWh$_e^{-1}$ for a set of generators installed at a municipal WwTP located in Iraklio, Greece. Gómez *et al.* (2010) estimated a minimum electricity generation cost of 11.0 ct€ kWh$_e^{-1}$ at WwTPs facilities in Spain. Morin *et al.* (2011) found an electricity cost of 7 ct€ kWh$_e^{-1}$ via biogas co-generation through the mono-digestion of 150,000 inhabitants' municipal WwTP sludge in Quebec, Canada. These figures are in the line with the calculated representative generation cost of electricity. For the Bio-SNG option, no assessments of large areas were found in that most of the available information is based on case studies and oriented to estimate generation cost at a typical plant.

In spite of the inherent difficulty in generalising the market's prices for secondary energy at a national level for a specific time-frame, the above-mentioned values can be employed as a reference in the short-term for the development of a national strategy that addresses the sludge generation problem via a waste-to-energy approach. This strategy should be based on a macro-policy for the handling of wastes with similar characteristics, offering consistent incentives than can lead to a sustainable way of achieving environmental and economic benefits.

7.2.6. Preliminary Conclusions

This section has shown how the introduction of a technology to control an environmental issue, wastewater treatment specifically, resulted in the appearance of a new environmental problem (i.e. sludge). In this way, anaerobic digestion may offer a solution through a waste-to-energy approach. For the two state-of-the-art options to the treat WwTP sludge, biogas-to-energy and biogas-to-upgrade, it was found that the economic limit heavily penalised the energy potentially available based on the technical limit. Furthermore, it was found that at national scale 63% of the electricity's technical potential would be competitive with conventional generation, whereas this share would reach approximately 58% for Bio-SNG; all of these percentages consider the average energy prices for 2011. As far as Bio-SNG generation is concerned, its injection only makes sense in large scale production, so it is heavily dependent on the amount of residual substrate available for processing.

It is observed that there is a high concentration of energy potential in only two regions of the country, which is attributed to the high population density present in only a few areas. This implies that there are numerous small-scale WwTPs in which either electricity or Bio-SNG is not adequate to be produced at a commercial scale, being in this way landfilling the immediate possibility of handling.

Both assessed options are hardly competitive without the introduction of incentives such as feed-in tariffs for energy generation or another indirect mechanism of subsidisation. Nevertheless, in comparison with the Bio-SNG option, a greater number of electricity projects may run profitably, and a significantly larger number might become profitable once the steady increase in electricity prices is considered. Consequently, the biogas-to-energy route is more effective and larger environmental externalities are present when no-subsidies from the state are considered.

Under a hypothetical scenario in which subsidisation was contemplated for the promotion of a waste-to-energy policy, the generation of electricity seems to be the most advantageous because a similar number of WwTPs (24 for biogas-to-energy and 21 for biogas-to-upgrade) would be profitable, but the annual cost for the state would be significantly lower. Taking into account these results, evidence suggests that a policy towards the electricity pathway should be promoted under the current economic context of the country.

7.3 Livestock Farming Sector

The production of biogas through anaerobic digestion has recently garnered considerable attention as an option for the generation of energy with significant environmental, social and political benefits, especially in the rural sector. However, and in contraposition with other alternatives, it is associated with a series of uncertainties that make it difficult to generalise either technical or economic assessments at a large-scale. This is principally due to the diversity and amount of substrates potentially suitable as raw material, the geographical distribution of the resource, scale of generation and environmental and energy policies.

As previously done for municipal solid waste and wastewater treatment, the potential analysis is carried out for the livestock farming sector, which involves the assessment of energy from the anaerobic processing of manure by mono-digestion. The same structured methodological approach put forward in chapter 4 and already applied is once again employed, providing the same economic indicators to allow a cross-assessment comparison between the conversion routes (i.e. electricity or Bio-SNG) as well as among sectors.

7.3.1. Introduction

Anaerobic digestion is particularly attractive when searching for an environmentally friendly solution for the manure generated by farms (Hom-Nielsen, *et al*. 2009; Berglund &. Borjesson 2006). On the one hand, the intensification of farming industries has enabled the inherent benefits of the economies of scale for edible goods production, and on the other hand the increased production of edible goods has been accompanied by significant volumes of manure during processing, involving higher cost and posing a risk to the environment. Although manure has historically been employed as a natural fertiliser to increase the quality of farmland and return nutrients to the soil, its use can be responsible for the eutrophication of waterways and losses of nitrate or phosphate when it is applied at non-optimal rates (Randall, *et al*. 2000).

In recent years, Chile’s livestock industry has experienced considerable development; the country was an importer of dairy products up until 2001, and then became a net exporter due to a surplus in production. For instance, the poultry industry supplies most of the internal demand with 594,000 t y^{-1} (data from 2010), accounting for 45% of the total demand of meat.

Pork follows with 498,000 t y^{-1} (expressed as dressed meat) and has exhibited steady growth during the last decade (6.7% annually). Both are attributable to a higher demand from export markets like South Korea and Japan and the internal increase in consumption (ODEPA 2012). The dairy industry is made of approximately one hundred medium and large milk supplying plants principally located in the central and southern zones (ODEPA 2012). In the context of this expansion in the feedstock industry, the country ought to confront this new environmental issue in accordance with the new challenges to reach long-term economic competitiveness in a sustainable fashion. In these terms and based on scientific evidence, the introduction of anaerobic technologies as an approach to overcoming this environmental issue is seen as a promising solution.

In Chile, the introduction of on-farm anaerobic technology has taken place slowly and only in last few years. Total biogas generation only reached 0.4 PJ y^{-1} in 2011 (Ministry of Energy 2011), but, nonetheless, preliminary evaluations have shown that the theoretical potential of biogas from the digestion of manure is roughly 15 PJ y^{-1} (Chamy, *et al.* 2007), indicating that less than 3% of the potential from these sectors is being realised so far.

7.3.2. Livestock Characterisation

Table 7.3.1. Livestock (per 1,000 heads) by category and region in Chile (Ministry of Agriculture 2007).

	Bovine	**Sheep**	**Swine**	**Equine**			**Goat**	**Camelid**		**Wildboar**	**Deer**	**Rabbit**	**Total**
Country region´s name				*Horse*	*Mule*	*Donkey*		*Alpaca*	*Llama*				
Región de Tarapacá (I)	0.1	10.0	1.4	0.0	0.1	0.6	2.3	3.5	23.7	0.0	0.0	6.7	**48.5**
Región de Antofagasta (II)	0.3	10.5	1.9	0.5	0.0	0.8	6.2	0.2	5.6	0.0	0.0	8.6	**34.6**
Región de Atacama (III)	7.1	5.2	1.4	3.9	0.7	3.4	39.2	0.0	0.0	0.0	0.0	2.5	**63.6**
Región de Coquimbo (IV)	41.3	84.2	3.8	25.7	3.9	8.8	404.6	0.1	0.2	0.0	0.0	2.9	**575.4**
Región de Valparaíso (V)	102.7	30.3	173.8	26.7	0.7	1.0	45.5	0.2	0.2	0.0	0.0	2.9	**384.0**
Región de O'Higgins (VI)	83.4	157.6	860.0	26.8	0.2	0.0	18.5	0.5	0.1	0.0	0.0	5.1	**1,152.3**
Región del Maule (VII)	258.2	155.1	93.4	54.0	0.5	0.1	40.1	0.4	0.0	0.2	0.5	1.5	**604.1**
Región del Bío-Bío (VIII)	449.4	173.7	179.8	51.3	0.1	0.0	47.3	0.1	0.2	0.9	0.2	3.1	**905.9**
Región de la Araucanía (IX)	668.1	277.9	199.6	30.9	0.1	0.0	50.8	0.5	0.7	1.0	0.7	2.2	**1,232.6**
Región de los Lagos (X)	1,047.2	315.2	79.8	22.8	0.0	0.0	11.1	0.5	0.3	0.9	4.4	0.9	**1,483.1**
Región de Aysen (XI)	193.8	304.9	2.7	12.2	0.1	0.0	12.1	0.2	0.0	0.0	0.0	0.1	**526.2**
Región de Magallanes (XII)	141.8	2,205.3	1.7	10.2	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.1	**2,359.6**
Región Metropolitana de Santiago	101.3	24.0	1,292.7	24.5	0.2	0.1	12.3	0.0	0.1	0.2	0.0	5.7	**1,461.1**
Región de los Ríos (XIV)	621.6	116.1	34.3	14.3	0.0	0.0	9.3	0.5	0.4	0.7	0.1	0.3	**797.7**
Región de Arica y Parinacota (XV)	2.3	18.2	2.3	0.3	0.1	0.1	6.0	19.1	17.4	0.0	0.0	1.0	**66.9**
Total country	***3,719***	***3,888***	***2,929***	***304***	***7***	***15***	***706***	***26***	***49***	***4***	***6***	***44***	***11,696***

The total area of Chile is 756,102 km^2, and the country is divided into fifteen administrative regions. The climatological diversity of the country enables the production of various kinds of livestock products. The total livestock is composed of an estimated 11.7 million heads (Ministry of Agriculture 2007) and is comprised of 32% bovine, 33% sheep and 25% swine. Table 7.3.1 lists the data organised by administrative region. As can be observed, the livestock is mainly concentrated in Región de Magallanes (XII) (20%), Región de los Lagos (X) (13%) and Región Metropolitana (XIII) (12%).

7.3.3. Methodology

The methodology for the potential analysis of this sector follows the same procedures that were used in the previous sectors, providing the same technical and economic indicators. Besides, a similar analysis can be carried out by using the supply-cost curves to evaluate the necessity of subsidies, the most adequate conversion route and the fraction of the economic potential that can run profitably under the current economic conditions.

7.3.3.1 Methodology for the Technical Potential

The primary information on the existing farms in Chile used for the assessment was provided directly by the Department of Studies and Agrarian Policies (ODEPA), branch of the Ministry of Agriculture. This electronic database includes the totality of existing heads of livestock within the country (data from 2007) and is segregated by the type of livestock (bovine, sheep, swine, etc.) for each farm at a county level, which is made of approximately 87,000 farms distributed all across the country. With this data, the technical potential (π_t) of the *biogas-to-energy* (BTE) and *biogas-to-upgrade* (BTU) pathways can be calculated for each *j*th-farm by applying Equation 7.3.1 and Equation 7.3.2.

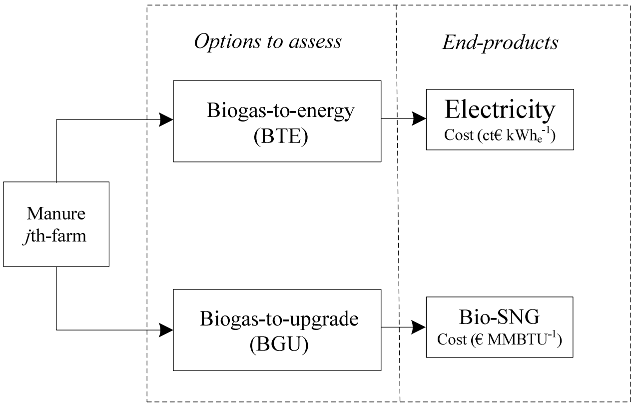

Figure 7.3.1. Conversion pathways to assess for the utilisation of manure for the production of either electricity or Bio-SNG through mono-digestion.

$$\pi_{t,j}^{BTE} = \sum_k N_{j,k}\, M_k\, S_k\, R_k\, \Delta\widetilde{H}_{\text{LHV}}^{\text{CH4}}\, \eta_a\, \eta_e\, A_e \qquad \begin{cases} A_e = 1; \forall\, \pi_{t,j}^{BTE} > 8kW_e \\ A_e = 0; \forall\, \pi_{t,j}^{BTE} \le 8kW_e \end{cases} \qquad \text{Equation 7.3.1}$$

$$\pi_{t,j}^{BGU} = \sum_k N_{j,k}\, M_k\, S_k\, R_k\, \eta_a\, A_u \qquad \begin{cases} A_u = 1; \forall\, \pi_{t,j}^{BGU} > 5Nm_{CH_4}^{3}\, h^{-1} \\ A_u = 0; \forall\, \pi_{t,j}^{BGU} \le 5Nm_{CH_4}^{3}\, h^{-1} \end{cases} \qquad \text{Equation 7.3.2}$$

In which $(N_{j,k})$ represents the number of livestock heads in the *j*th-farm of the *k*th-species; $\Delta\widetilde{H}_{LHV}^{CH_4}$ is the lower heating value of methane and estimated as 50,000 kJ kg^{-1} (Avallone, *et al.* 2007); and (η_e) is the electrical efficiency. Table 7.3.2 lists the employed parameters, estimated from the literature and used for the estimation of the technical potential, which are for the *k*th-species: M_k is the amount of manure produced per head of livestock yearly; S_k is the volatile-to-total solid ratio; R_k is the yield of biomethane per volatile solid; LSU_k is the livestock unit; and the manure availability factor is (η_a), the fraction of manure that is recoverable. By using the values shown in Table 7.3.2, the biogas yield reaches 0.37 Nm^3 LSU^{-1} d^{-1} for dairy and 0.59 LSU^{-1} d^{-1} for swine. These values are conservative when compared with data reported in the literature (Deublein & Steinhauser 2011).

Table 7.3.2. Parameters employed for the calculation of biogas potential of liquid manure. M: average animal weight; S: volatile sold and total solid ratio; R: biogas yield; and η_a: manure availability factor.

Livestock $(k=\overline{1,n})$	Manure per head M (kg$_m$head^{-1}y^{-1}) $^{(a)}$	Volatile-to-total solid ratio S (kg$_{vs}$ kg$_m$$^{-1}$) $^{(a)}$	Specific methane yield R (Nm^3 kg$_{vs}$$^{-1}$)	Livestock unit (LSU) $^{(h)}$	Availability factor $^{(i)}$ η_a
1. Dairy	20,090	0.12	0.230 $^{(b)}$	1.2	0.45
2. Beef	7,261	0.12	0.230 $^{(b)}$	0.6	0.45
3. Veal	2,059	0.04	0.230 $^{(b)}$	0.6	0.45.
4. Other (Ox, butt, etc.)	15,695	0.12	0.230 $^{(b)}$	0.7	0.45
5. Sheep–Ovine	394	0.23	0.248 $^{(b)}$	0.05	0.35
6. Swine	6,132	0.10	0.265 $^{(b)}$	0.5	0.8
7. Equine (Horse, mule, and donkey)	8,377	0.20	0.165 $^{(b)}$	1.1	0.1
8. Goat	958	0.22	0.248 $^{(b)}$	0.05	0.1
9. Camelid (Alpaca and llama)	958	0.22	0.165 $^{(c)}$	1 $^{(g)}$	0.1
10. Wild boar	6,132	0.10	0.265 $^{(c)\,(d)}$	0.5 $^{(g)}$	0.1
11. Deer	958	0.22	0.165 $^{(e)}$	0.1 $^{(g)}$	0.1
12. Rabbit	58	0.18	0.174 $^{(f)}$	0.01 $^{(g)}$	0.1

$^{(a)}$ ASAE (2003), $^{(b)}$ Pascual (2012), $^{(c)}$ estimated as equine, $^{(d)}$ estimated as swine, $^{(e)}$ estimated as equine, $^{(f)}$ Li *et al.* (2011), $^{(g)}$ assumed, $^{(h)}$ Deublein and Steinhauser (2011), $^{(i)}$ Batzias *et al.* (2005).

A Boolean restriction was included to set up the minimal output-capacity for the conversion units, defined as A_e and A_u for the *biogas-to-energy* and *biogas-to-upgrade* routes as indicated in Equation 7.3.1 and Equation 7.3.2[2]. Thus $8\,kW_e$ was considered as the minimum output- capacity for reciprocating engines, while $5\,Nm^3_{CH_4}h^{-1}$ was the value for upgrading units. These values correspond to the smallest nominal capacities of commercial units according to technical information (Petersson & Wellinger 2009; ASUE 2011).

7.3.3.2 Methodology for the Economic Modelling

The unitary cost of production of secondary energy c_j from the *j*th-farm was estimated by applying the economic model showed in Equation 7.3.3.

$$c_j \pi_{t,j} = \alpha I_j + C_{o\&m,j} + C_{p,j} - R_j \qquad \text{Equation 7.3. 3}$$

In which, for each *j*th-farm, $\pi_{t,j}$ corresponds to the technical potential; α is the capital recovery factor; $C_{o\&m,j}$ is the operation and maintenance cost; $C_{p,j}$ is the procurement cost of biomass at the processing point; and R_j represents the revenues potentially obtainable from selling by-products such as heat or digestate. Afterwards, the gathered information and biomass supply model was integrated into the economic modelling previously presented for the calculation of the distribution of the unitary cost of production for all the sources of biomass under investigation.

Due to the conditions of farms in the country, no commercialisation either for surplus heat from the cogeneration units or digestate from the anaerobic treatment of manure was assumed. Additionally, it was assumed that the manure was processed in situ, hence without associating any cost of transportation.

7.3.3.3 Methodology for the Economic Potential

The mathematical procedure for the calculation of the representative generation cost, worked out as the log-normal mode of the distribution of unitary cost of energy generation, and the associated economic limit, can be found in detail in Chapter 4 or as illustrated in the sectors already assessed.

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[2] This Boolean operator was not used for the potential analysis of the previous sectors because no technical potential was lower that 8 kW_e or 5 Nm^3h^{-1} for biogas-to-energy or biogas-to-upgrade, respectively.

7.3.4 Results

Figure 7.3.2 and Figure 7.3.3 display the supply-cost curves for the biogas-to-energy and biogas-to-upgrade pathways assessed for the mono-digestion of manure. The technical potential for the former option reached 887 $GWh_e y^{-1}$, whereas its economic potential bordered 780 $GWh_e y^{-1}$ at a representative generation cost of 25 ct€ kWh_e^{-1}. For the biogas-to-upgrade route the technical limit reached 225 $MMNm^3 y^{-1}$, with economic potential reaching 182 $MMNm^3 y^{-1}$ at a representative generation cost of 98 € $MMBTU^{-1}$.

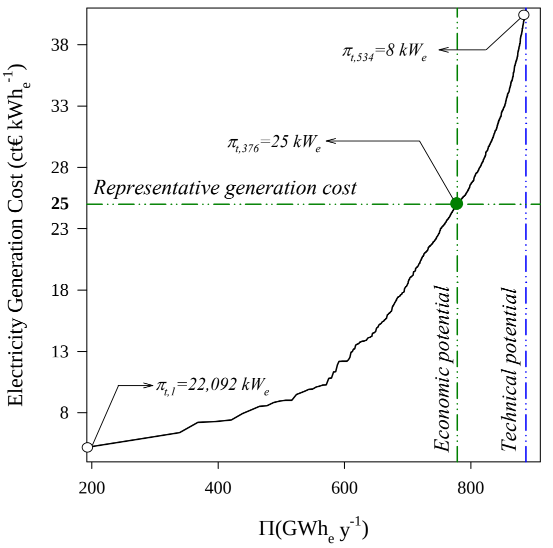

Figure 7.3.2. Supply-cost curve for the biogas-to-energy pathway by mono-digestion of manure.

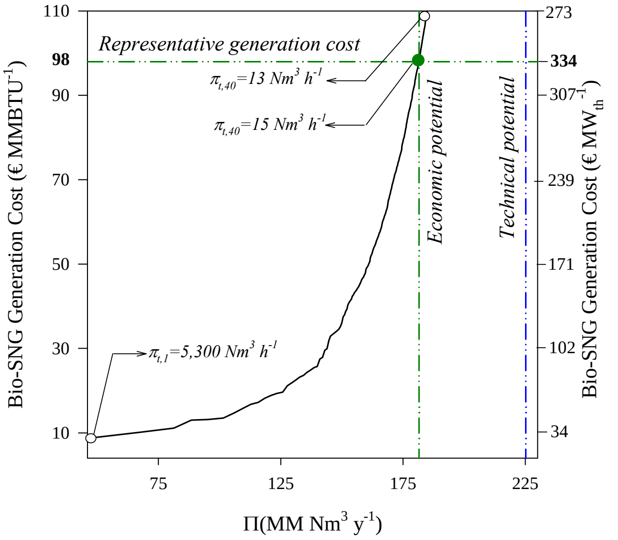

Figure 7.3.3. Supply-cost curve for biogas-to-upgrade pathway by mono-digestion of manure.

Figure 7.3.4 and Figure 7.3.5 reveal that the technical potential from manure processing is highly concentrated in Región Metroplitana (XIII) and estimated to account for approximately 62% and 64% for electricity and Bio-SNG production, respectively. The second highest concentration is found in Región de la Araucanía (IX), which has 11% and 10% of the electricity and Bio-SNG technical potential. Additionally, it was found that on the national level the technical potential of electrical power was primarily on the small-scale, in the 20-250 kW_e range, and accounted for 71% of the country's total. A similar tendency was observed in the technical potential of Bio-SNG, in which approximately 80% of the potential was concentrated on a scale lower than 1 MM $Nm^3 y^{-1}$.

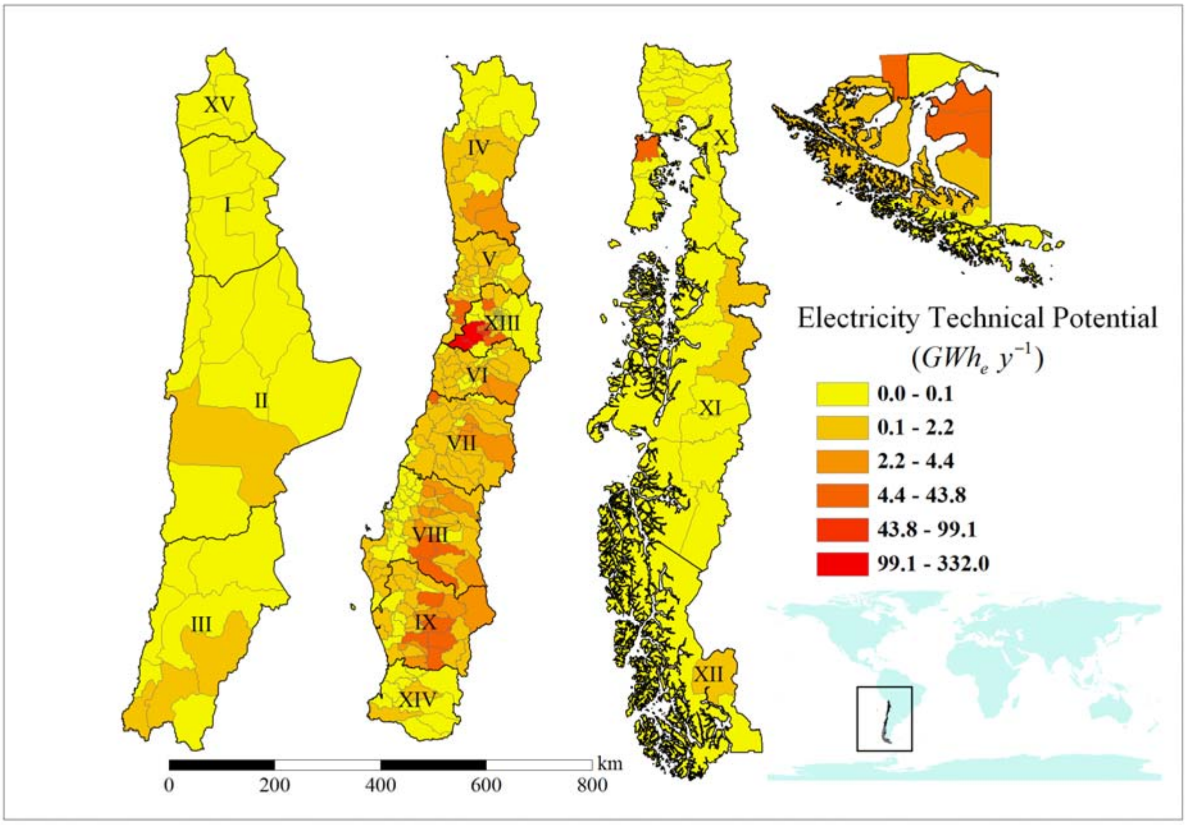

Figure 7.3.4. Technical potential of electricity from mono-digestion of manure.

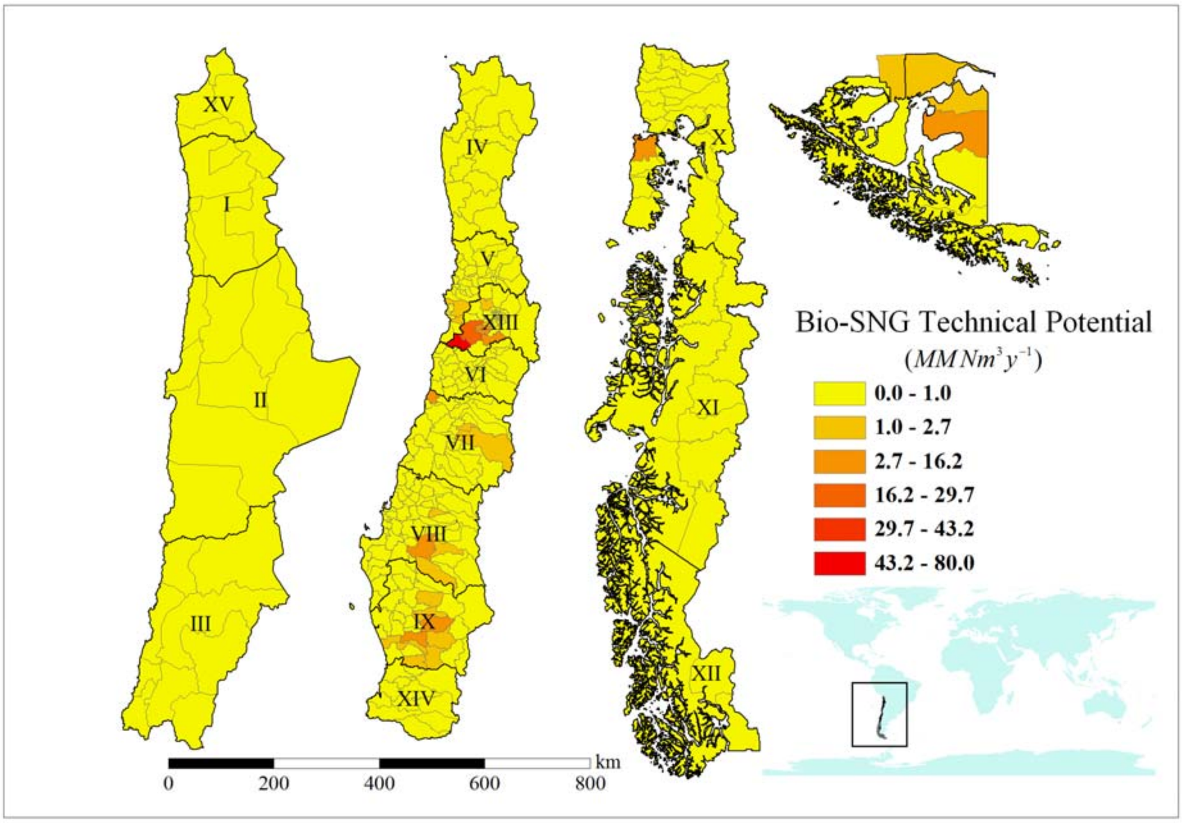

Figure 7.3.5. Technical potential of Bio-SNG from mono-digestion of manure.

7.3.5 Discussions

Only a modest fraction of the total number of farms in the country (approximately 370 from 87,000, or less than 1%) was found to offer adequate conditions to develop biogas projects. This is because the majority of them were constituted of a limited number of livestock, which severely restricted the amount of biogas units technically feasible. Additionally, a large amount of the technical potential of electricity for mono-digestion of manure could be found in the low scale, the 10-250 kW$_e$ range, and is strongly concentrated in only some geographical areas. A similar tendency was also observed for the possibility of producing Bio-SNG, for which the scale rarely surpassed 1 MM Nm^{3}y^{-1} and was concentrated in a few regions.

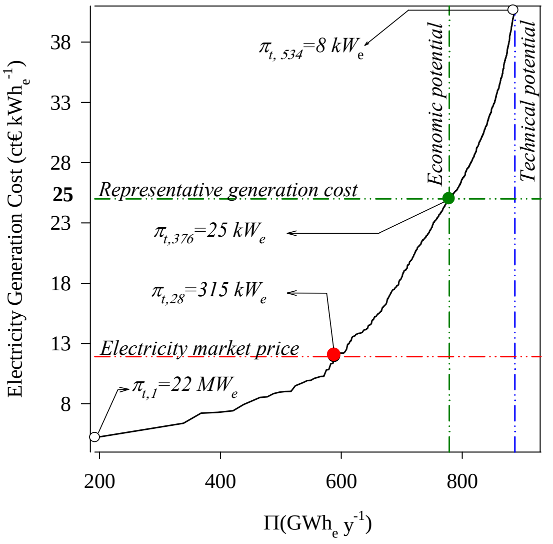

Figure 7.3.6. Supply-cost curve for the biogas-to-energy pathway by mono-digestion of manure.

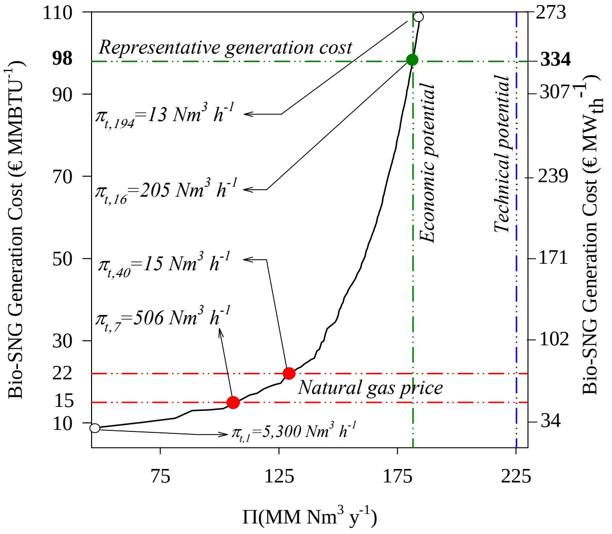

Figure 7.3.7. Supply-cost curve for biogas-to-upgrade pathway by mono-digestion of manure.

For the electricity alternative, as seen in Figure 7.3.6, it was observed that there is an important fraction of the economic potential that could be profitable when a referential market price of electricity of 12 ct€ kWh$_e^{-1}$ is considered, representative for projects at the low scale. In these terms, this is the most attractive part of the potential made of 28 plants, and it should be targeted for enhancing biogas production.

With the market price of natural gas (see Figure 7.3.7) currently ranging from 15 to 22 € MMBTU^{-1} roughly, most of the cost associated with the economic potential of the gas-to-upgrade route, the Bio-SNG option, hardly seems competitive without heavy subsidies. More importantly, approximately 80% of the Bio-SNG technical potential is in a range lower than 1 $\mathrm{MM\ Nm^3 y^{-1}}$, a scale that is not commercially attractive for these sorts of projects, at least in practical terms.

Table 7.3. 3. Energy potential of the biogas-to-energy and biogas-to-upgrade of manure utilisation.

	Route of conversion	
Economic indicator	Biogas-to-energy (BTE)	Biogas-to-upgrade (BTU)
Technical potential	1,067 $\mathrm{GWh_e y^{-1}}$	225 MM $\mathrm{Nm^3\ y^{-1}}$
Economic potential	779 $\mathrm{GWh_e y^{-1}}$	182 MM $\mathrm{Nm^3\ y^{-1}}$
Minimum cost of production	5.2 ct€ $\mathrm{kWh_e}$	8.7 € $\mathrm{MMBTU^{-1}}$
Representative cost of production	25.0 ct€ $\mathrm{kWh_e}$	98 € $\mathrm{MMBTU^{-1}}$
Needed feed-in tariff	13.0 ct€ $\mathrm{kWh_e}$	83-76 € $\mathrm{MMBTU^{-1}}$
Needed subsidy	23 MM €	198-124 MM €

The potential analysis was conducted for the decentralised generation of biogas when manure was used as substrate. Another option to assess is the centralised use of manure as substrate, which may improve the economics of the whole process. However, this option implies a location analysis for a centralised-processing plant, normally associated with an optimisation problem under geospatial restrictions. Furthermore, centralised manure usage involves the additional cost of slurry transportation with low solid content, and a potential instability in the substrate supply because it involves dependency on third-parties, contracts and the creation of business models and mechanisms of partnership affiliation.

The great variability of biomethane yield from manure digestion is a well-known fact principally linked with the sort of substrate and operating conditions of the reactor. Thus, the presented results should be considered referentially, as an order of magnitude taking into consideration the limitations intrinsically related to the technologies considered for the evaluation and their economic implications.

7.3.6 Preliminary Conclusions

For the farm sector, two principle tendencies are observed. Firstly, the electricity generation option seems to be more advantageous than the possibility of producing a gaseous biofuel. This is because the greatest fraction of the technical potential is concentrated in a low power range for both electricity or Bio-SNG. Under this condition, the Bio-SNG option exhibits a considerable increase in cost, much more significant than for electricity when the representative generation cost and the number of plants that account for the economic potential of each option is compared. Secondly, and when the electricity option is considered, there are only two regions, Región Metropolitana (XIII) and Región de la Araucanía (IX), accounting for more than 73% of the technical potential, which are not necessarily the regions (except the Metropolitan) that concentrate the largest number of livestock heads.

7.4 Agricultural Sector

The anaerobic digestion of crop residue may provide a significant amount of energy in the context of biogenic residues currently available in the country. Nonetheless, the uses are wider ranging than those of the biomass from the previously evaluated sectors, and with an associated competition due to other uses that can significantly reduce its availability. In addition, the procurement of crop residue involves collection, conveyance, storage and pre-treatment before the digestion takes place, hence involving extra cost that are absent when the biomass is generated and used in situ. On the other hand, the possibility of collecting larger amounts of biomass may enable the implementation of biogas projects of larger capacity, associating lower specific investment and likely taking advantages of economies of scale which may in turn lower the cost of energy production.

7.4.1 Introduction

The continental surface of Chile accounts for 75.6 millions of hectares (ha). From this, 34.8 millions ha are unproductive, which makes up 46.1% of the national continental surface. The land used for agro-pecuarian exploitation constitutes less than 10% of the national surface, from which 1.1% corresponds to land without any sort of restriction. The remainder exhibits limitations because of topography, desertification, increasing of salinity, lack of irrigation, the presence of heavy metals, etc. (Saa-Vidal, *et al*. 2010).

Table 7.4.1. Use of land in Chile (Saa-Vidal, *et al*. 2010).

Use type	Use	Land capability(*)	Surface (ha)	Percentage (%)
Agricultural arable lands	Without restrictions	I	111,346	0.15
		II	652,818	0.86
	With restrictions	III	1,762,559	2.33
		IV	2,106,619	2.79
Subtotal			**4,633,342**	**6.13**
Non-arable agricultural lands	Cattle	V	2,271,444	3.00
	Cattle-forestry	VI	6,219,736	3.22
	Forest	VII	13,430,602	17.76
Subtotal			**21,921,462**	**28,99**
Non-agricultural lands		VIII	14,200,000	18.78
Unproductive land			34,869,936	46.11
Total			**75,624,760**	**100**

(*) Land capability has been defined according to standards of U.S. Department of Agricultural (Gilo 2010).

Chilean agriculture and horticulture are mainly focused on five sectors, they are: i) major fruits and vine; ii) vegetables; iii) annual crops; iv) industrial crops; and v) livestock farming, secribed as follows (Saa-Vidal, *et al*. 2010):

- **Major Fruits and Vine:** Due to its exceptional climatological conditions, Chile has significant competitive advantages for the production of these sorts of crops in the central zone, which in general terms have land that is in high demand and of high quality, climate, technology, capital and workforce. These requirements have created conditions so that mainly large private companies control this business. The land usage tends to be intensive both in the planting stage and the subsequent stages of harvesting, using technical irrigation systems, great amounts of fertilisers and agrochemicals.

- **Vegetables:** The production of vegetables tends to be concentrated in the proximity of large consumer centres (i.e. medium and large cities). The management of the land is intensive in that the species have a short vegetative growing time, allowing more than one annual harvesting, although with a thorough handling of the land. The production of vegetables is carried out preferentially in land with capability I and II.

- **Annual Crops:** Annual cultivations are performed with a wide range of technologies and by using both irrigated and rainfed land across the country. Generally, it is associated with a high demand of workers and takes place in land with capability II, III and IV.

- **Industrial Crops:** The production of industrial crops such as raps, sugar beet, tobacco or sunflower depends on the demand of large buying companies, which normally provide technical assistance to the producers. Most of the cultivation of these crops takes place in land with capacity II, III and IV.

- **Livestock:** This activity is associated with a land demand of crops intended for fodder production and/or pasture use. It can be intensive in terms of land demand or highly concentrated if animals are stabled, for instance dairy, swine farming, etc.

Because preliminary rough estimations indicate that the main amount of biomass adequate for anaerobic digestion may be provided by annual crops (Chamy, *et al.* 2007), the potential analysis to be carried out in this chapter was focused on residues procured after harvesting them. Besides this, most of the available information on the agricultural sector is devoted to these crops due to their economic prominence.

The use of residue appears to be the most reasonable starting point for the development of a strategy focused on biogas as a source of energy because it brings direct environmental externalities. The use of energy crops, still a heated discussion at the political level, does not seem to be appropriate for implementation, at least in a first stage; it would be counterproductive for Chile to change the land currently used for food production in that it would force the country to revert to exports in order to address the internal consumption for biofuel production (Ramírez 2012). Although the biofuel alternative has not been thoroughly assessed at a national level yet, either technically or economically, preliminary evaluations indicate that the main constraints arise due to the limited potential available surface for the most promising crops both for liquid and gaseous biofuels (García, *et al.* 2012).

7.4.2 Annual Crops Characterisation

As can be observed in Table 7.4.2, the predominant species in terms of surface are wheat (40%), corn (19%), oats (15%) and potatoes (10%). At the regional level, 69% of wheat and 85% of oat crops are concentrated in Región del Bio-Bio (VIII) and Región de la Araucanía (IX), whereas corn is cultivated mainly in Región de O´Higgins (IX) and Región del Maule (VI), comprising 75% of the total area. Finally, potato plantations are dispersed across the country although more significantly concentrated in the south.

Table 7.4.2. Surface of annual crops (ha) (Ministry of Agriculture 2007).

								Regions								**Total**
Species	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	RM	XIV	XV	
Beer barley		0				226	626	1,363	7,509	431			53	977	24	**11,208**
Barley			3	507		125	155	1,449	1,631	752	90		4	9	4	**4,730**
Beans (a)				2	5	14	426	607	48							**1,102**
Beans(b)			5	280	253	691	4,717	2,802	616							**9,362**
Bread wheat		2	4	596	174	2,067	1,264	2,726	659							**7,493**
Chickpeas					246	869	896	925	2				778	3,957		**7,672**
Corn	1	153		659	1,127	46,705	29,407	12,019	685				264	14,418		**105,435**
Lentils			186			22	210	501	128				5,189	7		**6,243**
Mandioca			33		5								51	321		**410**
Oats (c)				25	170	830	1,255	20,033	48,290	6,272	334		22	1,180	3	**78,412**
Other cereals		4	66	137	720	902	533	696	1,039	405	3	15	1,705			**6,225**
Others	22	0		27	134	161	129	155	246	24	0	4	1,240			**2,144**
Peas				9	402	126	238	477	288	18	3		138	3,902	0	**5,601**
Grass peas				2	9	37	126	66	17				143	865		**1,263**
Potatoes	94	4	249	3,233	2,163	1,687	3,342	8,293	14,029	11,154	185	130				**44,562**
Quinoa	1,357	8		1		58			1							**1,424**
Rice (d)					48	101	17,333	4,146	0				24	28	5	**21,683**
Rye		1					353	278	291	6			12,010	3		**12,942**
Tricale						77	13	2,588	15,882	362						**18,922**
White wheat		18	1	1,133	1,595	5,176	22,781	67,742	93,623	11,379	21					**203,468**
Total	**1,472**	**190**	**548**	**6,610**	**7,050**	**59,874**	**83,803**	**126,864**	**184,984**	**30,802**	**637**	**148**	**21,618**	**25,667**	**36**	**550,303**

(a) for export, (b) internal consumption, (c) dray grain, (d) with peal.

Annual crop plantations have declined during the last decades. For the 2010-2011 period, for example, a decrease of roughly 18% can be observed in the planted area in comparison with that a decade ago. This decrease has not been uniform, with more substantial decreases occurring in wheat, vegetables, sugar beets, rape and potatoes. This fall has been partly counterbalanced by the growth of corn, oats, barley and lupine crops. On the contrary, a rise in the average productivity is observed in virtually all crops, reaching high values when compared at the international level (ODEPA 2012).

Table 7.4.3. Productivity of crops and total exploited surface at national level (Ministry of Agriculture 2007).

Species $(l=\overline{1,n})$	Average productivity p_l (qqm ha^{-1} y^{-1})	Total surface (ha)
1. Beer barley	50.62	11,108
2. Barley	41.52	5,983
3. Beans (for export)	20.81	1,153
4. Beans (for internal consumption)	17.02	9,633
5. Bread wheat	52.36	9,198
6. Chickpeas	8.94	2,940
7. Corn	108.32	102,955
8. Grass peas	8.34	255
9. Lentils	8.43	861
10. Oats	41.80	81,480
11. Others	n.a.	1,061
12. Others cereals	n.a.	6,187
13. Peas	14.10	1,258
14. Potatoes	154.54	53,731
15. Quinoa	6.08	1,427
16. Rice (with peel)	50.77	21,579
17. Rye	44.97	1,115
18. Tapicoa	1.35	5.18
19. Tricale	48.18	19,243
20. White wheat	47.77	219,126
Total country	-	**550,303**

7.4.3 Methodology

The methodology for the potential analysis of the mono-digestion of agro-industrial residue follows the same principles as those applied for all the previously assessed sectors, hence providing the same technical and economic indicators.

7.4.3.1 Methodology for the Potential Analysis

The annual amount of residue from seasonal crops was calculated using residue-to-crop production ratios, productivity per crop and planted area in a county. Because of the lack of more specific information, some parameters were assumed by applying a conservative criterion. The technical potential of *biogas-to-energy* and *biogas-to-upgrade* routes can be calculated through Equation 7.4.1 and Equation 7.4.2 as follows:

$$\pi_{t,i}^{BTE} = \sum_{l} M_l \; S_l \; f_l \; (1 - H_l\,)\, \Theta_l \; p_l \; a_i \; \Delta\widetilde{H}_{\mathrm{LHV}}^{\mathrm{CH_4}} \;\; A_e \, \eta_e \qquad \begin{cases} A_e = 1; \forall\, \pi_{t,i}^{BTE} > 8kW_e \\ A_e = 0; \forall\, \pi_{t,i}^{BTE} \leq 8kW_e \end{cases} \qquad \text{Equation 7.4.1}$$

$$\pi_{t,i}^{BTU} = \sum_{l} M_l \; S_l \; f_l \; (1 - H_l\,)\, \Theta_l \; p_l \; a_l \; A_u \qquad \begin{cases} A_u = 1;\; \forall\, \pi_{t,i}^{BGU} > 5Nm_{CH_4}^{3} h^{-1} \\ A_u = 0;\; \forall\, \pi_{t,i}^{BGU} \leq 5Nm_{CH_4}^{3} h^{-1} \end{cases} \qquad \text{Equation 7.4.2}$$

In which $\pi_{t,i}$ is the technical potential from the *i*th-county, either electricity or Bio-SNG. For the *l*th-crop species within the *i*th-county, M_l corresponds to the methane yield; S_l is the volatile-to-total solid ratio; f_l is the residue-to-crop production ratio; H_l is the humidity assumed at 15% (wet basis); p_l is the crop average productivity (see Table 7.4.3); Θ_l is the sustainable rate removal; and a_i is the area of the *i*th-county. The remaining parameters correspond as defined in Equations 7.3.1 and 7.3.2 in Section 7.3 *Livestock Farming Sector*. In this calculation, it is implicitly assumed that the total amount of biomass to convert into biogas within each county is done at a single centralised biogas plant. This assumption is put forward since there is no further information on the geographical distribution of crop residue after harvesting to conduct an assessment in greater detail. This point and its implications will be discussed more broadly in the section on economic modelling for cost estimation.

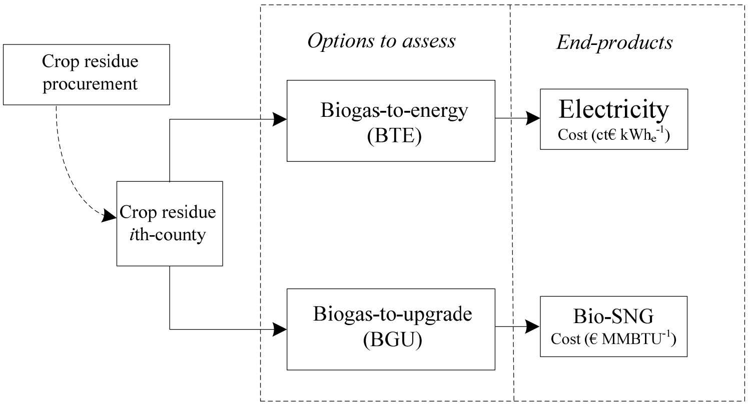

Figure 7.4.1. Conversion pathways to assess for the utilisation of crop residue for the production of either electricity or Bio-SNG through mono-digestion.

Table 7.4.4. Agricultural crops and parameters for the calculation of potential of biogas generation.

Agricultural crops $(l = \overline{1,n})$	Reside-to-crop production ratio f (kg kg^{-1})	Sustainable rate removal Θ (kg kg^{-1}) (a)	Volatile-to-total solid ratio S (kg$_{vs}$ kg$_{ts}^{-1}$)	Biomethane yield M ($\mathrm{Nm}^3_{\mathrm{CH_4}}\,\mathrm{kg}^{-1}_{\mathrm{vs}}$)
1. Beer barley	1.4 (a)	0.40 (a)	0.94 (d)	0.229 (d)
2. Barley	1.4 (a)	0.40 (**)	0.90(d)	0.229 (d)
3. Beans (for export)	2.1 (b)	0.40 (**)	0.90(**)	0.174 (e)
4. Beans (for internal consumption)	2.1 (b)	0.40 (**)	0.90(**)	0.174 (e)
5. Bread wheat	1.3 (a)	0.40 (**)	0.92 (**)	0.087 (g)
6. Chickpeas	2.1 (*)	0.40 (**)	0.90 (**)	0.200 (e)
7. Corn	1.4 (a)	0.50 (a)	0.98 (d)	0.317 (d)
8. Grass peas	2.1 (*)	0.40 (**)	0.90 (**)	0.200 (**)
9. Lentils	2.1 (*)	0.40 (**)	0.90(**)	0.200 (**)
10. Oats	1.5 (a)	0.40 (a)	0.58(g)	0.203 (g)
11. Others	1.0 (**)	0.40 (**)	0.90 (**)	0.200 (**)
12. Others cereals	1.0 (*)	0.40 (**)	0.70(**)	0.200 (**)
13. Peas	2.1 (*)	0.40 (**)	0.90(**)	0.200 (**)
14. Potatoes	0.4 (b)	0.40 (**)	0.90(**)	0.366 (h)
15. Quinoa	1.0 (*)	0.40 (**)	0.192(j)	0.241 (j)
16. Rice (with peel)	1.6 (a)	0.50 (a)	0.92(d)	0.195 (d)
17. Rye	1.8 (a)	0.40 (a)	0.92(j)	0.360 (i)
18. Tapicoa	1.0 (*)	0.40 (**)	0.90(**)	0.100 (**)
19. Tricale	1.3 (c)	0.40 (**)	0.93(j)	0.100 (**)
20. White wheat	1.3 (a)	0.40 (a)	0.92(**)	0.087 (g)

(a) Scarlat *et al*. (2010), (b) IPCC (1996), (c) Wikström and Adolfsson (2006), (d) Dinuccio *et al.* (2010), (e) Deublein and Steinhauser (2011), (f) Somayaji and Khanna (1994), (g) Lehtomäki *et al*. (2008), (h) Parawira *et al.* (2008), (i) Petersson *et al.* (2007), (j) Cropgen Database, (k) López-Dávila *et al.* (2012), (*) assumed as beans, (**) assumed.

The technical potential of the entire country, either for the *biogas-to-energy* or *biogas-to-upgrade route*, can be evaluated as the sum of all single technical potential on the totality of counties (n) as equation 7.4.3 shows:

$$\Pi^{BTE} = \sum_{i}^{n} \pi_{t,i}^{BTE} \qquad \Pi^{BTU} = \sum_{i}^{n} \pi_{t,i}^{BTU} \qquad \text{Equation 7.4.3}$$

7.4.3.2 Methodology for the Economic Modelling

The mono and co-digestion of crop residue implies intermediate steps (depending on the harvesting system) of collecting, hauling, packing, on-farm transporting and on-road conveyance of biomass to a processing facility since it is irregularly widespread across large areas, incurring an additional cost for the biogas production. Under these circumstances, it is necessary to estimate the cost of crop residue procurement by proposing a simplified model for the operations associated to its recovery, from the field after the annual harvesting to its supply at the gate of plant, as discussed in Chapter 4. Based on this, it was assumed that the shape of each county can be approximated through a square with side l and surface equivalent to the county's. Moreover, it was assumed that all the available biomass after harvesting had a homogeneous superficial density (measured for instance as $t\,m^{-2}$) and was conveyed to the geometric centre of the county; therefore, the geometric centre of the square. Assuming a tortuosity for on-road transportation, it is possible to demonstrate, after applying some integral calculus, that the average displacement distance for the transportation of biomass $\overline{d_s}$ at county-level can be calculated by Equation 7.4.4 (see Chapter 4, section 4.5).

$$\overline{d_{s,i}} = \frac{1}{6} l_i \tau (\sqrt{2} + \ln(1+\sqrt{2})) \qquad \text{Equation 7.4.4}$$

For the specific on-road transportation cost (c_e'), 1.8 € t^{-1} km $^{-1}$ was considered as representative according to Hetz *et al.* (2010). This value, when multiplied by the average displacement distance (Equation 7.4.4), leads to the total on-road transportation cost of biomass.

The majority of information available on the cost of collecting biomass from the field is focused on wheat straw and corn stover, basically because they are the dominant crops in a substantial number of countries (Marckert 2011; Scarlat, *et al.* 2010). Although crop residue has diverse characteristics affecting the cost of recovery, transportation and processing, the cost of collecting all crop residue from the field (which includes preparing, packing and on-farm transportation) was approximated without distinguishing their differences to wheat straw because of the lack of more specific data. Hetz *et al.* (2010) reported that the cost of collecting wheat straw after harvesting was in the 6-10 € t^{-1} range, hence a value of 8 € t^{-1} was approximated for the assessment.

Therefore, the total procurement cost of crop residue, which includes collecting and on-road conveyance, can be estimated by applying Equation 7.4.5.

$$C_{p,i} = (c_e^t \overline{d}_{s,i} + c_e^c)m_i \qquad \text{Equation 7.4.5}$$

In which $C_{p,i}$ is the procurement cost of biomass at the gate of plant in the *i*th-county; c_e^t is the specific on-road transportation cost; $\overline{d}_{s,i}$ is the average displacement distance for the transportation of biomass within the *i*th square-approximated county; c_e^c is the specific biomass collecting cost; and m_i is the total crop residue available yearly within the *i*th-county.

The unitary cost of production, either for the *biogas-to-energy* or *biogas-to-upgrade* pathway, was calculated following the same procedure applied in previous chapters, and according to Equation 7.4.6.

$$c_i \pi_{t,i} = \alpha I_i + C_{o\&m,i} + C_{p,i} - R_i \qquad \text{Equation 7.4.6}$$

In which $\pi_{t,i}$ is the technical potential of secondary energy from the *i*th-county, either electricity or Bio-SNG; I_i is the total capital investment; α is the capital recovery factor; $C_{o\&m,i}$ is the operation & maintenance cost for the biogas plant located in the *i*th-county; and R_i the revenue obtained from selling by-products such as digestate or heat.

Revenues from heat and digestate by-products were not considered in the cost estimation. Firstly, because there is no established market for the commercialisation of surplus heat in the country (i.e. district heating), and, secondly, due to the fact that the sale of digestate plays only a marginal role in terms of the economics of the process (Lantz 2012), and moreover its use is not regulated in the country.

7.4.3.3 Methodology for the Economic Potential

The mathematical method for working out the representative generation cost and the corresponding economic limit can be found in detail in Chapter 4, or as already illustrated in previous sectors. Following the same methodology, the estimation of the needed feed-in tariff and the total yearly needed subsidisation was calculated.

7.4.4 Results

For the mono-digestion of agricultural residue, the technical potential of electricity reached 1,360 GWh$_e$y^{-1} and the economic potential 1,112 GWh$_e$y^{-1} at a representative generation cost of 15.4 ct€ kWh$_e^{-1}$ (see Figure 7.4.2). On the other hand, the generation of Bio-SNG from this substrate offered a technical potential of 351 MMNm^{3}y^{-1} and an economic potential of 280 MMNm^{3}y^{-1} at a representative generation cost of 40 € MMBTU^{-1} (see Figure 7.4.3).

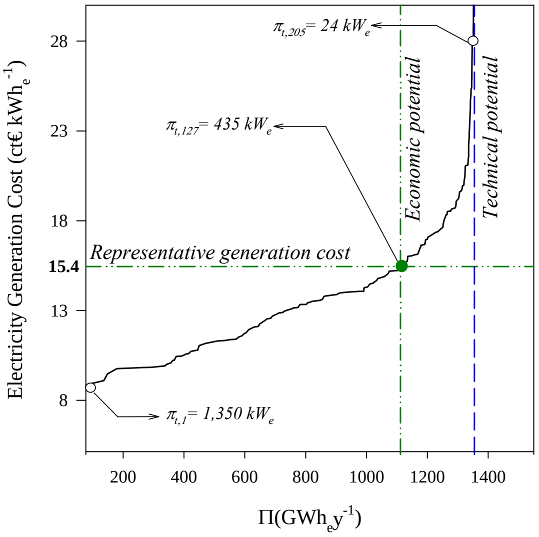

Figure 7.4.2. Supply-cost curve for biogas-to-electricity pathway by mono-digestion of agriculture residue.

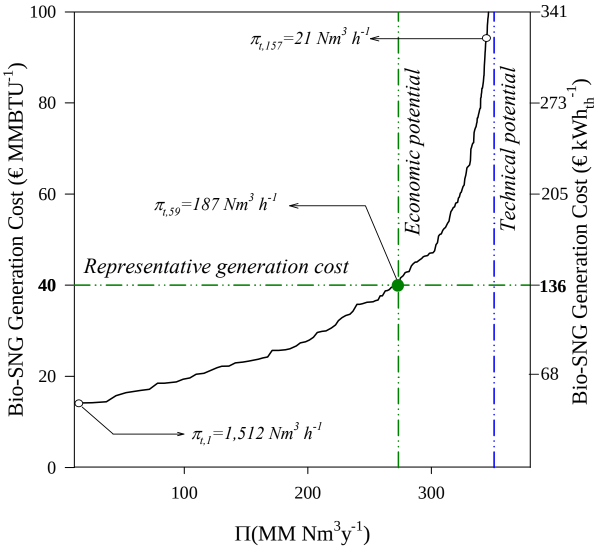

Figure 7.4.3. Supply-cost curve for the biogas-to-upgrade pathway by mono-digestion of agricultural residue.

A high concentration of this technical potential was observed in the low-power range (10-250 kW$_e$) and accounted for 46% of the total. However, the 500 kW$_e$-5 MW$_e$ range had 33% of the total technical potential. For the Bio-SNG option, more than 57% of the potential was concentrated in a range lower than 1 MM Nm^{3}y^{-1}, followed by 22% at the 1.0-2.7 MMN m^{3}y^{-1} scale. Geographically, the technical potential of electricity and Bio-SNG was concentrated in the Región de O´Higgins (VI) (32%), Región del Maule (VII) (19%) and Región de la Araucanía (IX) (18%) which represented almost 70% of the total, as seen in Figure7.4.4 and Figure 7.4.5.

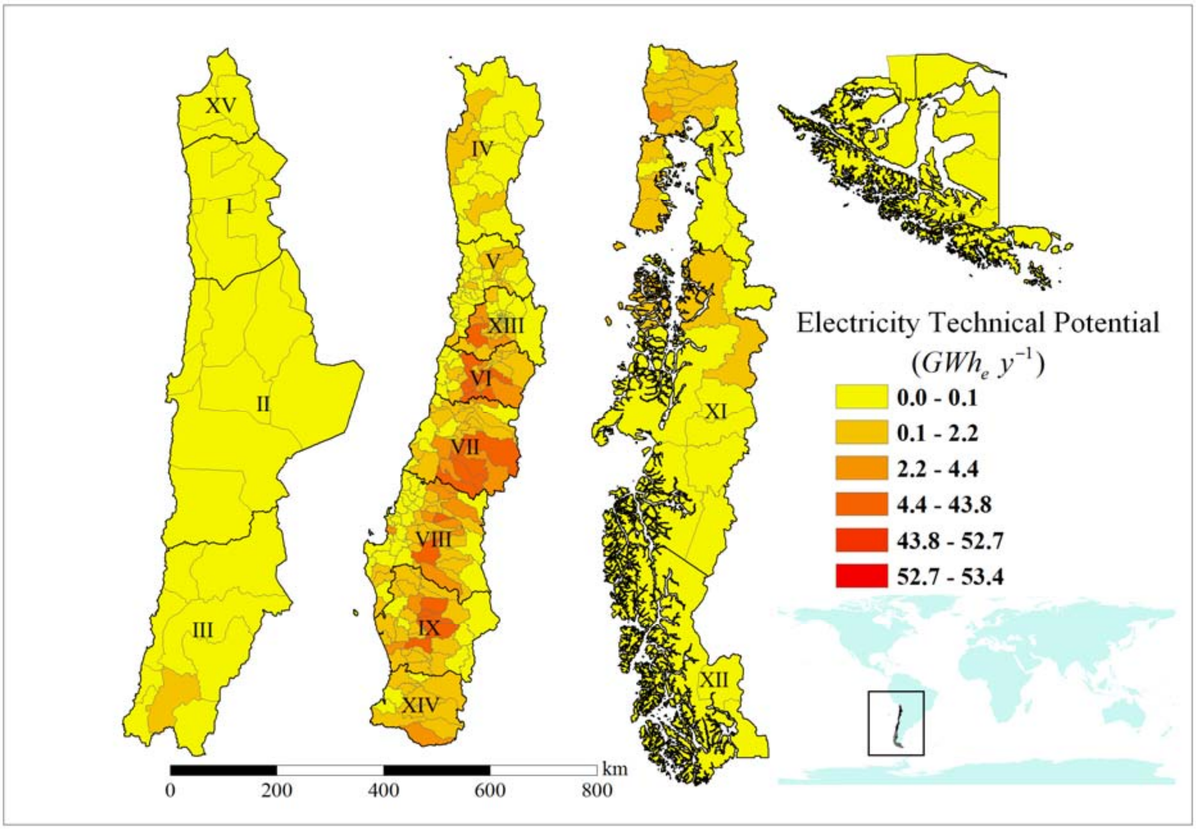

Figure 7.4.4. Technical potential of electricity from mono-digestion of agricultural residue.

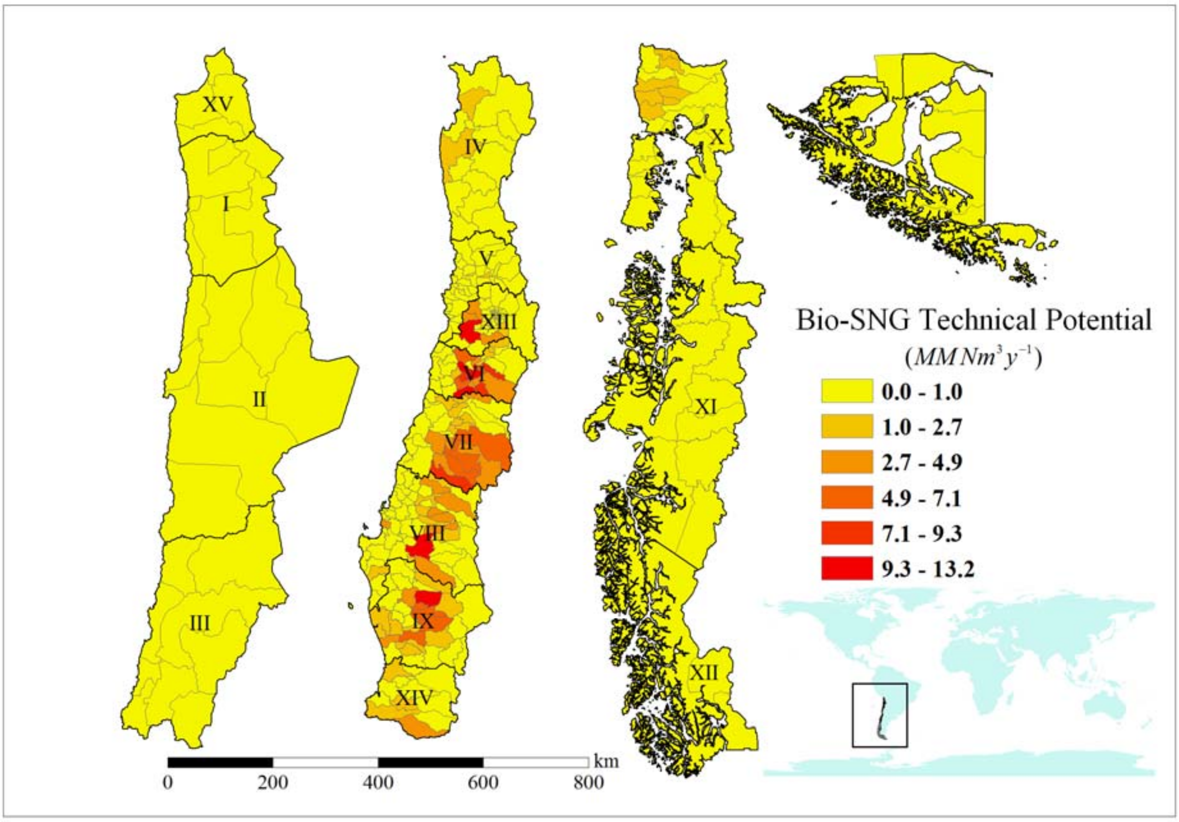

Figure 7.4.5. Technical potential of Bio-SNG from mono-digestion of agricultural residue.

7.4.5 Discussions

For the electricity alternative, as observed in Figure 7.4.6, there is a fraction of approximately 600 GWh$_e$y^{-1} that may run profitably, when 12 ct€kWh$_e^{-1}$ is considered as the electricity market price. This realisable potential is made of 31 biogas plants with power capacity from 1.4 MW$_e$ MWe to 94 kW$_e$. To achieve the economic potential, a generation subsidy of roughly 3.4 ct€kWh$_e^{-1}$ would be necessary.

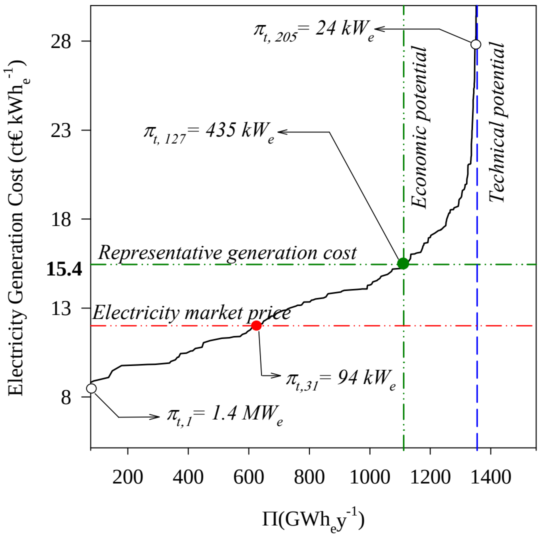

Figure 7.4.6. Supply-cost curve for biogas-to-energy pathway by mono-digestion of agricultural residue.

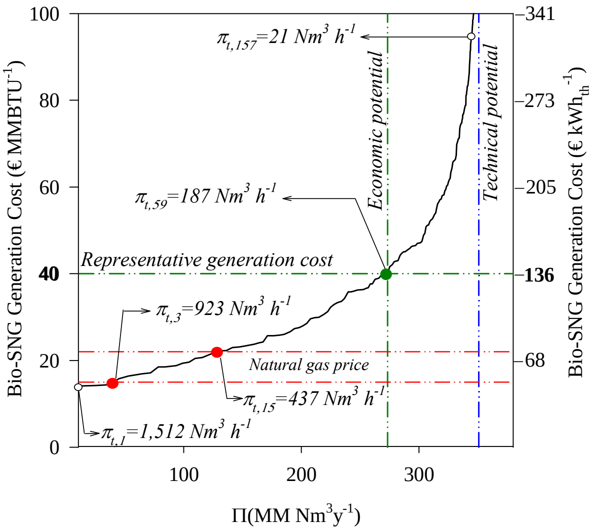

Figure 7.4.7. Supply-cost curve for biogas-to-upgrade pathway by mono-digestion of agricultural residue.

As shown in Figure 7.4.7, the biogas-to-upgrade route has only three units offering a cost of production lower than the market price of natural gas, although with capacities in the commercial scale. In spite of this advantageous condition, this high cost linked with relatively high capacity (in the context of biogas plants) is explained by the additional cost of production associated with the procurement of biomass (crop residue), which raises it somewhat, an aspect not present in the previously assessed sectors. This fact can be observed in the high associated generation subsidy (25-18 € MMBTU^{-1}) if this alternative were wanted to become profitable. Besides, the total annual subsidisation for Bio-SNG is approximately 82 MM€, almost five orders of magnitude greater than that of electricity, and with a considerably lower number of plants, 59 versus 127 (see Figure 7.4.6 and Figure 7.4.7).

Table 7.4.4 summarises the main economic indicators characterising the crop residue sector for the two possibilities of biogas processing, biogas-to-energy and biogas-to-upgrade.

Table 7.4.5. Energy potential of the biogas-to-energy and biogas-to-upgrade routes for crop residue utilisation.

Economic indicator	Route of conversion	
	Biogas-to-energy (BTE)	Biogas-to-upgrade (BTU)
Technical potential	1,355 $GWh_e y^{-1}$	351 MM Nm^3 y^{-1}
Economic potential	1,112 $GWh_e y^{-1}$	280 MM Nm^3 y^{-1}
Minimum cost of production	8.3 ct€kWh_e^{-1}	14.1 € $MMBTU^{-1}$
Representative generation cost	15.4 ct€kWh_e^{-1}	40 € $MMBTU^{-1}$
Needed feed-in tariff	3.4 ct€kWh_e^{-1}	25-18 € $MMBTU^{-1}$
Needed subsidy	17 MM€	82 MM€

7.4.6 Preliminary Conclusions

As observed for the previous sectors, the biogas-to-energy pathway implies a larger number of plants that can run without relying on subsidisation for energy generation (31 plants – see Figure 7.4.6). On the other hand, the biogas-to-upgrade exhibited a minimum cost of production (STAS) only slightly lower than the market price of natural gas, which makes the mono-digestion of this substrate hardly competitive.

As mentioned earlier, a significant geographic concentration of the technical potential, either electricity or BioSNG, was observed in three administrative areas, which correspond to Región de O´Higgins (VI), Región del Maule (VII) (19%) and Región de la Araucanía (IX) (18%). This being so, the implementation of bioenergy policy to boost biogas production should be considered as a priority to target.

7.5 Co-Digestion of Agro-Industrial Residue

Although crop residue, as previously described, can be converted anaerobically as if they were a single substrate, the option of mixing them with other feedstock such as manure offers significant advantages, among them an increase in biogas yield, operation of the reactor at higher solid concentration thus offering a larger gas flow at the same capacity, and more stable operation. The co-digestion is, however, limited both to the availability of feedstock, when the manure slurry is used as a substrate to increase solid concentration, and the total concentration of solids in the reactor, when a wet-technology is being used. These aspects will basically determine the possibility of implementation.

7.5.1 Introduction

The production of biogas from manure can be stepped up when co-substrates are added to make the biogas yield and the content of methane in the gas rise (Deublein & Steinhauser 2011), thus improving reactor efficiency and the economics of the plant. This enhancement can be explained because of the synergism in the reacting medium and the addition of some missing nutrients (Mata-Alvarez, *et al.* 2000).

The possibility of carrying out co-digestion is plausible, as livestock industries are normally located near the agricultural complex where residue might be available. However, the supply of biomass is restricted by logistical issues and the cost related to the procurement of substrates; the availability of manure is not necessarily associated with that of crop residue, and, conversely, the availability of manure at adequate scale is not necessarily associated with crop residues supplied at a proper rate. Nonetheless, considerable attention has been paid to the assessment of biogas by co-digestion in large areas (Szkliniarz & Vogt 2012; Zubaryera, *et al.* 2012), mainly as a consequence of the environmental gains as previously mentioned, but also because of the opportunities for rural development and the contribution this could make to reach the goal of renewable energy generation.

7.5.2 Methodology

The methodology for the potential analysis of co-digestion by mixing agro-industrial residue (i.e. manure and the material left on the field after the annual harvest) follows the same procedure applied for all the previously assessed sectors. Because this assessment only considers the possibility of mixing the substrates at a proper rate and concentration under the restrictions imposed by the geographical distribution of the feedstock, the specific parameters such as biomethane yield, rate of manure generation, crop productivity, etc. are the same here as those presented in sections 7.3 and 7.4.

7.5.2.1 Methodology for the Potential Analysis

As depicted in Figure 7.5.1, the co-digestion involves mixing a co-substrate (crop residue in this case) with manure for the purpose of improving the biogas generation. Nevertheless, the supplementary solid that can be added to the manure slurry is limited by the operating conditions of the anaerobic technology being employed. In general terms, anaerobic digestion technologies are classified into wet-fermentation and dry-fermentation. The former operates with a total solid concentration lower than 10-15% (dry basis), whereas the latter is adequate for a total solid concentration higher than 20% (Karthikeyan & Visvanathan 2013; Abbassi-Guendouz, *et al.* 2012). The dominant technology for the treatment of agricultural residues is wet fermentation (Karellas, *et al.* 2010), and, for the national potential analysis, it was used as the reference in this assessment. Thus, a total solid concentration in the digestor (x^m) of 15% as maximum limit was set up.

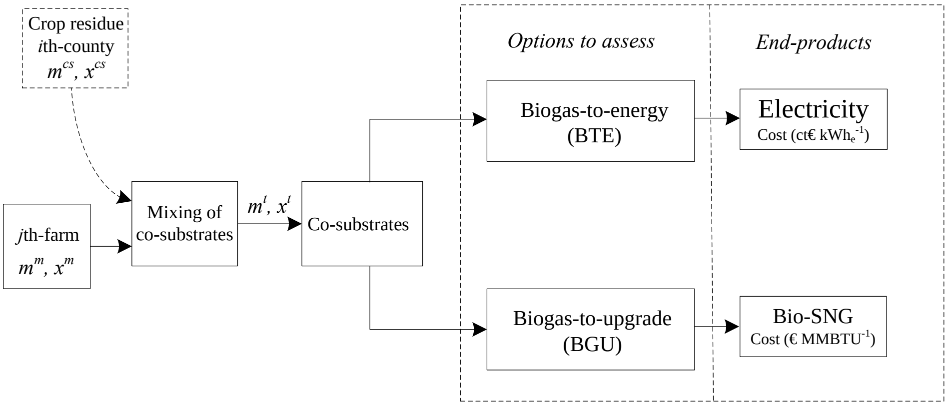

Figure 7.5.1. Conversion pathway for co-digestion of manure and crop residue.

The information provided in Table 7.3.1 can be used to calculate the solid concentration of the manure for each type of livestock. For instance, the concentration of total solid for dairy manure is 14%, while swine is 13%. For the assumed humidity of agricultural residue, 15% wet basis, its total solid concentration is 85%.

It can be demonstrated, by applying a mass balance (see Figure 7.5.1), that the maximum amount of co-substrate tolerable for a wet-fermentation mixing manure and crop residue, and the total mixed substrate to digest can be calculated with the following equations:

$$m_{\max}^{cs} = m^{m}\,\frac{(x^{m} - x_{\max})}{(x_{\max} - x^{cs})} \qquad \text{Equation 7.5.1}$$

$$m^{t} = m^{m}\,\frac{(x^{m} - x^{cs})}{(x_{\max} - x^{cs})} \qquad \text{Equation 7.5.2}$$

In which $m_{\max}^{cs}$ is the maximum amount of co-substrate to add for a wet-fermentation with manure; m^{m} is the total available manure per farm; x^{m} is the total solid manure concentration; x^{cs} is the total solid concentration of the co-substrate, in this case crop residue; and $x^{\max}$ is the maximum total solid concentration within the reactor for a wet co-fermentation, set up at 15% as previously indicated.

The availability of both substrates for co-digestion (i.e. manure and crop residue) depends on both the spatial distribution of farms and location of annual crops, which cannot necessarily be proportional or supplied because of the distance, in practical terms. Due to the fact that the assessment was conducted using the county as the smallest geo-administrative control area, a necessary condition for the co-digestion was that the totality of biomass (crop residue in this case) in each county (m_{i}) must be at least equal to the maximal amount of co-substrate to be added $(m_{\max}^{cs})$ to the totality of the farm-based units within that county. The latter can be expressed by a Boolean operator (A_{c}) to differentiate when the co-digestion can be performed or not, as indicated by Equation 7.5.3 and Equation 7.5.4.

$$\pi_{t,j}^{BTE} = \sum_{j} m_{j}^{t}\; S_{c}\, R_{c}\, \Delta\tilde{H}_{LHV}^{CH_4}\; \eta_{a}\, \eta_{e}\, A_{e}\, A_{c} \qquad \begin{cases} A_{e} = 1; \forall\, \pi_{t,j}^{BTE} \geq 8kW_{e} \\ A_{e} = 0; \forall\, \pi_{t,j}^{BTE} < 8kW_{e} \\ A_{c} = 1; \forall\, m_{i} \geq \sum_{i,j} m_{\max,j}^{cs} \\ A_{c} = 0; \forall\, m_{i} < \sum_{i,j} m_{\max,j}^{cs} \end{cases} \qquad \text{Equation 7.5.3}$$

$$\pi^{BGU}_{t,j} = \sum_i m^t_j \, S_c \, R_c \, \eta_a \; A_u A_c \qquad \begin{cases} A_u = 1; \; \forall \; \pi^{BGU}_{t,j} > 5 Nm^3_{CH_4} h^{-1} \\ A_u = 0; \; \forall \; \pi^{BGU}_{t,j} \leq 5 Nm^3_{CH_4} h^{-1} \\ A_c = 1; \; \forall \; m_i \geq \sum_{i,j} m^{cs}_{\max,j} \\ A_c = 0; \; \forall \; m_i < \sum_{i,j} m^{cs}_{\max,j} \end{cases} \qquad \text{Equation 7.5.4}$$

In which R_c corresponds to the yield of biomethane for co-digestion estimated in 250 $Nm^3_{CH_4} kg_{vs}$ as a representative value (Lehtomäki, *et al.* 2007), and S_c is the volatile-to-total solid ratio calculated for the mixing of manure and crop residue.

The technical energy potential of the entire country derived from the co-digestion of crop residue and manure either via the *biogas-to-energy* or *biogas-to-upgrade* route can be calculated by adding up the technical potential for all the *i*th-counties as Equation 7.5.6 indicates.

$$\Pi^{BTE}_t = \sum_j \pi^{BTE}_j \qquad \Pi^{BTU}_t = \sum_j \pi^{BTU}_j \qquad \text{Equation 7.5.6}$$

7.5.3.2 Methodology for the Economic Modelling

The economic modelling was conducted according the same procedure already applied for the evaluation of livestock farm and agricultural sectors (sections 7.3 and 7.4, respectively), and consequently by using identical economic and technical parameters. In these terms, the cost of feedstock supply was estimated by using the square-shape approximation of the county where the biomass is available. Moreover, no use or commercialisation of the by-products heat and fertiliser were considered on account of the same reason above given.

7.5.3.3 Methodology for the Economic Potential

The mathematical method for computing the representative generation cost and the corresponding economic limit can be found in detail in Chapter 4 or as already illustrated in previous sectors. Following the same methodology, the estimation of the needed feed-in tariff and the total yearly needed subsidisation was calculated.

7.5.3 Results

The possibility of co-digesting manure with agricultural residue offered an increase in the economic limit for the electricity generation option and provided the same representative generation cost as the mono-digestion of manure. As observed in Figure 7.5.2, the co-digestion raised the economic potential from 780 $GWh_e y^{-1}$ to 1,140 $GWh_e y^{-1}$ at a representative generation cost of 25 $ct€\,kWh_e^{-1}$. This greatly increased the number of biogas plants that could achieve the minimal technical conditions to operate. As seen in Figure 7.5.2, whereas the economic limit of biogas-to-energy from mono-digestion of manure was made up of 367 plants, with nominal capacities from 22 MW_e to 25 kW_e, the economic limit of biogas-to-energy via co-digestion accounts for 1,108 plants with nominal capacity in a similar power range.

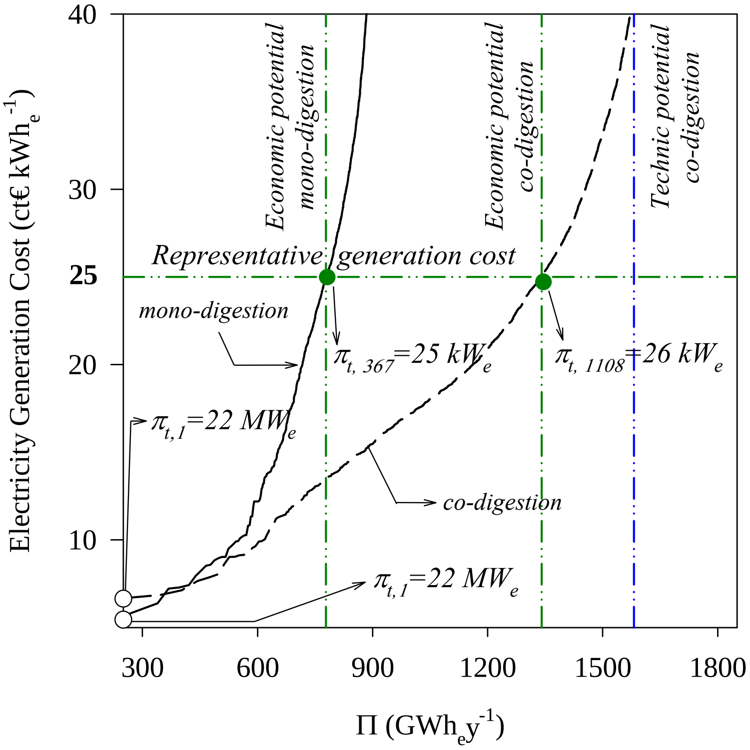

Figure 7.5.2. Supply-cost curve for the electricity generation of co-digestion of manure and crop residue.

Although the increase in electrical potential by the co-digestion was significant at 46%, the power capacity was still concentrated in the low scale and accounted for 39% in the range from 10 to 250 kW_e, and 31% were lower than that of 10 kW_e. Potentials exceeding 5 MW_e were exceptional, and constituted less than 3% of the technical potential.

The assessment of the biogas-to-upgrade route was conducted following the same methodological approach applied to the biogas-to-energy pathway by considering co-digestion; however, the results led to an increase in the Bio-SNG potential predominantly in the low range, with the consequence that the representative generation cost reached extremely high and empirically unprecedented levels. Nevertheless, counties were found where it would be possible to develop Bio-SNG exploitation projects at commercial scale, although they represented no more than 15% of the total technical potential. Similar to the mono-digestion option, only two regions concentrated more than 61% of the technical potential, Región Metropolitana (XIII) and Región de la Araucanía (IX).

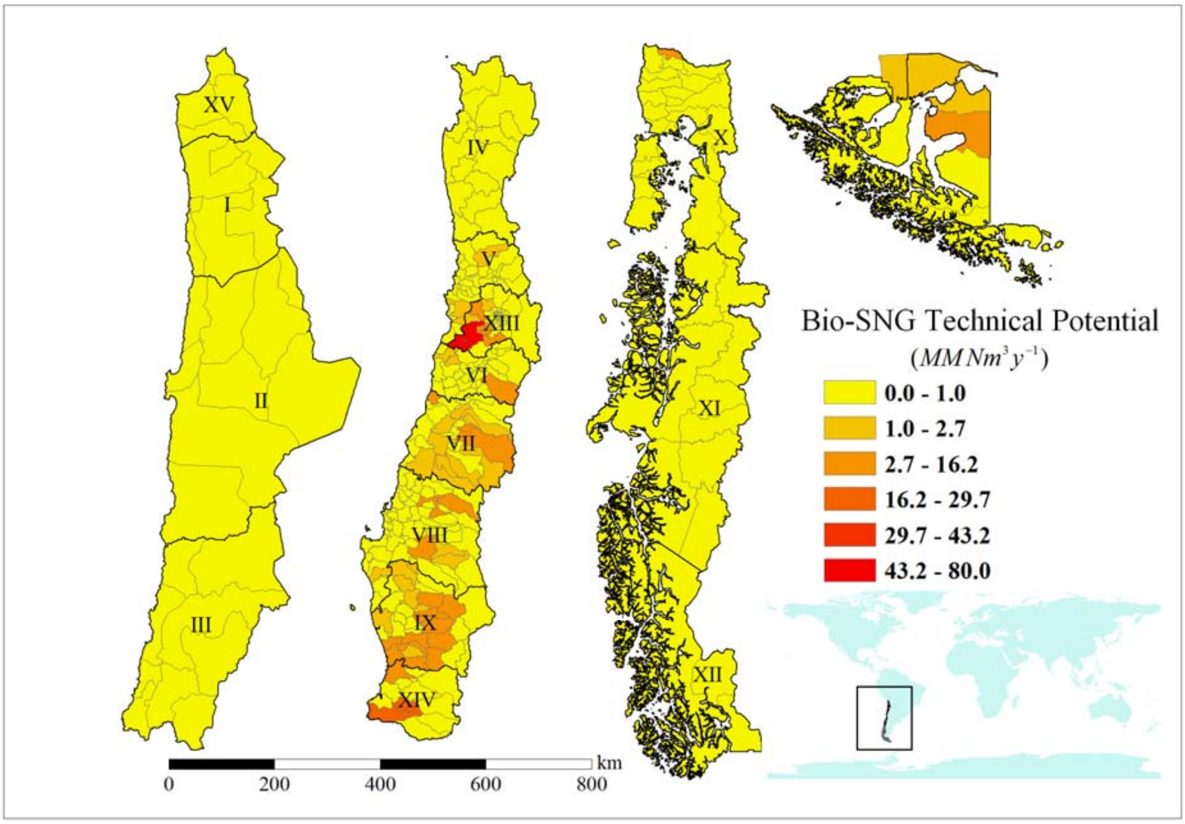

Figure 7.5.3. Technical potential of Bio-SNG from co-digestion of manure and agricultural residue.

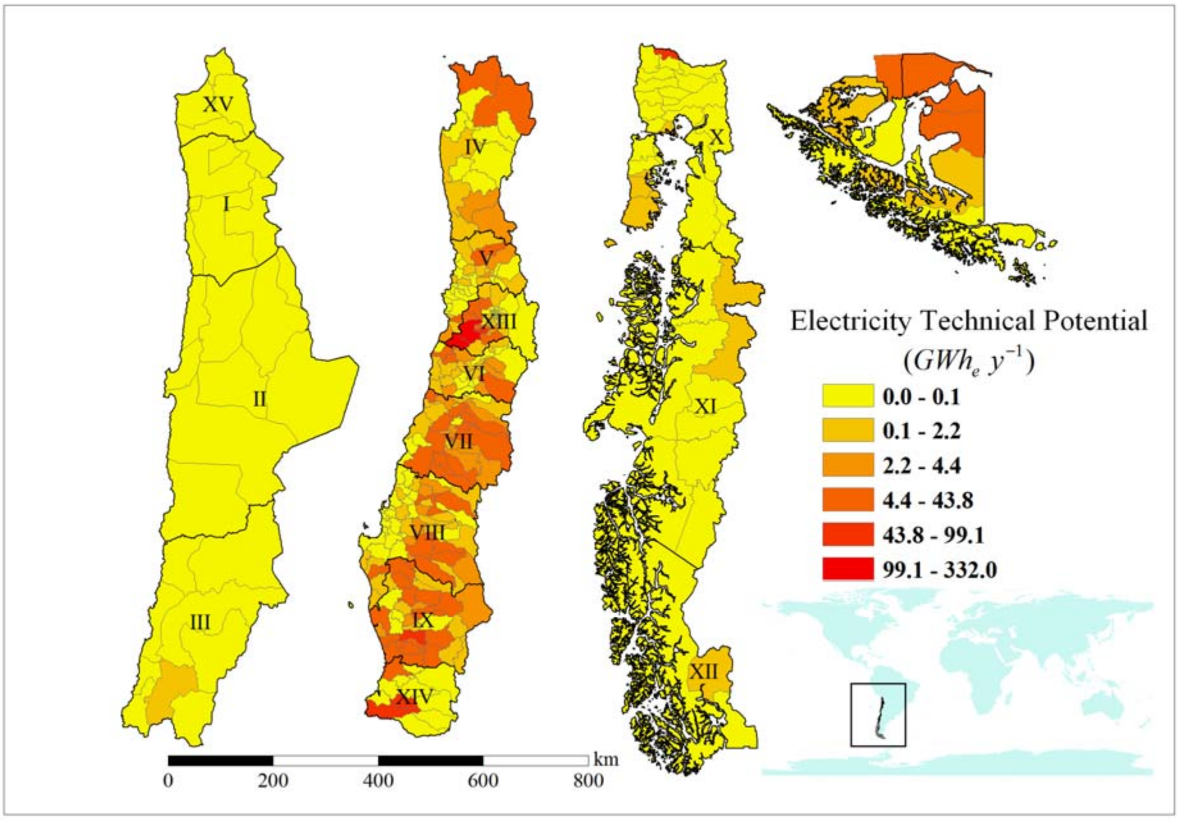

Figure 7.5.4. Technical potential of electricity from co-digestion of manure and agricultural residue.

Additionally, it was found that the technical potential of electrical power on the national level was heavily concentrated on the small-scale, in the 10-250 kW_e range, and accounted for 71% of the country's total. A similar tendency was observed in the technical potential of Bio-SNG, in which approximately 80% of the potential was concentrated on a scale lower than 1 $MMNm^3y^{-1}$, with only 12% in the 1.0 - 2.7 $MMNm^3y^{-1}$ range.

7.5.4 Discussions

As previously indicated, the representative generation cost for electricity generation was not modified as a consequence of the co-digestion in spite of being increased substantially the technical and the economic potential, the later from 779 GWh_ey^{-1} to 1,338 GWh_ey^{-1}. Consequently, the co-digestion gave rise to the number of biogas plants making up the economic potential, from 376 to 1,108, almost three times the order of magnitude.

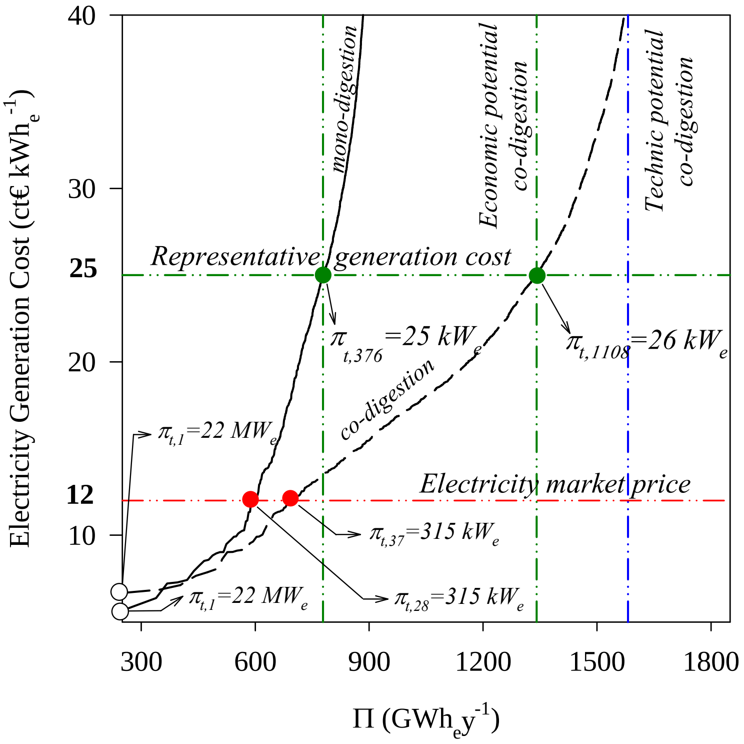

Figure 7.5.5. Supply-cost curve for the electricity generation of co-digestion of manure and agricultural residue.

Although the same methodological approach used for the assessment of the biogas-to-energy route was applied, the results led principally to an increase in the Bio-SNG potential in the very low range, with the consequence that the representative generation cost rose to high levels; however, this should not be used as a means of evaluation because it is only relevant in a theoretical context and has no practical meaning; therefore, it was not included in Table 7.5.1. Nevertheless, counties were found where it would be possible to develop Bio-SNG exploitation projects at commercial scale.

Table 7.5.1. Energy potential of biogas-to-energy and biogas-to-upgrade for co-digestion of agro-industrial residue.

Economic indicator	Route of conversion	
	Biogas-to-energy (BTE)	Biogas-to-upgrade (BTU)
Technical potential	1,582 GWh$_e$y^{-1}	429 MM Nm^{3}y^{-1}
Economic potential	1,338 GWh$_e$y^{-1}	-
Minimum cost of production	5.2 ct kWh$_e^{-1}$	-
Representative generation cost	25.0 ct kWh$_e^{-1}$	-
Needed feed-in tariff	13.0 ct kWh$_e^{-1}$	-
Needed subsidisation	84 MM **€** y^{-1}	-

7.5.5 Preliminary Conclusions

On the basis of the assessment presented above, co-digestion is possible to be carried out in economic terms and its implementation may provide a significant increase in the economic potential of the electricity option. As observed systematically for the four sectors previously assessed, a high concentration of the potential is observed, and for this option (i.e. co-digestion of agro-industrial residues) in only two regions located in the south of the country. On the contrary, the biogas-to-upgrade route as the main option does not seem advantageous since the potential is concentrated mainly in the low scale, in which the Bio-SNG option exhibits a highly sensitive cost of production. In these terms, the biogas-to-energy pathway offers greater flexibility in terms of the potential and distribution of biomass available in the country.

8. Interpretation and Discussions of Findings

The literature, with reference to biomass potential, is extensive, and the technical potential of bioenergy has been relatively well-mapped for numerous regions and countries; however, the economic potential has been less thoroughly investigated and in numerous cases is poorly understood. The critical review presented in the introductory chapter points out how numerous publications in the field of bioenergy offer misleading definitions of the potential limits, accompanied by a weak formulation of the theory of potential analysis leading to an erroneous interpretation of results.

The main advantage of the formulation of a potential analysis theory based on cost-supply curves, as put forward in the present research, lies in the possibility of technical and economic comparisons of processes or technologies in spite of their dissimilar operation principles (gasification, direct combustion or pyrolysis, for instance), if the end-products are the same. It, therefore, becomes an ideal tool not only for a cross techno-economic analysis for different sorts of technologies and conversion pathways, but also for the comparison of the potentials and the economic indicators between different sources of raw material addressed as *sectors* in this research. In these terms, the usefulness of the cost-supply curve goes beyond mere technical assessment since they also offer the chance to conduct a cross-sector analysis, relevant in the decision-making process and designed to elucidate and organise a hierarchy of priorities in public policy formulation. In addition to this, the integration of the technical and economic data obtained from the potential analysis into a GIS enables the prospect of differentiating between regions or other sorts of geopolitical jurisdiction. This plays a crucial role in developing specific policy when considering criteria such as local development, concentration of population or development of rural areas by facilitating the generation of employment.. In this sense, the assessment performed across this research for Chile should be worked out as one relevant for decision-making in the near future because present-day technologies were mainly employed to outline the chances of energy production in economic terms but also the limitation of the usage and treatment of the resources currently available.

It is worth underlining that high-quality information is crucial to the successful assessment of boienergetic potential. Although reliable and validated financial, social and other statistical data are widely available for Chile, there are limited high-quality environmental or other pertinent information for boienergetic assessments available. This drawback stems from the difficulty of procuring information or the cost of doing so. To undertake this research project, the necessary set of input data for the four assessed sectors was constructed manually after drawing from the most accurate sources of primary information on environment and industry, such as environmental impact assessment reports, agricultural and livestock census as well as indirect data issued from institutions directly involved in the matter (i.e. authoritative sources of information). The consistency of data was validated by generating indicators obtained through mass and energy balances, and afterward comparing them to international data or to other secondary sources of information. Along with this issue, each of the data sets was organised with regard to geographical zones (i.e. region, province and county) and with links that allow a direct identification of any particular source of biomass placed within the country. By these means, the results presented in Chapter 7 are based on the best available information, and they are reliable and updated.

With regard to the investment and cost-estimating appraisal for anaerobic digestion technologies, another crucial aspect for the economic modelling and, consequently, for the cross-economic assessment proposed, there are uncertainties intrinsically related with this sort of evaluation. In particular, for the case of Chile, for anaerobic technology because it was only introduced on industrial scale in early 2000 and the financial information is highly restricted by data owners. Auxiliary equipment installations to fulfil specific environmental standards such as off-gas treatment units or material specifications can bring additional uncertainties in the investment and cost estimates. As highlighted in Chapter 6, the mathematical regressions employed for economic modelling are aimed at calculating the economic limits and cost based on a statistical approach at the macro-scale, and it is not highly advisable to use them to assess the financial feasibility of case-to-case biogas projects.

Results from *biogas-to-energy* assessment showed that the maximum contribution from the four sectors could be no larger than 3,027 $\mathrm{GWh_e y^{-1}}$ when observing the economic potential. If this figure is compared with the national electricity net generation of 61,038 $\mathrm{GWh_e y^{-1}}$ (data from 2009), the share of bioenergy accounts for approximately 5 % of the total. A slightly higher share is observed if the national consumption of natural gas, which reaches 3,219 $\mathrm{MMNm^3 y^{-1}}$ (data from 2009), is compared with the total economic potential of 705 $\mathrm{MMNm^3 y^{-1}}$ from the *biogas-to-upgrade* route, accounting for 22% of the total. In this frame, landfill offers the greatest potential for all sectors, while at the same time providing the lowest representative generation cost for both electricity and Bio-SNG. When the option of directly using a *waste-to-energy* route of conversion is taken into consideration, the economic potential of municipal solid waste (MSW) is significantly greater than that of MSW achievable when recovering landfill gas (two times order of magnitude). Moreover, a considerable concentration of the potential is observed in only one administrative region, *Región Metropolitana*. These results suggest that the usage of MSW as a source of energy is a relevant option and it should be prioritised when contemplating a macro-public policy.

On the contrary to MSW, wastewater treatment plants (WwTPs) account for the smallest energy potential although it has a similarly high concentration in the same administrative region as the above-mentioned sector. Currently, most of this potential is being exploited in the form of Bio-SNG (injected into the natural gas grid), as discussed in Chapter 7. A biomethane generation of over 20 MM Nm^3 y^{-1} from the processing of sludge generated in one WwTP takes places nowadays, a large scale-production that is a direct consequence of the high concentration of population and the type of technology chosen for the purification of wastewater, making this case unique in the context of the country. Its exceptionality may suggest further analysis for the use of this methane, for which an alternative use such as transportation should be considered. The availability of this energy carrier in a mega-city demands additional evaluation with the inclusion of socio-environmental variables.

Crop residue represents the second largest potential of renewable methane, which is highly concentrated in southern Chile (i.e. VI, VII and IX region) and with its largest fraction generated after the wheat and corn harvest. Because this biomass is suitable for other uses such as fuel for electricity generation via direct burning, raw material for the recovery of lignin or chemicals, or to be used in stables for bedding, as has been traditionally done, it is the most inclined to suffer a rise in trade price in the future, or scarcity when other commercial uses come through. Additionally, livestock manure offers a significant fraction of the potential for electricity or Bio-SNG generation, and as observed for all the sectors under analysis, it exhibits a high concentration in only one region, *Región Metropolitana*. Despite the considerable number of farms scattered across the country, there are few that fall under the conditions necessary to develop biogas exploitation projects. Additionally, the potential manure-based plants are in the low range of power, and principally adequate for electricity generation.

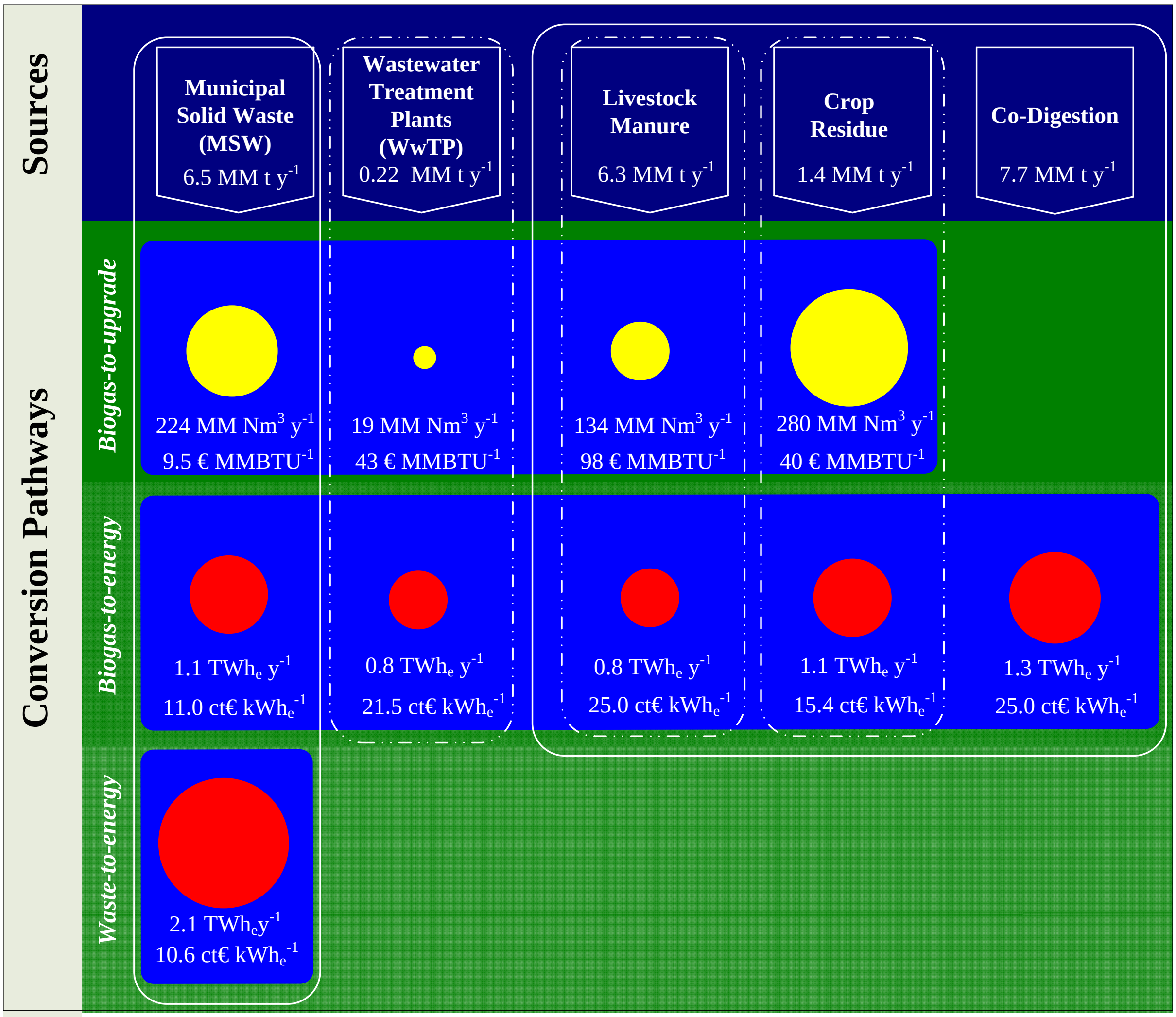

Figure 8.1. Energy map for the assessed sector considering conversion route, end-products and economic indicators.

As far as the co-digestion of manure and crop residue is concerned, because the condition for the simultaneous supplying of both feedstock is present in a noteworthy extent in the country when its geographic distribution is considered, this option can significantly increase the number of economically competitive biogas units (see Table 8.2). Furthermore, co-digesting agro-industrial residue is advisable in that the major operation stability of higher methane yield of the mixed feedstock and improvement on account of a economy of scale can be taken advantage of.

The results that arose from the economic evaluations are consistent in terms of indicating that the economics of bioenergy is the main barrier for massive implementation, and it signifies, in general terms, that there would be a limited attractiveness for the market to supply Bio-SNG or electricity from biomass feedstock, irrespective of how much the price of secondary energy carriers may rise in the long-term. The representative generation cost shows that Bio-SNG is significantly more expensive than natural gas under the economic conditions for the generality of cases; the existence of a market-attractive fraction of the economic potential of Bio-SNG is more an exception than a tendency in that Bio-SNG projects are profitable only under particular circumstances. Apart from landfills, for which both electricity and Bio-SNG are attractive further the economic limit, bioenergy is hardly competitive without introducing subsidies or other market drivers in order to make a significant fraction of the economic potential profitable. Table 8.1 summarises the main indicators obtained form the techno-economic potential analysis, in addition to what feed-in tariff will be necessary to make the economic potential profitable when the projection of prices of secondary energy (i.e. electricity and natural gas) for 2012 is employed for the calculation.

Table 8.1. Main technical and economic figures obtained from the potential analysis for biomethane generation in Chile.

***Biogas-to-upgrade* route**	Municipal Solid Waste	Livestock (manure)	Crop Residue	Wastewater treatment Plant	Co-Digestion
Technical limit (MM $Nm^3\ y^{-1}$)	260	225	351	24	429
Economic limit (MM $Nm^3\ y^{-1}$)	224	182	280	19	-
Representative cost (€ $MMBTU^{-1}$)	9.5	98	40	43	-
Generation subsidy (€ $MMBTU^{-1}$)	-	83-76	25-18	28-21	-
Needed subsidy (MM € y^{-1})	-	198-124	192-85	7-5	-

***Biogas-to-energy* route**	Municipal Solid Waste	Livestock (manure)	Crop Residue	Wastewater treatment Plant	Co-Digestion
Technical limit ($GWh_e y^{-1}$)	1,078	1,067	1,355	85	1,582
Economic limit ($GWh_e y^{-1}$)	1,061	779	1,112	75	1,338
Representative cost (ct€ kWh_e^{-1})	11.0	25.0	15.4	21.5	25.0
Generation subsidy (ct€ kWh_e^{-1})	-	13.0	3.4	9.5	13.0
Needed subsidy (MM € y^{-1})	-	23	17	2	84

***Waste-to-energy* route**	Municipal Solid Waste
Technical limit ($GWh_e y^{-1}$)	3,032
Economic limit ($GWh_e y^{-1}$)	2,959
Representative cost (ct€ kWh_e^{-1})	10.6
Generation subsidy (ct€ kWh_e^{-1})	-
Needed subsidy (MM € y^{-1})	-

For the *biogas-to-energy* pathway the generation subsidy ranges from 3.4 ct€ kWh_e^{-1} for crop residue to 13.0 ct€ kWh_e^{-1} for manure digestion or co-digestion with crop residue substrates.

In general terms, these values are in line with the feed-in tariff applied in countries where subsidies for generation have been implemented, such as Germany, Spain, USA or Switzerland (Mendoca 2007). The introduction of generation subsidies in a time horizon implies that an investment must be supplied by the state, as shown in Table 8.1.

When assuming that common clusters of barriers are lacking feedstock availability, technological uncertainties and perception of high financial risk in biogas projects, the state role should be focused on facilitating investment conditions by giving support in order to reduce the associated investment risk, coordinating the actors involved in biogas industry and creating macro-policies that can capture the difference between the sectors (or sort of substrate). From the outcomes of this research, it is possible to propose that the municipal solid waste sector should be considered as a sector of high priority for the implementation of any bioenergy programme. The results that arose from this research, and are summarised in Table 8.2, indicate that the MSW sector may bring the largest number of projects (in proportion) that could run without subsidisation from the state. Besides, the introduction of *waste-to-energy* systems (the former so-called *incineration*) should be evaluated as an option for the medium term. In addition to this, other aspects not directly linked with bioenergy but equally relevant, such as improving in recycling and segregation of organic fraction, thus avoiding its landfilling, should be integrated, coordinated and consolidated at the inter-ministerial level.

The livestock farming sector should be targeted through a differentiated policy because of a few particularities. Firstly, it is associated with an agro-industry located in rural areas, normally many miles from energy generation centres, in which the decentralised energy generation may become more competitive for avoiding the cost of energy transportation. Secondly, the assessment conducted in Section 7 shows that the option of electricity generation is more economically advantageous than the Bio-SNG option, with a significant portion of the potential concentrated in the low scale (10-250 kW_e) and only two administrative regions (XIII and IX region). Finally, anaerobic digestion enables the use of the digestate as a fertiliser without interfering with the current end-use of manure in farms, and the potential use of heat when operating under a CHP scheme, which can be useful for washing and cleaning milking parlours. This group of particularities suggests the development of a specific support programme from a public agency more directly linked to the livestock industry.

Table 8.2. Main technical and economic figures for biogas projects commercially appealing, and zone of high concentration of the technical potential of energy.

***Biogas-to-energy* route**	MSW	Livestock (manure)	Crop residue	WwTPs	Co-digestion
Commercial potential (GWh$_e$y^{-1})	1,073	589	612	55	2,760
Number of projects	27	28	32	5	38
Minimum scale (kW$_e$)	170	315	2,100	260	315
Maximum scale (MW$_e$)	53	22	53	5.1	22
Region with higher technical potential	XIII 67 % VIII 8%	XIII 62% IX 11%	VI 32% VII 19% IX 18%	XIII 49%; VIII 15%	XIII 41% IX 20%

***Biogas-to-upgrade* route**	MSW	Livestock (manure)	Crop residue	WwTPs	Co-digestion
Commercial potential (MM Nm^3 y^{-1})	256-259	130-160	37-130	11-12	-
Number of projects	22-28	7-16	3-15	2	-
Minimum scale (Nm^3 h^{-1})	12,606	205-506	923-437	1,238	-
Maximum scale (Nm^3 h^{-1})	40-133	5,256	1,512	150	-
Region with higher technical potential	XIII 67 % VIII 8%	XIII 62% IX 11%	VI 32% VII 19% IX 18%	XIII 49%; VIII 15%	XIII 41% IX 20%

***Waste-to-energy* route**	MSW
Commercial potential (GWh$_e$y^{-1})	2,990
Number of projects	23
Minimum scale (MW$_e$)	1.7
Maximum scale (MW$_e$)	161
Region with higher technical potential	XIII 67 % VIII 8%

The large variability of feedstock biogas yields has been reported and discussed in literature, showing significant discrepancies attributable not only to the physicochemical characteristics of the substrate and the anaerobic reactor setup, but also external conditions such as environmental temperature. If a mesophilic operation (in the 30-40 °C range) is assumed for the anaerobic digestion without distinguishing the sort of substrate and the enormous climatological variability of Chile, the location of biogas plants can be considered as a factor that may impact the biogas potential to some extent.

The bioenergy resources based on non-virgin biomass in the country are not fully employed mainly because of the previously mentioned economic constraints, and presumably because of uncertainties related to technologies and energy prices, which can create obstacles and introduce barriers for stakeholders and investors. This state of affairs is contingent on the fact that legislation governing electricity in Chile establish the premise that tariffs have to reflect the cost of the whole energy generation chain, a signal to companies and end-consumers to optimise the efficiency of the economy of the whole system. Moreover, the country's *laissez-faire* approach to energy production makes it difficult to conceive any sort of direct subsidisation for a specific type of renewable, whatever it is. In this context, it seems more appropriate that the state should play an active role in the coordination of a design for a coherent and long-term bioenergy policy to boost the implementation of biogas-based projects that can operate without relying on subsidies for generation. For the reason discussed below and in the event of wishing to increase of bioenergy from biogas in the energy system, it should be boosted through programmes specially designed for this purpose, and in such a way that proven technology has preference to non-mature options, a key aspect that can reduce technological uncertainties. This aspect is highly relevant for consideration since public agencies normally aimed at enhancing economic development severely penalise the use of state-of-the-art technologies for their “lack of innovation” because bioenergy projects are misunderstood by the public agencies as being merely technology transfer initiatives.

The assessment was conducted in accordance with a coherent and highly structured methodology aimed at comparing two conversion routes by using proven technologies for the production of either electricity or Bio-SNG as end-products. This methodological approach was crucial to understanding the potential of bioenergy for the country and the economic constraints. In the event that anaerobic digestion technologies were introduced into the country at a massive scale, along with the economically beneficial impacts such as displacement of fossil fuel consumption, with the subsequent reduction in emission of greenhouse gases, reduction of consumption of inorganic fertiliser or the generation of a new local industry, the environmental benefits from the treatment of biomass normally addressed as residues would be highlighted. This being so, bioenergy has a common thread across policy domains such as environmental, agricultural, energy and technological development, and as such, it can provide a focal point for joined-up thinking from public agencies and organisations directly involved in the matter.

This research did not take into consideration the implementation of the commercial potential. To assess what fraction of the economic potential or commercial potential can be implemented in the future was beyond the scope of this thesis, and it should be tackled in further research.

9. Conclusions

From the results previously presented and discussed it is possible to reach the following main conclusions:

- The *biogas-to-energy* conversion route offers the greatest number of projects that may be economically competitive, thus running without relying on subsidies from the state. This fraction of the economic limit should be targeted in such a way that it can be incorporated to enhance the bioenergy participation within the energy matrix of Chile in the near future.

- The *biogas-to-upgrade* route can be profitable under exceptional conditions and is heavily penalised by the amount of biomass available, thus plant capacity. As observed, the injection of Bio-SNG is favoured only when the biomass potential reaches a critical supply that enables the existence of the benefits of economies of scale for a biogas processing plant.

- Among the sectors analysed, municipal solid waste (MSW) offers the largest potential and economic attractiveness. Landfills can provide low-cost biomethane, a favourable economy of scale and the control of fugitive emissions. In addition, the option of introducing *waste-to-energy* technologies when the latest technological improvements, the increasing cost of electricity and the new environmental challenges for the country are observed, it is an alternative that be should considered for its introduction. Livestock as well as crop residue and wastewater treatment plant sludge also offer a cost-effective fraction of their potential although they are proportionally more limited.

- The option of co-digesting manure and crop residue is technically feasibly considering the geographical areas where both feedstocks are currently concentrated. This option can improve the economy of scale of biogas plants and allow integration between farms and local suppliers of biomass in the existing agro-industrial complex.

- In the event that a feed-in tariff were introduced to boost the generation and supply of biomethane, the *biogas-to-energy* route would be, for this framework, still more attractive in economic terms than the *biogas-to-upgrade* one. This conclusion, however, is based on the assumption that heat as a by-product and that there would be no introduction of environmental indicators or any other environmental penalisation.

- It is systematically observed that there is a high concentration of the energy potential in only some administrative areas of the country, which suggests that the implementation of a bioenergy policy should be focused on zones of priority development organised hierarchically according to their potential or another equivalent criteria, and articulated by local government.

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