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DEDICATION

This thesis is for my family and friends for their support and motivation, for the long time away and their faith in me.

To my parents, because they showed me the importance of a good education and their conviction that I can achieve any goal I set for myself.

To my brothers, because they have always believed in me, for their long chats and jokes that make the distance shorter.

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ABSTRACT

Energy is needed for our development; however, all over the world there is a growing energy crisis, especially in oil-dependent countries. Chile is no exception, its energy production depends mainly on thermoelectric plants, that generate electricity based on oil and its sub-products, such as natural gas imported from Argentina which have suffered several disruptions; and hydroelectric plants distressed by climatic factors as droughts. Few projects on renewable energy are functioning and there is a growing need to increase conscience and free Chile of its oil dependence by promoting the use of its own resources.

The implementation of biomass energy generation projects, specifically WTE technologies, can address not only the energy problem but also the potential environmental and health problem in the management and final disposal of waste. The purpose of this study is to contribute to the satisfaction of the energy needs of present and future generations through the analysis and evaluation of new technologies that will address not only the energy crisis but also reduce the potential risks of waste disposal and the environmental pollution. The main objective is to analyze the potential of biomass energy generation in Santiago de Chile, through the evaluation of five different WTE technologies and the analysis of the effective constraints on energy generation to propose steps for the organization and implementation of a biomass energy system. The evaluation was done with the support of the GEMIS software and the multi-criteria analysis software NAIADE and included environmental, technological and socio-economical aspects.

The results show that the WTE technologies have energy generation potential and they could contribute to the energy security of the country; but their best strength is in economical savings that they could contribute to the country and their capacity to reduce emissions in the substitution of fossil fuel sources: These assets are the ones that could be promoted to integrate WTE into the energy matrix.

Keywords: *renewable energies, technologies, waste, energy generation*

RESUMEN EJECUTIVO

La energía es necesaria para nuestro desarrollo; sin embargo, alrededor del mundo hay una creciente crisis energética, especialmente en los países dependientes del petróleo. Chile no es la excepción, su producción energética depende principalmente de plantas termoeléctricas que generan electricidad a base de petróleo y sus sub-productos, como gas natural importado de Argentina, que ha sufrido severas interrupciones; y de plantas hidroeléctricas afectadas por factores climáticos como las sequías. Pocos proyectos de energías renovables están funcionando y hay una creciente necesidad de aumentar la conciencia y liberar a Chile de su dependencia del petróleo al promover el uso de sus propios recursos.

La implementación de proyectos de generación de energía a partir de la biomasa, específicamente tecnologías para la producción de energía a base de residuos, puede atenderse no sólo la problemática energética sino también los potenciales problemas ambientales y de salud en el manejo disposición final de residuos. El propósito de este estudio es contribuir a la satisfacción de las necesidades energéticas de presente y futuras generaciones a través del análisis y evaluación de nuevas tecnologías que no sólo atiendan la crisis energética sino que también reduzcan los riesgos potenciales de la disposición de residuos y la contaminación ambiental. El objetivo principal es analizar el potencial de la generación de energía a partir de la biomasa en Santiago de Chile, a través de la evaluación de cinco diferentes tecnologías para la producción de energía a base de los residuos y analizar las diferentes barreras en su generación energética para proponer lineamientos en la organización e implementación de un sistema de energía a partir de la biomasa. La evaluación se realizó con el apoyo del software GEMIS y el software de análisis multi-criterio NAIADE incluyendo aspectos ambientales, tecnológicos y socio-económicos.

Los resultados demostraron que las tecnologías para la producción de energía a base de residuos, WTE, tienen potencial de generación energética y podrían contribuir a la seguridad energética del país; pero su mayor fortaleza está en los ahorros económicos que podrían generarle al país y su capacidad para reducir emisiones en la substitución de las fuentes de combustibles fósiles. Estas ventajas son las que se deben promover para la integración de las tecnologías WTE in la matriz del sistema energético.

Palabras claves: *energías renovables, tecnologías, residuos, generación energética*

ZUSAMMENFASSUNG

Energie ist wichtig für unsere Entwicklung, allerdings gibt es weltweit eine wachsende Energiekrise besonders in ölabhängigen Ländern. Chile ist keine Ausnahme. Die chilenische Energieproduktion hängt hauptsächlich von thermoelektrischen Werken ab, die auf Basis von Öl und dessen Subprodukten, wie importiertes Erdgas von Argentinien, Elektrizität erzeugen. Desweiteren werden Wasserkraftwerke zur Energieproduktion genutz. Diese sind jedoch durch klimatische Faktoren wie Wassermangel nur bedingt nutzbar. Wenige erneuerbare Energieprojekte funktionieren und es gibt ein wachsendes Bedürfnis das Bewusstsein zu erweitern und Chile durch die Förderung des Gebrauches eigener Ressourcen von seiner Ölabhängigkeit zu befreien.

Die Durchführung von Biomasse-Energiegenerationsprojekten, spezifisch WTE Technologien, kann nicht nur das Energieproblem, sondern auch das potenzielle Umwelt- und Gesundheitsproblem im Abfallmanagement, sowie in der Abfallentverwertung, beheben. Zweck dieser Studie ist es, durch eine Analyse und Bewertung von neuen Technologien, die nicht nur auf die Energiekrise, sondern auch auf die potenziellen Gefahren der Müllbeseitigung und Umweltverschmutzung abzielen, zur Befriedigung der Energiebedürfnisse der gegenwärtigen und zukünftigen Generationen beizutragen. Das Hauptziel ist, durch die Bewertung von fünf verschiedenen WTE Technologien und die Analyse deren Einschränkungen, das Potenzial der Energieproduktion durch Biomasse in Santiago de Chile zu analysieren, um Schritte für die Organisation und Durchführung eines Biomasse-Energiesystems vorzuschlagen. Die Bewertung wurde mit Hilfe der GEMIS Software und der Mehrkriterien-Analyse-Software NAIADE durchgeführt und schloss sozialwirtschaftliche und technologische Umweltaspekte ein.

Die Ergebnisse zeigen, dass die WTE Technologien ein Potential zur Energieproduktion haben und sie zur Energiesicherheit des Landes beitragen könnten Ihre größte Stärke liegt in der wirtschaftlichen Ersparnis, welches dem Land und dessen Kapazität, Emissionen mit Hilfe von alternativen Möglichkeiten zu fossilen Brennstoffen zu reduzieren, beigesteuert werden kann. Diese Vorteile sind es, die gefördert werden sollten, um WTE in die Energiematrix zu integrieren.

Schlüsselwörter: *Erneuerbare Energien, Technologien, Abfall, Energieproduktion*

ACRONYMS AND ABBREVIATIONS

B.C.	Antes de Cristo	Before Christ
BID	Banco Interamericano de Desarrollo	Inter-American Development Bank
CBA	Análisis Costo-Beneficio	Cost-Benefits Analysis
CDM	Mecanismo de Desarrollo Limpio	Clean Development Mechanism
CER	Centro para las Energías Renovables	Center for Renewable Energies
CEWEP	Co-federación de plantas de producción de energía a base de residuos de Europa	Confederation of European Waste-to-Energy Plants
CHP	Cogeneración	Combined Heat and Power
CNE	Comisión Nacional de Energía	National Commission of Energy
CONAMA	Comisión Nacional del Medio Ambiente	National Commission of Environment
CORFO	Cooperación de Fomento de la Producción	Corporation for the Promotion of Production
DSW	Residuos Sólidos Domésticos	Domestic Solid Waste
ERNC	Energías Renovables No Convencionales	NCRE- Non Conventional Renewable Energies
EU27	27 países de la Unión Europea	European Union, 27 countries
GDP	Producto Interno Bruto	Gross Domestic Product
GEMIS	Global Emission Model of Integrated Systems	Global Emission Model of Integrated Systems
GHG	Gases de Efecto Invernadero	Greenhouse Gases
GTZ GmbH	Cooperación Técnica Alemana	Deutsche Gesellschaft fuer Technische Zusammenarbeit
IEA	Agencia Internacional de Energía	International Energy Agency
INE	Instituto Nacional de Estadísticas	National Institute of Statistics
LAC	América Latina y el Caribe	Latin American and the Caribbean
MADM	Toma de Decisiones Multi-atributo	Multi-Attribute Decision Making
MCDA	Análisis Multi-criterio	Multi-Criteria Decision Analysis
MCDM	Toma de Decisiones Multi-criterio	Multi-Criteria Decision Making
MODM	Toma de Decisiones Multi-objetivo	Multi Objective Decision Making
MSW	Residuos Sólidos Municipales	Municipal Solid Waste
MWe	Megawatts de electricidad	Megawatts of electricity
NAIADE	Novel Approach to Imprecise Assessment and Decision Environments	Novel Approach to Imprecise Assessment and Decision Environments
OECD	Organización para la Cooperación y Desarrollo Económico	Organization for Economic Cooperation and Development
OLADE	Organización Latinoamericana de Energía	Latin American Organization of Energy
R&D	Investigación y Desarrollo	Research and Development
RISE	Instituto de Investigación para Energía Sostenible	Research Institute for Sustainable Energy
SEIA	Sistema de Evaluación de Impacto Ambiental	Environmental Impact Assessment System
SEREMI de Salud	Secretaría Regional Ministerial de Salud	
SIC	Sistema Interconectado Central	Central Interconnection System
SING	Sistema Interconectado del Norte Grande	North Big Interconnection System
UNDP	Programa de las Naciones Unidas para el Desarrollo	United Nations Development Program
WTE	Producción de energía a base de residuos	Waste to Energy

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CHAPTER 1. INTRODUCTION

1.1. OVERVIEW

Human development depends on the availability of energy sources for its activities. However, the use and distribution of energy have contributed to negative environmental impacts. In addition, non-renewable sources of energy are not available in all countries and, in many cases, developing countries invest part of their finances in the purchase of oil, bunker, coal, or electricity to cover their energy necessities and guarantee national availability for industries, commerce and households.

In Latin America the energy matrix is based principally on conventional energy sources: oil, coal, natural gas and some big scale hydroelectric plants. But the main oil deposits are located in México and in the Andean region driving the other Latin-American countries to depend on the oil offer of producer countries and the world. Chile is not an exception, since its small oil production has been decreasing at a -12.16% rate from 2006 to 2008 (Programa Chile Sustentable, 2008), and its energy supplies depends on the importation of oil and natural gas. Moreover, its energy matrix is composed by 60% of fossil fuels sources.

Many countries such as Chile that have the energy potential for the implementation of renewable energies still depend on non-renewable sources. This is partially due to the high cost of implementation of renewable energy technologies and effective constraints on energy sources, such as: physical availability, technology, economics, environmental concerns and competing uses, and demand for relevant energy qualities (Hille, 2007). In the case of Chile, this is accentuated for its competitive energy market. However, Chile has taken measurements to promote the renewable energies: biomass, wind, solar, geothermal, tidal and small hydro.

On the case of biomass, some studies have been carried out for biomass potential but on the specific case of MSW, only biogas from landfills have been evaluated.

Therefore, this study evaluates alternative technologies for the use of biogenic waste based on the availability of this source of energy, in order to identify the most recommended energy generation technology to apply; and analyzes the constraints regarding energy generation for the Metropolitan Region of Chile. It is important to mention that the biomass object of this study is the organic part of the municipal waste that is disposed in the three landfills that serve the study area.

1.2. OBJECTIVES

1.2.1. Main Objective

- To analyze the potential of biomass energy generation in the city of Santiago, Chile.

1.2.2. Specific Objectives

- To evaluate different alternative technologies for the use of biomass in Santiago based on an economical, environmental and technical analysis.
- To analyze the effective constraints on energy generation based on biomass in Santiago, Chile.
- To propose guidelines for the organization and implementation of a biomass energy system in Santiago.

1.3. JUSTIFICATION

Energy is needed for our development; however, all over the world there is a growing energy crisis. The methods applied until now have been based on oil, coal, natural gas consumption, and atomic energy that have proved to be temporary solutions or big sources of pollution in some cases. The main oil sources are depleting and oil-dependent countries depend on the fluctuations of the oil market that affect their economies and put in danger their energy security.

Chile depends mainly on thermoelectric plants that generate electricity based on oil, bunker and its sub-products, such as natural gas imported from Argentina with several disruptions and hydroelectric plants distressed by climatic factors as droughts. Chile is more affected by the crisis because it depends on non-renewable energy sources imported from other countries. Few projects on renewable energy are being considered and there is a growing need to increase conscience among authorities and citizens in relation to the best approach to confront the energy problem and to encourage the implementation of projects that free countries of their dependence on oil and promote them to use their own resources for energy generation. If beside this, it is considered that most energy sources used right now are sources of environmental pollution and have contributed to global warming, it can be said that the analysis and implementation of renewable energy sources is a necessary step.

There are a variety of renewable energies, and Chile's geographic locations offers great potential for the implementation of renewable energies: biomass, wind, solar, geothermal and small hydro. Even though biomass is included in the renewable energies measurements, the biggest development of renewable energies in the last year in Chile has been on wind energy. Some studies on biomass in the agricultural, industrial and MSW sector have been done, but in the case of MSW, they have only considered the use of biogas generated from the landfills, they have not included the use of Waste-to-Energy technologies.

This study focuses on the use of WTE technologies using only the biogenic part of the MSW to provide insides on these kinds of technologies and promote the use of the MSW. If the main source of energy proposed is biomass or organic residues from the city, the environmental and health problems from waste disposal well known in many countries of Latin American are addressed. Also, as a result, more structural waste management systems would be promoted. Moreover, the WTE technologies would contribute to the energy security of the country and the reduction of emissions with the substitution of fossil fuels for energy generation.

The purpose of this study is to contribute to the satisfaction of the energy needs of present and future generations by analyzing and evaluating new technologies that will address not only the energy crisis but also reduce the potential risks of waste disposal and reduce the environmental pollution as well as the climate problem.

This study is part of a big project called Risk Habitat Megacity. It aims to provide strategies for sustainable urban development by overcoming the ecological, social and economic risks of mega-urbanization. Geographically the research concentrates on Latin American megacities and large agglomerations. Santiago de Chile is the 'anchor city' for the initiative and hosts its coordination and the dissemination of results.

1.4. HYPOTHESIS

This study will support the implementation of biomass energy generation in Santiago-Chile and Latin America; which will address not only the energy crisis but also reduce the potential risks of waste disposal and reduce the environmental pollution in the region as well as the climate problem.

CHAPTER 2. LITERATURE REVIEW

2.1. ENERGY GENERATION FROM WASTE

2.1.1. Energy definition and energy sources

Energy is defined in accordance with Max Planck as the skill of a system to provoke an external action (Kaltschmitt et al, 2007). Based on this definition the following forms of energy can be identified: mechanical energy, electromagnetic, thermal and chemical radiation. These forms of energy can be obtained of diverse sources as fossil fuels, biomass, solar, water and wind. Nevertheless, in all the processes of transformation of the primary forms from energy to others, a loss of energy exists in the shape of heat, what means that the available final energy is in percentage terms a minor to the initial primary energy.

In Figure 2.1., it is depicted the conversion chain of the diverse primary energy sources and the types of losses during their transformations.

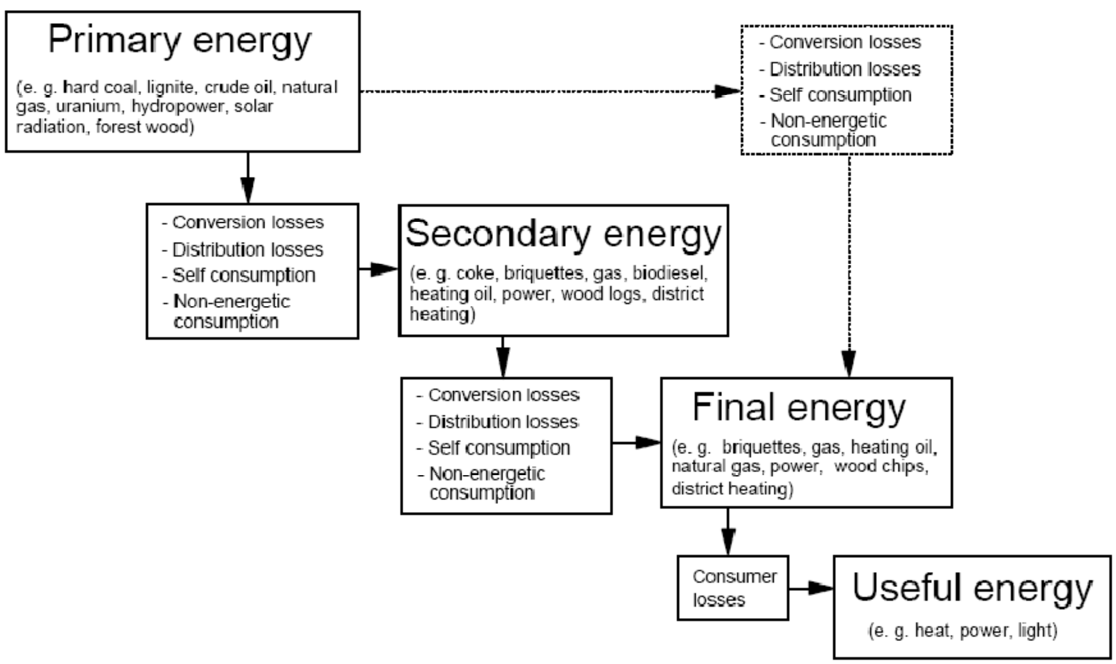


Figure 2.1. Conversion chain of Energy
Source: Renewable Energy: Technology, Economics and Environment. Kaltschmitt et al, 2007

The energy sources, in turn are known as available energy sources and these energy sources can be renewable and non-renewable resources based on the resource of which they are obtained.

In this sense, renewable energies are defined as those energies that come from renewable resources, that is to say, resources that are renewed constantly and do not become exhausted. They are considered to be those renewable energies that have his origin in the solar radiation. This means that, not only the solar energy produced straight by the radiation of the light is renewable, but also are renewable energies the ones unleashed by the warming of the surface of the Earth, hydraulics and wind. Those that seemingly are inexhaustible and have been caused by physical phenomena of big importance as geothermal and tides are also considered renewable energies. Nevertheless, this definition does not mention the biomass energy, which takes its energy from the sun for its growth and formation.

2.1.2. Biomass as energy source

Biomass was and still is the main source of energy worldwide and it is one of the most important sources in developing countries, principally as its traditional use as firewood. However, its use as non-conventional source of energy is being promoted among developed and developing countries. Bioenergy projects are centered in the use of crops, agricultural residues and domestic waste as inputs for biogas generation and the use of its residuals as organic fertilizers (Bandi, 2006). Examples of biomass energy are residues from the paper or wood products industries, residues from sugar industries (e.g. bagasse), fuel grown on energy plantations, organic waste from households, animal excreta, black liquor, vegetal oil and others.

Waste is defined, in accordance with Tchobanoglous (1994), as any material discarded by human activity, which without having immediate utility it transforms into something undesirable. A similar concept is presented by the World Health Organization (1997), defining solid waste as a set of solid materials of organic and inorganic origin that do not have practical utility or commercial value, for the person or activity that produces them. In Chile, according to the Decree 189 – 2005 *Reglamento sobre condiciones sanitarias y de seguridad básicas en los rellenos sanitarios,* which establishes the sanitary and basic security conditions in landfills; solid residue, garbage or waste are substances, elements or objects which the generator eliminates, intents to eliminate or is forced to eliminate. Domestic solid waste are solid residues or garbage generated in households and in such establishments like household buildings, commercial, local places of food expense, hotels, educational establishments and jails.

In the context of this study, biomass will be analyzed as the organic fraction of domestic waste, lopping from parks and gardens, agricultural residues, sewage sludge and other potential municipal waste that are disposed in the landfills of the metropolitan area of Chile. It is important to mention, as will be explained later on this study, that the municipal solid waste, organic and non-organic residues, is disposed in landfills without previous separation.

2.1.3. Energy recovery from waste

Human beings have been generating waste since their appearance on Earth. At the beginning, waste was considered only a disturbance and it became an issue when the first settlements were established in 10000 B.C. In 400 B.C. was created the first municipal dump in Athens. In Europe, the disposal of any kind of waste was throwing it outside the windows. Later on, when diseases such as the bubonic plague, cholera and others appeared; new sanitary rules were created and dumping of waste in the streets was banned. In 1874, an organized incineration of collected trash began functioning in Nottingham-England. The Europeans were the first ones that looked for ways to dispose waste without burying it due to the lack of available land. They learned to control the combustion of trash and discovered how to obtain energy from incinerating organic waste. In the 1940s, methane produced from the anaerobic digestion of municipal waste was used to generate electricity in the United States and other countries (Kenneth, 2003).

In recent years, there have been initiatives being developed around the world that consider different technologies for treating waste and for getting some advantages from it, such as generating energy and heat.

The following are some examples of projects that have been implemented around the world and their contribution to energy generation from waste:

- In the European Union, Waste-to-Energy (WTE) Plants can supply 12 million inhabitants with electricity and 11 million inhabitants with heat. In 2007, 54.309.524 tons of waste was treated in waste to energy processes which represented approximately 20% of the municipal waste generated in the European Union 27 (CEWEP, 2010). The waste-to-energy cycle (Figure 2.2) shows the benefits in tons of fossil fuels saved by using waste to produce energy and heat.

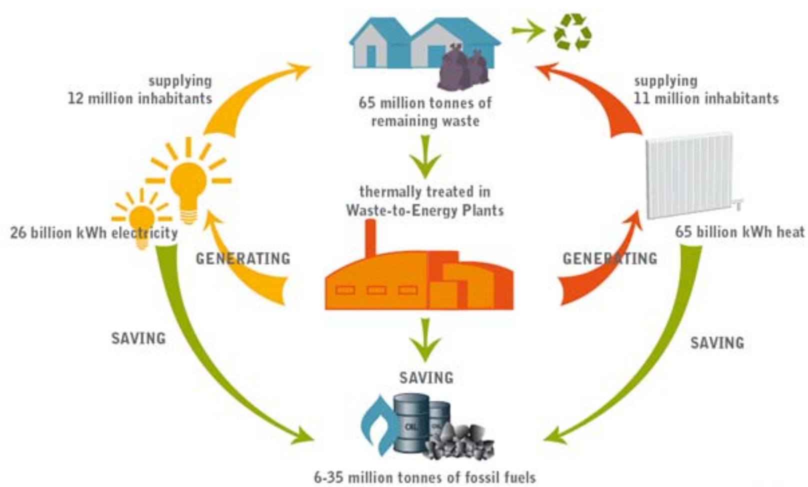


Figure 2.2. Waste to Energy cycle. Confederation of European Waste-to-Energy Plants, CEWEP.

- In the United States, WTE is considered when municipal solid waste is burned in a controlled environment to create steam or electricity; through this process the volume of solid waste is reduced by about 90%. In 2004, there were 89 WTE plants operating in 27 states. WTE was used to manage 33.1 million tons or 14% of trash in the U.S in 2003. WTE plants in the U.S. generate enough electricity to power nearly 2.3 million homes (Keep America Beautiful Organization, 2006).

- A WTE facility, located in Florida, has the capacity to burn 3,150 tons of garbage every day that means about one million tons of garbage every year. The process can produce up to 75 MW per hour of electricity. It sells about 60 MW to Progress Energy for distribution within the community, and the remainder powers the plant itself. This electricity powers approximately 45,000 homes and businesses every day (Pinellas County Utilities Waste-to-Energy, 2010).

- In Sweden, waste incineration provides heat to 800. 000 homes, around 20% of all the district-heating produced. It also provides electricity to almost 250. 000 homes (Avfall Sverige AB, 2009).

- In Australia, there are over 50 landfill power generation sites, with a combined capacity of more than 150 MW. Landfill gas generators are located in every state and territory of Australia and they generally operate as base load power producers (Clean Energy Council, 2010).

- In Mexico, in 2001 in the city of Monterrey with nearly 4 million inhabitants, over 4,500t of municipal solid waste were disposed per day in the *Simeprodeso* landfill, methane from the landfill was harnessed for energy recovery while reducing methane emissions. The energy is fed into the local net to help drive the public transit system by day, and light city streets by night, and to provide power for over 15,000 homes (Soyez & Grassl, 2008).

- In Chile, few projects have been implemented with energy generation results, most of the waste recovery projects are focused on biogas production and Clean Development Mechanisms schemes. These projects will be described in Chapter 4.

These projects and many others have been implemented using diverse technologies, chosen in dependence on different criteria that can go from availability of land, economic aspects, environmental benefits (carbon credits, emission, others) to national policies, legislations and many others. Some successful projects are the result of previous and recent studies, such as:

- The study *Gasification of biomass wastes and residues for electricity generation,* which integrates circulating fluidized bed gasifier and combined cycle for electricity generation, and concludes that this technology as waste treatment option seems promising and that gasification of biomass residues and waste streams is technically and economically feasible and is likely to have limited environmental impacts. (Faaij, 1997).

- The study *Sustainable biomass production for energy in Malasia* identifies policy, technical and economical barriers because of the lack of local manufacturers, appropriate finance/credits mechanisms and local experts (Koh, 2003).

- *National and regional generation of municipal residues biomass and the future potential for WTE implementation*, concludes that the used of municipal residues biomass provides a non-seasonal electricity or heat to urban areas, reduces GHG and reduces land pressure for waste disposal sites (Gregg, 2009).

- *Assessment of sustainable energy potential of non-plantation biomass resources in Tailand,* concludes that the total potential of non-plantation biomass resources calculated for year 1997 represented 17% of the total primary energy consumption on the same year (Sajjakulnukit *et al*, 2005).

- *Analysis of biomass residues potential for electrical energy generation in Albania*, concludes that the electrical energy produced is equivalent to 45.8% of total Albania annual electrical consumption (Karaj, 2010).

2.2. ALTERNATIVE TECHNOLOGIES FOR "WASTE TO ENERGY" INITIATIVES

For the purposes of this study, "Waste to Energy" initiatives will be considered all technologies that used waste to produce energy, specifically focusing on the organic part of the waste that it is object of this study. Moreover, the use of landfill gas for energy generation is also introduced in this "Waste to Energy" concept since it is the alternative being implemented in Chile right now.

In order to be able to suggest the most recommendable technology for a "Waste to Energy" projects, first it is necessary to know the processes involved in the transformation and treatment to generate energy from waste and the technologies available, their characteristics and their advantages and disadvantages. Therefore, in this section, a general overview of the processes and existing technologies will be described.

2.2.1. Processes for energy provision from biomass

An energy supply chain based on biomass encompasses all processes from cultivation of energy plants or provision of residues, by-products, or organic waste up to final energy supply (such as district heat or electrical energy).

In Figure 2.3, it is represented the biomass sources and the forms they can be treated through conversion processes and obtain a form of energy, being electric power or heat. In the end, a certain supply chain is determined by the framework conditions which in turn depend on biomass production (supply side) on the one hand and final energy provision (demand side) on the other hand. Further deciding factors are economic and technical (and administrative) framework conditions that have a significant effect with regard to putting a supply chain into practice (Kaltschmitt *et al*, 2007).

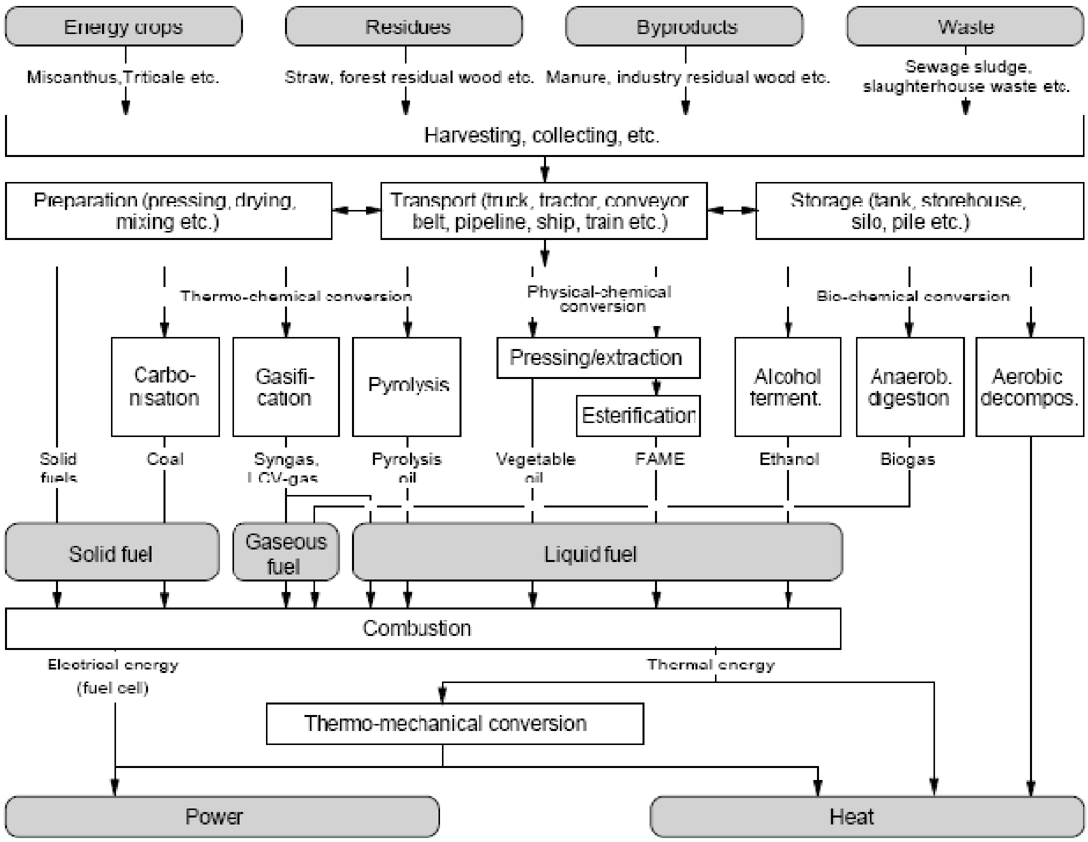


Figure 2.3. Possibilities of energy provision from biomass (grey shaded fields: energy carriers, not grey shaded fields: conversion processes; simplified presentation without considering light as useful energy; FAME fatty acid methyl ester; reactions that occur in fuel cells are regarded as "cold" combustion).
Source: Renewable Energy: Technology, Economics and Environment. Kaltschmitt et al, 2007.

Biomass is usually treated by thermo-chemical conversion, physical-chemical conversion and bio-chemical conversion to obtain biogas or ethanol, charcoal, bio-oil and carbon dioxide. These processes are detailed below based on Kaltschmitt et al (2007).

a. Thermo-chemical conversion:

By thermo-chemical conversion processes (such as gasification, pyrolysis, and carbonization) solid biofuels are transformed into solid, liquid, and/or gaseous secondary energy carriers primarily using heat.

Gasification: Within thermo-chemical gasification solid biofuels are preferably converted into a gaseous energy carrier. For this purpose an oxygen-containing gasification agent (such as air) is added under-stoichiometrically to convert e.g. the carbon of the biofuels into carbon monoxide, and thus into gaseous energy carriers.

Pyrolysis: For pyrolysis solid biofuels are treated exclusively by the use of thermal energy with the goal to maximize the share of liquid products. Such pyrolysis processes are based on the pyrolytic decomposition of biomass at high temperatures in the absence of oxygen.

Carbonization: Carbonization refers to the thermo-chemical conversion of solid biofuels aiming at a maximum output of solid products (charcoal). Also for this process organic matter is thermally decomposed.

The combustion process is explained in section 2.2.2, since it does not convert the biomass into a sub-product but it generates directly heat from the biomass to be used for electricity or thermal energy generation.

b. Physical-chemical conversion:

Physical-chemical conversion includes all possibilities of a provision of energy carrier on the basis of oil seeds. For these processes biomass containing vegetable oil or fat serves as starting material which is first separated into a liquid and solid phase. The first one is then extracted from the solvent used in its previous process.

c. Bio-chemical conversion:

Bio-chemical processes use micro-organisms or bacteria, and thus biological processes, to convert biomass into secondary energy carriers or useful energy.

Alcohol fermentation: After appropriate preparation biomass containing sugar, starch, or cellulose can be decomposed into ethanol based on an alcoholic fermentation in an aqueous medium.

Anaerobic digestion: By means of bacteria organic substances under anaerobic conditions (i.e. conversion in the absence of air) can be digested. One product of such an anaerobic digestion is a vapor-saturated gas mixture (biogas) consisting roughly of about 60 % of methane (CH_4) and 40 % of carbon dioxide (CO_2).

Aerobic fermentation: For aerobic fermentation also biological processes are applied to decompose biomass in the presence of oxygen. The main oxidation product of this process is carbon dioxide (compost formation). Within this processes heat is released.

2.2.2. Types of technologies available

From the conversion processes mention above, many different technologies derive ranging from combustion, gasification to pyrolysis as shown in Figure 2.4. However, for the purpose of this study only the green part in Figure 2.4 will be analyzed and evaluated, with a specific focus on electricity generation.

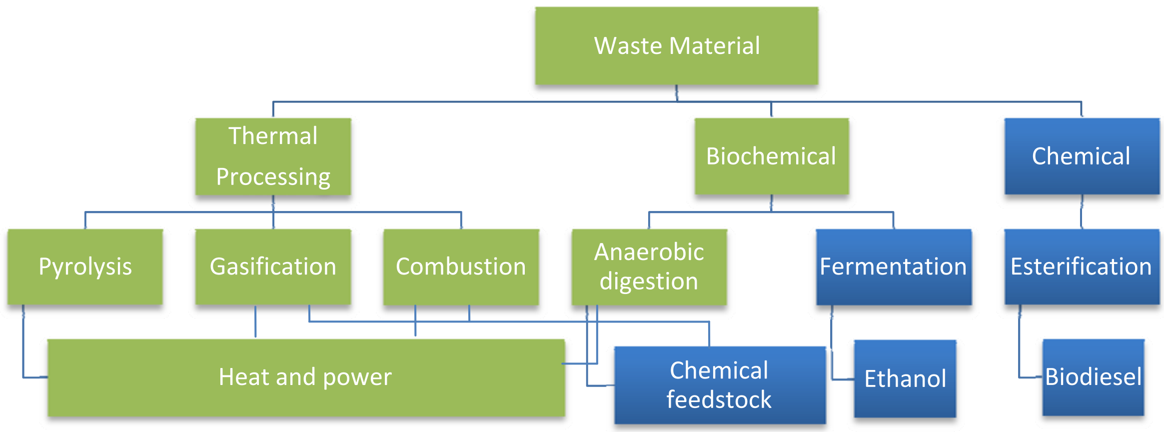


Figure 2.4. Pathway from waste into energy conversion
Source: Modified from Research Institute for Sustainable Energy, 2010 (www.rise.org.au)

In this section, the technologies available to transform waste into energy will be briefly described including a comparison of their advantages and disadvantages.

The following information, if not indicated differently, is provided based on Bandi *et al* (2006).

2.2.2.1. Combustion technologies:

Combustion technologies play a major role throughout the world, producing about 90% of the energy from biomass. Combustion technologies convert biomass fuels into several forms of useful energy e.g. hot air, hot water, steam and electricity.

The simplest combustion technology is a furnace that burns biomass in a combustion chamber. A biomass-fired boiler is a more adaptable technology that converts biomass to electricity, mechanical energy or heat. Biomass combustion facilities that generate electricity from steam-driven turbine generators have a conversion efficiency of 17-25%; cogeneration can increase this efficiency to almost 85%. Large-scale combustion systems use mostly low-quality fuels, while high quality fuels are more frequently used in small application systems. Commercial and industrial combustion plants can burn many types of biomass ranging from woody biomass to municipal solid waste (MSW).

On a larger scale, solid waste (including agricultural and forestry residues), can be combusted in furnaces to produce process heat to feed steam turbine generators. Power plant size is often constrained by the availability of local feedstock and is generally less than 25 - 40 MWe. However, by using dedicated feedstock supplies, such as the co-location of incinerators at waste disposal sites, the size can be increased to 50 -75 MWe, gaining significant economies of scale (Research Institute for Sustainable Energy, 2010).

Municipal solid waste incineration is a mature and reliable technology for a complex and heterogeneous feedstock. For example, in the Netherlands most of the waste generated per annum (50 Mton) is recycled, leaving only a relatively small portion (5.5 Mton) for final treatment in 11 waste incinerators (grate fired), which have average electric efficiency rates of 22%, or as high as 30% in the newly built lines. Associated pollutant emissions can be effectively controlled with state-of-the-art techniques (OECD/IEA, 2006).

2.2.2.2. Thermal gasification technologies:

Gasification is one of the most important ongoing Research-and-Development areas in biomass for power generation as it is the main alternative to direct combustion. The gas created consists of carbon monoxide, carbon dioxide, hydrogen, methane, trace amounts of hydrocarbons, water nitrogen and various contaminants such as char particles, ash and tars.

Gasification is a form of pyrolysis carried out with more air and at higher temperatures (800-1000ºC) in order to optimize the gas production. The resulting gas is more versatile than the original solid biomass. The gas can be burnt to produce heat and steam or used in internal combustion engines or gas turbines to produce electricity (OECD/IEA, 2003).

In techno-economic terms, the gas can be used in more efficient combined-cycle power generation systems, which combine gas turbines and steam turbines to produce electricity. The conversion process - heat to power - takes place at a higher temperature than in the steam cycle, making advanced conversion processes thermodynamically more efficient. In environmental terms, the biogas can be cleaned and filtered to remove problematic chemical components (OECD/IEA, 2003).

Gasification technology is not new, the process has been used for almost two centuries (in the 1850s, much of London was illuminated by “town gas”, produced from the gasification of coal).

The main advantages of gasification are:

1. Higher electrical efficiency, e.g. 40+% compared with combustion 26-30%, while costs may be very similar;
2. The possibility for substantial new developments such as advanced gas turbines, fuel cells, etc.;
3. Possible replacement of natural gas or diesel fuel use in industrial boilers and furnaces;
4. Distributed power generation where power demand is low;
5. Displacement of gasoline or diesel in an internal combustion engine.

In general, at a small scale, gasification promises higher efficiencies. However, at a larger scale, improvements in combustion are now also achieving higher efficiencies. The advantages of gasification systems arise from high efficiency in converting biomass to a gas and in utilizing heat from combustion of the gas produced. This includes larger scale power generation of up to 100 MWe with integrated gasification combined cycle (IGCC) processes, which demonstrate predicted electricity production efficiencies of 40% to 50% compared with only 25% to 35% via traditional combustion. Small-scale power generation systems (up to 5 MWe) use engines that offer up to 35% efficiency. So far, neither of these thermochemical conversion processes has been able to penetrate markets to any significant extent. This is primarily due to high costs and a perception that the technologies must still be proven at large scales.

2.2.2.3. Pyrolysis technologies

Pyrolysis is the process of decomposition at elevated temperatures (300-700°C) in the absence of oxygen (OECD/IEA, 2003). Pyrolysis is defined as incineration under anaerobic conditions and is another option for WTE that is being investigated. Pilot projects using pyrolysis for plastic wastes, and for mixed municipal solid waste potentially have very high-energy efficiencies (Research Institute for Sustainable Energy, 2010).

The main advantage of pyrolysis over gasification is a wide range of products that can potentially be obtained, ranging from transportation fuels to chemical feedstock (e.g. adhesives, organic chemicals, and flavoring) that offer good possibilities for increasing revenues. Considerable amount of research has gone into pyrolysis in the past decade in many countries. Any form of biomass can be used (over 100 different biomass types have been tested in labs around the world), but cellulose gives the highest yields at around 85-90 wt-% on dry feed. Liquid oils obtained from pyrolysis have been tested for short periods on gas turbines and engines with some initial success, but long-term data is still lacking.

In the 1990s several fast pyrolysis technologies reached near-commercial status (Renewable Energies Technologies, 2002):

- Six circulating fluidized bed plants have been constructed by Ensyn Technologies, with nominal capacity up to 50 t/day operated for Red Arrow Products Co., Inc. in Wisconsin.
- DynaMotive demonstrated the bubbling fluidized bed process at 10 t/day of biomass and is scaling up to 100 t/day inVancouver, Canada,.
- BTG operates a rotary cone reactor system at 5 t/day and is proposing to scale the plant up to 50 t/day in The Netherlands.
- Fortum has a 12 t/day pilot plant in Finland.

2.2.2.4. Anaerobic digestion technologies also known as biogas technologies

Landfill gas is an adventitious fuel that is a by-product of current land filling practices and hence occurs only after MSW has been disposed of in a totally non-sustainable way. The anaerobic digestion of the buried solid organic waste produces the landfill gas naturally, as the bacterial decomposition of the organic matter continues over time. It is an extremely low efficiency way of recovering energy from MSW (Research Institute for Sustainable Energy, 2010).

The methane produced in landfill sites normally escapes into the atmosphere, unless the landfill gas is captured and extracted by inserting perforated pipes into the landfill. In this process, the gas will travel through the pipes under natural pressure or a slight vacuum to be collected and used as an energy source, rather than simply escaping into the atmosphere to contribute to greenhouse gas emissions. The burning of the methane to produce carbon dioxide and water also reduces the greenhouse impact of landfill, as carbon dioxide is a less potent greenhouse gas than methane. In theory, up to 300m^3 of biogas per ton of waste can be extracted from a landfill gas site over a ten-year lifetime. This represents an energy content of about 5 GJ (gigajoules). In reality, because of the nature of landfill designs and construction, and the high component of non-putrescibles in the MSW, landfill gas projects produce only between twenty-five and fifty percent of their theoretical gas potential (Research Institute for Sustainable Energy, 2010).

Anaerobic digestion with biodigesters is a successful technology for the production of biogas and is now used commercially all over the world - especially for waste effluents such as waste water, sewage sludge, and abattoir waste streams, as well as for the biological portion of municipal solid waste. While liquid state technologies are currently the most common, recently developed solid state fermentation technologies are also widely used, especially for substrates with moisture content in the range of 30% to 40% wt. Technically, anaerobic digestion technologies are very reliable; however, they are site specific and their scaling up capacity is limited; thus their market attractiveness is somewhat restricted (OECD/IEA, 2006).

A significant change in biogas technology, particularly in the case of larger industrial plants, has been a shift away from energy alone towards more environmentally acceptable technology which allows the combination of waste disposal with energy and fertilizer production in both developed and developing countries. This has been helped by financial incentives, advances in energy efficiency, dissemination of the technology and the training of personnel.

Biogas is also increasingly being used to generate electricity. Although there are some technical problems (i.e. traces of many compounds such as hydrogen sulphate and halogenated hydrocarbons), there are good prospects. It is technically feasible to upgrade biogas to about the same quality as natural gas by removing carbon dioxide in the biogas, and the methane level increases from the usual 40-60% to about 95%. This approach leads to a potential competitiveness with natural gas.

2.2.2.5. Cogeneration technologies:

Cogeneration is defined as the combined production of two forms of energy (electric or mechanical power plus useful thermal energy) in one technological process. The electric power produced by a co-generator can be used on site or distributed through the utility grid, or both.

Cogeneration systems recapture thermal energy that would otherwise be wasted, usually from a heat engine that produces electricity (such as a steam turbine, gas turbine, or diesel engine), and use it for space conditioning, industrial processes, or as an energy source for another energy component. A typical cogeneration system consists of an engine, steam turbine, or combustion turbine that drives an electrical generator (Demirbas, 2007).

Known under various names such as CHP, distributed generation, on-site generation, small-scale generation, district energy systems, etc., comprises at least four different thermodynamic processes of combined heat and power production:

1. Use of air as a medium;
2. Use of steam;
3. Utilization of heat rejected from a separate combustion process;
4. Use of thermodynamics as those found in a fuel cell.

Combined heat and power (CHP) applications are attractive for several reasons: overall efficiency is increased substantially, the technology is reliable and the need to identify a heat client is manageable. However, the combination of both the heat and power energy vectors makes CHP applications more site specific than when using each energy vector separately. In order to reduce operational costs, it is often necessary to implement multi-fuel operation, which increases the complexity of the feeding system and the flue gas cleaning. This results in some degree of increased maintenance. Recently, more attention is directed towards polygeneration systems that can produce power, heat and cooling, thereby maximizing overall efficiency (OECD/IEA, 2006).

Biomass cogeneration is the use of biomass, solid wastes, and residues to produce heat and electricity.

2.2.3. Advantages and disadvantages of the different technologies

The advantages and disadvantages of each technology have great influence in the selection of the most appropriate one for energy generation. For example, biomass with high moisture content are preferred for anaerobic digestion, pyrolysis or biofuels and dry solid biomass are preferred for combustion or gasification. Characteristics such as efficiency, source of energy required, emissions and waste generated, and others are taken into account during the selection process.

The conversion of biomass to any useful form of energy has a width range of applicable technologies from low-cost technologies used in rural areas to advanced technologies used for biofuels production and energy generation. The International Energy Agency (IEA, 2006) reported that thermal processing currently attracts the most interest; gasification received the most Research and Development support largely because it offers higher efficiencies compared to combustion; and pyrolysis was at a relatively early stage of development, but it offers the benefits of a liquid fuel with concomitant advantages of easy storage and transport.

The key differences between thermal and biological conversion lie in the time involved, the end products and the resulting residues. Biological conversion is a slow process – typically taking hours, days, weeks (anaerobic fermentation) or years (landfill gas by digestion) to complete reactions - and delivers single or specific products such as ethanol or biogas (which contains up to 60% methane). Thermal conversion is characterized by very short reaction times (typically seconds or minutes) and its ability to deliver multiple and complex products. Often, thermal conversion uses catalysts to improve the product quality or spectrum. Biological conversion effectively converts only a fraction (about 50% to 60%) of the total feedstock (e.g., sugars or cellulose), resulting in large residual streams that can be used for other commercial purposes (e.g., compost or animal fodder). In contrast, thermal treatment converts the entire feedstock, leaving only ashes (about 2% to 4% weight) (OECD/IEA, 2006).

Table 2.1 presents a brief comparison on the most relevant characteristics of the existing technologies for energy generation based on biomass. Most of the technologies are already being implemented and others have great potentials.

Table 2.1. Comparison of the advantages and disadvantages of different biomass energy generation technologies

Characteristics	Combustion	Cogeneration	Pyrolysis	Anaerobic digestion		Gasification
				Landfill gas	Biodigesters	
Sources of energy	Burns many types of biomass (wood, MSW, others) Moisture Content<50%	Uses heat rejected from a separated combustion process. Biomass, solid wastes, and residues to produce heat and electricity.	any form of biomass, mixed municipal solid waste	Landfill waste	Agricultural waste, manure, and waste effluents: waste water, sewage sludge, abattoir waste streams, biological portion of municipal solid waste	Any form of biomass, plastic waste, mixed municipal solid waste
Efficiency	17-25%	cogeneration ~ 85%	potentially have very high-energy efficiencies (cellulose ~ 85-90 wt-% on dry feed)	Max. 50% recovered biogas	higher biogas rates and shorter residence times in the digester	40 – 50% in gas turbines or 30% in gas engines
Products generated	Heat, electricity	Heat and electricity	Coke, bio-oils, syngas– heat, electricity	Biogas up to 50% – heat, electricity, fuels	Biogas 50-65% CH_4 – heat, electricity, fuels	Syngas: CO and H2 – to burn, heat, steam, electricity
Waste generated	Dust, Ash	Dust, Ash	char	Leachate	Fertilizer	char particles, ash, tars
Emissions	Flue gas: CO_2, NO_x, H_2O, N_2, heavy metals	Particulates, SO_2, and NO_x	CO_2, hydrocarbon gases, methane, nitrogen	CO_2, H_2S, H_2O	CO_2, H_2S, H_2O	CO_2, CH_4, trace amounts of hydrocarbons, water nitrogen
Stage of technology	Adaptable technology. pile burning, grate fired (stationary, traveling, vibrating), suspension fired and fluidized bed (bubbling (BFB) and circulating (CFB)).	30kW to 30MWe established technology, micro –CHP emerging technology	In research –lab tested, proposed e.g. Pyrotech Chile in IV Region, project of pyrolysis and gasification 20MW, in revision in Environmental Impact Assessment System - SEIA	Not perfected e.g. 2MWe energy production from landfill gas in Loma Los Colorados landfill in Metropolitan region in Chile	Successful / reliable technology e.g. pig manure, VI region, Chile; and others	Not new, but in research and development. e.g. Lahti Energia Oy, Finland: new gasification plants will be functioning 2012 producing 50MWe and 90MWth (www.metso.com)
Energy substitution	Fossil fuels	--	Fossil fuels, chemicals,	Natural gas, fossil fuels	Natural gas, fossil fuels	natural gas, diesel fuel,

			adhesives, others			gasoline
Costs	~1.660.000 USD (Corpora Tresmontes S.A., Valparaiso, biomass combustion, vapor generation 7530KVA)	Cost competitive with conventional power	~ 70.000.000 USD (Pyrotech Chile 20MW project)	~40.200.000 USD (electricity generation central, with transmission lines, 14MW(2010)-28MW (2024))	~14.000.000 USD (10.870 ton/year biogas from agricultural residues and poultry manure, Valparaiso)	~ 70.000.000 USD (Pyrotech Chile 20MW project) Gas cleaning expensive/ economic barriers Reduction NOx, SO_2 and other pollutants emissions by 80 to 90%
Availability	Commercial status	Commercial status	Not reached commercial status	Commercial status	Commercial status	Some companies selling
Requirements for optimization	Cleaning of flue gases	--	Gas cleaning and filtering	Methane enrichment	Methane enrichment	Gas cleaning and filtering

Source: created by author, based on IEA (2003, 2006, 2007), Fowler (2009), Sistema de Evaluación de Impacto Ambiental, www.seia.cl (2010)

Other considerations:

Biomass can be combined with fossil fuel technologies (directly mixed or indirectly in separate streams) by co-firing solid biomass particles with coal; mixing synthesis gas, landfill gas or biogas with natural gas prior to combustion; blending diesel with biodiesel and gasoline with bioethanol; and using flexible fuel engines in vehicles. Worldwide more than 150 coal-fired power plants in the range 50-700 MWe have operational experience of co-firing with woody biomass or wastes, at least on a trial basis. However, this mix technology is not included in this study because it includes the use of non-renewable energies, fossil fuels, combined with biomass energy and does not represent renewable energies projects that want to be evaluated in this study.

Regarding environmental concerns in landfills, effluents, animal manures, wet process wastes, or sewage treatment plants involved as WTE projects, odor pollution can be a nuisance that need to be controlled. Conversely, well designed, anaerobic digestion plants can reduce the odor from animal waste feedstock with the residual odorless effluent able to be returned to the land as a nutrient source. In addition, ash resulting from combustion or gasification of biomass is either collected as bottom ash from the furnace or, in larger plants, as the fly ash by separation from the exhaust gases in the flue. Straw and grasses tend to have large volumes of ash (8-12% of the original dry weight) than woody biomass (1-5%). Gasification can produce less ash from the same feedstock by comparison with its combustion (OECD/IEA, 2007).

The ash can have a value as a low nitrate fertilizer or as a raw material in the brick and cement industries. The nature of the ash, access to nearby land, soil types, and existing soil nutrient levels will determine if the practice of returning it to the land may be feasible in order to recycle some of the nutrients and trace elements and to use it for soil conditioning. Ash contents vary with the source of biomass and can often include a concentration of heavy metals if the biomass was co-fired with coal or originated from soils on land carrying a treatment process where sewage or other liquid wastes and soil conditioners are applied (OECD/IEA, 2007).

2.3. MULTICRITERIA DECISION ANALYSIS METHODS FOR WTE TECHNOLOGY SELECTION

Although numerous biomass energy technologies are promoted as alternative substitutes to fossil fuels, scientists and policymakers continue to lack a meaningful and systematic framework able to holistically compare different energy conversion technologies. Therefore, many methodologies have been used for this purpose, but there is not standardization of the methods applied. The Multi-Criteria Decision Analysis, MCDA, are methodologies which support the decision making process when it is necessary to select or rank different alternatives considering different criteria. The MCDA help to deal with the information evaluate the criteria and generate rankings of alternatives or specific scenarios to facilitate the decision of stakeholders.

The strengths of MCDA includes resolution of conflicts, transparency in decisions, process-oriented, multidisciplinary and holistic approach, quantitative and qualitative information, can be modified to include criteria of stakeholders (Browne, 2009).

In this section, a literature review is conducted based on MCDA. Concept definitions, characteristics, types of MCDA and some advantages and disadvantages analyzed in previous studies will be considered.

2.3.1. Definition of multi-criteria analysis

Multi-Criteria Analysis is a decision-making tool developed for complex multi-criteria problems that include qualitative and/or quantitative aspects of the problem in the decision-making process. In a multi-criteria analysis a numerical value is assigned to each criterion expressing its relative importance (Polatidis, 2006). This reflects the corresponding criterion weight. The analysis of weights – through ranking and rating- and their interpretation completely depends on the selected multi-criteria model.

A criterion is a principle or standard that a thing is judged by. A Criterion can, therefore, be seen as a 'second order' principle, one that adds meaning and operationality to a principle without itself being a direct measure of performance. Criteria are the intermediate points to which the information provided by indicators can be integrated and where an interpretable assessment is formed (Mendoza, 1999).

Ranking involves assigning each decision element a rank that reflects its perceived degree of importance relative to the decision being made. The decision elements can then be ordered according to their rank (Mendoza et al, 1999).

Rating is similar to ranking, except that the decision elements are assigned 'scores' between 0 and 100. The scores for all elements being compared must add up to 100. Thus, to score one element high means that a different element must be scored lower (Mendoza et al, 1999).

2.3.2. Characteristics of a multi-criteria decision analysis

Multi-Criteria Decision Methods is a branch of decision making. It is a branch of a general class of operations research models which deal with decision problems under the presence of a number of decision criteria. This major class of models is very often called MCDM. This class is further divided into multi objective decision making (MODM) and multi-attribute decision making (MADM) (Pohekar, 2004).

These methodologies share common characteristics of conflict among criteria, incomparable units, and difficulties in selection of alternative (Pohekar, 2004):

- In MODM the alternatives are not predetermined but instead a set of objective functions is optimized subject to a set of constraints. The most satisfactory and efficient solution is sought. In this identified efficient solution it is not possible to improve the performance of any objective without degrading the performance of at least one other objective.
- In MADM a small number of alternatives are to be evaluated against a set of attributes which are often hard to quantify. The best alternative is usually selected by making comparisons between alternatives with respect to each attribute.

Decision making under uncertainty and decision support systems are also prominent decision making techniques.

The decision making procedure under MCDA involves making a choice between different elements that the decision maker examines and assesses via a set of criteria. These elements are part of an overall set of actions or alternatives; Figure 2.5 (Cavallaro, 2005). The criteria represent the tools which enable alternatives to be compared from a specific point of view. The evaluation or comparison is done through a matrix that tabulates, for each criterion–alternative pair, the quantitative and qualitative measures of the effect produced by that alternative with respect to that criterion. The matrix may contain data measured on a cardinal or an ordinal scale.

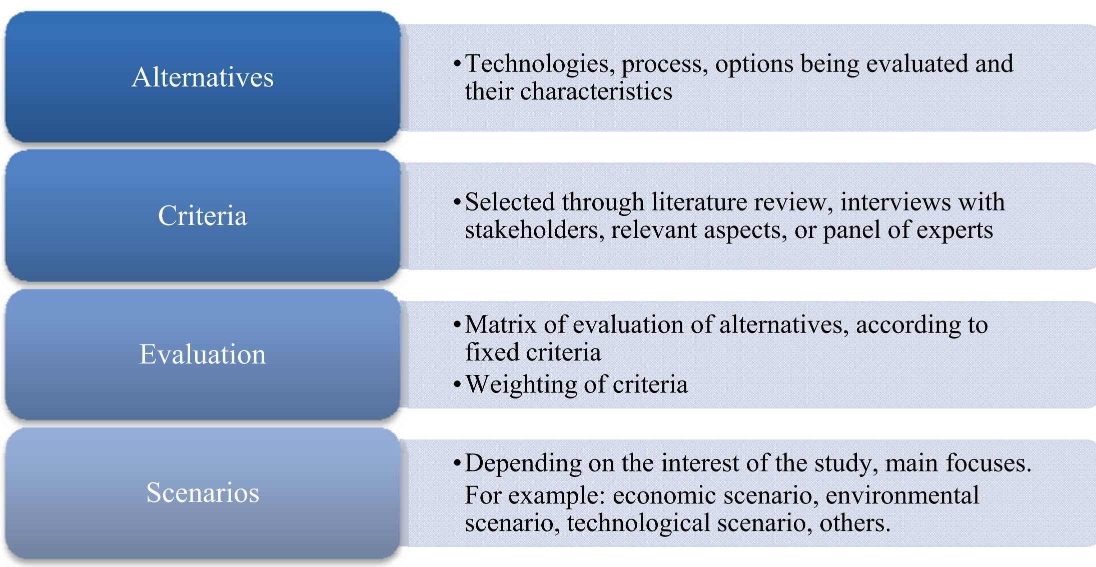


Figure 2.5. Elements of a Multi-criteria Decision Analysis. Source: created by author

The scenarios are done through assumptions created considering the interest of the study, main focuses and objectives.

2.3.3. Types of multi-criteria decision analysis

The main families of methodologies based on the study *Selecting an Appropriate Multi-Criteria Decision Analysis Technique for Renewable Energy Planning* (Polatidis, 2006), as shown in Figure 6, include:

1. Outranking methods, such as the Elimination Et Coix Traduisant la Realite (ELECTRE)family, the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) I and II methods, and Regime Method Analysis;
2. Value or utility function-based methods, such as the Multi-Attribute Utility Theory (MAUT); the Simple Multi-Attribute Rated Technique (SMART); the Analytic Hierarchy Process (AHP); and the most elementary multicriteria technique, the Simple Additive Weighting (SAW);
3. Other methods like Novel Approach to Imprecise Assessment and Decision Environment (NAIADE), Flag Model, Stochastic Multiobjective Acceptability Analysis (SMAA).

These methodologies have been analyzed and compared in many studies, for example Al-Shemmeri (1997), Zopounidis (2002), Pohekar (2004), Polatidis (2006), Buchholz (2009), Wang (2009) and in projects developed to improve the accuracy and comparability of future resource assessments for energy by reducing heterogeneity, increasing harmonization and exchanging knowledge such as the Biomass Energy Europe, BEE, project (Rettenmaier, 2008). However, the BEE project is in process and does not have its final results yet.

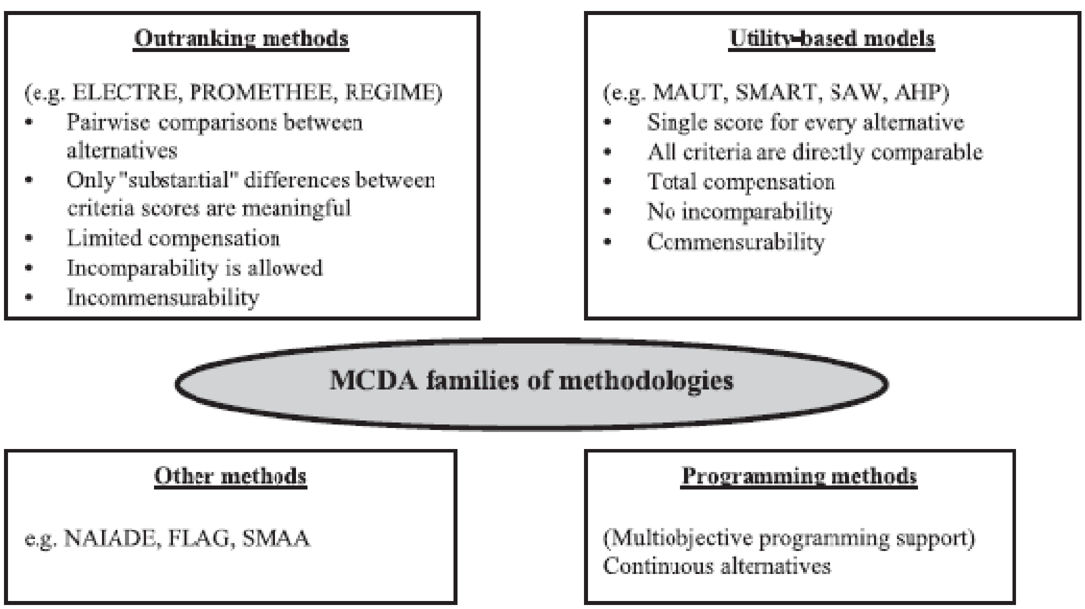


Figure 2.6. Multicriteria methologies
Source: Selecting an Appropriate Multi-Criteria Decision Analysis Technique for Renewable Energy Planning. Polatidis, 2006.

In general, the MCDA provides a reliable methodology to rank alternative Renewable Energy Sources projects in the presence of numerous objectives and constraints. However, none of the different multi-criteria analyses is considered the best for all kinds; there are no better or worse techniques, only techniques that fit better to a certain situation or not.

Some examples of studies that implemented MCDA in their analysis are presented in Table 2.2.

Table 2.2. Examples of studies with MCDA implementation

Year	Author	Title	Abstract
2008	Bollinger	Multiple criteria decision analysis of treatment and land-filling technologies for waste incineration residues	Alternatives of incineration residues that need specific treatment and/or land-filling technologies. The variety of local situations and appraisals led to the choice of very different solutions, the ELECTRE III multicriteria method was used. The purpose of this study was to provide the background for a national policy that would apply to all future projects.
2009	Browne et al	Use of multi-criteria decision analysis to explore alternative domestic energy and electricity policy scenarios in an Irish city-region	Multi-criteria decision analysis (MCDA) was used to assess 6 policy measures or scenarios relating to residential heating energy and domestic electricity consumption, using an Irish city-region as case study.
2009	Buchholz et al	Multi Criteria Analysis for bio-energy systems assessments	Evaluates the potential of Multi Criteria Analysis (MCA)to facilitate the design and implementation of sustainable bioenergy projects.
2007	Burton and Hubacek	Small beautiful? A multi-criteria assessment of small-scale energy technology applications in local governments	A local case study of renewable energy provision in the Metropolitan Borough of Kirklees in Yorkshire, UK, and apply a multi-criteria decision analysis methodology to compare the small scale schemes implemented in Kirklees with large-scale alternatives.
2009	Wang et al	Review on multi-criteria decision analysis aid in sustainable energy decision-making	This article reviewed the corresponding methods in different stages of multi-criteria decision-making for sustainable energy. The criteria of energy supply systems are summarized from technical, economic, environmental and social aspects.
2005	Cavallaro	A multi-criteria approach to evaluate wind energy plants on an Italian island	A preliminary assessment regarding the feasibility of installing some wind energy turbines in a site on the island of Salina (Aeolian islands—Italy). A multi-criteria method applied in order to support the selection and evaluation of one or more of the four solutions proposed.
2001	Brand et al	STEEDS: A strategic transport–energy–environment decision support	The outcome of a European research project called STEEDS (Scenario-based framework to modeling Transport technology deployment: Energy–Environment decision Support).able to assist the policy makers in exploring the influences on market take-up of different transport technologies under various exogenous scenarios and policy options and in assessing the energy and environmental impacts of these technology mixes. The decision-making analysis was made with NAIADE.

CHAPTER 3. METHODOLOGY

3.1. DELINEATION OF STUDY AREA

In order to identify the potential biomass energy source and the most recommended biomass energy generation technology to apply. The study considers the biomass energy sources available in the metropolitan area of Santiago, specifically considering the organic fraction of domestic waste, lopping from parks and gardens, sewage sludge and other potential municipal biomass waste that end up in the three landfills located within the area: Loma Los Colorados, Santa Marta and Santiago Poniente. A map showing the location of the three landfills can be found in Annex 8.1.

In other words, the study focuses on the biomass waste generated in the metropolitan area of Santiago that is deposited in the three landfills. Of all the municipal solid waste generated in the metropolitan area, 98.96% is disposed in landfills, 1% is disposed in a controlled dumping site and 0.04% in a non-controlled dumping site (CONAMA, 2010). Therefore, the solid waste that is deposited in the three landfills of the metropolitan is a reliable sample of the universe of study.

3.2. DATA COLLECTION

The gathering of data was done through different tools: literature review of previous research studies and interviews with experts in the different governmental institutions and visits to the landfills in the metropolitan area.

3.2.1. Literature review and previous research studies

Chile and its metropolitan area has been and still is being studied through the Megacity Risk Habitat project and other local institutions, such as the National Commission of Energy, CNE, and the National Commission of Environment, CONAMA; supported by investigation institutions, universities and consulting companies. These entities have generated relevant information that was used as base information for this study.

The information reviewed from previous studies from the energy sector and waste management sector focus on topics such as: renewable energies promotion, solid waste management, biogas potential, Clean Development Mechanism in Chile, energy potential of solid waste in Chile, domestic solid waste management, and characterization of municipal solid waste.

Other studies, documents and literature reviewed were books on renewable energies technologies, booklets on available technologies, scientific journals and studies on energy generation based on solid waste, waste-to-energy projects, biomass energy, waste management, methodologies for multi-criteria decision analysis, multi-criteria decision making tools, and related topics.

3.2.2. Interviews with experts

The interviews were directed to local institutions responsible of the waste management system in the metropolitan area and the renewable energies sections within the energy sector. The purpose of the interviews was to clarify doubts regarding the base information reviewed and analyzed, to better understand the systems structure and functions, the focus of each institution regarding the waste use for energy generation, possible or existing constrains, new initiatives or programs, relevant aspects such as characteristic and management of waste, involvement in the sector and others.

The interviews provided information regarding solid waste management, collection systems, residues treatment and disposal, legal framework, policies and initiatives.

The field visits were combined with interviews with representatives of the landfills, which provided information regarding characteristics, functioning and process of the transference stations and landfills, biogas collection, leachate treatment, the Clean Development Mechanism projects and flaring of biogas, characteristics of the biogas generated, energy generation, future and other projects.

The interviews were opened, non-structured, with focal points to maintain the thread of discussion. This allowed to deepen the discussion when was of importance for this study and to obtain the opinions and comments of the interviewee. In Annex 8.2 and 8.3, it can be found the list of experts and institutions interviewed, and a table with the relevant information that was asked during the interviews.

3.2.3. Field visits

The visits to the landfills were done with the support and collaboration of Ingeniería Alemana and ProAmbiente, two consulting companies that have worked with the private companies that own the landfills in the metropolitan region. The visits are listed in table 3.1.

Table 3.1. Visits of landfills in the metropolitan area

Landfill name and company	Date of visit	Representative - position
Landfill Loma Los Colorados and Transference Station Quilicura – KDM	March 11th, 2010	Martine Odou – Project Engineer
Landfill Santa Marta- Santa Marta consortium	March 18th, 2010	Gisselle Carrasco – Manager Assistant

The visits to the sites allowed the *in situ* observation of the waste disposal treatment. The landfill Santiago Poniente –ProActiva Chile was not visited during the field research due to the unwillingness of the company to receive visitors. Therefore, all information provided from this landfill is provided based on literature review, interviews with experts and information from local institutions such as the Regional Ministerial Secretary of Health also known as SEREMI de Salud and the National Commission of Environment also known as CONAMA. However, the lack of this visit does not affect the results of the study, since the information required for calculating the potential of energy generation was obtained from the reports and documents delivered by each landfill to the responsible national institutions: CONAMA, SEREMI de Salud and the Environmental Impact Assessment System, known as SEIA.

3.3. SELECTION OF TECHNOLOGICAL ALTERNATIVES

The technology selection was done based on the information provided in the literature review, focusing on previous studies that analyzed technical alternatives for energy generation from waste, agricultural biomass, MSW and others. From the alternatives reviewed, only those that could be applied in biogenic solid waste and MSW were selected.

The technologies considered for WTE projects based on biogenic waste from the MSW of the Metropolitan area of Chile were: combustion, pyrolysis, thermal gasification, biodigesters and landfill gas for energy generation. The last one is considered for comparison of the "business as usual" alternative.

Table 3.2. Alternative technologies selected

Number	Technologies	Conversion	Processes	Energy source
1	Incineration	Thermo chemical	Combustion	Any form of biomass mc<50%
2	Pyrolysis	Thermo chemical	Pyrolysis	Any form of biomass
3	Gasification	Thermo chemical	Gasification	Any form of biomass
4	Biodigesters	Bio chemical	Anaerobic digestion	Organic waste
5	Landfill gas	Bio chemical	Anaerobic digestion	Municipal solid waste

Each technology apart from the landfill gas is being studied and improved. Many have different technical process and characteristics. For this study, the characteristics and parameters consider for each technology were based on the ones with higher market attractiveness and technology strength. The selection was based in literature review and reports on the status of each technology:

The alternative of MSW incineration was also included due to its world wide use in energy generation and its potentialities; which made it relevant to be considered in the Chilean context.

The technologies selected were then analyzed and compared based on the advantages and disadvantages identified in the literature review. This comparison helped also to define some basic technological criteria for multi-criteria analysis of the technologies.

3.3.1. Selection of criteria and scale of values

The criteria selection was done within three main focuses: (1) technological, (2) environmental, and (3) socio-economical. These three focuses were selected due to their relevance in what is considered sustainable development, the political, economical and legal framework of the country and their main interests.

In each focus, a set of criterion was established to evaluate each technology in the analysis. Each criterion was proposed considering the characteristics of the technologies being evaluated, the country energy and waste management policies, legal framework (environmental laws, waste management laws, energy laws, NCRE law), and the results from the interviews with the stakeholders (private companies from the landfills, local and national institutions such as CNE, CONAMA, and the Non-Conventional Renewable Energies projects within the government, experts). However, the final selection was done based on availability of data to support the criteria for each technology. When a technology was lacking a criterion value, or could not be supported, the criterion was removed from the evaluation. Another consideration for the selection of a criterion was that its data has not been used for the calculation of another criterion, making one criterion dependent of the other, and therefore, influencing the results if used both in the matrix.

Finally, for the introduction of the criteria in the NAIADE matrix, each criterion was characterized, assigning to each the score type of the criterion if it is quantitative or qualitative, the units or values that were going to be used and the optimization consideration if the maximum value was the most important or the minimum value.

3.3.2. Analysis of each criterion

The criteria proposed for the multi-criteria analysis can be quantitative or qualitative. The qualitative criteria are evaluated based on the data gathered. However, the quantitative criteria need to be analyzed and processed before been used in the Multi-Criteria Decision Analysis model.

The processing and analysis of the criteria was done with the support of GEMIS software and on calculations with different equations for calculating potentials. The equations will be explained in the section 3.4.

The GEMIS software provides a data base of energy generation technologies, and allows the comparison of each technology, and estimates CO_2 equivalent emission from each type of technology and energy source used from a Life Cycle Analysis point of view. It also allows for entering own data and products with different characteristics for LCA. It was used to analyze each technology and their characteristics, and estimate CO_2 equivalent emission from each based on the related quantitative criteria considered in the study. The used of GEMIS allowed having a more objective and detailed criteria evaluation.

Finally, the information processed, calculated and gathered was introduced in the Multi-Criteria Decision Analysis software to obtain the alternative technology most recommended. Details of MCDA and GEMIS software are provided in the following section.

3.3.3. Multi-Criteria Decision Analysis model and supporting tools

3.3.3.1. Global Emission Model of Integrated Systems, GEMIS

The GEMIS software is another supporting tool used for the preparation and analysis of the criteria used in the MCDA model.

GEMIS is the acronym for Global Emission Model for Integrated Systems, and was selected because it offers information on energy carriers (process chains, and fuel data) as well as different technologies for heat and electric power generation. Besides fossil energy carriers (hard coal, lignite, oil, natural gas), also renewable energies, household waste, uranium, biomass (e.g. fast growing woods, rape) and hydrogen are covered in GEMIS. The process data are given for a variety of different countries, and a special set of data (called "generic") refer to the situation in developing countries.

GEMIS can perform complete life-cycle computations for a variety of emissions, and can determine the resource use (CER, CEC, CMR, land use). GEMIS allows also assessing the results of environmental and cost analyses: by aggregation of emissions into so-called CO_2 equivalents, SO_2 equivalents, and tropospheric ozone precursor potential (TOPP), and by a calculation of external costs (Institute for Applied Ecology, 2007).

It also allows for entering own data and products with different characteristics for more realistic scenarios. However, the strength of the GEMIS model to allow user adaptations is also a danger: When adjusting data, GEMIS only checks the formal correctness of process chain structures, the content of data adjustments cannot be checked by GEMIS (only exception: fuel changes).

In this study, the GEMIS version 4.5 was used to analyze each alternative technology and their characteristics, and estimated CO_2 equivalent and TOPP equivalent emission from each based on the related quantitative criteria considered in the study.

3.3.3.2. Novel Approach Imprecise Assessment and Decision Environments, NAIADE method

This study uses a multi-criteria analysis, MCDA, to process the proposed variables and determine the potential of biomass energy generation in Santiago city, as well as recommend the more appropriate technology for its implementation.

After reviewing the different studies of alternatives for a MCDA, the Novel Approach Imprecise Assessment and Decision Environments method was selected because it is accessible, open source software, flexible for the real world applications; it allows working with uncertainties, variety of information in the form of quantitative and qualitative data and conflict analysis procedures. In this study, NAIADE version 2.0 was used. This method was designed by Munda in 1995 and it is described base on the NAIADE Manual and Tutorial Version 1.0 (Joint Research Centre of the European Commission, 1996).

NAIADE is a discrete multi-criteria evaluation method that allows the measurements of the performance of an alternative with respect to an evaluation criterion. It allows the use of information affected by different types and degrees of uncertainty. The values assigned to the criteria for each alternative may be expressed in the form of either crisp, stochastic, fuzzy numbers or linguistic expressions. NAIADE is a discrete method because the set of alternatives is finite and it does not use traditional weighting of criteria. Using a pairwise comparison technique, NAIADE generates a ranking of alternatives (γ problem formulation).

Evaluation types in NAIADE

It allows for two types of evaluations: the first is based on the score-values assigned to the criteria of each alternative and is performed using an impact matrix (alternatives vs. criteria). The second analyses conflict among the different interest groups and the possible formation of coalitions according to the proposed alternatives (equity matrix: linguistic evaluation of alternatives by each group). However, it does not produce an 'optimal' scenario.

The *impact matrix* is generated through the following steps:

Step 1: Completion of criteria and alternative. The first column and first row of the matrix contain the criteria and alternatives respectively. The selection of the criteria and alternatives depend on the objective of the analysis. Each criterion has to be assigned parameters depending on its characteristics.

Firstly, the user has to input the value associated to each criteria according to each alternative. The user may assign a value in the form of a pure number or give a quantitative definition affected by different levels and types of uncertainty. In the case of fuzzy uncertainty, the user must define the membership function of the fuzzy number. In the case of stochastic uncertainty the user has to choose the probability density function.

The following data is required in the characterization of each criterion, and has to be introduced or selected by the evaluator:

- Criterion name
- Measurement Unit
- Description
- Score type: qualitative, quantitative (crisp, fuzzy, stochastic, numeric and fuzzy)
- Goal type: maximize, minimize
- Filter based on the pairwise comparison
- Credibility level based on distance of pairwise comparison and cross-over point

Finally, it is possible to give a value using a qualitative evaluation expressed by pre-defined "linguistic variables", such as "Good", "Moderate", "Very Bad" and so on. The linguistic variables are treated as fuzzy sets.

NAIADE allows the use of all these types of values when they are consistent with each alternative/criterion, i.e. it is not possible to assign different "types" (i.e.: linguistic, fuzzy, stochastic) to the same criterion for different alternatives (all alternatives must be evaluated for the same criterion and the types of criterion must be the same for all alternatives).

Step 2: Preference relations and pairwise comparison of alternatives

The comparison of criteria scores (values) of each pair of (alternatives) actions is carried out by means of the semantic distance. This comparison is based on *preference relations,* expressed by the user, for each single criterion starting from the distance between alternatives. *Preference relations* are defined by means of 6 functions that allows to express (depending on the distance between alternatives), for each criterion, an index of credibility of the statements that an alternative is *much better*, *better*, *approximately equal*, *equal*, *worse* and *much worse* than another. The credibility index goes from 0 (definitely non-credible) to 1 (definitely credible) increasing monotonically within this range and it is calculated by NAIADE.

The six preference relations can be depicted as shown in Figure 3.1. The "c" represents the cross over values where the functions equal 0.5 and "d" is the distance between two functions.

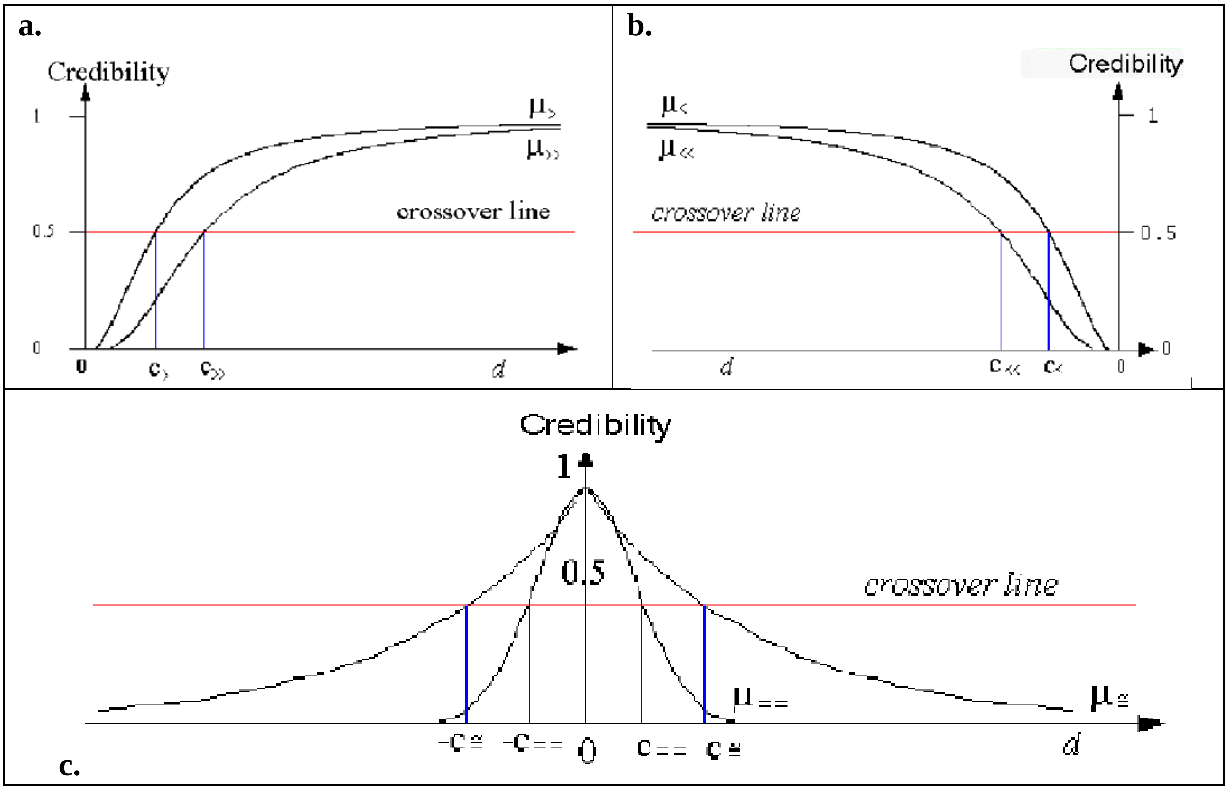


Figure 3.1. Graphics of the six preference relations, a. represents the relations "*much better*" and "*better*", b. represents the relations "*much worse*" and "*worse*", and c. represents the relations "*approximately equal*" and "*equal*".

Step 3: Aggregation of all criteria

Through an aggregation algorithm of the credibility indexes, NAIADE calculates a *preference intensity index* of one alternative with respect to another. In particular the α parameter is used to express the minimum requirements on the credibility indexes. Only those criteria whose indexes are above the α threshold will be counted positively in the aggregation. The *intensity index* $\mu*(a, b)$ of preference * (where * stands for >>, > , ≅, =, << and <) of alternative *a* versus *b* is defined as follows:

Eq. 3.1

$$\mu * (a,b) = \frac{\sum_{m=1}^{M} max(\mu * (a,b)_m - \alpha . 0)}{\sum_{m=1}^{M} |\mu * (a,b)_m - \alpha|}$$

Also the *entropy* concept is used. Entropy is calculated as an index varying from 0 to 1 that gives an indication of the variance of the credibility indexes that are above the threshold, and around the crossover value 0.5 (maximum fuzziness). An entropy value of 0 means that all criteria give an exact indication (either definitely credible or definitely non-credible), whereas an entropy value of 1 means that all criteria give an indication biased by the maximum fuzziness (0.5).

Step 4: Ranking of alternatives.

NAIADE allows for a ranking of alternatives based on the *preference intensity indexes* $\mu*(a,b)$ and correspondent entropies $H*(a,b)$. The final ranking comes from the intersection of two separate rankings. The first one $\Phi+(a)$ is based on the *better* and *much better* preference relations and with a value going from 0 to 1 indicates how *a* is "better" than all other alternatives. The second one $\Phi-(a)$ is based on the *worse* and *much worse* preference relations, its value going from 0 to 1 which indicates how *a* is "worse" than all other alternatives . $\Phi_+(a)$ and $\Phi_-(a)$ are calculated as follows:

Eq. 3.2

$$\emptyset^+(a) = \frac{\sum_{n=1}^{N-1} \left(\mu_{\gg}(a,n)^\cap C_{\gg}(a,n) + \mu_{>}(a,n)^\cap C_{>}(a,n) \right)}{\sum_{n=1}^{N-1} C_{\gg}(a,n) + \sum_{n=1}^{N-1} C_{>}(a,n)}$$

Eq. 3.3

$$\emptyset^-(a) = \frac{\sum_{n=1}^{N-1} \left(\mu_{\ll}(a,n)^\cap C_{\ll}(a,n) + \mu_{<}(a,n)^\cap C_{<}(a,n) \right)}{\sum_{n=1}^{N-1} C_{\ll}(a,n) + \sum_{n=1}^{N-1} C_{<}(a,n)}$$

3.4. DATA PROCESSING

The data obtained in literature review, interviews and field visits was prepared, processed and transformed from the initial raw data gathered for the study. Other calculations for the analysis of each criterion, such as resource availability and potential energy generation in the context and scope of this study where done.

3.4.1. Resources availability – biogenic waste and DSW available in the Metropolitan area

The Municipal Solid Waste, MSW, availability depends on the domestic waste production *per capita* and the number of inhabitants. For the baseline of this study, the available DSW of the Metropolitan area was calculated considering the reported solid waste generation in the CONAMA registry of year 2008 (CONAMA, 2009) with 14,41% of recycling (CONAMA, 2010).

The total available amount of waste was calculated with Equation 3.4 (Noord et al., 2004):

Eq. 3.4.

$$Available\ waste\ (kton) = [Pop.(1000)] * \left[Annual\ waste\ prod.\left(\frac{ton}{inhabitant}\right)\right] * \left[1 - \%\left(\frac{recycling}{composting}\right)\right]$$

The projected available waste was calculated for 22 years from the baseline 2008, considering an increase of recycling, based on the "Santiago Recicla" plan up to 25% in 11 years (CONAMA, 2009) with a growth rate of 1,10% up to year 2030. The projected population and a DSW per capita production of 1,5% in a conservative scenario were considered based on the "Estudio de Preevaluación del Aprovechamiento Energético de los Residuos Sólidos Urbanos" study which focuses on the energetic used of landfill gas done by Ingeniería Alemana (2010), see Annex 8.4.

The biogenic waste was calculated considering the classification of biogenic waste provided by Energy Information Administration (2007), see table 3.3; and the composition percentage of domiciliary solid waste, DSW, of the metropolitan region done by CONAMA & UCV (2006). It is assumed that the biogenic waste fraction remains the same towards 2030 since studies available for the Metropolitan region on waste generation and composition differ greatly one from another and a good projection on biogenic waste fraction cannot be made based on their data.

Table 3.3. Municipal Solid Waste (MSW) categories in Biogenic and Non-biogenic groups

Biogenic	**Non-Biogenic**
Newsprint	Plastic
Paper	PET
Containers & packaging	HDPE
Textiles	PVC
Yard trimmings	LDPE/LLDPE
Food wastes	PP
Wood	PS
Other biogenic	Other plastics
Leather	Rubber
	Other non-biogenic

Source: Energy Information Administration, 2007

3.4.2. Potential energy generation calculations

There are different kinds of potentials to be calculated: theoretical, available, technical, realistic and realizable. Each kind of potential has different scales and characteristics:

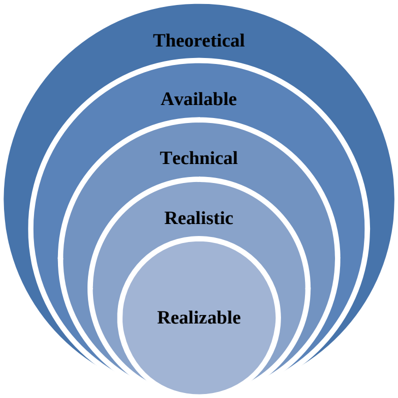


Figure 3.1. Potential types

The *theoretical potential* of a renewable energy source is the total physical energy flow of that source.

The *available potential* is the energy flow that can be harvested, without affecting other uses of the source. For example, the waste available potential for energy generation is the one that is not being used for recycling or composting.

The *technical potential* is the available potential with the restrictions in technology (efficiency, characteristic of the input required).

The *realistic potential* is the part of the technical potential that is achievable after non-technical factors are considered, such as public and social acceptance, environmental impacts, market barriers, economical aspects.

The *realizable potential* is at a certain point in time and takes into account maximum market growth rates over all countries.

In this study the available and technical potentials were analyzed and considered in order to establish the availability of the resource and the potential available based on the technical options. The available potential was calculated with Equation 3.7, considering the resource availability for DSW and biogenic waste portion, as explained in section 3.4.1. The heating value of the waste was used, in order to estimate the potential energy generation of the available waste in the projection made. The heating values for the area of study, however, have not been calculated in other studies; consequently, several sources were reviewed and the most accurate data selected based on: the source of the information, the method to calculate it if described, the country or region mention compared to Chile.

The technical potential was calculated for each technology based on Equation 3.9. Since each technology has different processes and products, it is necessary to use a common unit to compare them. In this study, the comparison is done based on energy production [GWh] (Eq.3.9.) for each technology.

Eq. 3.5.

$$Net\ amount\ available\ waste(kton) = [Available\ waste\ (kton)] * [\%available\ for\ energy\ production]$$

Eq. 3.6.

$$Biodegradable\ waste\ avaiable\ (kton) = [Net\ amount\ available\ waste\ (kton)] * [\%\ biodegradable\ fraction]$$

Eq. 3.7.

$$Fuel\ input\ (GJ) = [biodegradable\ waste\ available(kton)] * [specific\ energy\ content(GJ/ton)]$$

Eq. 3.8.

$$GJ\ output(GJ) = Fuel\ input\ (GJ) * efficiency$$

Eq. 3.9.

$$Production\ (GWh) = [GJ\ output\ (GJ)] * [1/3600]$$

In order to obtain the energy generation values, the values of each factor were modified in correspondence with the technical characteristics of each technology. The conversion factors for each technology were used based on literature review and can be revised in Annex 8.5.

3.4.3. Environmental and socio-economical aspects

3.4.3.1. Environmental aspects

The environmental aspects were measured for each technology using the software GEMIS and introducing specific data for the waste, biogenic waste and landfill gas characteristics from the area of study. At the same time, the technologies in the database in GEMIS were selected based on the specific alternative technologies that this study analyzes.

A scenario in GEMIS was created to compare the five technologies considering 1MWh electricity generation. All allocations for bonuses or carbon credits automatically assigned in the program were deactivated to eliminate altered results since Chile does not consider these benefits yet. Also the scenario was set to include only emissions and waste generation from the technologies usage not from their construction or mobile transports. This means that the results do not show a Life Cycle Assessment, even though it is perfectly possible to include them, but it is not the purpose of the use of this tool in this study.

The results were presented in graphics created in Excel and a comparison on emissions generated was done between the five alternatives and the three main fossil fuels use for energy generation: diesel, natural gas and coal.

3.4.3.2. Socio-economical aspects

The socio-economical aspects were measured based in two features: energy value and green value.

The energy value is the value of the energy generated with the five technologies. This study does not pretend to give a financial and economic analysis of the five options, but to give an overview of all five alternatives, compare and analyze them to choose the better alternative. Therefore, the energy value was calculated considering the ‘avoided cost’ of energy when substitute the fossil fuels by WTE technologies. For this, the cost of electricity generation of the three main fossil fuels was calculated for the baseline year 2008 and multiply for the amount of energy that each alternative technology generate with Equation 3.9. The results were presented in a graphic comparing the five technologies with the three fossil fuel options.

The green value is the value of the energy generated with the alternative technologies considering: (1) the emissions reduced when fossil fuels are substituted and (2) the revenues that could be obtain in the carbon market when the WTE technologies are introduced into the CDM projects. The CO_2eq emissions reduction was calculated multiplying the emission factors of the three fossil fuels for Chile based on UNFCCC (2006) and the total energy generated for each technology minus the emissions that each technology generated. The green value in the carbon market was calculated multiplying the CO_2eq emissions reduction for the value of a Certified Emission Reduction, better known as CER, which is used to sell one ton of CO_2eq in the carbon market. Each CER represents one ton of CO_2eq and the price used was the lowest value paid in 2008 equal to 14,00 Euros or US$ 9,8 with a conversion rate for 2008 of 0,7US dollar per 1 Euro.

3.5. IDENTIFICATION OF BARRIERS AND CONSTRAINS FOR THE IMPLEMENTATION OF A BIOMASS ENERGY SYSTEM

The barriers and constrains for the implementation of the alternative technologies were identified through the analysis and processing of the data gathered; evaluating the interests and focuses of the governmental health, environment and energy institutions, as well as the structure of the energy market and initiatives taken up until now.

The barriers and constrains identified were used as basis for the third and final specific objective "Propose guidelines for the organization and implementation of a biomass energy system in Santiago"; taking into account successful and futile initiatives of other countries.

CHAPTER 4. CASE STUDY

This study aims to evaluate alternative technologies for the use of biomass waste as a source of energy in the Metropolitan Region of Santiago, Chile; in order to identify the most recommended technology to apply; and to propose steps for the organization and implementation of a biomass energy system. Hence it was necessary to study both sectors involved in this topic: the energy sector and the waste management system. Therefore, in this chapter both sectors are described in detailed, as follow:

- The first section includes general information about the country and its metropolitan area to get a better idea of its condition.
- The second section focuses on the energy sector. Since the energy sector in Chile is not a decentralized system that serves only to the metropolitan area; a description of the country energy matrix, its principal energy sources, policies and legal framework, its organization and the role of the renewable energies is provided.
- The third section describes the situation of the waste management system in the metropolitan area, based on information gathered through interviews, literature review and in-situ visits. This section details information such as its organization, responsibilities, and the way it works from its collection to its disposal, including the kind of waste and amounts.
- The fourth and final section of this chapter presents background information regarding previous "waste into energy" projects and other initiatives that have been or are in the process of being implemented in Chile.

4.1. GENERAL INFORMATION

The Republic of Chile is located in South America, between the latitudes 17º 30' y 56º 30' S. It covers an area of 2.006.096,3 km^2 (Instituto Nacional de Estadísticas Chile, 2007) bordering Bolivia, Peru, Argentina, The Pacific Ocean and South Pole (Figure 4.1.).

Chile climate is diverse as is its geography. Three climatic regions can be described: (1) the north, the Atacama Desert, one of the driest regions in the world, characterized by hot and arid weather in the lowlands and occasional summer showers in the Andean highlands; (2) the middle, from 30° to 43° S, has a Mediterranean climate, with mild, wet winters, averaging 11°C, and long, dry summers, averaging 18°C; (3) the south, a region of mountains and fjords, with high winds and heavy rains. Annual rainfall ranges from no recorded precipitation in some parts of the north to 50–100 cm in south-central Chile, to more than 406 cm in some southern regions.

Figure 4.1. Political map of Chile
Source: www.mapsofworld.com

Chile is divided in 15 regions, each region is divided by provinces and each province is divided into "comunas" administered by municipalities.

Its population for 2002 was 15.116.435 inhabitants, based on the XVII National Population and Households Census. The population has been projected to 16.598.074 and 17.094.270 inhabitants for 2007 and 2010 (Instituto Nacional de Estadísticas Chile, 2007), respectively.

In The Human Development Report 2007-2008 (UNDP, 2007), Chile ranked 40^{th} out of 179 countries, reaching a 0,874 Human Development Index and a Gross Domestic Product per capita of 12.997 USA dollars (6.5%) for 2006. In the Human Poverty Index (HPI) for developing countries, Chile ranked 8^{th} out of 135 developing countries with a calculated HPI-1 of 3.3%. Chile is also the second Latin-American country to enter to the Organization of Economic Cooperation Development, OECD.

The metropolitan region of Santiago (Figure 4.2.) has 6 provinces and 52 comunas. It has an area of 15. 403, 2 km^2 and it has 6. 061.185 inhabitants based on the XVII National Population and Households Census of 2002, with a population density of 393, 5 inhabitants/ km^2.

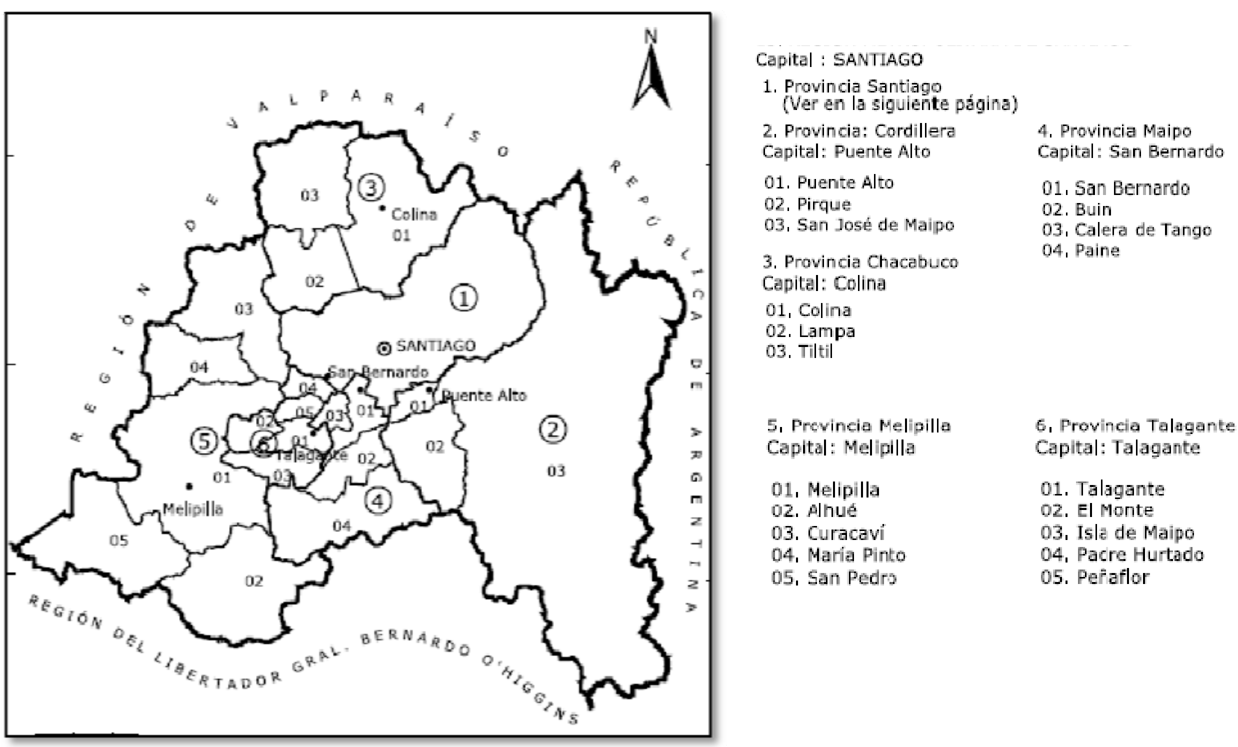


Figure 4.2. Map of the Metropolitan region of Santiago and its comunas.
Source: INE, 2007

4.2. ENERGY SECTOR IN CHILE

4.2.1. Principal energy generation sources

Chile has an installed energy capacity of 12.847MW; its energy matrix is based mainly on fossil fuels (60.2%), large hydropower (38,2%) and Non-Conventional Renewables Energies such as biomass cogeneration and wind energy (1.6%), as shown in Figure 4.3 (CNE, 2008).

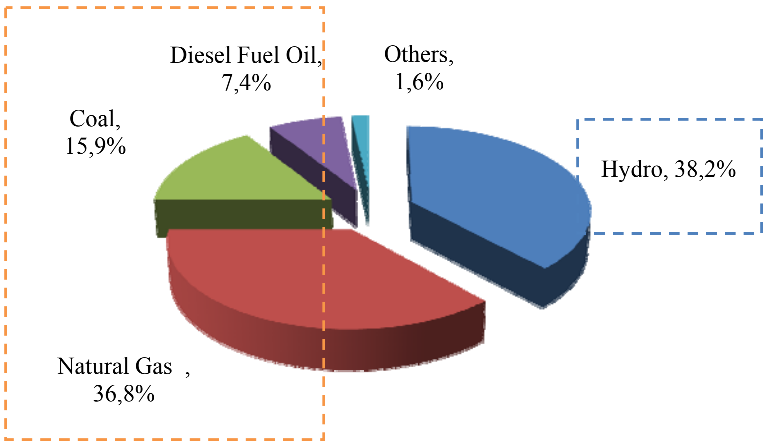


Figure 4.3. Chile installed capacity based on energy sources 2007.
Source: CNE, 2007

The 90% of fossil fuels consumed in Chile is imported; Chile produces only 0,03% of the Latin America and Caribbean (LAC) oil production, with a growing rate of -12,16% from 2006 to 2008. The same happens with natural gas, Chile imports from Argentine 60% of the natural gas it consumes, and produces only 0,79% of the LAC natural gas production. Even though, Chile produces certain among of coal, in 2006, it imported 2,79Mton, hence depending on other countries to cover its coal demand. (OLADE, 2007).

In the case of local sources of energy such as hydropower and biomass; Chile has thermoelectric power plants using biomass sources based on a cogeneration technology and a tree plantations approach, with a production of 190,9 MW (Pontt, 2008). Large hydroelectric projects are not being promoted anymore because they have a high environmental impact due to dam construction and deflection of natural course of rivers; nowadays, hydro power plants lower than 20MW are being considered.

It is relevant to mention that Chile has a Commission of Nuclear Energy created to analyze the possibilities of installing a nuclear power plant in Chile. However, the latest study published by the Ministry of Energy (Tokman, 2010), with the support of the Chilean Commission of Nuclear Energy, concluded that in this moment Chile does not fulfill the requisites for the incorporation of nuclear energy to its energy matrix; however, it is still being considered for the future.

4.2.2. Energy consumption sectors

As shown in Figure 4.4, in 2007, electricity was mainly consumed by the mining and industrial sector with 37% and 31% respectively, followed by the residential and commercial-public sectors with 17% and 14% (CNE/GTZ, 2009).

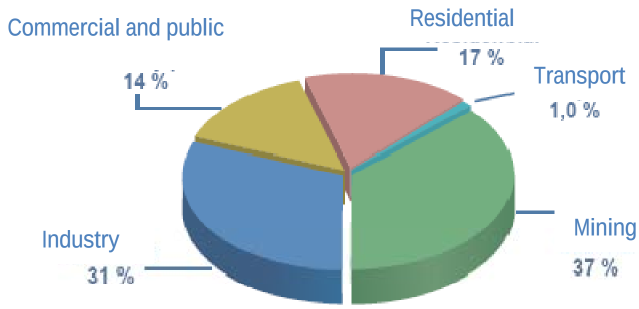


Figure 4.4. Energy consumption sectors 2007. Source: CNE/GTZ, 2009

In the year 2008, the gross energy consumption per capita was 3.327 kWh/year (CNE, 2008), lower than the world average for 2007 with 4.173 kWh/year; but higher than that of its neighbor country for 2007, Argentina, with 2658,66 kWh/year (World Bank, 2007).

4.2.3. Energy Market in Chile

The National Energy Market in Chile is formed by a group of generation, transmission and distribution companies. Together they supplied a combined demand of 52.901GWh (Aporte Potencial ERNC y Eficiencia Energética, 2008) in 2005.

The market is divided in four electric systems, as shown in Figure 4.5: (1) Sistema Interconectado del Norte Grande (SING) with 30,17% of the installed capacity, (2) Sistema Interconectado Central (SIC) with 69,01% of the installed capacity, (3) Sistema de Aysén with 0,28% of the installed capacity, (4) Sistema de Magallanes with 0,54% of the installed capacity.

The private energy sector in Chile focus on "immediate demand market" prices and gives more importance to existing investments or new generation projects that require short time and low initial capital investment; which are the opposite characteristics of renewable energy projects. Moreover, there is freedom in deciding technology, size, and delivery date of energy power plant installation (Breinstein, 2008); which is considered a way to promote competence between private companies.

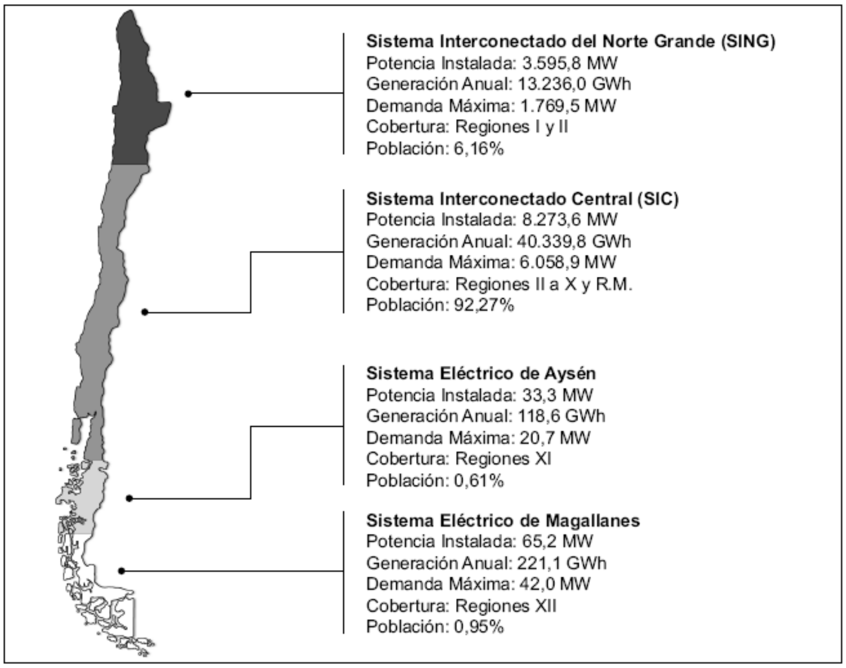


Figure 4.5. Chile Electricity Systems and data for 2005
Source: Aporte potencial de ERNC y Eficiencia Energética a la Matriz Eléctrica 2008-2015, 2008.

This competitive market also has freedom of electricity generation prices; regulated only in the transmission and distribution of electricity. Two kinds of markets co-exist, as shown in Figure 4.6, spot market for generators excesses and deficit, and contract market which establishes an obligation to buy and supply in a fixed price. Prices are set through four modalities: spot prices, free prices, knot prices, and distribution prices.

Regarding energy demand, consumers are classified in three big groups: regulated clients, free or not regulated clients, and clients with right to opt for a regulated or free tariff (Aporte potencial de ERNC y Eficiencia Energética a la Matriz Eléctrica, 2008)

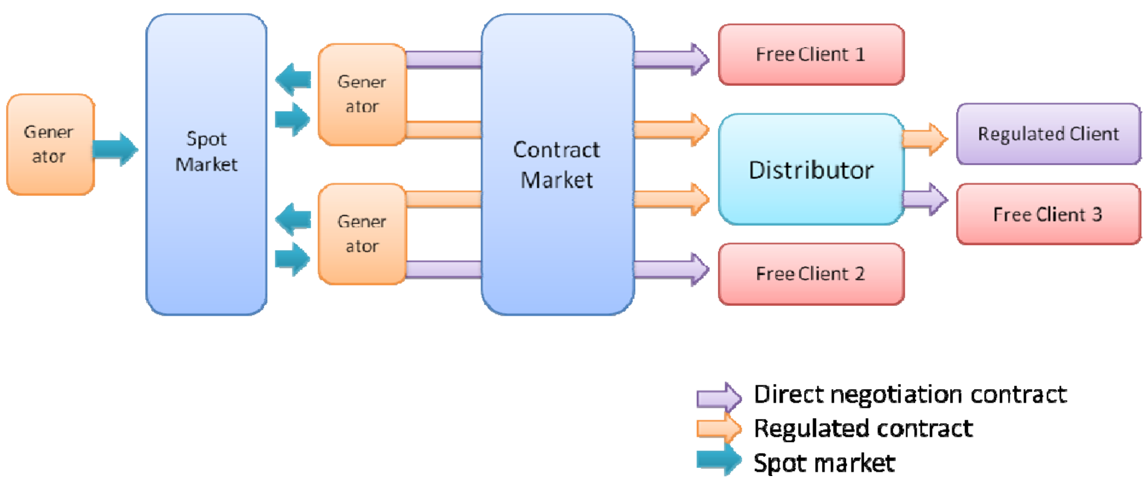


Figure 4.6. Chile Electricity Market. Source: Translated from Las Energías Renovables No Convencionales en el mercado eléctrico chileno, CNE/GTZ, 2009

4.2.4. Energy Policy and Legal Framework

Since the creation of the Electric Services General Law in 1982, the electricity market of Chile was structured in three sections: generation, transmission and distribution of electricity, these last two sections under price regulation. Simultaneously, there was a process of privatization and the government was since then responsible for the regulation, supervision and planning of generation and transmission inversions (Aporte potencial de ERNC y Eficiencia Energética a la Matriz Eléctrica, 2008).

The National Commission of Energy (CNE) is the organ responsible of the creation of regulatory policies and their fulfillment and it is the official advisor on energy matters, sets and calculates prices of the energy chain. However, based on the new Law No. 20.402, the new Ministry of Energy was created in February 2010. This modified the structure of the energy sector, making the new ministry responsible for the creation and coordination of plans, policies and norms for the development of the sector; and putting under its mandate the National Commission of Energy (CNE), Superintendent of Electricity and Combustibles and Chilean Commission of Nuclear Energy. Other institutions created in the energy sector are the Sub secretary of Energy, the Agency for Energy Efficiency and the Center for Renewable Energies (CER) in the Corporation for the Promotion of Production (CORFO).

On the context of the energy crisis created by the reduction of the Argentinean natural gas imports in 2004 and the water scarcity in 1998, 1999, 2007 and 2008 (Rodríguez, 2005; Grosso, 2008) that affected the hydroelectric supply and in response to citizen’s proposals; Chile included in its energy law the Non-Conventional Renewable Energies, ERNC in Spanish. The government reformed the Electric Law in 2004, 2005, and 2008, and established an obligatory goal of 5% of NCRE integrated to the electric matrix from 2010 up to 10% to 2024 (Programa Chile Sustentable, 2008).

Therefore, Chile energy policy acknowledges the necessity of modifying the actual structure, where the state take a strategic role in the energy matrix and remove exclusivity from the private sector that controls supply of energy to the country. Chile government took a more active role to confront the energy crisis and provided, in the Energy Law amendment of 2005, direct incentives to the development of new energy projects and greater flexibility in the adjustment of energy prices, Table 4.1.

Table 4.1. Law Reforms of 2004 and 2005, regarding NCRE promotion

Ley Corta I (Ley 19.940 march, 2004)	Ley Corta II (Ley 20.018 may, 2005)
• Opens up the wholesale market for small generators under 9MW. • Access to distribution net for small generators under 9MW. • Exemption of mainline toll for NCRE sources. o < 9MW total exemption o 9MW – 20MW partial exemption	• Exclusive market for NCRE, similar prices for generation companies that get contracts with distribution companies.

Source: Poniachik, 2006

In April 2008 was enacted the new Law for the development of Non-Conventional Renewable Energies (Law No. 20.257). This new law establishes that each electricity company that takes more than 200MW from the electricity systems must make sure that 10% of the electricity consumed is generated from Non-Conventional Renewable Energies, being hired or owned. This percentage will be achieved gradually beginning with 5% between the years 2010 to 2014, and increasing 0,5% annually until reaching 10% in 2024.

4.2.5. Renewable Energies in Chile

Due to its geographic position, Chile has a large renewable energies potential for solar, wind, geothermal, biomass and hydro sources. The latest two have been more exploited, but mostly hydro energy generation has been main part of its energy matrix.

The energy crisis and reforms in the Electric Law encouraged studies evaluating the potential of renewable energies nationally. The latest study was done by Universidad Técnica Federico Santa María and Universidad de Chile. This study presented the gross potential of renewable energies in Chile and the potential technically feasible for 2025 (Table 4.2).

Table 4.2. Renewable Energy Sources for Electricity Generation in Chile

Renewable Energy	Gross Potential* MW	Technically Feasible Potential 2025* MW	Installed capacity 2005** MW
Wind	40.000	1.500	2,0
Solar thermal	40.000-100.000	1.051	0
Solar Photovoltaic	1.000	500	0
Geothermal	16.000	1.500	0
Biomass	13.675	3.249	190,9
Hydro	20.392	3.003	112,8 (mini hydro)
Tydal	NA	NA	0
TOTAL	191.067	10.803	285,7

Source: *Aporte potencial de ERNC y Eficiencia Energética a la Matriz Eléctrica, 2008-2015, 2008.
** Poniachik, CNE, 2006

For the promotion of the renewable energies in Chile some initiatives have been taken which include:

- The Non-Conventional Renewable Energies project was created in August 2004 with the support of Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), German Bank of Development (KtW), Federal Institute of Geosciences and Natural Resources (BGR, Germany) and National Commission of Environment (CONAMA, Chile). It has as main objective to contribute to the insertion of NCRE in the energy matrix. The project aims to the development of policies, regulations and instruments, the improvement of local capacity, the promotion of diffusion mechanisms and the facilitation of decisions in the private sector.
- The creation of the Center for Renewable Energies (CER) in Corporation for the Promotion of Production (CORFO) in August 2009, which will provide information regarding latest studies and advances in the renewable energies around the world.
- The International Agency of Renewable Energies creation signature, which took place in Germany in January 2009 and has as objective to promote the renewable energies and

facilitate information regarding potentials, practices, financial mechanisms, and technology.

- A memorandum of cooperation in the energy sector, signed with the United States of America in June 2009, with the purpose of technical support and tools transference for the development of instruments for promoting renewable energies.

These initiatives are focused in three main areas: information and dissemination, legal framework and regulations, and funding and financial support.

CORFO is responsible for the funding and financial support of Non-Conventional Renewable Energies in Chile, its main instruments are:

- Co-financing for pre-investment in preliminary phase
- Co-financing for pre-investment in advanced phase
- Credit line CORFO Environment applicable for NCRE
- Credit line CORFO NCRE
- High Technology Program – for innovations

The first two are mechanisms for pre-investment and both credit lines are mechanisms for investment. All instruments have requirements, and cover only a percentage. Usually for the first two, they finance 50% of the total amount of investment or up to US$60.000 for first stage pre-inversion projects or US$ 160.000 for advance stage pre-inversion projects; the credit lines can finance up to US$15.000.000. The funds are available for national or international companies that fulfill the requirements and are available through three national banks. The banks receive the application and when approved, they request the funds from CORFO.

However, few projects are actually functioning and others are in the process of approval. In 2008 there were 40 projects in the Environmental Impact Assessment System (SEIA in Spanish) that represent 640MW, and the credits from CORFO were funding 120 studies for wind, hydro, biomass, biogas, and geothermal projects that are in their pre-investment phase. Nowadays, the portfolio of Non-Conventional Renewable Energies has grown to 2570MW in the SEIA from which 2024MW of it have been approved and 2057MW are specifically wind energy initiatives (GTZ, 2010).

4.3. WASTE MANAGEMENT SYSTEM IN THE METROPOLITAN REGION OF SANTIAGO DE CHILE

The waste management system in Chile has the same problems as any Latin American country. In the last decades, there have been changes in the consumption patterns generating less organic residues in the waste stream of the urban areas, there are few recycling programs most of them independently implemented, and the final disposal is still the main problem of the waste management being dumping sites and landfills the most common way of disposal.

The waste management system in Chile is responsibility of each municipality or comuna, as they are called. Each one is responsible of the collection, management and final disposal of the municipal solid waste (MSW) generated within its area. All the activities related to the management of waste in Chile respond to its Integrated Management of Solid Waste Policy created in January 2005 and its legislation: Regulations for Landfills Management, Decree 189-05; Regulations for Management of sludge from water treatment plants, Supreme decree No. 004; Minimum norms for dumping sites management, resolution No. 02444; and other official Chilean norms.

This sector as well as the energy sector, responds to different governmental entities, each one with specific responsibilities: the health authority based on the Ministry of Health (MINSAL) and the Regional Ministerial Secretary of Health (SEREMI de Salud) in charge of monthly supervisions; the National Commission of Environment (CONAMA) for regulation and information source with a new Information System for waste management project; the ministerial-regional Secretary of Housing and Urbanisms (MINVU); the Sub secretary of Regional and Administrative Development (SUBDERE); and the local government, municipalities of each comuna.

4.3.1. Generation of municipal solid waste

In 2007, the Domestic Solid Waste registry of CONAMA reported 8.211 metric ton/day or 2.997.038 metric ton/year of MSW generated in the metropolitan area of Santiago; from which 14, 41% was recycled and the rest (approximately 2.6 million ton) was taken to final disposal sites.

In 2008, a total of 2.699.016 metric ton/year of Domestic Solid Waste were disposed in the metropolitan area; of which 98,96% was disposed in landfills, 1% was disposed in controlled dumping sites and 0,04%, in a non-controlled dumping site (CONAMA, 2010). This is due to the fact, that in the last years, the metropolitan region underwent a process of elimination or closure of dumping sites that did not comply with the environmental regulations; and three private landfills were opened, one in 1998 called “Loma Los Colorados” (Til Til) and two in 2002 called “Santa Marta” (Lonquén) and “Santiago Poniente” (Rinconada de Maipú).

Nowadays, beside the three landfills in the metropolitan region remains one controlled dumping site called “Popeta” (Melipilla) and one uncontrolled dumping site “Alhué” (Melipilla). It is also projected the closure of these two dumping sites and the installation of a new landfill; nevertheless, there are no other considerations regarding the disposal of solid waste. The amount generated in the metropolitan area in 2008 represented 47% of the solid waste generated in the whole country.

A study on the characterization of domestic solid waste (DSW) in the metropolitan area of Chile by CONAMA & UCV (2006) states that the organic matter in 1973 was 73% and that this decreased to a minimum of 42,29% in 2000.

The composition of the DSW can be seen Table 4.3 for different periods:

Table 4.3. Composition of municipal solid waste in different years in the metropolitan region CONAMA

Composition (% wet weight)	1983	1990	1996	2000	2004
Biodegradable fraction	81.1	82.99	65.18	64.14	72.26
Organic matter	62.2	68.14	44.91	42.29	54.23
Paper and cardboard	18.9	14.85	20.27	21.85	18.03
Plastic	4.4	5.82	12.5	14.09	7.49
Textiles	3.6	3.85	4.66	5.04	1.32
Metal	2.5	2.17	2.38	2.46	0.92
Glass	1.3	1.44	1.84	2.12	9.89
Ashes and debris	6.5	0	5.47	5.07	0.87
Others	0.6	3.73	7.43	6.54	7.02

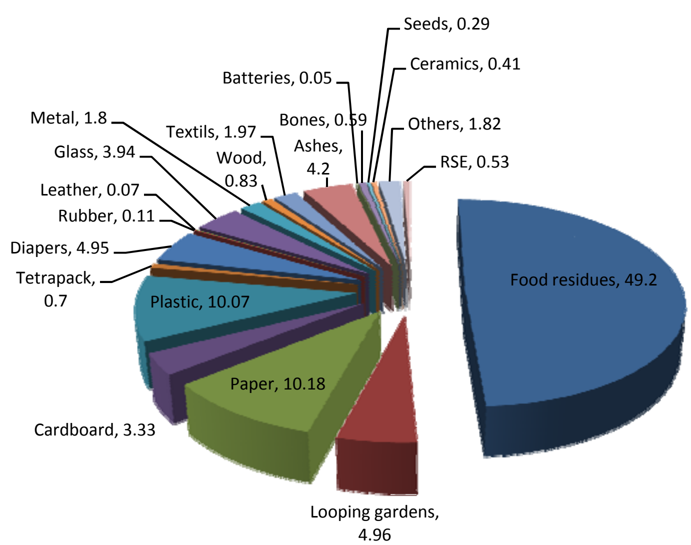
Source: CONAMA & UCV (2006)

Note: The table presents a compilation of different studies that was presented in the document cited.

As shown in Table 4.5, different studies have been done to characterize the municipal solid wastes in the metropolitan region of Santiago but their results differ greatly one from another. This is due to the fact that Chile does not have a standardized methodology for waste characterization and some of the studies are based on projections and others are based on estimates from punctual locations.

The study of Characterization of Domestic Solid Waste in the Metropolitan Region by CONAMA & UCV (2006) intended to improve the basis of solid waste information and was made based on statistical samples divided into different socio-economical levels and the wet and dry seasons, obtaining the results shown in Figure 4.7.

a.



b.

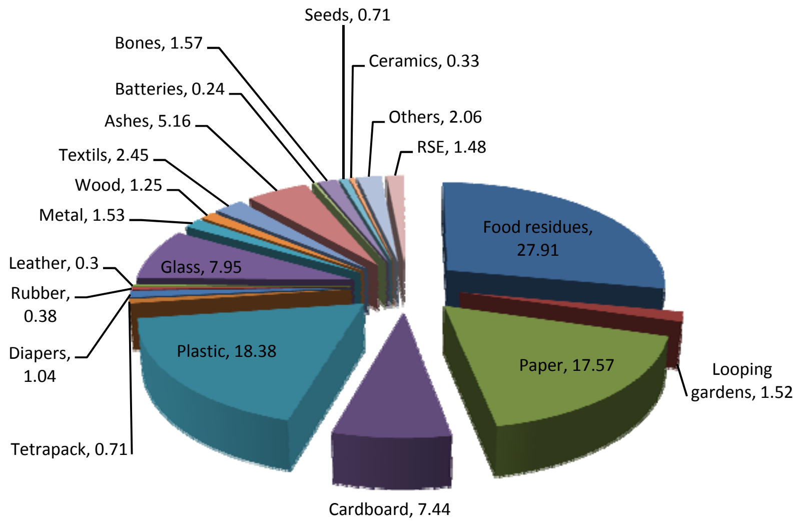


Figure 4.7. Composition of Municipal Solid Waste in the metropolitan region: a. Residential sector, b. Commercial sector. Source: created by author based on CONAMA & UCV (2006)

4.3.2. Management and final disposal of the municipal solid waste

The Solid Waste Management includes the collection, transport, treatment and final disposal of the waste. In Chile, based on the Integrated Management of Solid Waste Policy (CONAMA, 2005), the main purpose in the waste management initiatives should be not to generate the waste and if generated then the target should be to reduce, reuse or recycle, afterwards should be the treatment and finally the disposal. The policy also mentions that the solid waste sector has three main problems: weak institutionalization, insufficient regulation controls and a lack of coordination among all the governmental entities involved.

However, the hierarchy of waste management mentioned in the policy is not yet being implemented in Chile. There are only isolated initiatives for minimization or recycling; in fact, most of the municipalities consider handling the solid waste an annoyance deal with by hiring private companies. These companies are paid for the collection and/or final disposal of the MSW; which does not encourage recycling initiatives. Part of this is due to the decrease of the cost per ton of waste disposed compared to other alternatives (CONAMA, 2005). Because of that, sometimes market interests give more relevance to final disposal than reuse or recycling; in the case of the last one, at times recycled materials are more expensive than raw materials (CONAMA, 2010). However, this is without considering other environmental and costs benefits.

In the study area the management of solid waste is not that different. The municipalities depending on their budgets and population’s waste management service payments, based on household’s value, can hire private services or have their own waste collection vehicles.

4.3.2.1. Recycling initiatives

Waste recycling is an activity promoted as municipal programs in a few comunas of the metropolitan region: Santiago, Ñuñoa, La Reina, Pudahuel, Providencia, La Pintana, La Florida and María Pinto (CONAMA & UCV, 2006). There are some infrastructure installed for recycling in other municipalities such as Las Condes (Figure 4.8.) and Vitacura; and some others have composting initiatives such as María Pinto and La Pintana.

Figure 4.8. Recycling point, Las Condes, RM

In a study done by CONAMA Metropolitana Region (2005) to evaluate the recycling systems of some municipalities in the metropolitan region, four municipalities were studied: Ñuñoa, La Florida, La Reina and La Pintana. The first three had a separated collection system of non-organic residues, and the last one had a separated collection system of organic residues from open-air fairs, lopping from parks and gardens and composting plant. The result obtained from an economic analysis of these projects based on a 10-year projection and the Net Present Value (NPV) showed that all recycling systems implemented in the four municipalities have a positive NPV for the projection considered, and are more convenient than the traditional non-recycling systems.

There is also a new initiative called "Santiago Recicla" from CONAMA Region Metropolitana, Intendencia Metropolitana de Santiago and Fundación Casa de la Paz, which promotes the integration of private and public activities for a more sustainable and efficient waste management in 28 comunas within the Metropolitan Region. It aims to increase domestic solid waste recycling to 25% within 11 years by implementing separation in the source in some pilot municipalities (CONAMA RM, 2009).

4.3.2.2. Landfill sites

After the collection and in some cases separation of waste, the MSW is taken to the final disposal sites. In this part, only the three landfills object of this study will be described in detail.

Landfill Lomas Los Colorados is run by the private company KDM. It is located in Til til at 63 km north of the metropolitan urban area, has an area of 210ha in a 800ha property, and a total capacity of 120 million metric tons, with projected closure in 2055. It receives 62% of the MSW of the metropolitan region, it serves to 24 municipalities and particular clients, with a reception of approximately 155.418 metric ton/month registered in 2008 (Ingeniería Alemana, 2010) or 5.100 metric ton/day of solid waste (SEREMI de Salud Región Metropolitana, 2009) and 300-400 metric ton/day of digested sludge from the Waste Water Treatment Plant (WWTP) La Farfana product of the anaerobic digestion and biogas generation. Almost 50% of all its solid waste is organic. It has a transference station in Quilicura (Figure 4.9.a.) located outside of the urban area, where residues are compacted in silos that are later transported to the landfill by train. Each silo can hold up to 25ton and the train takes around 15 silos per each of the 10 trips per day. In the transference area, only the looping for parks and construction debris are separated from the rest of the waste.

The landfill follows the United States Environmental Protection Agency (USEPA) standards in landfill construction, compacting of residues, monitoring of parameters (emissions, underground water and biogas), leachate collection and treatment, biogas collection. Also, it is certified with ISO 9001 and ISO 14001. It began flaring up the biogas (Figure 4.9.c.) and in March 2007 began its Clean Development Mechanism (CDM) project, burning up initially 5000 m^3/hr and reaching 7000 m^3/hr now. In 2009, the company began producing electricity with two motors of 1MW each (Figure 4.9.d.), which is planning to expand to 14MW in 2010 and to extend it to 28MW by 2024. The electricity production project will be explained in section 4.4 of this chapter.

Figure 4.9. Photos of the landfill Lomas Los Colorados, a. Transference station Quilicura, b. Landfill waste deposition and biogas pipelines, c. Biogas flaring towers, d. Electricity generation motor

Landfill Santa Marta is run by the private consortium Santa Marta. It is located in Talagante at 12 km south of the metropolitan urban area, it has an area of 77ha in a 296ha property, with projected closure in 2022. In 2008, it received about 83.000 metric ton/month of waste of the metropolitan region, serving 17 municipalities and particular clients, with a reception of approximately 3.200 metric ton/day (SEREMI de Salud Región Metropolitana, 2009). It has a transference station called Puerta Sur located in San Bernardo outside of the urban area, where residues are transferred to bigger containers of 25 metric ton, without any other treatment done to the waste. The landfill receives daily about 120 containers from the transference station and 30 garbage trucks from surrounding municipalities that travel directly to the landfill site.

The landfill follows also USEPA construction standards, compression of residues, monitoring of parameters (emissions, underground water and biogas), leachate collection and treatment (Figure 4.10.c.), and biogas collection. It is certified with ISO 9001 and ISO 14001, which include other environmental projects such as reforestation (Figure 4.10.b.) of the surrounding hills. It began flaring up the biogas in five chimneys (Figure 4.10.d.) and since 2007 has a CDM project burning up to 4500 m^3/hr of biogas containing 55% CH_4 and it expects to reach 6500 m^3/hr by the end of 2010.

a.

b.

c.

d.

Figure 4.10. Photos of the landfill Santa Marta, a. Landfill waste deposition, b. reforestation project, c. Leachate treatment plant, d. Biogas flaring towers

Landfill Santiago Poniente is run by the private company ProActiva Chile. It is located in Rinconada de Maipú to the southwest of the metropolitan region at 22km from the urban area and 1,5km from the closes population. It has an area of 66ha in a 326ha property, with projected closure in 2025. In 2008, it received approximately 36.400 metric ton/month of waste of the metropolitan region; serving 12 municipalities and particular clients with a reception of approximately 1.400 metric ton/day (SEREMI de Salud Región Metropolitana, 2009). It does not have a transference station.

The landfill follows construction standards, compression of residues, monitoring of parameters (emissions, underground water, leachate treatment plant and biogas), leachate collection and treatment, biogas collection and it is certified with ISO 9001 and 14001. It began flaring up the biogas in 2009, burning up to 2000 m^3/hr in two chimneys. It is planning to buy a new chimney to increase the biogas flaring. However, it does not have a CDM project yet.

4.4. PREVIOUS WASTE INTO ENERGY PROJECTS AND OTHER INITIAVES IN CHILE

As mention in section 2.1.3., there have been several projects around the world on energy generation from municipal solid waste. The energy generated from these projects is then used to supply homes with electricity through the grid or heat through district heating. In Chile, these initiatives have not reached such level of development, since Waste-to-Energy projects are considered in Chile a private enterprise; however, in this section, the most relevant initiatives will be described.

The private companies that administrate the landfills have found in the CDM and in energy generation a new source of income and are interested in taking advantage of them. Two of the three landfills located in the metropolitan area have CDM projects and are flaring up the biogas generated in their installations with this purpose. One of them, Lomas Los Colorados, is also producing electricity from the landfill gas.

Other initiatives in the metropolitan area include the WWTP La Farfana that is selling the biogas generated to the Metrogas Company. In December 2009, a pyrolysis and gasification project for the IV Region was introduced in the Environmental Impact Assessment System (SEIA) to produce 20MWe. Other initiatives include some research studies being done by the University of Conception, UDEC, in its Unit for Technological Development.

4.4.1. Loma Los Colorados Landfill and its energy generation project

The Project began as a CDM initiative in 2007 flaring up to 5000 m^3/hr of biogas which has increased to 7000 m^3/hr. In 2009, KDM decided to introduce two internal combustion motors WAUKECHA of eight cylinders, and 1MWe generation capacity each. The biogas goes into a process of humidity removal and biogas enrichment before being use for the engines. Each motor receives an approximate of 593m^3/hr of biogas and produces around 800kWh. The rest of the biogas is still flared. For this reason, KDM introduced a new project to expand the energy generation from 2MW to 14MW in 2010 and up to 28MW until 2024. This project has already been introduced in the Environmental Impact Assessment System, SEIA, and it will include an electricity generation central, a substation and a transmission line to supply energy for free clients or the Sistema Interconectado Central, SIC, energy system. The project is expected to generate 230.000MWh annually (SEIA, 2010).

4.4.2. Waste Water Treatment Plant: production and selling of biogas

Metrogas is the largest natural gas distributor in Chile. This company began research on other alternatives for gas supply way before the Argentina natural gas crisis; however, when the natural gas was abundant and relatively cheap, the alternative gas projects were left behind until there was a need for other sources of gas. In October 2008, Metrogas decided to use the biogas generated through anaerobic digestion in the waste water treatment plant of La Farfana, which by that time 80% was being flared and 20% was used in boilers (Chapple, 2009). The biogas has now an enrichment treatment and is sent through a 13,5km gas pipeline going to Metrogas "town gas" industry. La Farfana produces between 50.000m^3 to 60.000m^3 of biogas and processes 60% of the waste water from the metropolitan area (ElectroIndustria, 2010). The biogas produced in La Farfana has between 60-65% CH_4 and a high heating value of 24,30MJ/m^3; the enriched biogas has 95% CH_4 and it supplies 35.000 homes for cooking and heating (Metrogas, 2009). The project was introduced in the CDM projects proposal with the methodology NM 0262: Biogenic methane use as Town Gas Factory feedstock and methane emission reduction of flare efficiency, and it is waiting for approval.

Metrogas is interested in future biogas use projects from the other waste water treatment plant and the landfills located in the metropolitan area. This idea is not new, between 1985 and 1999 the biogas from controlled dumping sites was used to produce town gas and supply part of the population.

4.4.3. Pyrolysis of domestic and industrial solid waste by Pyrotech Chile

In December 2009, a minimization and cogeneration project for the treatment of domestic and industrial solid waste through the pyrolysis and gasification process with energy generation was introduced in the Environmental Impact Assessment System, SEIA, of Chile. The project is proposed to be developed in the IV Region, in Coquimbo and La Serena. It is expected to process 750 ton/day in 10 modules of 2MW each and produce 20MWe in a gas turbine (SEIA, 2010).

4.4.4. Researches done by the University of Conception

The bioenergy department for the Unit for Technological Development (UDT in Spanish) has developed several projects regarding the study of biofuels, enrichment and conditioning of biogas and biomethane, alternative uses such as transport fuel, pyrolysis reactor tests, gasification of solid waste, and many others (UDT, 2010):

- Creation of a domestic solid waste management strategy for the Biobío region based on the generation and use of biomethane as a natural gas substitute
- Obtainment of high value chemical products and liquid fuel through thermo-chemical conversion of biomass - BtFC
- Energy generation through gasification of solid waste in the Bio-Bio region
- Synthesis and application of ionic liquids for biogas purification.

- Biogenic methane as transport fuel
- Environmental management of the production and use of biogenic gases
- Generation and used of biogenic in Chile as a Natural Gas Substitute – SNG in Spanish.
- Technical-economical study for the production of Bio-ethylene from forest biomass in the VIII region
- Design and Construction of a three phases reactor for flash pyrolysis

Even though these studies and initiatives, the National Commission of Environment has not given importance to the use of MSW in the production of energy. The interest of CONAMA, as was stated in the interviews with representatives of this institution, is that:

> "… an adequate disposition of the municipal solid waste is done and that it complies with the legislation and norms; without relevance of the type of technology applied. The market and private companies have to comply with the environmental legislation and are evaluated through the Environmental Impact Assessment System, SEIA, and monitored and supervised".
>
> (Fernando Farías, personal communication)

Moreover, the Chilean government took a loan of 200 million dollars from the Interamerican Development Bank, BID, for the improvement of conditions of the waste management, closure of dumping sites and creation of landfills.

The National Commission of Energy, even though, it has shown interest in the analysis of other alternative renewable energy sources, doing studies of the Potential of biomass and the Potential of biogas; the latest focuses mostly on the production of biogas from landfills not the conversion of the MSW or its organic fraction with other alternative technologies. The calculations done in the Biogas Potential (CNE/GTZ, 2007) consider the amount of MSW generated in Chile and the potential biogas production when recovered from the landfills.

In conclusion, the energy generation based on municipal waste or its organic fraction has not been a relevant topic in the governmental institutions of Chile and poor considerations have had alternative technologies for the final treatment of municipal solid waste.

CHAPTER 5. RESULTS ANALYSIS AND INTERPRETATION

This chapter presents the results analysis and interpretation. It is divided in four main sections:

- The first section focuses on the availability of the waste for energy generation. It presents the analysis of the resources availability and their technical potential for energy generation based on the different existing technologies for energy generation and their characteristics.
- The second section focuses on the technologies analysis and the criteria or characteristics considered for their evaluation. It includes the results obtained through the GEMIS software and the environmental, technical and economic considerations for the technologies studied.
- The third section presents the results of the Multi-Criteria Decision Analysis Model NAIADE applied, including the ranking of the technologies obtained, analysis and discussion of the results.
- The fourth section presents some guidelines for integration of Waste-to-Energy technologies in the energy matrix. It presents the barriers identified during the analysis of the energy sector and waste sector, legislation and country's situation and proposes steps for overcoming this barriers and introducing it to the energy system.

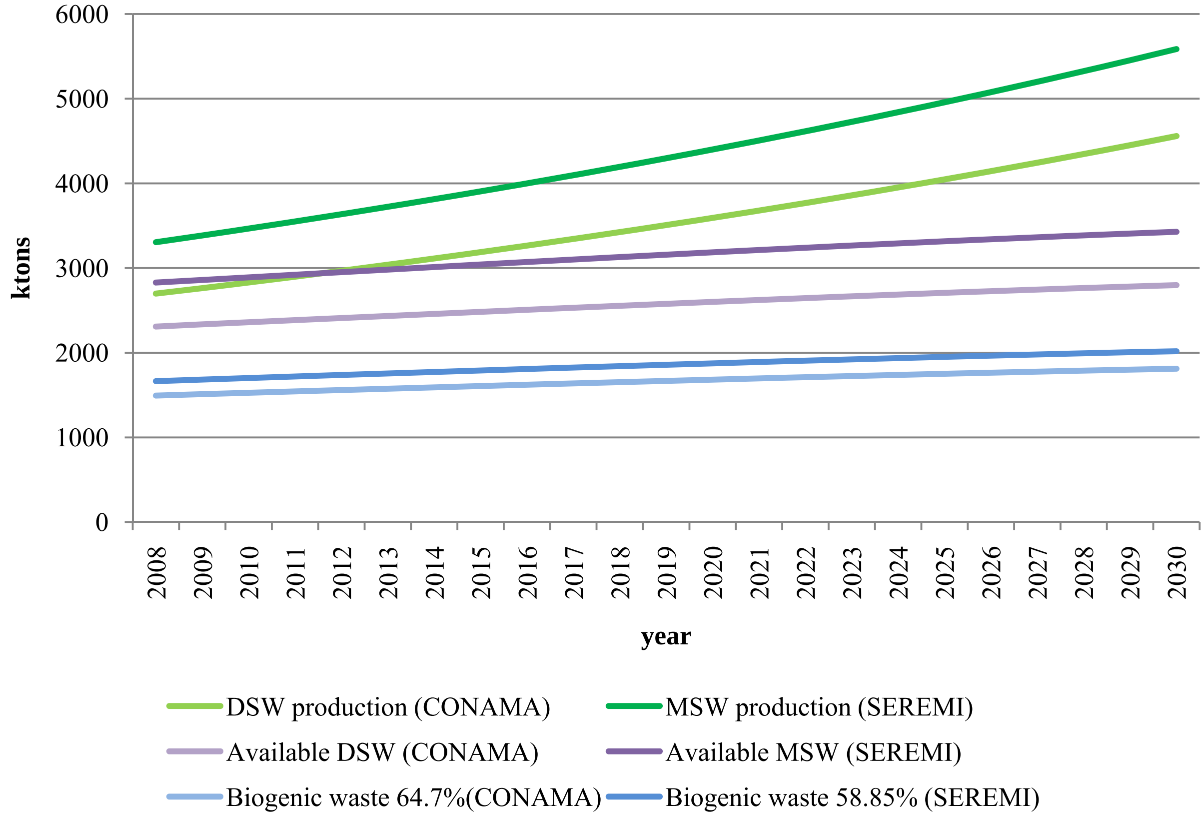
5.1. WASTE AVAILABILITY FOR ENERGY GENERATION

5.1.1. Biogenic waste and DSW available in the Metropolitan region of Santiago de Chile

The solid waste generated in the metropolitan region of Santiago de Chile is reported through different sources or local institutions. The SEREMI de Salud has reports from each landfill containing the monthly quantities of solid waste received. These reports do not detail the source of the solid waste; and they include not only the solid waste coming from households or commercial areas, but also the particular and industrial waste that can be assimilated. On the other hand, CONAMA has a MSW registry that keeps information on the domestic solid waste disposed in each landfill coming from the 52 municipalities in the metropolitan region. Consequently, 18.37% more waste is reported in SEREMI de Salud compared to CONAMA.

If both sources are used in the projections (Graphic 5.1), the per capita production increases in the calculations of SEREMI (1.34 kg/inhab/day) compared to CONAMA (1.10 kg/inhab/day) in the year 2008 and continues increasing at the same growth rate in the following years. On the other hand, the biogenic waste percentage is considered smaller in SEREMI data (58.85%) compared to CONAMA (64.7%). This is due to the fact that the biogenic waste percentage used for the SEREMI data is based on the commercial sector data provided by CONAMA and CUV (2006). When comparing the biogenic waste amounts, the SEREMI amount is 10.25% higher than the CONAMA amount.

It is important to mention that the study of CONAMA & CUV (2006) was based only on the commercial and residential sectors of the metropolitan region; hence, it does not include the industrial waste that is disposed in the landfills of the region. In the same way, the programs for increasing the recycling and composting percentage, which are also considered in this projection, are directed only to the domestic and commercial areas. Since the information gathered during this study is based on residential or domestic solid waste studies, the CONAMA calculations are used to keep the accuracy of the results.



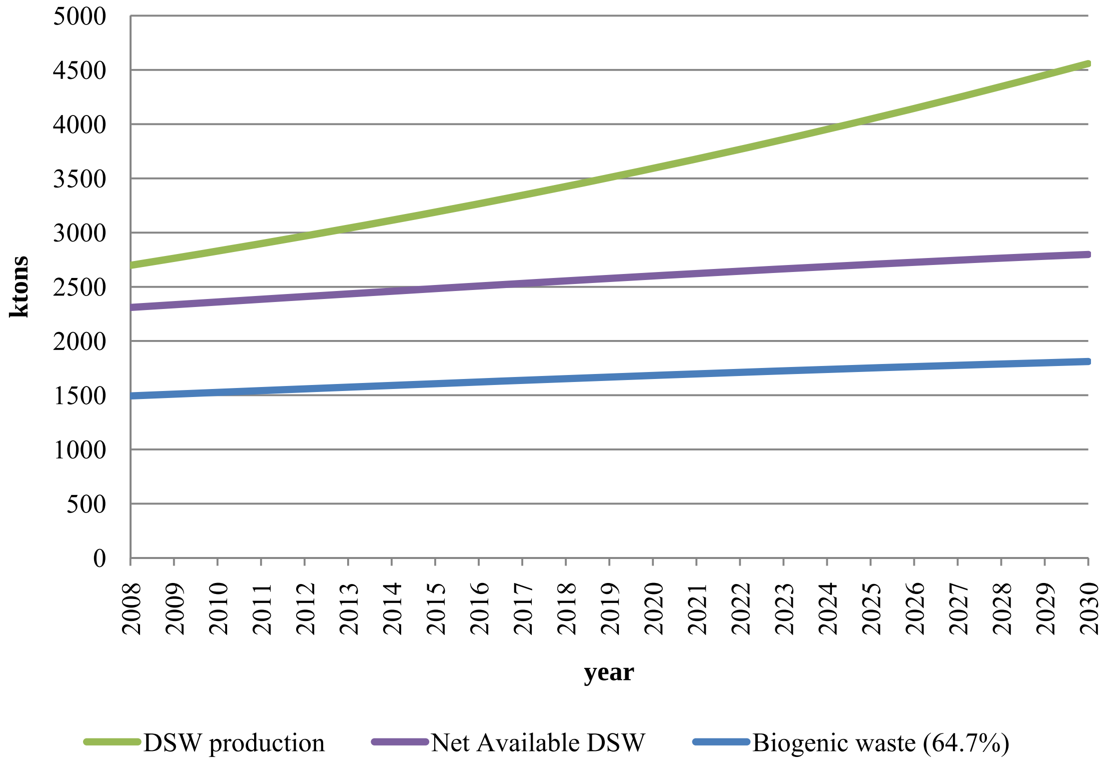
Graphic 5.1. Comparison between data from SEREMI de Salud (MSW) and CONAMA (DSW)

Based on the CONAMA projections (Graphic 5.2.), the resources availability was calculated considering the domestic waste production per capita and the number of inhabitants in the area of study.

The 2.697.976 tons of DSW production is provided based on the CONAMA registry of 2008 and the production per capita for 2008 was calculated based on that amount. The yearly increase in production per capita was calculated using a growth rate of 1,5%. The last census done in Chile was in 2002; for that reason, a population projection for the year 2008 was used and the projection for the following years was based on a yearly inter-census growth of 0,9%. The recycling and composting projection was based on the "Santiago Recicla" plan and a growth rate of 1,1% was calculated. Based on the Equation 3.4, an amount of Net Available DSW was calculated for each year from 2008 to 2030, details of the results and equations can be seen in Annex 8.4.

The Net Available DSW in 2008 represents 85,5% of the DSW production in the year 2008, and it is projected to decrease to 61,39% in 2030 due to the expected growth in recycling and composting. However, this will not affect the amount of Net Available DSW. The Graphic 5.2 shows that, in the following years, there will be a constant flow of more than 2,3 million tons of

Net Available DSW per year in the metropolitan area; which without altering or interfering with other uses, will be available to be disposed, treated or used for energy generation.



Graphic 5.2. Domestic Solid Waste projections based on CONAMA data.

Since the DSW includes the non-biogenic part as well as the biogenic part of the waste and this study focuses mainly on the biogenic part, a more detailed calculation was done to obtain the amount of biogenic waste available; considering a constant percentage of biogenic waste of 64,7 based on the study done by CONAMA & UCV (2006). The Graphic 5.2 also shows that there will be a constant flow of more than 1,5 million tons of biogenic waste per year, increasing from 1,49 million tons in 2008 to 1,81 million tons in 2030.

The results show that there is and there will be available sources of waste that could be used without affecting other projected practices or uses for these residues, such as recycling or composting.

5.1.2. Biogenic waste potential in the Metropolitan region of Santiago de Chile

Based on the Equation 3.4, the fuel output potential for the biogenic waste can be calculated based on the specific energy content and the amount of biogenic waste. The calculation is based on the year 2008 since it is the baseline year for the projections.

Since there is not a calculated heating value for the solid waste of the metropolitan area, several sources were reviewed.

Table 5.1. Different heating values assigned for MSW from several sources

	Heating Value		Moisture content %	Unit	Source
Latin America	5028	6285	N.A.	kJ/kg	OPS (Acurio, 1998)
USA	11732	16844	30,1	kJ/kg	OPS, (Acurio, 1998)/Ingeniería Ambiental & Medio Ambiente, 2000
Mexico		5800	50	kJ/kg	Yarto, 2006 (Mexico)
Provincia de Quillota, Valparaiso-Chile		13852	50,7	kJ/kg	Ingeniería Ambiental & Medio Ambiente, 2000
Comuna Santiago-Chile		7626	60	kJ/kg	Ingeniería Ambiental & Medio Ambiente, 2000
Argentina		16618	51,4	kJ/kg	Ingeniería Ambiental & Medio Ambiente, 2000
La Serena -Chile	10018	11011	59,7	kJ/kg	Ingeniería Alemana, 2010

Note: N.A. Not Available. *OPS, Organización Panamericana de la Salud –Panamerican Health Organization

As it can be seen in Table 5.1, the heating value calculated in La Serena by Ingeniería Alemana (2010) is within the developed countries range due to the laboratory method that was used to increase the results of the heating value measurements. Under this basis and considering that Chile is a transition country not a developed country, the values from La Serena, USA and Argentina may be too high for the Metropolitan region in view of the fact that the MSW of the Metropolitan region has a high percentage of organic matter and moisture. The heating value of Mexico, which is also a transition country, is within the OPS range for Latin American developing countries. The heating value reported for Comuna Santiago-Chile, surpasses for 21,3% the range for developing countries but it is secondary source and no details of its original sources or methods applied are given, therefore, they are considered uncertain. In view of this, it was considered for this study the OPS high heating value of 6285 kJ/kg for the DSW of the metropolitan area.

Using the heating value selected 6,285 GJ/ton and the biogenic waste amount from 2008, 1494,051 kton, it can be estimated a fuel input of 9.390.110,535 GJ. However, not all available potential can be used or transformed into energy due to losses in the processes and efficiency of the technology used for the energy conversion. In the following section, the estimations of energy generation are described for the alternative technologies.

5.2. TECHNOLOGIES APPRAISAL RESULTS

5.2.1. Technologies considered for WTE projects

The technologies considered in this study for WTE projects, their characteristics and considerations are described as follows:

- The landfill gas data used was based on *in situ* data available from the two landfills visited in the metropolitan region of Santiago and the values obtained in biogas composition, biogas recovery, and conversion factor for energy generation in these installations.

- The combustion technology worldwide implemented for energy generation from waste is the incineration. The parameters for the incineration technologies were extracted from a data overview of "Potentials and costs for renewable electricity generation" by Noord et al, 2004.

- The anaerobic digestion technology most commonly used is liquid state technologies or biodigesters, even though there is the solid state fermentation being applied for substrates with moisture content between 30% to 40% wt. Also the mesophilic biodigester is more common than the thermophilic biodigester and it has lower energy requirements, process less sensitive to ammonia and lower humidity in biogas. The parameters considered for mesophilic biodigesters considering typical biogas yield and electricity yield were extracted from data from SLR Holdings Limited by Yates (2008).

- The thermal gasification technology most common is the downdraft-fixed bed reactors, because it is simple , reliable and proven; however, it has a limited scale-up potential to about 500kg/h and a maximum feed moisture content of around 35% wet basis. On the other hand, the circulating fluidized bed gasifier is relatively easy to scale up to 100MWth or 25-50 MWe, it has good temperature control, greater tolerance to particle size range, technically proven and it has high market attractiveness. Hence, the circulating fluidized bed gasifier is the selected technology for this study. The parameters to calculate the energy potential were based on the study "Comparing Waste-to-Energy technologies by applying energy system analysis" by Munster and Lund (2009).

- Finally, the pyrolysis technology generates bio-oil, char and gas in different proportions in dependence on the process and the input source. Fast or flash pyrolysis is currently the most used pyrolysis; it generates approximately 60-75% liquid, 12-20% char and 13-20% gas products with heating values of 17-23MJ/kg, 30MJ/kg and 10-20 MJ/Nm^3 respectively. It accepts MSW feed moisture content between 15-40% (FAO, no date).

5.2.2. Technical potential for energy generation

The technical potential for energy generation is calculated considering the different technologies that are analyzed in this study. Each technology potential is calculated for one year of waste generation and their corresponding parameters and conversion factors.

The calculations were based on the year 2008 data, shown in Table 5.2, since it is the baseline of the data projections, and was taken from the CONAMA registry. It is considered that besides the recycling and composting percentage of the waste, the rest of the waste can be used for energy generation.

Table 5.2. Data calculations for 2008

Parameters	Alternatives				
	Landfill gas	Anaerobic Digestion	Incineration	Gasification	Pyrolysis
DSW [kton]	2697,976	2697,976	2697,976	2697,976	2697,976
X % available for energy production	85,590	85,590	85,590	85,590	85,590
Net amount of Available DSW [kton]	2309,198	2309,198	2309,198	2309,198	2309,198
X % biodegradable fraction	64,7	64,7	64,7	64,7	64,7
Biogenic waste available [kton]	1494,051	1494,051	1494,051	1494,051	1494,051

All technologies used the *biogenic waste available [kton]* data in Table 5.2 for the calculation of their energy generation; only the landfill gas energy potential was calculated with the *Net amount of available waste* data in Table 5.2.

The results are presented for each technology. Details of the conversion factor sources are included in Annex 8.5.

5.2.2.1. Landfill gas

The landfill is the activity being implemented in Chile for waste disposal. Since landfills generate biogas, the biogas is extracted and managed under the Decree 189/2008 of Landfills in Chile. As mention before, the three landfills have biogas wells and flaring towers, but only Loma Los Colorados generates electricity. There is a national study that calculates the global theoretical amount of landfill gas produced in Chile and another one calculates its projections. However, no specific details for the metropolitan area are given.

Table 5.3. Energy production of the landfill gas for the year 2008 data

Parameters	Values
Gas conversion[m3 biogas/ton DSW.]	60
Electricity generation conversion factor[m3/MWhe]	550
Landfill gas recovery [%]	50
Fuel input [m3 biogas]	69.275.929,75
Power [MWh]	125.956,236
GJ output [GJ] energy	453442.4493
Production[GWh]	125,956

It is estimated that 125,956 GWh per year could be generated taking into consideration that maximum 50% of the landfill gas generated can be recovered, that 60 m^3 of biogas can be generated from one ton of DSW based on the "Biogas potential" study done in Chile. The electricity generation conversion factor of 550 m^3 of biogas per MWh generated was based on the actual electricity generation data from Loma Los Colorados landfill, with a biogas composition of 48% CH_4, 37% CO_2 and 1.8% O_2.

If compared with the results from the "Biogas potential" study 371.707 MWh per year of electricity generation in Chile, and being that the metropolitan area produces approximately 60% of all the waste generated in the country and from this only 85% is disposed in landfills; it can be said that the results from this study are within range and variations are present due to the different conversion factors that can be used for these calculations depending on the source used.

5.2.2.2. Anaerobic Digestion

This technology is based on the use of biodigesters and designed for the recovery of the total amount of biogas generated in the process. The biogas conversion is considered $100m^3$ of biogas per ton of organic matter and 0,61MWh of energy generated per ton of organic matter.

Table 5.4. Energy production of the landfill gas for the year 2008 data

Parameters	Values
Gas conversion[m3 biogas/ton M.O.]	100
Electricity generation [MWh/ton]	0,61
Fuel input [m3]	149.405.088,5
Fuel energy content [MJ/m3]	18,855
Power [MWhe]	911371,040
GJ output [GJ] energy	3280935,74
Production[GWh]	911,371

The results show that 911,371 GWh per year could be generated with the biogas from biodigesters. This is 7,24 times more than the energy production with the landfill gas recovery and transformation.

5.2.2.3. Incineration

This technology requires the heating value of the solid waste to be burned; hence, the heating value selected in section 5.1.2 is also used here. Based on this data, the results from the energy production calculations of the incineration technology are presented as follows:

Table 5.5. Energy production of the incineration technology for the year 2008 data

Parameters	Values
Specific energy content LHV [GJ/ton]	6,285
Fuel input [GJ]	9.390.109,80
Efficiency	0,565
GJ output [GJ] energy	5.305.412,04
Production [GWh]	1.473,73

The fuel input is the same as in the available potential calculated for biogenic waste. However, the result of the energy output is lower due to the efficiency of the technology, which considers energy losses and energy consumed in the conversion process. In this case, the efficiency factor includes Combined Heat and Power; hence it increased from 0,195 (without CHP) to 0,565. The energy production with the incineration is 11,7 times higher than with landfill gas and 1,62 times higher than with biodigesters.

5.2.2.4. Gasification

Even though the gasification process is not new, the gasification technologies are technologies in research and development. There are few studies provided with details of the technologies efficiencies and factors.

Table 5.6. Energy production of the gasifier technology for the year 2008 data

Parameters	**Values**
Specific energy content LHV [GJ/ton]	6,285
Fuel input [GJ]	9.390.109,812
Conversion efficiency	0,778
GJ output [GJ] syngas	7.305.505,434
Electricity efficiency	0,47
GJ output [GJ] energy	3.433.587,554
Production [GWh]	953,774

This technology is based on the production of syngas from the gasification process and its use for energy generation. The conversion efficiency is related to the production of the syngas and the electricity efficiency to the generation of electricity. In these processes there are many losses and the final energy production is 953,774 GWh per year; which is lower than the energy production from the incineration technology.

5.2.2.5. Pyrolysis

As mention before, pyrolysis generates three different products char, bio-oil and gas in dependence of the temperature ranges, process and input added. This characteristic, even though it is considered its main advantage, makes it difficult to calculate its energy generation in a theoretical basis.

Considering that flash pyrolysis is the process selected for this study and that it generates approximately 60-75% bio-oil, 12-20% char and 13-20% gas with heating values of 17-23MJ/kg, 30MJ/kg and 10-20 MJ/Nm^3 respectively; these values are used for the calculation of energy production, considering the lowest heating value in the range and an average percentage production of bio-oil, char and gas with a 100% conversion efficiency from the biogenic waste used as input. Each fuel input calculated for bio-oil, char and gas are then added considering an energy conversion efficiency of 22%, as shown in Table 5.7.

Table 5.7. Energy production of the flash pyrolysis technology for the year 2008 data

Parameters	**Values**
bio-oil %	67,5
Specific energy content [GJ/ton] bio-oil	17
Fuel input [GJ] bio-oil	17.144.233,91
char %	16
Specific energy content [GJ/ton] char	30
Fuel input [GJ] char	7.171.444,248
gas %	16.5
Specific energy content [GJ/ton] gas	10
Fuel input [GJ] gas	2.465.183,96
Electricity efficiency	0.22
GJ output [GJ] total	5.891.789,66
Production [GWh]	1636,61

The results in Table 5.7 show that even though pyrolysis has low electricity efficiency compared to the other technologies; under the conditions stated, it has a energy production 1,11 times higher than the incineration process, which makes it the higher energy production technology studied with 1636,61 GWh per year. However, it is important to consider that in this calculation, the three products from pyrolysis were considered for the energy production. If only the bio-oil produced would have been considered, the energy production would have been 1047,70 GWh; making this technology the number two in production, after incineration.

Considering the estimated gross energy consumption per capita in Chile of 3.327 kWh/year (CNE, 2008), it can be said that: for the lowest energy production estimated for landfill gas, 125,956 GWh per year, this energy could supply around 37.859 inhabitants; for the highest energy production estimated for pyrolysis, 1636,61 GWh per year, this energy could supply 491.917 inhabitants which represented 7.29% of the population of the Metropolitan Region in 2008.

5.2.3. Environmental aspects of the technologies

When considering the potential of energy generation and its technological alternatives, it is also necessary to consider the environmental aspects of each of these technologies; the technical potential for energy production is only one component within the evaluation and selection of the most appropriate technology for an energy project. Environmental and socio-economic aspects also need to be analyzed if considering a MCDA with a sustainable development focus.

As mention in section 2.2.3, the Waste-to-Energy technologies have mainly two environmental aspects: pollutants emissions and waste generation. Consequently, this study analyzes these two main environmental aspects based on the GEMIS software and the methodology proposed for this section.

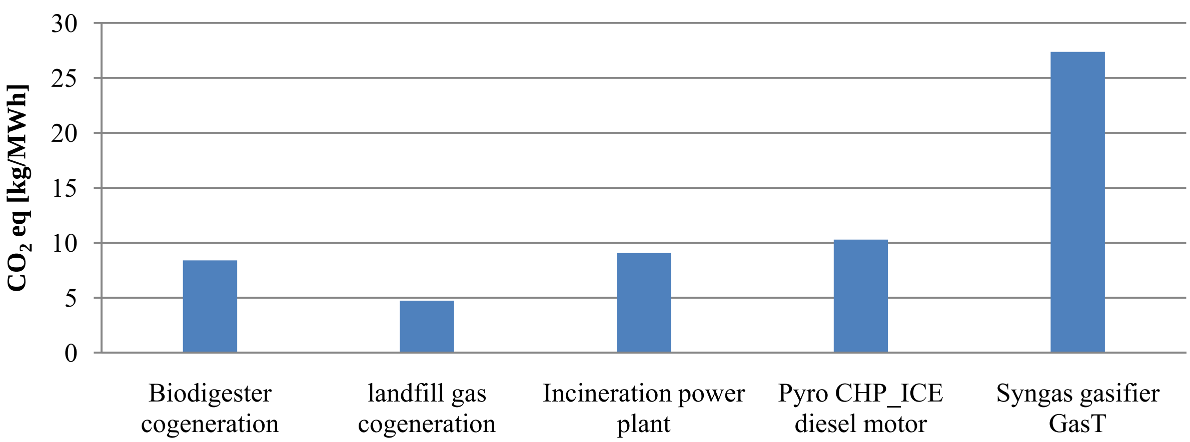
Specifically, this section analyzes pollutants emitted in the form of particulates, flue gas, greenhouse gases, H_2S, N_2 and trace amounts of heavy metals and hydrocarbons; as well as solid waste generated in the form of dust, ashes, fertilizer, char particles and liquid waste. Nonetheless, it is important to mention that some of the waste generated has alternative uses like the fertilizer for agriculture; and tars and char have high heating values which make them potential sources of energy.

Based on the scenario created in GEMIS for this study, the following results were obtained:

The GHG emissions are presented as CO_2 equivalents, including CH_4, N_2O and CO_2 emissions for each technology. The results, as can be seen in graphic 5.3, show that the gasification technology has a higher CO_2eq emissions compared to the other technologies; representing 27,38 kg CO_2eq/MWh, from which 68,29% corresponds to CO_2 emissions.

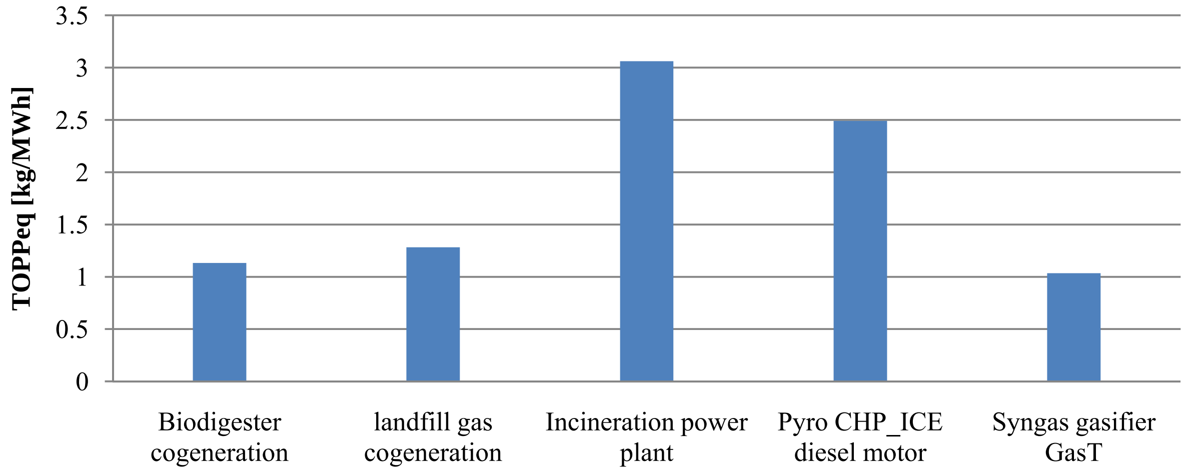
Evidently, the gasification technology is designed to transform waste into Syngas; therefore, high concentrations of gases are expected to be generated using this technology. When the Syngas is burned, a common combustion process takes place, which means that heat is released and gases such as CO_2 and CO are emitted. The results shown in graphic 5.3 do not represent the CO_2 generated in the conversion process of waste to Syngas, nor the CH_4 generated in the anaerobic digestion processes; it shows the emissions when electricity is generated.

It is also relevant to consider that the gases generated in these technologies have different heating values, biogas from a biodigester has a low heating value of approximately 23 MJ/m^3 and Syngas from a gasifier has a heating value in the range of 10-12 MJ/m^3. This means that to produce the same amount of energy, it is required more Syngas than biogas; consequently having more emissions the gasification technology than the biodigester technology. This is considering equal efficiencies.



Graphic 5.3. Calculated greenhouse gases emissions per MWh energy generation for each technology

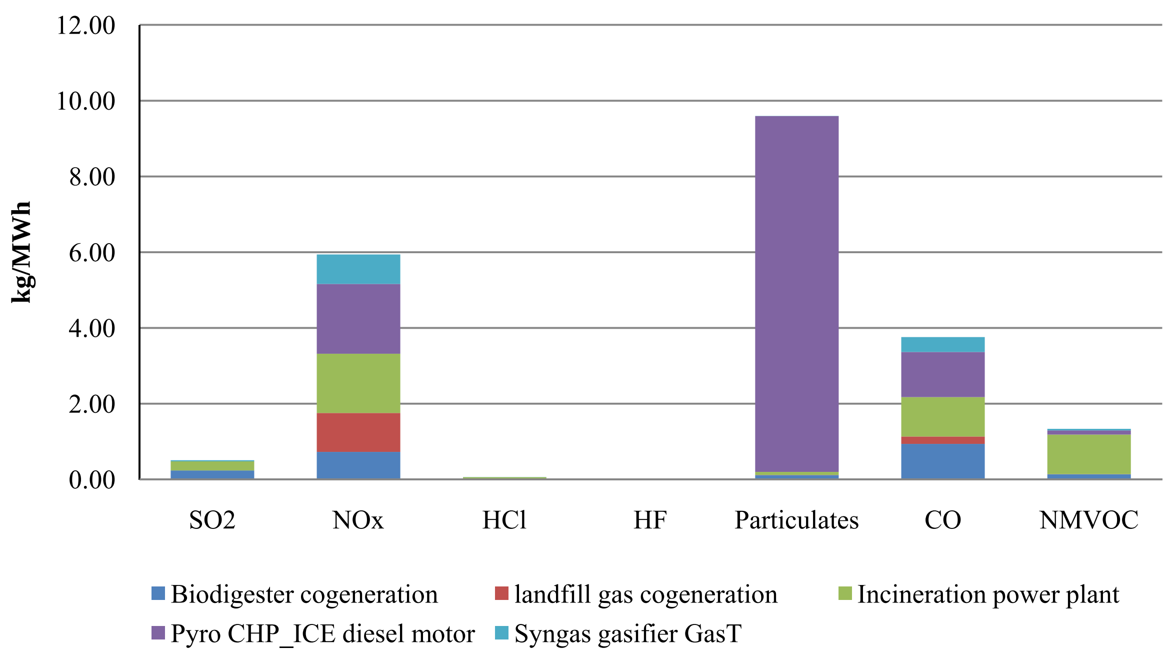
When compared under the Tropospheric Ozone Precursor Potential or TOPPeq which includes CO, NO_x, NMVOC, and CH_4 emissions; it can be seen that the incineration technology generates 3,06 kg/MWh, two times more TOPPeq than landfills; but similar to the pyrolysis technology which uses a diesel motor for energy generation and this increases its TOPPeq emissions. The gasification technology, on the contrary shows the lowest values of emissions.



Graphic 5.4. Calculated TOPP emissions per MWh energy generation for each technology

When analyzing the whole pollutants depicted in graphic 5.5, it can be seen that the incineration technology has higher contributions in four of the seven pollutants represented: SO_2, HCl, HF, and NMVOC; and the pyrolysis technology has the highest contributions on the other three pollutants: NO_x, Particulates and CO. However, NO_x and CO emissions of incineration are closed in range to the ones from pyrolysis, which is not the same case for SO_2, HCl, HF, and NMVOC emissions between both technologies. This explains why the incineration technology has the highest TOPPeq emissions.

If comparing in detail the pollutants in Graphic 5.5, the pyrolysis technology has the highest contribution in the particulate emissions 9,39 kg/MWh, representing the 97,8% of particulates emitted compared with other technologies.



Graphic 5.5. Contributions of emissions per technology in kg/MWh of energy generation

Other pollutants such as H_2S, NH_3, arsenic, cadmium, chrome, nickel, PAH and PCDD/F considered in this scenario are emitted by the pyrolysis and gasification technologies. The highest emission results belong to the gasification process and its highest emission among these pollutants are from H_2S with 0,00078 kg/MWh or 0,75 ton/year and from $NH_3$0,00026 kg/MWh or 0,25 ton/year. The other pollutants are emitted in lower amounts in the order of magnitude 10^{-6} to 10^{-18}, the values can be seen in Annex 8.6.

In order to have a wider view of the emissions from each technology, the emissions values for CO_2eq and TOPPeq are calculated based on energy production within a year using the results of production presented in section 5.2.2 of this chapter.

Table 5.7. TOPPeq and CO_2eq emissions calculated based on GWh production of each technology per year

	TOPPeq [kg/MWh]	TOPPeq [ton/TJ]	TOPPeq [ton/year]	CO_2eq [kg/MWh]	CO_2eq [ton/TJ]	CO_2eq [ton/year]
Biodigester cogeneration	1,13	0,31	1031,87	8,40	2,33	7653,33
landfill gas cogeneration	1,28	0,36	161,56	4,73	1,31	596,19
Incineration power plant	3,06	0,85	4512,37	9,06	2,52	13349,75
Pyro CHP_ICE diesel motor	2.49	0,69	4077,55	10,29	2,86	16842,77
Syngas gasifier GasT	1,03	0,29	987,12	27,38	7,60	26112,38

Even thought the results (Table 5.7) per year show high amounts of emissions, if compared with the CO_2eq emissions, based on UNFCCC (2006), of fossil fuels such as coal (92,708 ton CO_2eq/TJ), diesel (73,326 ton CO_2eq/TJ) and natural gas (55,829 ton CO_2eq/TJ); it can be seeing that the highest CO_2eq emission calculated in the five alternatives (7,6 ton CO_2eq/TJ) is 7,35 times lower than that of natural gas. Moreover, if the emissions of the five alternatives are compared with the emissions of landfills without capture or use of the biogas (1,9 CO_2eq ton/ ton MSW)based on Elias (2003); it can be seeing that the highest emission (0,0175 CO_2eq ton/ ton Biogenic waste) of the five technologies is 108 times lower.

The air pollutants, mainly tropospheric ozone, are great cause of concern to the Metropolitan Region since this area has reported in past years high concentration levels of air pollutants and in 2000 was declared saturated zone for particulate matter (PTS), PM10, CO and ozone, and latent for NO_x. Even though, previous studies showed that the main cause of these high emissions was the transport sector; initiatives were implemented to reduce ozone precursors, particulate matter, NO_x and SO_x in all sectors: commercial, industrial, transports, construction and residential. Therefore, great concern has to be paid when evaluating technologies that could generate TOPP and GHG emissions. Information on the sources and effects of the air pollutants in the Metropolitan Region can be found in Annex 8.7.

Regarding solid waste generation from the production of electricity with each technology; the results obtained in the GEMIS scenario show that the anaerobic digestion technology has 99,9% higher waste production, which is equal to 95,68 kg/MWh, than the other technologies. This waste is the biofertilizer that is really a by-product of the process and can be used in agriculture when confirmed innocuous.

The incineration technology generates the highest quantity of ashes, 541,77 kg of ashes per MWh generated, representing 98,98% more than the other technologies. The gasification technology generates 3,20 kg/MWh of ashes and 14,51 kg/MWh of overburden. Contrary to alternative used of the solid waste generated by the anaerobic digestion technology, the ashes generated in the incineration process do not have an alternative use and they must be disposed in an environmentally safety way, for example in landfills. However, the ashes represent only 10% volume of the initial biogenic waste volume, hence the space required for landfilling ashes compared with the size required for MSW landfilling is reduced by 90%.

5.2.4. Socio-economical aspects of the technologies

The last aspects to be considered are the socio-economical aspects of the technologies. This section intends to provide a general overview of the economical aspects of these technologies, such as the energy and green values obtained when using these technologies instead of the fossil fuel alternatives in the study area.

5.2.4.1. Energy value

When considering the energy value of an energy generation alternative, it is necessary to consider its source of energy. In this case, the biogenic part of MSW is the source of energy and since it is considered a waste, it is not sold by the municipalities; on the contrary, the municipalities pay for its disposal. Moreover, the payment for the disposal of the waste covers collection and transport of the waste to its final destination. Therefore, it is a free source of energy which is already generating revenues before being converted in energy.

Considering that the final disposal of the biogenic waste in Chile is, in most cases, landfills with flaring of biogas; generation of energy based on this source represents increased revenues for the waste-disposal companies.

The supply of this source was already projected in this study and established that there is a constant supply of biogenic waste of more than 1,5 million tons per year projected until the 2030 year. It is important to mention that waste is also a local source of energy that does not depends on import, it is not affected by climate alterations and there is no shortage of supply since as long as there is a population there is always generation of waste. This means that waste is an indigenous source of energy and therefore can contribute to the national energy security. In addition, it is not sensible to cost variations in the fossil fuels international market.

This signifies that the country could reduce its imports of fossil fuels for energy generation, based on the amount of energy generated in WTE plants; which can contribute to the national economy and the savings could be assigned to social or environmental projects. This savings which are also called 'avoided cost of fossil fuels' were estimated considering the energy production of each technology (section 5.2.2), and the cost and average specific consumption of the three fossil fuels used for energy generation in the SIC energy system in the year 2008: natural gas, coal and diesel.

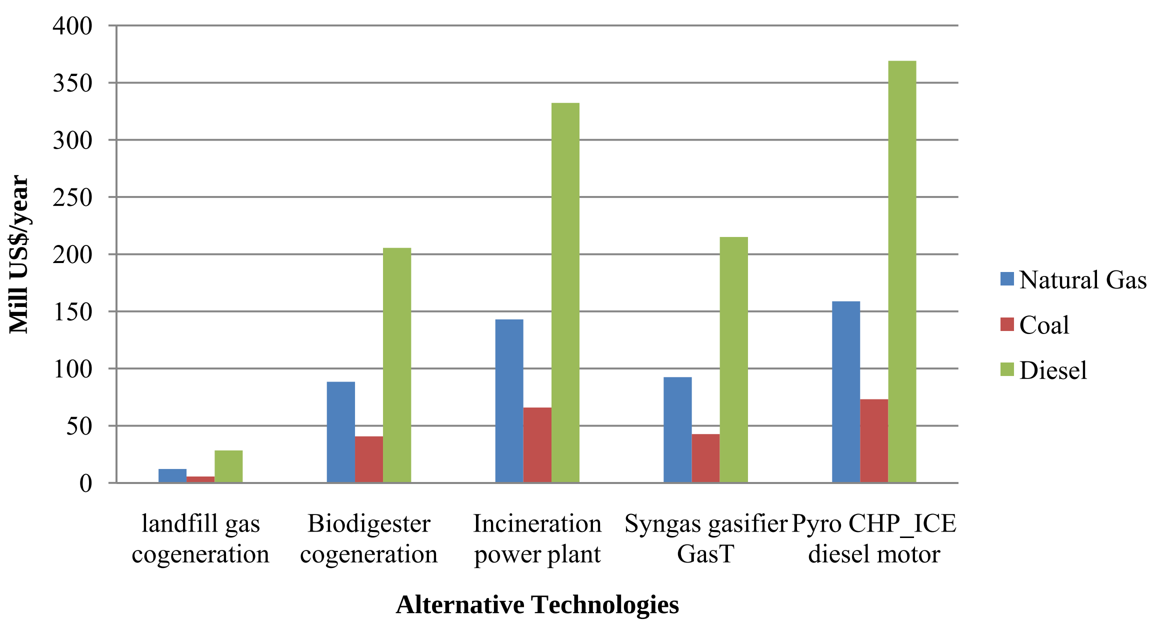
Table 5.8. Cost of electricity generation considering the fossil fuel source in the SIC energy system for the year 2008

Fossil Fuel Imported	Imports*			Cost of electricity generation per source	
	Amount [Units]	Costs [US$/Unit]	Total CIF cost [US$/year]	Average specific consumption [Unit/MWh]**	Electricity cost [US$/MWh]
Natural Gas (mill m^3)	1116,7	403,84	4,50962E+11	0,24	97,02
Coal (ton)	6.024.496,38	116,10	699466431,7	0,39	44,72
Diesel (m^3)	6.005.654,69	847,87	5.092.035.431	0,27	225,51

Source: *CNE, 2010 **CNE, 2008

The results, in Table 5.8, show that diesel is the fossil fuel with the highest electricity cost per kWh, followed by natural gas and coal. However, there are 28 power plants of diesel, 12 of coal and only three of natural gas considered in the technical report of the SIC energy system (CNE, 2008). As mention before, biogenic waste is not bought like fossil fuels; hence, its electricity cost based only in the source is cero (Table 5.9).

The substitution of any of the three fossil fuels for waste as energy source would mean an 'avoided cost' in proportion to the fossil fuel substituted and the amount of energy produced of the technology. Since each technology had different results in energy production, the highest 'avoided cost' estimated in 369.067.169,2 US$/year, corresponds to the substitution of diesel power plants for pyrolysis power plants; the lowest 'avoided cost' estimated in 5.632.540,04 US$/year, corresponds to the substitution of coal power plants for landfill gas energy generation (Graphic 5.6).



Graphic 5.6. 'Avoided cost' of electricity generation based on alternative technologies and fossil fuel costs

The potential 'avoided cost' of the WTE technologies contributes to the national economy and makes attractive the implementation of the technologies but from a country point of view. However, these savings do not represent benefits for the investors of the technologies and they have to consider other economic aspects when deciding the implementation of a WTE project and their own benefits.

The values are estimated for the year 2008 because is the base year for the energy production of each technology; therefore, is the year use for any comparison. However, it is important to mention that if analyzed the potential 'avoided cost' for the year 2010; it is necessary to consider that the price per unit for the three fossil fuels have changed, increasing for natural gas to 463,80 and decreasing to 93,60 and 456,90 respectively. This means that the electricity cost for 2010 is 111,4 US$/MWh for natural gas, 36,05 US$/MWh for coal and 121,52 US$/MWh for diesel. In the same way, the potential 'avoided cost' for the year 2010 is less than the calculated for the year 2008. In order to do the estimations for the year 2010, the energy production of each technology should be calculated for that year and the amount of biogenic waste of 2010 should substitute the value of 2008 in Table 5.9.

5.2.4.1. Green value

The green value of the energy generation alternatives is the reduction emission obtained with the implementation of the project; based on the baseline emissions before the introduction of the project or when cleaner technologies replace fossil fuels based technologies. The reduction emissions can be introduced into the Clean Development Mechanisms since Chile belongs to the Part No Annex 1 countries, has already ratified the Kyoto Protocol and in 2007 there were in Chile already 37 projects under the CDM scheme; two of these CDM projects are Loma Los Colorados landfill and Santa Marta landfill, two of the three existing landfills in the Metropolitan Region. This means that Chile is not new to the CDM implementation and has the organizational structure for the development of CDM projects within the country.

Moreover, Chile has implemented different funding systems to support energy, technologies, and environmental areas, including CDM projects, the program Todo Chile gives subsides and co-finances pre-inversion studies and specialized consulting for renewable energies projects and those eligible for CDM. Other funds are Fondo de Asistencia Técnica (FAT) and Fondo de Desarrollo e Innovación (FDI) that could be used to finance part of the studies.

The emissions reduction are quantified based on approved methodologies which can be developed and proposed to the CDM executive board or the already approved methodologies can be used. The analysis and evaluation is made for each project submitted and Certified Emissions Reductions or CER are emitted which can then be transacted in the Carbon Market. Consequently, this study will not give a detailed emissions reduction based on the CDM for each technology; but it will focus on the emissions reduction potential and the technologies possibilities to be included in the CDM.

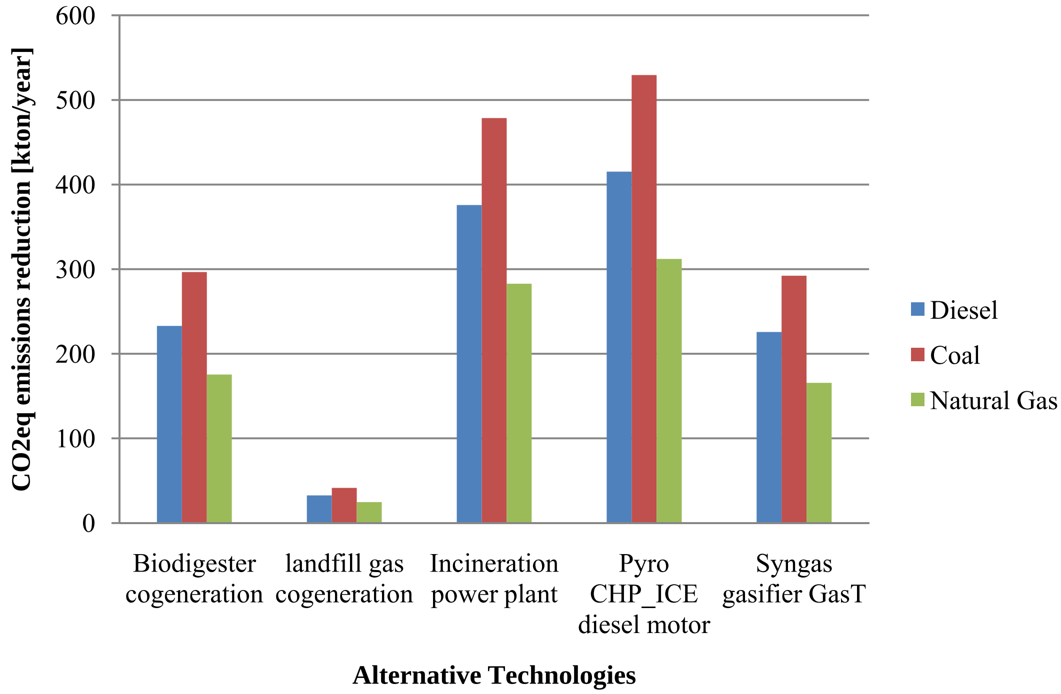
In a reviewed of the approved methodologies for CDM projects, there is a an approved baseline and monitoring methodology AM0025 "Avoided emissions from organic waste through alternative waste treatment processes" can be applied for projects on (1) anaerobic digestion with biogas collection and flaring or use it, (2) gasification to produce syngas and its use, (3) incineration of fresh organic waste for energy generation, electricity and/or heat; meaning that all technologies with the exception of pyrolysis can be considered for CDM projects. The pyrolysis technology is not considered since it is a technology still in the research and development state and has not been submitted for CDM nor had been its emissions evaluated. In reference to the capturing and flaring of methane from landfills, this methodology does not apply, but there exist other methodologies used for landfills.

In general, the AM0025 methodology addresses:

> "…project activities where fresh waste (i.e. the organic matter present in new domestic, and commercial waste/municipal solid waste), originally intended for landfilling, is treated either through one or a combination of the following process: composting, gasification, anaerobic digestion, RDF processing/thermal treatment without incineration, and incineration. The project activity avoids methane emissions by diverting organic waste from disposal at a landfill, where methane emissions are caused by anaerobic processes, and by displacing electricity/ thermal energy through the utilization of biogas, syngas captured, RDF/stabilized biomass produced from the waste, combustion heat generated in the incineration process. By treating the fresh waste through alternative treatment options these methane emissions are avoided from the landfill. The GHGs involved in the baseline and project activities are CO_2, CH_4 and N_2O."

Considering this, the reduction emission for the alternatives technologies can be estimated not only on the baseline emissions without the project but also considering the reduction emission for fossil fuel substitution. As it was stated in section 5.2.3, the emissions of any of the five alternative technologies considered are lower than the fossil fuel with lowest emissions. This means that the change from a fossil fuels based technology to a WTE technology would signify a reduction of emissions in energy generation.

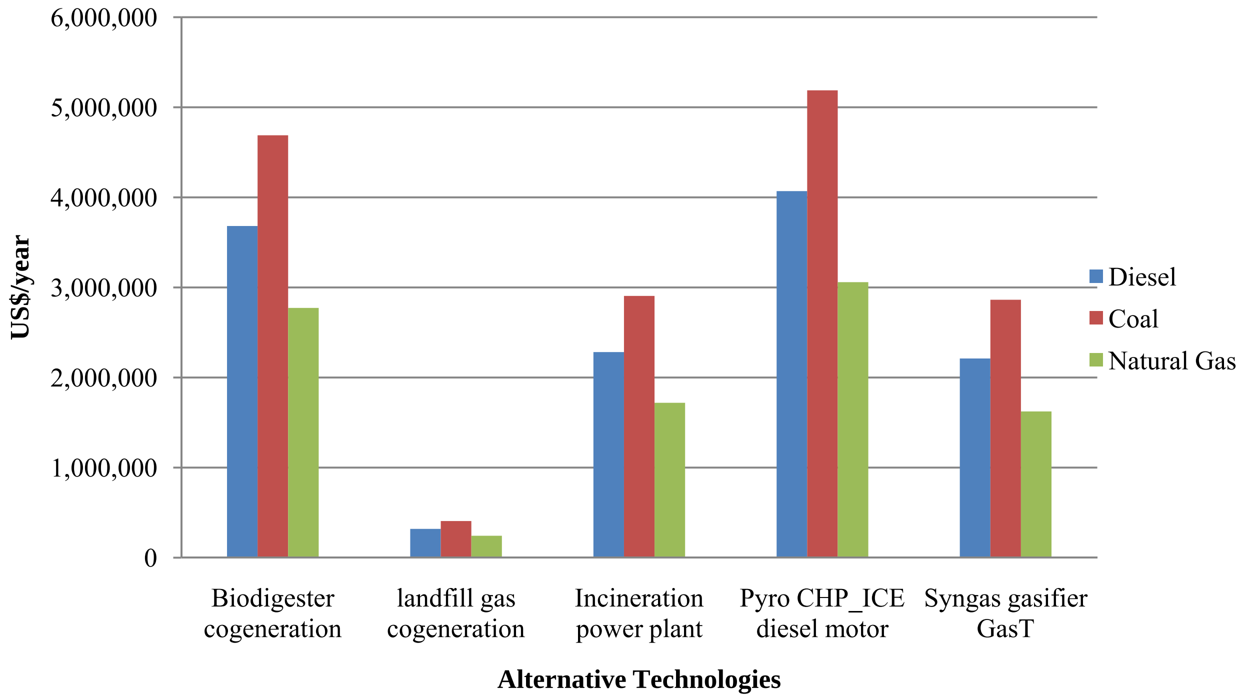
In general, emission reductions based on fossil fuels would depend on the fossil fuel selected for the reduction, which it has to be explained in the CDM project. In this study, three fossil fuels are compared and the results of potential reduction emissions of each alternative technology are included in Graphic 5.7. Coal, being the one with higher CO_2eq emissions 92,708 ton CO_2eq/TJ, is of course the one with higher reduction emissions if any of the alternative technologies substitute it in energy production. The lowest potential reduction emission is the use of landfill gas for energy production, the 'business as usual' alternative offers the less reduction emissions compared to natural gas, coal and diesel used in energy production.



Graphic 5.7. Emissions reduction of electricity generation based on alternative technologies substituting fossil fuels

If these results are transformed into CER equal to one ton of CO_2eq and considered its economic value for 2008 of 14 Euro or US$ 9,8 per CER; it can be calculated a roughly estimate.

The Graphic 5.8 shows that the highest CER revenue could be obtained with pyrolysis technology if introduced in the CDM. Even though it is the second higher emitter of CO_2eq from the five alternatives, as shown in results in Table 5.7, it is also the highest energy producer, which makes it the technology with highest emission reduction when compared to fossil fuel technologies. However, as explained before, the technology is still in a research and development stage and has not been considered in CDM methodologies. The second technology that could generate high revenues if introduced in the CDM is the incineration technology, also because it is the second energy producer.



Graphic 5.8. Potential economic value of reduction emission based on substitute technology considering lowest CER value of 2008

5.3. MULTI-CRITERIA DECISION ANALYSIS: TECHNOLOGY SELECTION

5.3.1. Description and evaluation of criteria

As explained in section 3.3.1, the selection of the criteria was based first on three main focuses: technological, environmental and socio-economical. The literature reviewed and interviews provided the basis for the selection of each criterion and based on the availability of data.

For the evaluation of the technologies the following technological criteria was selected considered:

1. The efficiency of energy conversion of the technology that was used to calculate the energy production for each technology. The cogeneration efficiency was used in order to increase energy generation and reduce losses in the conversion processes.
2. The requirements of pre-treatment for the input, in this case for the waste used.
3. The pre-treatment required for the use of the fuel generated.
4. The availability of the technology to be purchased or introduced into the country.
5. The technical maturity of the technology.

The efficiency of the conversion process into energy was selected since it is a relevant factor when considering energy generation, a good technology intends to be more efficient, generate more energy from the same amount of input than the other technologies.

The availability of each technology was considered because some of the technologies evaluated are still in the development process and have not reached commercial status; therefore, it needs to be considered for investors interests.

The technical maturity is also relevant when intended to introduce a technology into the market, since the most technical maturity a technology has, it is more secure the investment on it.

The pre-treatment of inputs was selected considering that most of the technologies require some kind of pre-treatment of the input (waste) used in the process; this could increase the cost of production and also increase the energy demand of the process. However, viewed from a social impact aspect, it could mean the employment of more people for the pre-treatment process.

The pre-treatment required for the fuel generated was selected since most technologies studied generate first an output or product that is used for energy generation, with exception of the incineration that generates heat and does not require a pre-treatment to be used for energy generation.

The energy production, estimated for each technology in section 5.2.2, was not considered in the technological criteria since it was introduced into the matrix in the form of 'avoided cost of primary energy'. The values of energy production were used to calculate the 'avoided cost' of producing energy from waste instead of fossil fuels; therefore, it was considered that introducing both values into the matrix would influence the results being that both would be dependable variables.

In the case of the environmental criteria, the negative environmental impacts as well as the positive environmental impacts were considered; both of them estimated and explained in section 5.2.3 of this study. The following criteria were evaluated:

1. Emissions of CO_2eq per MWh of energy generated
2. Emissions of TOPPeq per MWh of energy generated
3. Other emission consisting in H_2S, NH_3, As, Cd and Cr
4. The possibility of the technology to be introduced into the Clean Development Mechanisms
5. The CO_2eq savings from the fossil fuels substitution
6. The solid waste output of each technology

In the case of the socio-economic criteria, little data is provided in the literature when analyzing the WTE technologies; therefore, there is not data available on social aspects such as job creation on all five technologies been evaluated. This is because the gasification and pyrolysis technologies are in pilot or research stages and their studies have centered in technological and environmental aspects, which usually are of greater concern than the social aspects in those stages. On the case of the economic criteria, these were evaluated based on the energy value and the green value calculated in the section 5.2.4. Nevertheless, the Certified Emission Reductions was not included in the criteria, since it was calculated based on the CO_2eq savings; and as explained before, dependable variables were not introduced in the matrix. As a result the following criteria were selected for the socio-economic criteria:

1. Avoided cost of producing energy from waste instead of fossil fuels

2. Cost of technology per ton processed
3. Land requirement

The cost of technology and land requirements data were taken from a factsheet compilation of existing MSW technologies provided by CNE (2001). The fact that this information was gathered and provided by the National Commission of Energy of Chile, make it commendable to be considered in the study.

Table 5.9. Criteria characterization

Criteria	**Unit**	**Score type**	**Optimization of criteria**
Efficiency	%	Quantitative	Maximize
Availability	1. Commercial 2. Some commercial 3. Pilot	Qualitative	Maximize
Pre-treatment of input required	1. Separation, drying and griding 2. Separation and griding 3. None	Qualitative	Maximize
Pre-treatment for energy generation required	1. Cleaning and separation 2. Cleaning 3. Upgrading 4. None	Qualitative	Maximize
Technical maturity	1. Research 2. Testing 3. Not perfected 4. Proven	Qualitative	Maximize
CO2eq	kg/MW	Quantitative	Minimize
TOPPeq	kg/MWh	Quantitative	Minimize
Other emissions: H2S, NH3, As, Cd, Cr	Yes/No	Qualitative	Minimize
Solid waste output	kg/ton	Quantitative	Minimize
CDM possibility	Yes/Potential/No	Qualitative	Maximize
CO_2 savings for fossil fuels substitution	kton/year	Quantitative	Maximize
Land requirements per 1000 ton/day	Ha	Quantitative	Minimize
Cost of technology	USD $/ton	Quantitative	Minimize
'Avoided cost' primary energy	USD/year	Quantitative	Maximize

Note: In the NAIADE software, for availability, pretreatment of input, pre-treatment for energy generation and technical maturity, the numbers were assigned linguistic values, as follows: 4. Good; 3. More or less good; 2. Moderate; 1. More or less bad.

In the end, 14 criterions were selected to evaluate the five technologies (Table 5.9.); being the socio-economic criteria less than the technological and environmental criteria. This could create some weighting imbalance in the evaluation; however, in real life not every time the criteria used to evaluate projects is balanced and the NAIADE model is designed to work with real life situations. Moreover, the model does not based on weighting but in pairwise comparison and semantic distance; meaning that the ‘weight' is given to each criterion, which can be modified by the evaluators.

Each criterion was then analyzed based on these characteristics and the values assigned for each technology. The quantitative values, with the exception of the land requirements and cost of technology, were estimated in the first part of the study and their results were introduced into the matrix (Table 5.10). The qualitative values were assigned based on the analysis and review of different studies.

As explained before, some technologies required pre-treatment of input. In this case study, the biogenic waste used as input is not being completely separated in the source and few places separate it, but in the end, all waste is mix in the transference stations and then later in the landfills. Hence, for the implementation of the WTE technologies, with the exception of landfill gas, it is required a separation and classification process. The value then in this criterion is measured on how many pre-treatments are required for each technology. The technologies of incineration, gasification and pyrolysis required, besides the separation, drying and gridding of the input before being processed. The anaerobic digestion technology requires separation and gridding of the input; contrary to the other technologies, drying is not required since high moisture percentage is recommended for the digestion process.

In the case of the pre-treatment for energy generation, the biogas produced in the landfill and the biodigesters both need to be enriched to increase the percentage of methane from usually 50-60% to 90-95%. Also the biogas requires removal of H_2S because its presence contributes to corrosion and reduction of life span of engines and turbines when used for energy generation. The Syngas produced in the gasification technology requires also pre-treatment to be used in energy generation, since it is usually dirty with high levels of tars that must be removed. The bio-oil generated in the pyrolysis process needs to be separated, collected and sometimes upgraded to improve its characteristics. The heat generated from the incineration process is used directly for energy generation, without pre-treatment required.

In the case of technical maturity, pyrolysis is the technology in research phase and gasification is being tested in pilot plants located in USA, Europe and Asia; incineration and anaerobic digestion in biodigesters are been implemented, however, more implementation have been done in incineration technologies than biodigesters. Finally, landfills have been implemented around the world but have not been perfected considering energy generation because complete recovery of biogas has not been achieved. In the case of research and development technologies, it can be argued in the Chilean context that Chile has funding for innovative technologies promotion and the lack of technical maturity or availability in a technology may not necessary represent a limitation in its development; but it must be considered for the expected generation results. The values assigned in each technology for each criterion can be seen in Table 5.10.

Table 5.10. Multi-Criteria Decision Analysis matrix for the five technologies evaluation

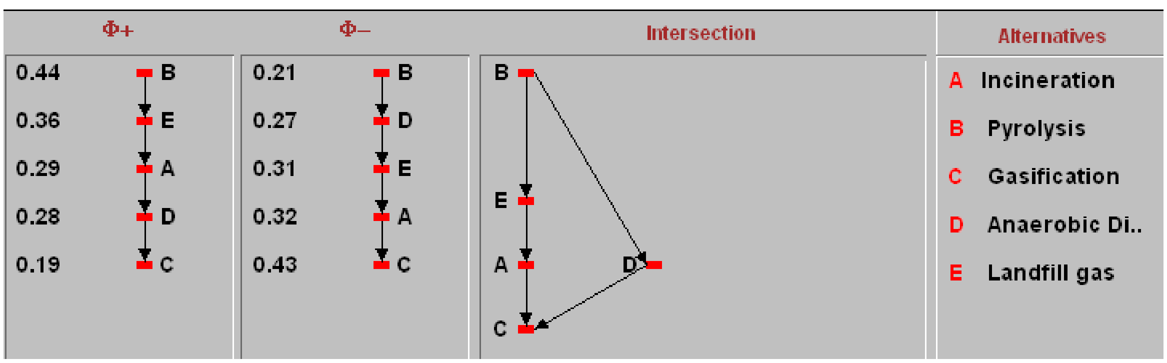
Criteria	Alternatives				
	Incineration	**Pyrolysis**	**Gasification**	**Biodigesters**	**Landfill gas**
Efficiency	0.57	0.22	0.47	0.42	0.24
Availability	Commercial	Pilot	Some commercial	Commercial	Commercial
Pre-treatment of input required	Moderate	Moderate	Moderate	More or less good	Good
Pre-treatment for energy generation required	Good	More or less bad	Moderate	More or less good	More or less good
Technical maturity	Good	More or less bad	Moderate	Good	More or less good
CO_2eq [kg/MWh]	9,06	10,29	27,38	8,40	4,73
TOPPeq[kg/MWh]	3,06	2,49	1.03	1,13	1,28
Solid waste output [kg/MWh]	541,77	2,83 E-06	18,01	98,02	0,00
Other emissions: H_2S, NH3, As, Cd, Cr	No	Yes	Yes	No	No
CDM possibility	Yes	Potential	Yes	Yes	Yes
CO_2eq savings for fossil fuels substitution [kton/year]	282,85	312,09	165,58	175,52	24,72
Land requirements [Ha] 1000 ton/day	7,00	3,00	3,00	4,00	14,00
Cost of technology [US$/ton]	125,00	70,00	200,00	115,00	8,00
Avoided cost' primary energy [US$]	142.974.785,37	158.776.684,66	92.530.947,28	88.417.195,22	12.219.695,65

5.3.2. Technology selection based on NAIADE model results

The recommended technology is the technology that brings more benefits in the general scheme when compared with the other technologies and based on the criteria selected for this evaluation. The amount and type of criteria may vary based on the evaluators, usually stakeholders that are involved in the decision making process. The MCDA helps to deal with the information and the variety of values used, just like they are used in the real world. It includes the uncertainties and integrates the different goals, as it is required in this study, where five technologies are being evaluated based on a general analysis of the different criteria and criterion characteristics. However, the software is not perfect and the problems encountered during this study will be discussed in the end of this section.

The matrix was introduced into the NAIADE software as was presented in Table 5.10; no changes were made in the semantic distance of each criterion, maintaining the pairwise comparison standard of the model. Nonetheless, each criterion was assigned its characterization based on Table 5.9, and the quantitative score type assigned the 'crisp' type for numeric values and the qualitative score type was 'linguistic' for ranking values.

The evaluation of the alternatives is presented in the graphic 5.9, where the partial ranking of alternatives is presented in the two first columns, followed by the final ranking as result of the intersection of the first two.



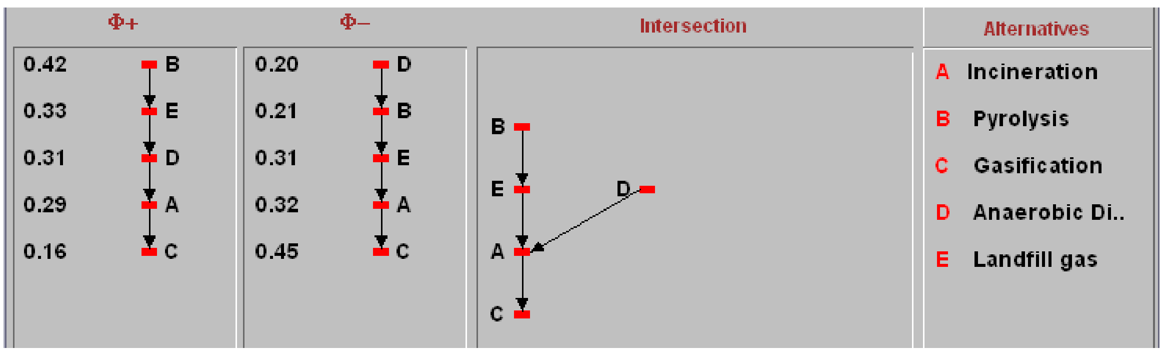
Graphic 5.9. NAIADE results with data from Table 5.10

The first two columns are calculated based on the partial preference intensity, the Φ+ represents how *much better* an alternative with respect to the others is; in this case, the higher value is for the pyrolysis, the *much better* alternative compared with landfill gas, incineration, anaerobic digestion and gasification.

On the contrary, the Φ- represents how *much worse* an alternative with respect to the others is; in this case, the highest value is for the gasification alternative, which is considered the *much worse* alternative compared with the others, and the lowest value is for pyrolysis. The results show in both cases that the pyrolysis is the *much better* alternative and that the gasification is the *much worse* alternative since both of them occupy the same place in both partial preference intensities. As a result, the intersection shows pyrolysis as the most recommended alternative when compared with the other alternatives on the basis of this study; followed by landfill gas. Incineration and anaerobic digestion have the same distance from pyrolysis but since anaerobic digestion is *less bad* than landfill gas and incineration is *worse* than landfill gas, then incineration follows the landfill gas alternative and anaerobic digestion is directly after pyrolysis. Finally, the less recommended technology is, as said, gasification.

These results require certain considerations, if reviewed again the values assigned to each criterion, the solid waste generation was included considering the results of the GEMIS analysis without taking into account that:

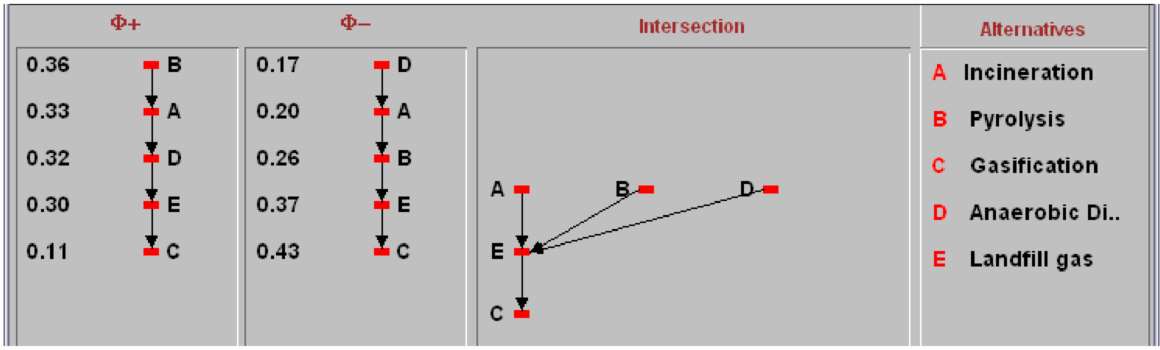
(1) The waste generated in the biodigester has the potential to be used as bio-fertilizer; therefore, it is a sub-product of the process and not a waste. In the results from GEMIS, the amount of 95,68 kg/MWh belongs to this part of the process, and 2,33 kg/MWh belongs to ashes generated. If the value of 98,02kg/MWh is removed from the NAIADE analysis and only the 2,33 kg/MWh are considered, the following results are obtained:



Graphic 5.10. NAIADE results with solid waste from anaerobic digestion considerations

The new results show that pyrolysis still is the best recommended technology and gasification the less recommended, but the anaerobic digestion is the *less bad* option and can be considered with the second option, landfill gas. However, in this option landfill gas is considered that does not generate waste and it is automatically assumed that the bio-fertilizer will be used and nor deposited in a landfill site.

(2) The generation of energy based on landfill gas may not generate solid waste as a process, which is showed in the GEMIS results; but the biogas is generated from solid waste that is disposed in landfills. Consequently, it can be said that a bigger amount of waste is generated in the landfill gas alternative than in the others, instead of the cero value assigned in GEMIS. When making this consideration and introducing it into the NAIADE model some modifications in the criterion characteristics have to be done. Since it is not provided an exact value of solid waste left after decomposition and extraction of the landfill gas, the numeric values of the criterion are changed into linguistic values and the following results are obtained:

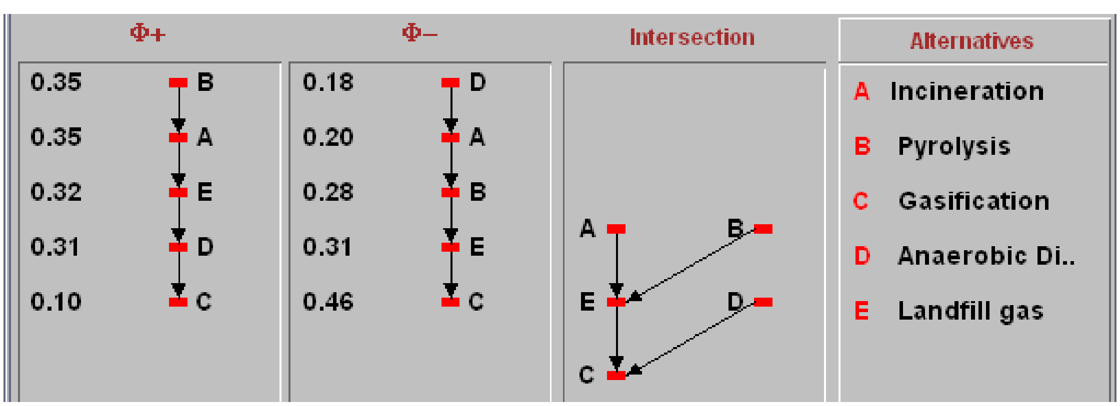


Graphic 5.11. NAIADE results with solid waste from landfill gas considerations

These new results were also varied considering the anaerobic digestion waste generation, both case, and the results represented the same intersection graphic. When considered that the landfill gas alternative has the most waste generation, the pyrolysis is not the only best recommended technology but also incineration and anaerobic digestion are recommended. In that case, the partial references in the first two columns can help understand the results. For example, incineration is not the *much better* or *less bad* alternative among the five technologies, but is among the three best recommended technologies because it occupied the second place in both partial references and the pyrolysis and anaerobic digestion alternatives occupy the first and third place in the Φ+ preference respectively and viceversa on the Φ- preference.

The first results and the two considerations show that when using a MCDA model it is necessary to specify the aspects that are taken into account when comparing the alternatives: what is considered and was is disregarded in the analysis; if the consideration is based only on energy generation and the waste generated from this process or if the waste generated before this process is also considered. The stakeholders must define the rules of the game before introducing the data into the model, so no further alterations to the result of the model are required.

The results also show that pyrolysis is always considered the best recommended alternative, even do it has the lowest values in availability, pre-treatment required for energy generation and technical maturity. Considering this, it was tested if the solid waste criterion influences the results on pyrolysis, since the results in GEMIS show low solid waste generation for this technology.



Graphic 5.12. NAIADE results without solid waste criterion

The new analysis, without the solid waste shows that pyrolysis and incineration are the best recommended technologies and gasification is still the less recommended technology. Meanwhile, anaerobic digestion and landfill gas are both in second place. Therefore, the solid waste criterion has not bigger effect on the pyrolysis results, but it does improve the incineration results.

Even though the NAIADE model can be manipulated, a well defined set of rules and clear considerations will ensure a successful result. As it was explained, NAIADE gives out the results without outranking them, meaning that many alternatives could occupy the first place, as shown in graphic 5.10, when the waste used for landfill gas was considered. In this case, NAIADE helped to determine the main alternatives that should be considered but the three alternatives should be reanalyzed if only the best is wanted.

Even though NAIADE model is considered very flexible for real world applications and a variety of data can be introduced in the matrix, the characterization of the criterions and the pair-wise comparison require mathematical skills and a deeper knowledge of stochastic variables and fuzzy theory. Therefore, skilled people must work with the stakeholders to introduce the data in the software. Also some confusion can be created when the results do not show outranking values. Finally, the lack of weighting can cause problems if more relevance wants to be given to one of the focuses, such as environmental criteria or economic criteria.

However, the NAIADE supported the decision making in the study and helped out in dealing with the information and obtaining a clearer view of the alternatives and relevant possibilities.

5.4. INTEGRATING WTE PROJECTS IN THE CHILEAN ENERGY SECTOR

Deciding which WTE technology could be the most recommended one in the Chilean context does not secure the introduction or consideration of this technology in the national energy sector. In fact, not only the WTE projects but the whole renewable energies projects for energy generation had encountered barriers for their introduction in the Chilean energy market. As explained in the case study, some changes have been made in the last few years at institutional and legal levels to facilitate the introduction of the renewable energies not conventional in the energy sector. Some success has been reached mainly in wind energy generation, but still WTE technologies are far from being considered an option for energy generation or for substituting landfill sites.

This section proposes some guidelines for the integration of WTE projects in the Chilean energy sector, considering first the barriers or constraints that these projects encounter in the Chilean energy context and then suggesting alternatives on how to overcome then.

5.4.1. Barriers to the implementation of WTE projects in the Chilean energy context

Based on all the information provided until now, it can be said that Chile has a great potential for implementing WTE in its energy sector; however, they are not promoted in the Non Conventional Renewable Energies scheme because of the following reasons:

Chile still holds an energy market system focused on "immediate demand market" prices, which gives more importance to existing investments or new generation projects that require short time and low initial capital investment. Moreover, the concept of efficiency in Chile energy policy is still focused on production of energy at the lowest cost and quick revenues. This shifts the interest of private investors to short time, low risk, low initial capital investment and high revenues of energy generation projects; leaving out projects such as WTE technologies.

The energy market structure promotes competence between private companies that control the energy system leaving out the government; which does not promote dynamic programs with social and environmental aspects. The environmental aspects such as 'avoided cost' from the substitution of fossil fuel are not considered in the Renewable Energies projects evaluations and the savings from this are not seen by the investors. The government considers that the market should establish the energy growth not the government; meaning that there is freedom to selected fossil fuel based technologies for energy generation. Nonetheless, the government had established a renewable energies goal of 10% of Non Conventional Renewable Energies integrated in the energy matrix for 2024. However, this goal is being reach by the new wind energy projects because in the renewable energies portfolio, wind energy has quicker revenues. For example, at the beginning of 2010, the renewable energies portfolio was 2570MW; from this 2057MW belong to 28 wind energy projects proposed to be implemented in the following years (Koenemund, personal communication).

Even thought there are funds and loans available for renewable energy projects which include WTE technologies, small generation companies consider that access to funds or loans for these projects is limited due to collateral request. Also there is a lack of knowledge of the alternative funding sources and alternatives such as the funding for innovative technologies provided by CORFO.

Chile bases its energy matrix on non-conventional sources of energy, justified on the economic growth and growing demand of energy that requires the duplication of the energy generated by 2020; in this case, the government was involved in the promotion of two LNG installations, which are not the most economical option but where considered under energy security reasons. It can be argue why this investment was not done on renewable energies technologies.

There are also other institutional barriers such as the lack of strong institutions that advocate renewable energies. Chilean authorities think they have created the necessary incentives to achieve the objectives to develop renewable energies, and consider that it is responsibility of the market to make the corresponding investments. They consider that the barriers lay within the market and must be solved by it, not by the authorities (Steinacker, 2007). The Chilean authorities provide some funding but they have decided not to include subsides to support renewable energies development (Koenemund, personal communication). Moreover, the Clean Development Mechanism is not promoted by Chilean authorities, leaving it more as an initiative of the private companies, for them to obtain more revenues. Some centers have been created to provide information and a guide for CDM in Chile was created to facilitate the CDM process for interested companies; but not particular interest lies in the Chilean authorities to promote it. The solid waste sector is also focused on the lowest cost of investment and high revenues, and local companies have a lack of experience on WTE technologies which makes energy generation market an unknown and risky investment. In the case of the waste management authorities, as quoted in the case study, they are only interested in the compliance with the environmental laws.

Other kind of barriers is the conception that the WTE technologies emit high concentrations of air pollutants, without considering in the global balance of emission that the substitution of fossil fuels energy generation to WTE would reduce air emissions in the national context.

The authorities consider that one of the major barriers for Non Conventional Renewable Energies developers will be getting funding, so authorities consider that small NCRE projects that begin functioning in a short period of time will be the ones that will contribute to achieve the objectives proposed and based on this way of thinking, they have opened the wholesales energy market to small projects under 9MW (Poniachik, 2006). Nonetheless, contracts to buy energy are short term (36 months or less) and do not favor or secure the renewable energies investment. Moreover, the Electric Law that promotes renewable energy projects also presents flexible mechanisms such as delays of one year, credits for renewable energies used the year before the modification of the law, and transference between companies to comply.

5.4.2. Guidelines for the integration of WTE projects in the Chilean context

There have been some improvements, more interest, and some level of conscience in Chile that have promoted positive changes for the transition toward renewable energies. The country has approved NCRE projects but they are not installed yet, and Chile still has to reach its objective, 5% of NCRE in the 2010 energy matrix and 10% in its 2024 energy matrix. Most probably, Chile will reach its goal of renewable energies for 2024 if the trend of renewable energies projects growth continues as it is. However, it is probable that it reaches its goal in installed capacity but not in generation. Since, as it was mention before, the majority of the RE projects approved is wind energy projects.

The measurements for promoting the NCRE in Chile has not benefit the diversity of the renewable energies option, including WTE technologies; since they continue to focus the growth of the energy sector on a competitive market.

Therefore the first step to promote the inclusion of other NCRE in the energy matrix, including WTE technologies, is to change the view of the government in respect to the energy sector.

First Step: Active role of the government

Regarding energy generation the government of Chile had been a “hands-off” kind of government, where the energy generation was control based on competence and market laws. Now, that the government has begun to have a more active role, this role has to be really reinforced and has to have continuity if it is going to be successful. There is a need to make it clear that, until now the government set the basis for the introduction of NCRE to the matrix, but cannot sit back and way for the market to change by itself. A more organized structure to control the energy market and its companies, as well as stronger actions needs to be maintained and supported by the government if changes are expected. A more “hands-on” attitude has to be implemented in order to change the previous strategy.

This includes the energy sector as well as the waste management sector since it is still considering the landfills as the only waste disposal option, without promoting other alternatives. More combine efforts should be directed by both sectors to promote WTE projects.

Second step: Stronger and stricter regulations

The regulations and reforms introduced also present flexible mechanisms that work as loopholes use for energy companies to avoid or postpone their obligations with NCRE objectives. The government needs stronger and stricter regulations that reduce loopholes and force energy companies to really invest in NCRE. Maybe instead of allowing for companies to delay 1 year or get credits from the year before; it would be best for companies to pay a yearly fine which will be then used for NCRE project funding.

Third step: Adaptation of the energy market

Chilean energy market must change its focus on "immediate demand market" prices. The free energy market that was promoted in Chile to induce competence among energy companies, it is now a barrier that must be modified to open up the market for NCRE. This mean that the energy market has to switch to NCRE, this can be done by giving more opportunities to NCRE projects, giving them priority in the energy matrix, making it an obligation to buy the energy from renewable energy sources and introducing alternative economic incentives that will force the energy companies to shift toward NCRE for example better electricity prices.

Four step: Modification of the efficiency concept

Regarding the concept of efficiency promote until now by Chilean energy policy has to be change. Efficiency cannot be considered only providing energy with the lowest cost, but has to be modified to a more modern approach where energy matters also consider environmental impact and energy security, which has not been provided by Chile energy matrix and brought the country to its energy crisis. There should be included the 'avoided cost' and emissions reduction in the evaluation of energy projects. In this way, NCRE projects would be more competitive.

Five step: Introduction of economic incentives

Market fees: Since energy companies still do not feel pressure to change to NCRE due to the market development, the government should also implement, not only economic incentives to NCRE, but market fees to Non-Renewable Energy sources such as pollution fees for emitting CO_2 and other pollutants to the environment making, this could be supported by establishing caps of emissions.

Subsides: Subsides are needed when trying to incorporate NCRE into an energy matrix, since NCRE have high investment cost and higher prices which do not compete with Non-Renewable Energy sources. Therefore, a good subside mechanism is need for the NCRE to compete in the energy matrix. These subsides can be in reduction of taxes, introduction of green bonus due to non-CO_2 emissions. Chile has already introduced a few subsides in the form of exemptions but they are mainly focus on small NCRE projects, big projects do not have this kind of subsides but are the ones with highest investment costs.

Six step: Modification and revision of the funding mechanisms

Even though there are funds available for NCRE projects, it is necessary to do an evaluation of the success of these funds, since the NCRE are growing only in the wind energy projects; which means that some modifications of the funding system are required. The government could also provide a funding office for NCRE that would help with procedures and sources of funds available. Also, the prerequisites of funding should be reviewed to include a bigger spectrum of participants.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

The Metropolitan area generates enough biogenic waste to be used in WTE projects for energy production with a constant supply. The available biogenic for 2008 was calculated in 1,49 million tons and it will continue to increase to1,81 million tons in 2030; providing a constant flow of more than 1,5 million tons of biogenic waste per year.

The highest technical potential of the five WTE alternatives considered belongs to pyrolysis, with 1636,61 GWh per year and the lowest belongs to the 'business as usual' option, landfill gas with 125,956 GWh per year. This energy could supply around 491.917 inhabitants or 37.859 inhabitants, respectively, of the population of the Metropolitan Region in 2008. The five alternatives studied: pyrolysis, gasification, incineration, anaerobic digestion and landfill gas could contribute to the energy security in the country.

In the environmental aspects, the gasification technology has a higher CO_2eq emissions compared to the other technologies; representing 27,38 kg CO_2eq/MWh; incineration has the highest TOPPeq emissions with 3,06 kg/MWh and the pyrolysis technology has the highest contribution in the particulate emissions with 9,39 kg/MWh. However, all five alternatives produce fewer emissions than the three fossil fuels: natural gas, coal and diesel, used to produce energy in Chile. The highest producer of solid waste is incineration followed by gasification.

In the socio-economical aspects, Chile could reduce its imports of fossil fuels based on the amount of energy generated in WTE plants; which can contribute to the national economy, since the WTE technologies use a cero cost input compared to the thermoelectric power plants. The amount of the savings depends on the price of the fossil fuels in the international market. In this study, it was estimated with the values from 2008, that about 97 to 225 US$/MWh of energy generated could be saved with WTE technologies. Also, revenues from the CDM could be obtained in the five technologies, since they reduce emissions when substituting fossil fuel sources. In both cases, the highest savings and emission reduction are achieved by the pyrolysis alternative.

The MCDA results showed that pyrolysis is the most recommended WTE technology followed by landfill gas and the less recommended WTE technology is gasification. However, when considered the solid waste in the landfills from which the biogas is produced, three alternatives occupy the first place: incineration, pyrolysis and anaerobic digestion.

When using a MCDA model it is necessary to specify the aspects that are taken into account when comparing the alternatives. The stakeholders must define the rules of the game before introducing the data into the model, so no further alterations to the result of the model are required. NAIADE helped to determine the main alternatives that should be considered but the three alternatives should be reanalyzed if only the best is wanted.

Deciding which WTE technology could be the most recommended one in the Chilean context does not secure the introduction or consideration of this technology in the national energy sector; some guidelines are required for the integration of WTE projects in the Chilean energy sector, and these guidelines must include changes in the government approach to the energy sector, changes in the energy market, regulations, economic incentives and in general a new switch to NCRE.

Even though Chile began some modifications in order to promote the NCRE in its energy sector, it still has a long way to go, since it insists in a competitive market and a "hands-off" attitude. Chile has great potential to transform more than 10% of its energy matrix to NCRE, but it needs to commit and accept that some changes are necessary.

The WTE technologies have great potential to be introduced into the market with the right support and promotion.

6.2. RECOMMENDATIONS

- The WTE technologies have great potential and should continue to be studied and considered as future alternatives for waste disposal and energy generation. They should be considered as part of the integrated waste management and not as a standalone initiative.

- The solid waste composition and their energy potential should be studied in detail in the Metropolitan area and develop studies with standardized methodologies that could be used as basis for future projects.

- The government institutions should work more closely together in order to integrate and promote the implementation of WTE, not only consider it a initiative of the energy sector or the waste management sector, but of the two sectors.

- The responsibility of the development of a sector should not be left in the hands of the private companies and their own interest. Governments should be responsible for the direction of the development and growth of the country and be more active.

CHAPTER 7. REFERENCES

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CHAPTER 8. ANNEXES

Annex 8.1. **Political distribution of the Metropolitan Region of Santiago – Region XIII and location of the three landfills**

Annex 8.2 **List of institutions and interviewees**

Annex 8.3. **Focal points of interviews**

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Annex 8.6. **Other pollutants calculations**

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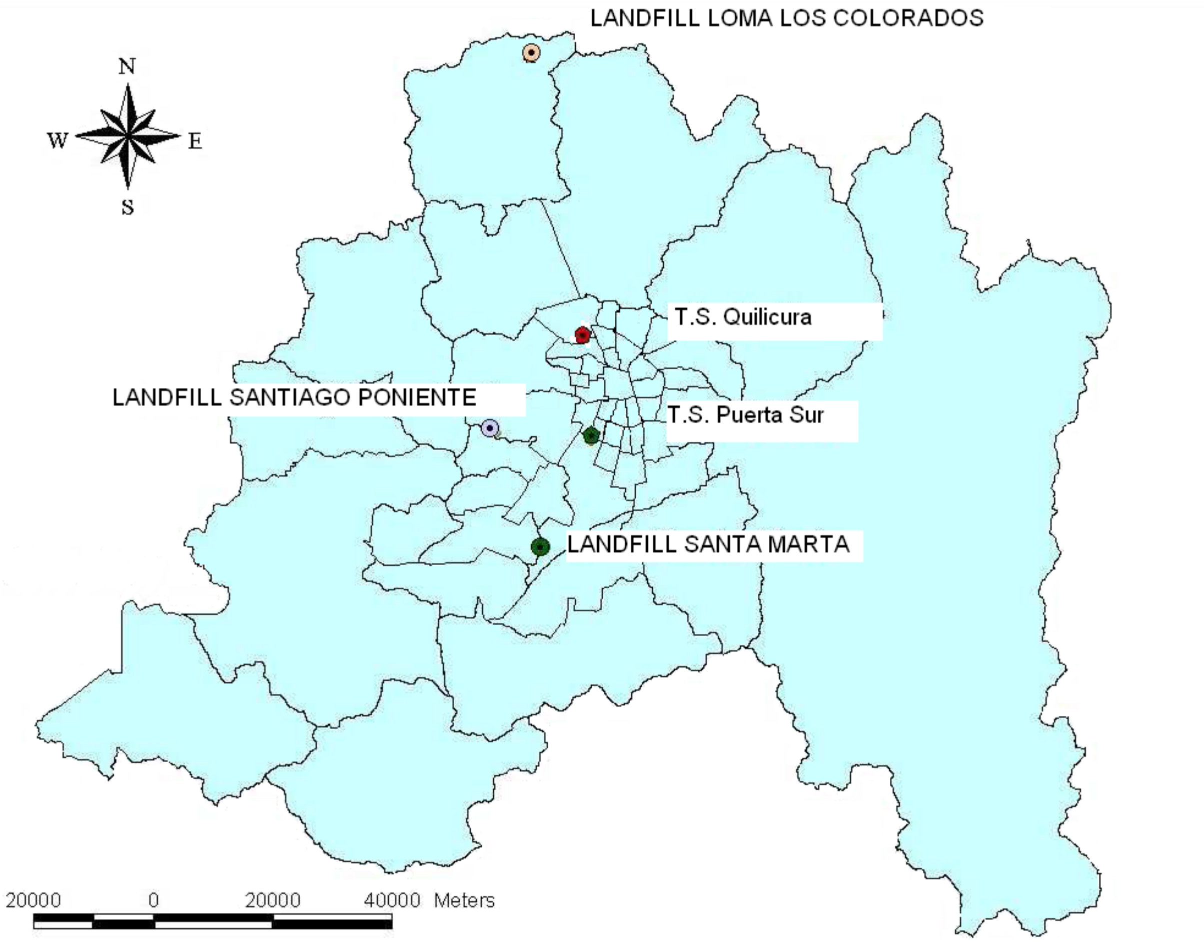
Annex 8.8. **Photos of landfills visited during the field work**

ANNEX 8.1.
POLITICAL DISTRIBUTION OF THE METROPOLITAN REGION OF SANTIAGO REGION XIII AND LOCATION OF THE THREE LANDFILLS



Source: Modified from *Abfall_Abwasser_Zwischenbericht_N°2*

ANNEX 8.2.
LIST OF INSTITUTIONS AND INTERVIEWEES

INSTITUTION	POSITION	INTERVIEWEE	DATE
Ingenieria Alemana	External consultant	Fernando Sepulveda	02.03.2010
Ingenieria Alemana	Project Manager	Sergio Gómez	09.03.2010
ProAmbiente	ProAmbiente Manager	Alberto Learreta Meca	09.03.2010
ProAmbiente	Assistant Manager	Millana Zamora	09.03.2010
CONAMA	Pollution Control Area CONAMA, Solid Waste Department	Genaro Rodríguez	10.03.2010
Loma Los Colorados Landfill KDM	Project Engineer KDM	Martine Oddou	11.03.2010
CONAMA	Climate Change Unit Director - Research Department	Fernando Farias	12.03.2010
GTZ	Responsible of the Project Support to Renewable Energies	Trudy Koenemund	16.04.2010
Santa Marta Landfill	Assistant Manager	Guiselle	18.03.2010
Santa Marta Landfill	Responsible Landfill	Richard Oyarce	
Centro de Energías Renovables, CORFO	Representantives CER-CORFO	Rodrigo García	19.04.2010
		Paz Bernaldo	
		Pamela Delgado	
CORFO	Director of the Clean Production Agreements Department	Ximena Ruz	19.03.2010
CONAMA	Responsible registry CONAMA	Andrea Allamand	23.03.2010

ANNEX 8.3.
FOCAL POINTS OF INTERVIEWS WITH ENERGY AND WASTE MANAGEMENT SECTORS

Sector distribution	Functioning, structure, loop-holes, infrastructure, organization, responsibilities distribution,
Legal framework	Environmental Law, Waste Management Law, Energy Law, Emissions (air quality laws, controls, plans), Renewable Energies Law
Programs/Initiatives	Financing, who and how, plans (governmental, municipal, local), supports, initiatives for Renewable Energy Projects and Waste Management in the next years
Focuses	Important or relevance in each program/ Initiative baseline for criteria definition/Projects and Interests
Criteria/Variables	Deduced from information collected in situ and literature reviews. Criteria selection based on policies, relevant aspects, topics of concerned mention in interviews.
Constrains	Constraints in local cases and information collected in situ, compared in literature reviewed, limits for development of projects
Waste characteristics	uses, disposal or reused, quantities available, location, treatment, physical characteristics, pre-treatment, conditions, existing infrastructure
Energy sector characteristics	energy for electricity and heat or gas network, uses, market, transmission and distribution, prices, priorities for energy generators

ANNEX 8.4.
CALCULATIONS OF THE PROJECTED AVAILABLE MSW AND BIOGENIC WASTE FOR ENERGY GENERATION IN THE METROPOLITAN REGION OF SANTIAGO

Annex 8.4.1. Equations used for the calculation of the available MSW and DSW in the Metropolitan region of Santiago

Equation for the total available amount of waste

No.	Name/unit	Factor
1	Number of inhabitants [1000]	x annual waste production [ton/inhabitant]
2	Annual waste production [kton]	x (1-% recycling/composting)
3	Available waste [kton]	

Source: (Noord et al., 2004)

Equation for technical potential calculation

No.	Name/unit	Factor
1	Available waste [kton]	x % available for energy production
2	Net amount of available waste [kton]	x % biodegradable fraction
3	Biodegradable waste available [kton]	x specific energy content [GJ/ton]
4	Fuel input [GJ]	x efficiency
5	GJ output [GJ]	x 1/3600
6	Production [GWh]	

Source: modified from Noord et al., 2004

Annex 8.4.2. MSW composition and recycling data in the Metropolitan Region of Santiago taken from CONAMA & CUV, 2006

COMPONENTS	RESIDENTIAL SECTOR	
	%Weight without recycling	%Weight with recycling
Organic matter	49.2	45.79
paper and cardboard	13.51	17.12
ceramics, ashes and debris	4.2	3.82
plastics	10.07	9.72
textiles	1.97	1.79
metal	1.8	3.72
glas	3.94	4.12
bones	0.59	0.54
others	14.71	13.38
Biogenic waste %	64.58	**64.7**

COMPONENTS	COMMERCIAL SECTOR
	% Weight
Food residues	27.91
Looping gardens	1.52
Paper	17.57
Cardboard	7.44
Plastic	18.38
Tetrapack	0.71
Diapers	1.04
Rubber	0.38
Leather	0.3
Glass	7.95
Metal	1.53
Wood	1.25
Textils	2.45
Ashes	5.16
Batteries	0.24
Bones	1.57
Seeds	0.71
Ceramics	0.33
Others	2.06
RSE	1.48
Biogenic waste %	**58.85**

Annex 8.4.3. Available DSW based on data from the National Commision of Environment, CONAMA

Year	No. of years	Inhabitants 2008 (0.9% intercensus growth*)	waste production (growth rate 1,5% *)	**DSW production** **	Recycling & composting *** (growth rate 1.1%)	**Available DSW**	**Biogenic waste** (64.7%****)
	Unit	Unit	kg/inhab/day	ton/year	fraction	ton/year	ton/year
2008	1	6,745,651	1.10	2697976	0.1441	2309198	1494051
2009	2	6806362	1.11	2763092	0.1551	2334536	1510445
2010	3	6867619	1.13	2829779	0.1661	2359753	1526760
2011	4	6929428	1.15	2898076	0.1771	2384826	1542983
2012	5	6991793	1.16	2968021	0.1881	2409736	1559099
2013	6	7054719	1.18	3039654	0.1991	2434459	1575095
2014	7	7118211	1.20	3113016	0.2101	2458971	1590954
2015	8	7182275	1.22	3188148	0.2211	2483249	1606662
2016	9	7246916	1.23	3265094	0.2321	2507266	1622201
2017	10	7312138	1.25	3343898	0.2431	2530996	1637554
2018	11	7377947	1.27	3424602	0.2541	2554411	1652704
2019	12	7444349	1.29	3507255	0.2651	2577482	1667631
2020	13	7511348	1.31	3591903	0.2761	2600178	1682315
2021	14	7578950	1.33	3678593	0.2871	2622469	1696738
2022	15	7647160	1.35	3767376	0.2981	2644321	1710876
2023	16	7715985	1.37	3858302	0.3091	2665701	1724708
2024	17	7785429	1.39	3951422	0.3201	2686572	1738212
2025	18	7855497	1.41	4046790	0.3311	2706898	1751363
2026	19	7926197	1.43	4144459	0.3421	2726639	1764136
2027	20	7997533	1.45	4244485	0.3531	2745758	1776505
2028	21	8069511	1.48	4346926	0.3641	2764210	1788444
2029	22	8142136	1.50	4451839	0.3751	2781954	1799924
2030	22	8215415	1.52	4559284	0.3861	2798945	1810917

*Provided by IASA,2010. Also year 1 population
** year 1 data from USW registry provided by CONAMA, 2008
***recycling fraction based on CONAMA RM, 2009
****biogenic waste fraction based on Residential waste fraction in CONAMA & UCV, 2006

Annex 8.4.4. Available MSW based on data from the Regional Ministerial Secretary of Health, SEREMI de Salud

Year	No. of years	Inhabitants 2008 (0.9% intercensus growth*)	waste production (growth rate 1,5% *)	**MSW production** **	Recycling & composting *** (growth rate 1.1%)	**Available MSW**	**Biogenic waste** (58.85%*****)
	Unit	Unit	kg/inhab/day	ton/year	fraction	ton/year	ton/year
2008	1	6,745,651	1.34	3305097	0.1441	2828833	1664768
2009	2	6806362	1.36	3384866	0.1551	2859873	1683035
2010	3	6867619	1.38	3466559	0.1661	2890764	1701214
2011	4	6929428	1.40	3550225	0.1771	2921480	1719291
2012	5	6991793	1.42	3635909	0.1881	2951995	1737249
2013	6	7054719	1.45	3723662	0.1991	2982281	1755072
2014	7	7118211	1.47	3813533	0.2101	3012309	1772744
2015	8	7182275	1.49	3905572	0.2211	3042050	1790247
2016	9	7246916	1.51	3999833	0.2321	3071472	1807561
2017	10	7312138	1.53	4096369	0.2431	3100542	1824669
2018	11	7377947	1.56	4195235	0.2541	3129226	1841549
2019	12	7444349	1.58	4296487	0.2651	3157488	1858182
2020	13	7511348	1.60	4400183	0.2761	3185292	1874545
2021	14	7578950	1.63	4506381	0.2871	3212599	1890615
2022	15	7647160	1.65	4615143	0.2981	3239369	1906368
2023	16	7715985	1.68	4726529	0.3091	3265559	1921781
2024	17	7785429	1.70	4840604	0.3201	3291127	1936828
2025	18	7855497	1.73	4957432	0.3311	3316026	1951481
2026	19	7926197	1.75	5077079	0.3421	3340211	1965714
2027	20	7997533	1.78	5199615	0.3531	3363631	1979497
2028	21	8069511	1.81	5325108	0.3641	3386236	1992800
2029	22	8142136	1.84	5453629	0.3751	3407973	2005592
2030	22	8215415	1.86	5585252	0.3861	3428786	2017841

*Provided by IASA,2010. Also year 1 population
** year 1 data from USW registry provided by CONAMA, 2008
***recycling fraction based on CONAMA RM, 2009
*****biogenic waste fraction based on commercial waste fraction in CONAMA & UCV, 2006

Note: The difference between the USW production and the Waste reported in the three landfills is MSW including industrial acceptable in municipal landfills, sewage sludge (private), other private sources.

ANNEX 8.5.
CALCULATIONS OF THE POTENTIAL ENERGY GENERATION FROM MSW AND BIOGENIC WASTE IN THE METROPOLITAN REGION OF SANTIAGO

Annex 8.5.1. Potential 'Avoided cost' of electricity generation substituting three fossil fuel based technologies for WTE technologies for the year 2008

	Waste as energy source		Cost of electricity generation per technology		Calculated production	'Avoided cost' of electricity [mill US$]		
WTE technologies	Amount [ton]*	Costs [US$/ton] *	Average specific consumption [ton/MWh]**	Electricity cost [US$/MWh]	[GWh/year]	Natural Gas	Coal	Diesel
Landfill gas	2309197,66	0	18,33	0	125,956	12.21969565	5.632540043	28.40397185
Anaerobic Digestion	1494050,88	0	1,64	0	911,371	88.41719522	40.75497516	205.520628
Incineration	1494050,88	0	1,01	0	1473,73	142.9747854	65.90272189	332.3365733
Gasification	1494050,88	0	1,57	0	953,774	92.53094728	42.65116586	215.0828055
Pyrolysis	1494050,88	0	0,91	0	1636,61	158.7766847	73.18644098	369.0671692

Note: * MSW available and biogenic waste year 2008
** Estimated based on energy production per technology and amount of waste to generate it

Annex 8.5.2. Emissions reduction of electricity generation based on alternative technologies substituting fossil fuels

CO2 emission factor by fuel type [ton CO2eq/TJ]	
DIESEL	73,326
COAL	92,708
NATURAL GAS	55,829

Source: UNFCC, 2006

Technologies	CO2eq [ton/year]
Biodigester cogeneration	7653,33
landfill gas cogeneration	596,19
Incineration power plant	13349,75
Pyro CHP_ICE diesel motor	16842,77
Syngas gasifier GasT	26112,38

Estimations of emissions reduction		Biodigester cogeneration	landfill gas cogeneration	Incineration power plant	Pyro CHP_ICE diesel motor	Syngas gasifier GasT
	TJ/year	3280,935743	453,4424493	5305,412044	5891,789665	3433,587554
	tCO2eq/TJ	2,33	1,31	2,52	2,86	7,60
Emission Reduction [ton CO2eq/TJ]	DIESEL	70,99333316	72,01119147	70,80974869	70,46731513	65,72101554
	COAL	90,37533316	91,39319147	90,19174869	89,84931513	85,10301554
	NATURAL GAS	53,49633316	54,51419147	53,31274869	52,97031513	48,22401554
Emission Reduction [kton CO2eq/year]	Diesel	232,92	32,65	375.67	415,18	225,66
	Coal	296,52	41,44	478.50	529,37	292,21
	Natural Gas	175,52	24,72	282.85	312,09	165,58
CER 2008* [US$/year]	Diesel	3.681.613,96	319.998,72	2.282.660,73	4.068.750,27	2.211.456,84
	Coal	4.689.343,02	406.127,22	2.905.853,48	5.187.858,01	2.863.644,82
	Natural Gas	2.771.891,77	242.246,68	1.720.076,71	3.058.481,56	1.622.697,52

Note: * CER 2008 value = 14 Euro; converted to US$ 9,8 (Conversion rate: 1Euro = 0,7 US$; October, 2008)

ANNEX 8.6.
OTHER POLLUTANTS CALCULATIONS FROM GEMIS

Option [kg]	H2S
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	9.41E-07
Syngas gasifier GasT	7.87E-04
Option [kg]	NH3
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	2.82E-10
Syngas gasifier GasT	2.62E-04
Option [kg]	As (air)
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	7.03E-13
Syngas gasifier GasT	1.49E-08
Option [kg]	Cd (air)
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	1.23E-12
Syngas gasifier GasT	3.07E-08
Option [kg]	Cr (air)
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	9.97E-13
Syngas gasifier GasT	1.82E-08

Option [kg]	Hg (air)
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	0
Syngas gasifier GasT	5.00E-09
Option [kg]	Ni (air)
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	5.14E-11
Syngas gasifier GasT	6.19E-07
Option [kg]	PAH (air)
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	1.83E-06
Syngas gasifier GasT	4.13E-10
Option [kg]	Pb (air)
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	0
Syngas gasifier GasT	5.81E-08
Option [kg]	PCDD/F (air)
Biodigester cogeneration	0
landfill gas cogeneration	0
Incineration power plant	0
Pyro CHP_ICE diesel motor	2.31E-18
Syngas gasifier GasT	5.40E-14

ANNEX 8.7.
AIR POLLUTANTS SOURCES AND EFFECTS IN METROPOLITAN REGION

Contaminantes criterio: fuentes y efectos

Contaminante	Fuentes	Daños en salud y otros	Características
SO_x, óxidos de azufre	Combustión de azufre contenido en combustibles fósiles; refinamiento de petróleo, fundición de metal, fabricación de papel.	Agudiza problemas de enfermos bronquiales al ser inhalado con material particulado.	Gas incoloro, pesado, soluble en agua con olor fuerte e irritante.
PTS, PM10, PM2.5 (primarios)	Muchas fuentes: polvo de calles levantado por tráfico, procesos de combustión, motores diesel, procesos industriales, incendios forestales, quema de biomasa, construcción.	Irritación membranas mucosas, aumento dificultades respiratorias, propiedades carcinógenas.	Partículas sólidas o pequeñas gotas incluyendo humo, polvo y aerosoles.
PM10, PM2.5 (secundarios)	Reacción química de precursores como SO_2, NO_2 y NH_3, condensación de productos de combustión.	Similares al anterior; más agudos debido a mayor poder de penetración y acidez.	Partículas sólidas muy finas.
NO_x, óxidos de nitrógeno	Combinación de nitrógeno y oxígeno atmosférico a altas temperaturas de combustión (motores y fuentes industriales); subproducto de la fabricación de fertilizantes, degradación de materia orgánica.	Irritación pulmonar, aumento susceptibilidad a virus.	Gas café rojizo, relativamente soluble en agua.
COV, compuestos orgánicos volátiles	Vehículos motorizados – evaporación de tanques de combustibles y carburadores; lavasecos, fugas de gas, procesos industriales, domésticos y de construcción que involucran solventes.	Irritación ocular y nasal, intoxicación, daño hepático y propiedades carcinógenas.	Muchos y variados compuestos de hidrógeno y carbón.
CO, monóxido de carbono	Combustión incompleta del carbono en combustibles (carbón, leña, petróleo, gas, gasolina) en fuentes industriales, residenciales y móviles.	Bloquea la hemoglobina, especialmente dañino para personas anémicas o con problemas pulmonares o cardiovasculares.	Gas tóxico incoloro e inodoro, ligeramente soluble en agua.
O_3, ozono	Producido por complejas reacciones fotoquímicas en la atmósfera, involucrando hidrocarburos, dióxido nitroso y luz solar.	Irritación ocular y nasal y agravamiento de problemas respiratorios	Gas azul pálido, apenas soluble en agua, inestable, de olor dulzón.
Pb, plomo	Combustión de gasolina con plomo, soldadura, pintura con plomo, operaciones de fundición de plomo	Tóxico para niños y personas mayores, afecta sistemas circulatorio, reproductivo y nervioso.	Metal existente en una variedad de compuestos.

ANNEX 8.8.
PHOTOS OF LANDFILLS VISITED DURING THE FIELD WORK

Annex 8.9.1.   Photos of Loma Los Colorados Landfill visited during the field work

Photo 1. In the transference station "Quilicura"

Photo 2. Compacting the waste in the silos

Photo 3. Putting the silos in the transference train to the landfill

Photo 4. Disposal of the waste in the landfill

Photo 5. Biogas collection well

Photo 6. The flaring up of the biogas

Photo 7. Energy generators

Photo 8. Transformer for grid connection

Annex 8.9.2. Photos of Santa Marta Landfill visited during the field work

Photo 1. Transference truck from the transference station "Puerta Sur"

Photo 2. Disposal of the waste in the landfill

Photo 3. Biogas collection well and pipelines

Photo 4. Biogas flaring controls