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MSc Thesis

Model for economic feasibility of municipal solid waste treatment methods

In Partial Fulfillment of the Requirements for the Degree of Master of Science under the Direction of

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and

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Department of Electrical Engineering, PUC-Rio

Submitted to the Vienna University of Technology
by

Sebastian MAIER

Vienna, September 2011
Date

Signature

Pontifícia Universidade Católica
do Rio de Janeiro

Sebastian Maier

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Rio de Janeiro
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Abstract

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The often criminally neglected field of municipal solid waste management, especially in less developed urban regions, will receive in the future their necessary attention. As a result of the increasing process of urbanization, on a global as well as local scale, and the accompanying progressive aggregation of capital, specifically human capital, production increases in areas such as consumption of goods are going to result in a dramatic rise in the amount of solid waste generation. Consequently emerging influences on the design of urban living space require more adequate and sustainable approaches for the treatment of municipal solid waste. Whether or not a particular waste treatment technology should be applied in a final waste disposal strategy will largely depend on the specific costs of the considered method. This thesis aims to demonstrate a methodology to calculate the price to treat one tonne of waste, paid to a treatment plant operator, that results in a value at which investment in such a plant becomes viable. In order to do so, a base model has been developed that incorporates both the revenues generated by the sale of electrical energy and the income from the gate fee, which is later expanded to include revenues from carbon credit sales. By applying this model to a case study which compares 20 future projects starting one per year over the time period 2011-2030, and taking into account the local conditions of Brazil, results in projections of treatment plant operation-sustaining gate fees. The comparison of these projections with the actual landfill fees paid in the metropolitan area of Rio de Janeiro sheds light on the conditions under which the considered waste-to-energy technology is economically feasible.

Keywords

Net Present Value. Municipal Solid Waste. Incineration. Clean Development Mechanism.

Contents

List of Figures

List of Tables

O Brasil possui diversos atributos de primeiro mundo, porém ainda trata o lixo que gera de maneira indecente, imoral e ilegal.

Adriana Vilela Montenegro Felipetto

I
Introduction

This introduction explains some of the motivational reasons for choosing this specific topic, a review of the bibliography to show existing works and studies in the relevant literature, a description of the specific objectives for this thesis as well as the potential contributions of this research. Finally, an outlook of the following sections is given.

I.1 Motivation

When the level of world urbanization crossed the 50 per cent mark in 2009, it was estimated that some 3.42 billion people were living in urban areas. Indeed, world population is expected to increase from 6.8 billion in 2009 to 9.1 billion in 2050, with almost all of this growth generated in urban population, which is expected to increase to 6.3 billion. It is estimated that in many countries more than 60 per cent of urban population growth is driven by natural increase (i.e. when the difference between births and deaths is positive) meaning the residual percentage depends on other factors [Sou04]. However, there is a significant diversity in rate of growth seen in different regions in the world, as shown in Figure I.1. The important fact is that almost all of the expected population growth in the world in the next 40 years is going to be generated by urban areas in less developed regions, with the developed world contributing comparatively little to the sum total.

The current and the prospective increase in population for the Brazilian case are by no means independent of the transformation on the world scale. In fact, the noted trends in urban and rural population growth follow global trends. The results of the demographic census in 2010 [Ins11] show that the Brazilian population grew from 169.8 million in 2000, when 81.2% of Brazilians lived in urban areas, to 190.8 million in 2010, when 84.4% of Brazilians were urbanized, shown below in Figure I.2. Furthermore, population is expected to rise from this level to 215.3 million in 2050, 93.6% of which would be urbanized [Ins08]. This tendency is underlined by the sheer size of Brazil's two most

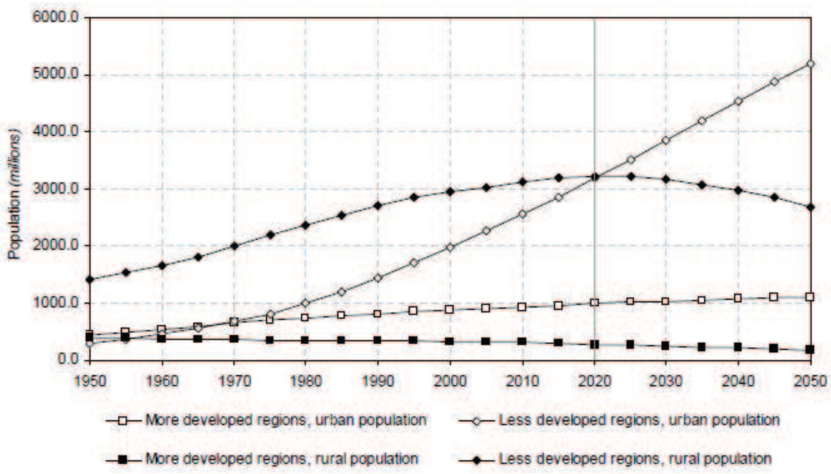

Figure I.1: World's urban and rural population by development group, 1950-2050. Source: [Uni10]

populous urban centres, with Sao Paulo and Rio de Janeiro expected to reach 21.7 and 12.7 million inhabitants respectively by 2025 [Uni10].

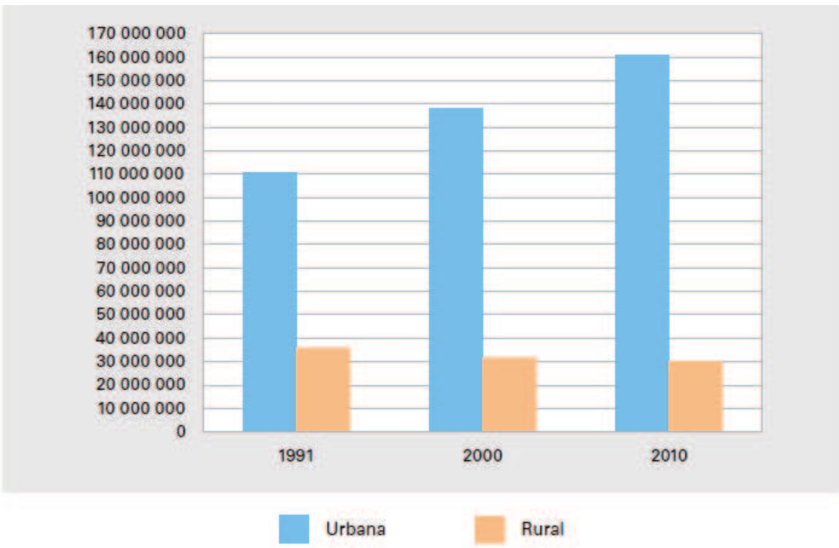

Figure I.2: Residential population for Brazilian domiciles, 1991-2010. Source: [Ins11]

According to a study published by the McKinsey Global Institute [Dob11] on the top 600 cities worldwide classified according to global GDP growth between 2007 to 2025, found that, by 2025 a mere 25% of global population would generate nearly 60% of global GDP - up from the 22% and 50% respectively for 2007. Given the above, the sheer increase in the number of urban areas, which is particularly pronounced in developing regions, and the simultaneous decline in rural population represent a clear and pressing issue in the new millennium [Uni01, Njo03]. Climate change, crime, energy, environmental, health, housing, mobility, unemployment, waste issues and many others are only a few of the challenges urban areas have to face [Obe09, The10, The11].

Clearly, the necessity of achieving sustainable development demands that the myriad of challenges associated with modern urbanization be tackled by a multi-disciplinary approach. The question of the disposal of manufactured solid waste is one such area where the application of a multi-disciplinary approach has the potential to positively influence the environmental and socio-economic issues noted above. For example, the IPCC's Fourth Assessment Report (AR4) [1] [Met07] cited a correlation between solid waste generation rates and relative income levels (see Table I.1). Population growth and its concentration also lead to the high energy demand of industrial, transport, heating, cooling, and commercial activities in cities, which consume the majority of the available energy. In turn, these consequences of increasingly worldwide urbanization, rising municipal solid waste (MSW) generation, and energy demand have a significant impact on climate change through the emission of greenhouse gases (GHG). According to the International Energy Agency's World Energy Outlook 2008 [Int08] study, cities in 2006 accounted for 67% of the global energy consumption and, at the same time, were responsible for approximately 71% of global, energy-related CO_2 emissions illustrated below in Figure I.3 [2]. Indeed, according to a Brazilian study [Dub07], undertaken in Rio de Janeiro, the solid waste sector was responsible for nearly 37% and the energy consumption sector for approximately 60% of GHG emissions in the city of Rio de Janeiro in 1998. [Dub07, Lei95, Hoo11]

Country	Low income	Middle income	High income
Annual income (US$/cap/yr)	825-3,255	3,256-10,065	>10,066
Municipal solid waste generation rate (t/cap/yr)	0.1-0.6	0.2-0.5	0.3 to >0.8

Table I.1: Municipal solid waste generation rates and relative income levels. Data source: [Met07]

Having identified the dependent relationships between waste, energy, and climate change issues, the next logical step should be to find and prepare an

[1] Intergovernmental Panel on Climate Change - IPCC

[2] Organisation for Economic Co-operation and Development - OECD

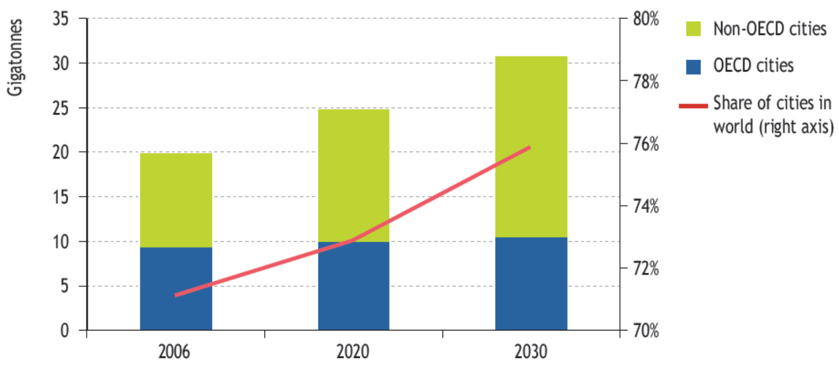

Figure I.3: Energy-related CO_2 emissions in cities in a reference scenario when compared in relation to an OECD membership. Source: [Int08]

interdisciplinary approach which respects the sustainable development of urban areas, rather than delivering a short-term solution with potentially negative long-term effects. Indeed, as the following shall make clear, the generation of MSW should be seen as an opportunity. The goal of one such interdisciplinary approach could be to help to break down the current relation between per capita waste generation rate and per capita GHG emissions, demonstrated in Figure I.4, while simultaneously producing a workable solution statement to generate energy from the treatment of MSW, which then acts as an energy source produced by the relative municipal region.

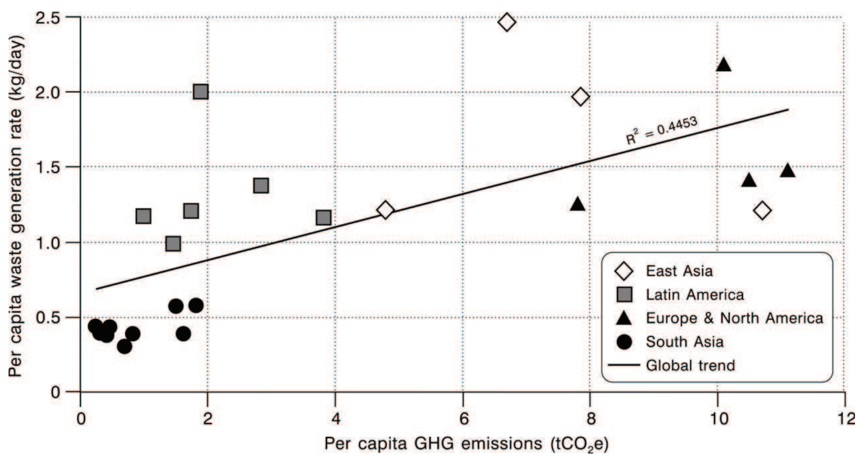

Figure I.4: Per capita GHG emissions (tCO_{2e}) and waste generation rate (kg/day). Source: [Hoo11]

I.2 Revision of bibliography

Understanding the increasing importance of addressing the issue of modern MSW production, the international and Brazilian scientific communities have recently undertaken an investigation and analysis of the issue. The main issues in the reviewed publications are energy conservation, CO_2 emission reduction, social and economic benefits, and a sustainable expansion of the energy sector related to the energetic usage of waste.

To begin, the United Nations Environment Program's (UNEP) publication Waste and Climate Change [Uni10b] provides a differentiation, potential climatic impacts and benefits of different waste management activities, such as a framework strategy addressed to national waste management. For example, the study noted that in 2005 the waste management sector worldwide accounted for approximately 3-5% of total anthropogenically emitted greenhouse gases, which correspondingly puts it in a strong position to become a major saver of emissions through waste treatment and disposal - third behind the prevention and recycling of waste. Along with detailed descriptions of waste management practices and their climate impacts, this publication highlights the significant interest in Clean Development Mechanism (CDM) activities focusing on the waste sector, which in 2009 accounted for around 18% of all active registered CDM projects, or 409 registered projects. Some of the potential opportunities offered by CDM are technology transfers from Annex 1 countries to non-Annex 1 countries, while preventing large amounts of waste and reducing at the same time GHG emissions of the receiving countries.

More recently, in 2005 Consonni et al. published, "Alternative strategies for energy recovery from municipal solid waste", divided into "Part A: Mass and energy balances" [Con05] and "Part B: Emission and cost estimates" [Con05b] - a comprehensive and comparative assessment of four strategies for electricity generation from MSW through a steam cycle. They then went on to present an expansion of these publications at the WTERT Meeting in 2006 [3] [Con05c] by defining a new system boundary which included one non-energy recovery path to express landfill disposal. Most importantly, the conclusions of them certified that pre-treatment of residual waste with the praiseworthy intention of increasing the heating value, included in strategies 2 and 3 (see Figure I.5), has little effect on the total efficiency. In addition this shows that, in relation to the total efficiency of the waste management strategy, the more that residual waste is pre-treated, the smaller the amount of energy recovered per unit of input. Corroborating these findings, a Life Cycle Assessment of the studied strategies delivers the conclusion that RDF production doesn't provide any economical or environmental benefit. Therefore, Consonni et al. recommend, based on their research findings, large combustors driven by residual waste as the most suitable practice to serve the solid waste

[3]Waste-to-Energy Research and Technology Council - WTERT

management needs of large municipal areas.

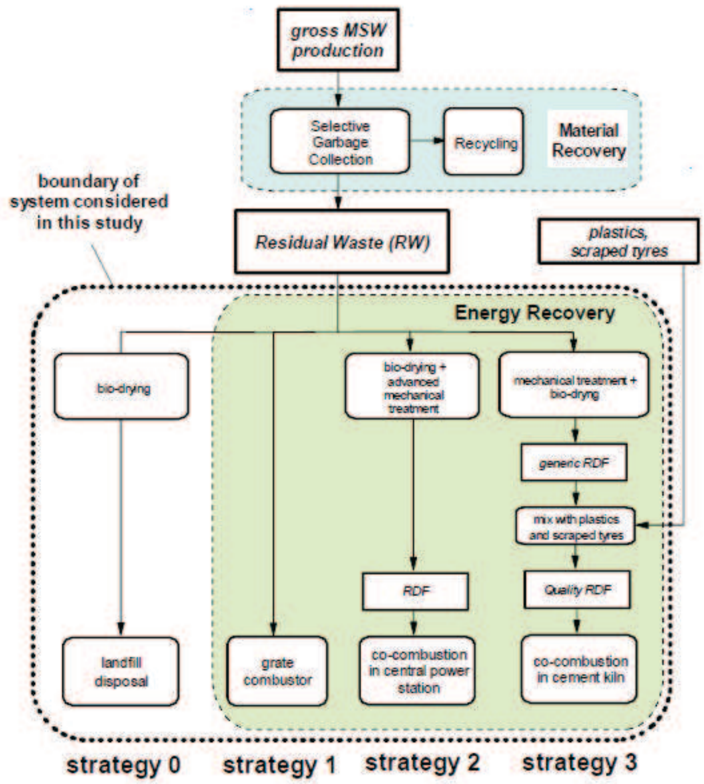

Figure I.5: Strategies and system boundary. Source: [Con05c]

With regard to the subject of MSW electrification, Oliveira & Rosa [Oli03] noted that the potential for energy production from MSW in Brazil tops 50 TWh/year, or the equivalent of almost 17% of total electricity consumption, which is quite feasible at competitive costs when compared with more traditional options like thermoelectric plants. In addition to its potential for energy production, selective garbage collection practices are also predicted to reduce GHG emissions by about 10 million tons [4] of carbon equivalent. Further, one must also note the potential socio-economic benefits that would accrue from such practices, which, at US$1.5 billion/year, account for nearly 27% of the total costs of traditional garbage collection at US$5.5 billion/year. As a result, though its operating costs are nearly triple that of its traditional competitor, selective MSW collection and treatment costs a mere US$75.00/ton compared to the US$275.00/ton required by traditional methods of disposal - more than three times less.

[4]shorthand for tonnes

In 2008, Oliveira et al. [Oli08] proved by the application of data envelopment analysis and sustainability analysis methodologies that the energetic use of waste in both methodologies is on the short-term the most sustainable input, and that it should thus be prioritized in the face of a sustainable development. Moreover, their research also indicated that local and global benefits are obtained, such as the creation of an estimated one million jobs in incineration and anaerobic digestion technology. Further, environmental advantages are also accrued by the avoidance of GHG emissions in the amount of 3,113 tCO_2/GWh through incineration and 5,223 tCO_2/GWh in anaerobic digestion, and producing an estimated 120,000 GWh/year in incineration and 85,000 GWh/year in anaerobic digestion, while simultaneously placing less demand on fuel imports.

In another study, Oliveira et al. [Oli10] examined the competitiveness of MSW electrification in the renewable energy sector, both in terms of its potential for GHG mitigation and as source of power. Interestingly, the study found that MSW electrification not only produced energy at 20-60% of the cost of wind power, but also had tremendous socio-economic-environmental benefits for society as a whole. This is surprising, because whereas both wind and small hydro require significant government subsidies in order to remain competitive, MSW electrification does not. The authors conclude that it would be more efficient to apply incentives to the use of waste for electricity generation, rather than applying them to wind power plants. In this way, an energy source.

I.3 Objectives and Contributions of the research

Motivated by the pressing need for creating an economically feasible sustainable approach to urban solid waste treatment, a methodology for a mathematical base model for the comparison of future per tonne waste treatment costs for energy and for traditional MSW treatment, will be developed in the course of this thesis. Therefore, the primary focus of our base model is to demonstrate a clear mathematical equation to calculate the necessary waste price paid to an operator of a MSW treatment plant at which investment in such a plant becomes viable. This base model will then be applied to the specific case of Rio de Janeiro by examining 20 hypothetical future investment projects.

Subsequently, our base model will then be expanded to consider the economic aspects of potential GHG mitigations due to the application of sustained conversion technologies. As we shall see, this expanded model delivers crucial information about the economic impact of Clean Development Mechanism (CDM) project registration, which necessarily alters the required waste price. For this purpose the emission reductions of a particular project will be estimated under the current body of rules and regulations in the case of Rio de Janeiro.

The findings of our research thus clearly calculate the break-even waste price under real conditions and under CDM project conditions. While the above cited publications provide certain information on the Brazilian situation, this thesis aims to provide entirely new information and analysis on the subject of MSW electrification in Brazil, both with and without carbon credits. The problem with existing studies is their tendency to focus more on the investor's benefit in the form of a specific rate of return, rather than the more practical course of determining a break-even waste price, in the form of a negative fuel price, which guarantees a common market return for the investment. These results and their resultant consequences allow the establishment of a sustainable long-term waste management and waste treatment strategy, with the added benefit of supplemental energy generation as well. To that end, this model also provides an output for the constant waste price in R$/tonne, which can then be used by future policy makers to obtain sustainable goals in the field of MSW treatment. Different options for future projects have also been integrated into this model, allowing it to be used independent of the context of time.

I.4 Structure of the work

The thesis is divided into 7 chapters, including this one.

The second chapter walks us through the topic-specific terminology (i.e. relevant terms and definitions), including background information about the generation of municipal solid waste and the waste treatment methods considered in this thesis. The aim of this part is to get the reader familiar with the topic before the bulk of the thesis begins.

Chapter 3 deals first with the current trends in MSW and then with the municipal solid waste situation in Rio de Janeiro. Therefore, the history of origins, the "business as usual" scenario relating to the treatment of MSW, and the resulting costs arising from it are determined within this chapter.

Chapter 4 contains a description of the problem, a methodology to calculate the necessary waste price, and a formal description of the model for calculating the economic feasibility of municipal solid waste treatment methods.

In Chapter 5 we aim to define the previously formulated model in a mathematical way, including the essential, global input and output variables, as well as the model for investment costs, the base model for waste price, and, finally, the expanded model respecting a CDM registration.

Chapter 6 primarily assigns representative values to input variables related to local market conditions considered under our research objectives and subsequently runs the base model as well as the model with carbon credits, before finally analyzing the results.

Chapter 7, the last chapter of this thesis, summarizes our findings, provides some concluding remarks, and then delivers an outlook on future works.

II
Terminology

This terminology section delivers a comprehensive overview of the terms and definitions used within this work - not only simple literary interpretations of relevant terms, but detailed descriptions of the conversion technologies. Having achieved this, as a result we will then have established a conceptual environment that serves as a solid base for the rest of our work. We begin with a working definition for MSW. In combination with the definition for MSW, we develop a management strategy for the life cycle of MSW. Subsequently, energy recovery practices like incineration and the combined cycle process are presented. Finally, a standard practice is presented, which includes the net present value method as well as the basics of decision-making for investment projects in the energy industry.

II.1 Municipal solid waste and emissions

The syntactical meaning of municipal solid waste, or MSW, can be analyzed by breaking the term down into its constituent parts. “Waste” consists of materials not produced for the market and therefore not called prime, or end products, which the user wants to dispose of for lack of further interest in usages like production, transformation, or consumption. “Waste” generation takes place during the consumption of end-products, the intermediate processing and production steps, the extraction of raw materials, and during other human activities. The characteristic “solid” classifies the physical state of the material, as opposed to “liquid”. “Municipal” signals the creation of the waste within the boundaries of a city or town [Uni10b]. [Org08]

According to Brazilian norm NBR 10004:2004 [Ass04], “solid waste” is defined as waste in a solid or semisolid state resulting from activities in the industrial, domestic, medical, commercial, and agricultural sectors such as services and other related activities. Included in this definition are sewage sludges from water treatment systems, liquids generated in equipment, installations for pollution control, and liquids with particularities that forbid disposal in waters and the public sewer line. Further, waste is classified within this cited Brazilian norm into:

(a) Waste class I - Dangerous

(b) Waste class II - Not dangerous

  – Waste class II A - Not inert
  – Waste class II B - Inert

However, in their study [Emp08], the Brazilian Federal Energy Planning Company, or EPE [1] , extended the question of solid waste classification according to origin and physical characteristic, summarized below. Classification by origin:

– urban: from residences, commercial activities, street sweeping, pruning of trees and the like,
– industrial: generated by transformation processes, and
– agricultural: arising from productive activities in the prime sector.

Classification by physical characteristics:

– inert materials: glass, metal, earth and ash, and
– combustible materials: paper, cardboard, plastics, wood, gum, leather, food, and others.

This classification, termed "the proper composition of municipal solid waste", has had a great influence on the calculation of emissions according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [Egg06], since the amount of fossil carbon and degradable organic carbon varies significantly for different waste types. For example, this cited report documents how waste types such as food waste, wood, textiles, and garden waste contain the most degradable organic carbon, whereas plastics, rubber, synthetic leather, and electronic waste are primilary responsible for the fossil carbon amount in MSW. Moreover, the 2006 IPCC Guidelines state that waste volume is providing meaningful information for the estimation of carbon dioxide (CO_2), methane (CH_4), and nitrous dioxide (N_2O) emissions. To compare these different greenhouse gases and their future climate impacts, a Global Warming Potential (GWP) has been calculated for each gas relative to CO_2, with values given for time horizons of 20, 100, and 500 years, shown in Table II.1

[1] In Portuguese: Empresa de Pesquisa Energética - EPE

[Sol07, Fug01]. Table II.1 shows, for instance, that for a 100-year horizon, the emission of 1kg CH_4 causes a climate impact which is mathematically equal to the emission of 25kg of CO_2.

Greenhouse gas	GWP 20-yr	GWP 100-yr	GWP 500-yr
Carbon dioxide (CO_2)	1	1	1
Methane (CH_4)	72	25	7.6
Nitrous oxide (N_2O)	289	298	153

Table II.1: Global Warming Potentials relative to CO_2. Data source: [Sol07]

The fact that the expected Global Warming Potential of different GHG gases varies becomes more important in the context of MSW treatment, as landfilled waste is one of the major methane sources worldwide. For example, methane specifically produced by anaerobic decomposition in the landfill is responsible for about 11-12% of global anthropogenic CH_4 emissions into the atmosphere [Rit07, Ako08]. According to Scheutz et al. [Sch09], qualitative GHG emissions from landfilling are classified as either direct emissions (i.e. those generated or saved due to waste treatment activity) or indirect emissions (i.e. those occurring outside the landfill), of which the latter are subdivided into upstream and downstream parts. Indirect upstream emissions consist of CO_2, CH_4, and N_2O resulting from the production of fuel, consumption of electricity, and infrastructural needs. On the other hand, downstream emissions can be further subdivided into both "negative" savings and "positive" emissions, where the savings are constituted by the substitution of fossil fuels and from the carbon bound in the landfill, while direct GHG emissions consist of the CH_4, N_2O, and CO_2 generated according to the fossil and biogenic origin, non-methane volatile organic compounds (NMVOC), and carbon monoxide (CO) caused by waste decomposition, fuel combustion through machineries, leachate treatment, and other fugitive effects.

Manfredi's et al.'s [Man09] overview of the absolute GHG emissions generated in different landfill scenarios is summarized in Table II.2. They took four different landfilling technologies under consideration. The worst case is presented as a generally unmanaged dump, designed for the disposal of many different kinds of waste. The other cases include a so-called "conventional disposal" that incinerates landfill gas in flares, an "engineered landfill" with efficient gas processing for energy recovery, and, lastly, an engineered landfill for low organic waste treatment. For the first three landfilling scenarios mixed waste, meaning half household and half inert waste, is chosen as the fuel input. The fourth scenario accepted only low organic waste. On the whole, the research findings presented in Table II.2 indicate the crucial importance of including emission savings due to the generation of electrical energy, at the very least in order to improve the greenhouse gas balance of the observed waste disposal site.

Landfilling scenarios	Upstream (indirect)	Operating (direct)	Downstream (indirect)	Net
Dump (mixed waste)	0	561 to 786	0	561 to 786
Conventional landfill (mixed waste)	2 to 12	-71 to 150	0	-69 to 162
Engineered landfill (mixed waste)	2 to 16	-71 to 150	-5 to -140	-74 to 26
Engineered landfill (low organic waste)	2 to 10	-50 to -13	0	-48 to -3

Table II.2: Absolute GHG emissions for landfill scenarios (in kg CO_{2e} / ton wet waste). Data source: [Man09]

II.2 Solid waste management

Today, Municipal Solid Waste Management (MSWM) plays a key role in providing modern urban management support by improving the organizational capacities and collaboration between the various public and private sector protagonists responsible for modern waste management. The goals of MSWM are identified as the protection of the health of the population, the promotion of environmental quality and sustainability, the support of economic productivity, and the generation of economic opportunities [Sch96]. The management of solid waste relates to the supervised treatment of solid waste material, beginning with the generation of waste at its source through the processing intermediate steps to disposal [Org08].

A key element in the description of an integrated solid waste management is the waste management hierarchy shown in Figure II.1. This hierarchy clearly outlines the most fundamental aspects of modern MSWM activities and is thus the one most frequently adopted by national and regional policy makers. The idea behind the hierarchy is to classify and rank the ensemble of possible MSW operations according to their energy production, and environmental benefits, pictured in descending order in Figure II.1. Considering the need for sustainable development and the conservation of resources, this hierarchy does act as a strategic guideline to help choose among different management practices. [Uni05]

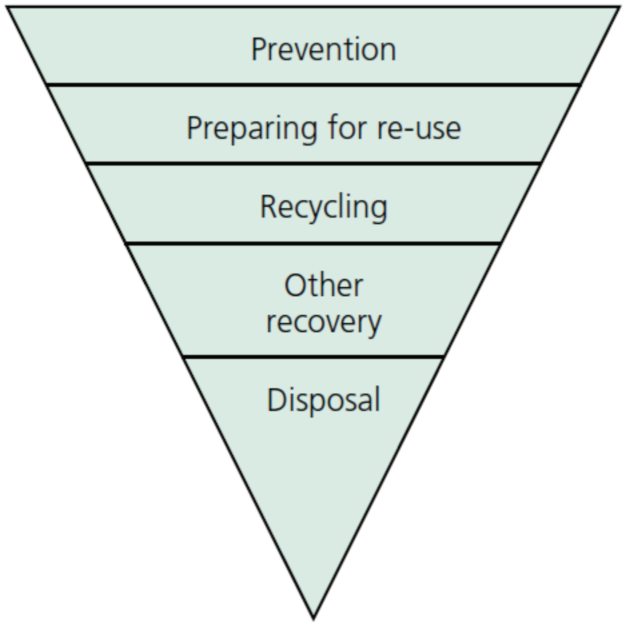

Figure II.1: Waste management hierarchy. Source: [Dep11]

The European Union implemented the waste management hierarchy as a priority order in management legislation and policy in Article 4 of DIRECTIVE 2008/98/EC [The08]. Their directive considers one-to-one the body of the above hierarchy. For them, the “prevention” of waste, or the avoidance of waste production and reduction of the generated amount, takes top priority. As a result, measures have to be taken before a material, substance, or product becomes waste, such as those that reduce the quantity of waste, pollution and other harmful effects, and which extend the useful life of products. For the second highest priority in the waste hierarchy, “preparing for re-use”, recovery operations, such as the inspection, cleaning, or repairing of discarded products and their components, are prepared in such a way that the reworked products can be re-used for the same purpose for which they were originally designed. Third is the process of “recycling” meaning any recovery process by which waste is reprocessed into its initial state. In fourth place, “Other recovery” refers to waste used as fuel or in some other capacity of energy generation, such like incineration, accelerated digestion, or other biological transformation processes. “Disposal”, such as the process of landfilling, is the last considered option. Because it does not consist of recovery, this is really the final option for waste processing, and is thus the one accorded the least priority in the waste hierarchy.

However, the waste management hierarchy provides no information about the economic relation between the different operations, nor information about expected system costs. All mentioned waste management practices have associated costs just as they bring financially quantifiable benefits. In some special cases it is possible that the overall costs of a project, meaning the entire spectrum of social, environmental, and financial considerations, may exceed the benefits. This fact has to be considered when planning new actions in the waste treatment landscape. [Uni05]

II.3 Incineration

As a process of thermal treatment, the incineration of waste is applied to a wide range of waste, including both mixed and pretreated MSW such as hazardous and medical waste. Of course, the incineration of the waste itself represents only one part of the complex waste treatment method required for the oxidation of the combustible substances contained in waste. During the burning of the heterogeneous material, flue-gases will be created that contain the majority of the available fuel energy in the form of heat. The combustion process begins when the organic substances in the waste reach the necessary temperature, or ignition point, and come into contact with oxygen (the heat having vaporized the organic substances). Virtually all of the combustion phase takes place instantly after reaching the gas phase, and it is at this point that energy is released. The need for additional fuels can be avoided when the composite of waste and oxygen feature a sufficient calorific value. [The06, The00]

Energy generated by the thermal treatment of waste, often known in the literature as energy from waste and waste-to-energy (abbreviated as EfW or WTE production plants), is considered in this work in combination with the fuel type MSW. Typical incineration values are shown in Table II.3, with LHV denoting the lower heating value. Key components of such a typical plant, using classical technology for untreated MSW, are a waste bunker, a waste feeding process, a grate-based combustion system, a boiler, a turbine and a flue-gas cleaning unit. Regulations sometimes require a waste pretreatment unit, provided in the form of a mechanical recycling assembly, located before the waste bunker. Typical conditions for the boiler steam are temperatures between 380-420°C and pressures of 40 bar. After this steam has passed through the steam turbine the resulting flue-gas is cleaned. Pollutants in the flue-gas are mostly removed by the injection of activated carbon and lime, while fly ash and other reaction products are mostly eliminated with what is commonly known as a downstream baghouse filter and acid gas scrubbers. [Spl10]

Electricity efficiency (% of LHV)	15-30
LHV (kWh / unit tonne wet waste)	413-825
Heat efficiency (% of LHV)	60-85
LHV (MJ / unit tonne wet waste)	5,940-8,415

Table II.3: Waste-to-energy conversion efficiencies. Data source: [Ast09]

The core component of WTE plants and, recommended, with sufficient cooling, by the European Commission [The06] as the best available technique for MSW incineration, is a grate-based combustion system, the one shown in Figure II.2. Inputs for the grate are waste, a feeding mechanism, as well as primary and secondary air supplies to contribute oxygen to the combustion process. Outputs are flue-gas and bottom ash. Spliethoff [Spl10] claims that the main objective of the grate is to provide a good mix while the fuel is transported through the various combustion process zones. The fuel remains for about an hour on the grate, at which point the sub processes are totally finished. This combustion process, which takes place in the grate furnace, can be divided into the following phases:

- Drying and devolatilization
- Gasification and combustion
- Burnout zone
- Secondary combustion

According to the mandate of the Intergovernmental Panel on Climate Change [Egg06], or IPCC, the emissions caused by the oxidation of solid waste, considering incineration as energy recovery, are reported in the Energy Sector. Of course, a distinction between fossil and biogenic carbon dioxide (CO_2) emissions is necessary, because only the emissions of fossil origin (i.e. plastics, rubber, certain textiles, and others) are included in national CO_2 statistics, whereas carbon dioxide emissions from biogenic origin (e.g. food, paper) are classified as biogenic emissions of short carbon cycle and are therefore not included in national estimates. Nevertheless, the absolute amounts of emissions are controlled by the fuel composition, meaning the amount of carbon in the

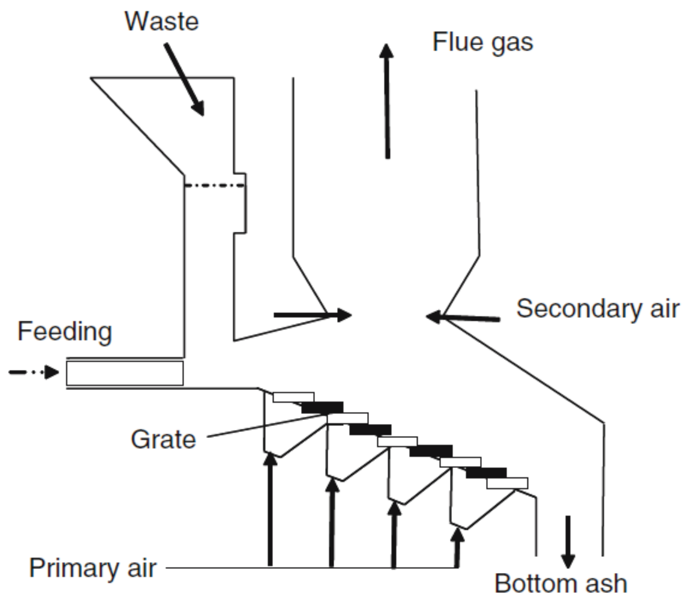

Figure II.2: Schematic drawing of a grate-based combustion system for MSW. Source: [Spl10]

MSW, which can vary considerably according to different demographic and technological conditions [Ast09].

A summary of qualitative and quantitative GHG emissions caused by the incineration of MSW, sub-classified by Gentil [Gen09] into upstream indirect, operating direct, and downstream indirect emissions, is presented in Table II.4. The absolute emissions in this table agree well with the results of an European study [Ast09] of low carbon intensive electricity generation. The table shows both numbers, one from each study, for each sub-classification. The first section of the table is devoted to indirect upstream emissions, or emissions resulting from mandatory energy and material contributions required for the operation of the system. Waste treatment technology, in this case the WTE plant, generates direct GHG emissions through the oxidation of the solid waste containing combustible substances. Finally, GHG emissions occurring downstream have a negative sign. This means that indirect downstream emissions from the incineration process are actually GHG savings, generated through the avoidance of methane emissions from a landfill.

The Decision Maker's Guide to Incineration of Municipal Solid Waste, published by the World Bank [The99] in 1999, identified important factors influencing the assessment of incineration plant feasibility in the waste management strategies of major cities in developing countries. For this purpose, a

Upstream (indirect)	
CO_2, CH_4 and N_2O from: Production of fuel and materials, consumption of heat and electricity, infrastructure	7 to 62
Operating (direct)	
CO_2 from: Fossil part of MSW CO_2 from: Biogenic fraction of MSW CH_4 and N_2O: Trace gases	347 to 371
Downstream (indirect)	
CO_2 from: Heat and electricity production by combustion of substituted fossil fuel Avoided GHG emissions from: Substituted raw materials and virgin aggregates by the recovery of metals from ash or rather bottom ash CO_2, CH_4, N_2O, CO and $NMVOC$ from: Transport of fly ash and APC residues	-480 to -712
Net emissions	-126 to -279

Table II.4: Summary of qualitative and absolute GHG emissions from incineration (in kg CO_{2e} / ton wet waste). Data source: [Sch09, Ast09]

meaningful selection of the identified advantages of MSW incineration plants is presented below. It should be noted that these advantages sometimes correlate with positive secondary effects, which can simultaneously lead to, for instance, the substitution of lower ranked practices in the waste management hierarchy shown earlier in Figure II.1.

- Waste reduction: Probably the greatest advantage of incineration technologies when compared with other waste treatment activities is a high reduction rate of volume (by 80 to 95 percent) and weight (by 70 to 75 percent).
- Location: The costs of waste transportation can be reduced through an on-site arrangement close to the source of generation, meaning that localization in urban areas is achievable and desirable.
- Energy production: Relatively constant generation and distribution of electrical, which can be fed into an existing power grid, and thermal energy, which can be fed into a local heating network, is desirable.
- GHG mitigation: WTE plants reduce GHG emissions through the elimination of methane gas emissions from the waste cycle and through the possible substitution of fossil fuel consumption in the energy chain.
- Residues: The resultant slag can be used as building material, such as for road construction.

– Carbon credits: As incineration presents an alternative waste treatment technology in comparison to traditional practices like landfills, financial benefits through avoided emissions can be achieved by applying methodology AM0025 “Avoided emissions from organic waste through alternative waste treatment processes” [Uni06], and therefore contribute positively to the feasibility of WTE plants.

On the other hand, the process of incineration, is associated with disadvantages according to the criteria established as preconditions to a successful application, as stated in the following:

– Costs: High investment costs, relatively high cost for operation and maintenance, dependency on foreign currency, and thus high waste treatment costs.
– Environmental protection: Large impacts on air pollution control and flue-gas cleaning, which are also dependent upon local regulations and laws.
– Complexity: WTE plants require skilled staff for their operation and possible maintenance work.
– Fuel requirements: The minimum amount of yearly treated MSW must not fall below 50,000 metric tons/year, the lower calorific value of the incinerated MSW may not fall below 6 MJ/kg and must be on average at least 7 MJ/kg.
– Management requirements: A well experienced and established MSWM system must already be functioning, downstream activities like landfills must be well operated, and stable general frameworks in the form of public and private stakeholders must be in place in order to make planning for a minimum 15-year operation practicable.

II.4 Combined cycle process

In order to achieve a high degree of waste-to-energy efficiency, high Carnot-coefficients and high exegetical efficiencies, thermal power stations should combine the exhaust-gas heat of a gas turbine with a downstream steam turbine process. This is feasible, as the gas turbine allows high inlet temperatures, while the steam turbine permits a low outlet temperature close to the ambient temperature [Cra09]. In addition, the application of conventional MSW incinerators delivers an unavoidable restriction when compared to a stand alone steam turbine process. As a result of the aggressive nature of the flue gas, the maximum temperature and pressure of the boiler’s steam is limited to 400°C / 40 bar. The lower temperature and pressure also limit the thermal efficiency of the process [Kor99, Goh07]. A well known solution to this common WTE technical challenge, which respects existing boiler limits, is to apply the combined cycle approach with an external superheater. Applying this method allows the exhaust from a gas turbine to continue heating the already superheated steam from the MSW boiler. [Rib10]

In order to increase the steam temperature in practical applications from the previously mentioned boiler limit of 400°C / 40 bar to higher levels, theoretical studies have offered different approaches. Korobitsyn [Kor98], for one, investigated several alternative possible configurations for the integration of gas turbines within the MSW incinerator cycle. Specifically, he compared a conventional MSW incinerator with four sophisticated integration concepts, which all provide an external superheating process positioned behind a gas turbine to achieve an increase in steam temperature. Accordingly, it was found that a hot windbox configuration with superheating was the most attractive solution (see Figure II.3). Moreover a combustion of waste is considered by Korobitsyn, where the high pressure of the gas turbine exhaust flow is needed to pass air through the arrangement in the grate-based combustion system. Steam temperatures higher than 400°C are assured by passing the steam coming from the incineration boiler with a pressure between 80-100 bar to an external superheater arranged in the gas turbine exhaust dust, where corrosive gases produce no effect. In this configuration, the externally located superheater has construction benefits in the form of a simpler design and a smaller surface area, while allowing the same increase of steam temperature as a heat recovery steam generator.

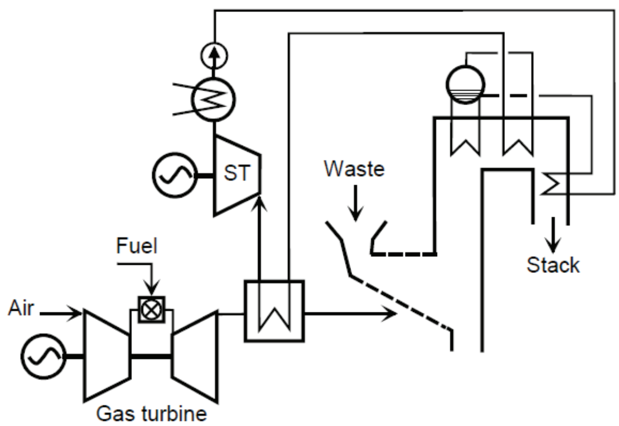

Figure II.3: The hot windbox configuration with superheating. Source: [Kor98]

The performance analysis done by Korobitsyn for the investigated cases shows several advantageous MSW treatment conditions, especially for the hot windbox configuration whose results are presented in Table II.5. Based on the lower heating value, overall plant efficiency improved to 37.3% from the 24.9% efficiency of the conventional MSW incinerator. As one of the main objectives of MSW incineration is the reduction of the amount of waste, and as a low share of natural gas (NG) in the fuel input mix, and high efficiency is demanded, the hot windbox approach has the highest MSW share in comparison with all other combined cycle processes. In fact, the MSW share is 65.5%, while also having the highest efficiency at 29.5%, based on MSW in relation to his reference case with just 24.9%. The last column in Table II.5 shows the specific surface area required by the external superheater in the hot windbox configuration. In general, this configuration is only 15% more expensive, than WTE plants, which work in parallel with a heat recovery steam generator and thus require twice as much total boiler surface area.

Fuel input	
MSW share (%)	65.51
Natural gas share (%)	34.49
Power output	
Steam turbine share (%)	70.44
Gas turbine share (%)	29.56
Efficiency	
based on total output (%)	37.28
based on MSW (%)	29.54
Specific surface area (m^2/MWe)	340

Table II.5: Summary of results for the hot windbox configuration. Data source: [Kor98]

The main disadvantage of combined cycle WTE plants burning natural gas is the high demand for natural gas. Consequently, this implies a lower MSW share for the plant, which is, of course, contrary to the original intention of applying WTE plants to treat the waste. Nevertheless, exceptional cases where combined cycle WTE plants are used for energy purposes are also known. Motivated by this imbalance, Ribeiro & Kimberlin [Rib10] propose a new WTE power plant concept based on the classic combined cycle process. This concept reduces the amount of natural gas required, while simultaneously boosting the waste share of exported net energy. Known as Optimized Combined Cycle (OCC), due to its high efficiency, MSW with a high moisture content can be used. According to the authors, this is achieved by four steps:

1. Introducing condensing heat exchangers to capture low temperature heat from the boiler flue gases.

2. High steam temperatures in external superheaters using hot clean gases heated with duct burners.

3. Mixing the exhaust gases of a small gas turbine with hot air preheated in a specially designed heat exchanger.

4. After the duct burner and heat exchangers, the gas is then used as combustion air to the MSW boiler such that all the energy stays in the system.

The numerical results of their calculation for a WTE plant using the OCC concept is shown in Table II.6. To reach an optimum design point simultaneously from a thermodynamic, MSW composition, and economical point of view, Ribeiro & Kimberlin run an elaborate computer simulation using specifically developed plant software. Moreover, Table II.6 also delivers a comparison of two almost identical WTE plants where one uses the OCC configuration. This leads to the observation, that the plant with the OCC configuration reaches a 76.48% MSW share in fuel input, which equals a decrease in natural gas consumption of 44.64%. Further, the OCC configuration's power output based on MSW increased to 68.38%, from 22.48% in the original Bilbao plant. The plant efficiency based on the use of MSW as fuel input increased to 32.65%, from 31.66% in the original Bilbao Plant. In addition to the already low natural gas demand of the OCC plant, it is mentioned that there is the possibility of substituting the natural gas with biodiesel, gasified ethanol, or biogas [Ram09].

The results of a calculation for the environmental impact caused by running an OCC WTE plant, in the form of GHG emissions, are summarized in Table II.7. Ribeiro & Kimberlin calculated firstly the emissions based on MSW for a conventional WTE plant, with a capacity of 792 tons per day, a capacity factor of 90%, and an 11.6 % share of fossil carbon content of the used waste, with emissions resulting in 110,660 tons of CO_2 per year. Afterwards they included in a second step a gas turbine consuming 21.84 MWth of natural gas (NG) to realize an OCC configuration, while considering specific methane emissions of 0.2 tons CO_2 per MWh burned NG. Altogether with the emissions caused by the burning of NG in the amount of 34,437 tons per year, total project emissions are calculated to 145,097 tons per year or, in

Configuration	OCC	Bilbao
Fuel input		
MSW share (%)	76.48	31.84
Natural gas share (%)	23.52	68.16
Power output		
MSW share (%)	68.38	22.48
Natural gas share (%)	31.62	77.52
Steam turbine share (%)	83.77	54.00
Gas turbine share (%)	16.23	46.00
Efficiency		
based on total output (%)	36.51	44.84
based on NG (%)	49.06	51.00
based on MSW (%)	32.65	31.66

Table II.6: Summary of results for a 792 tpd MSW boiler with OCC configuration and for the original Bilbao Plant without OCC. Data source: [Rib10]

terms of the daily waste input, 501.93 kgCO_2/ton MSW. Additionally, Ribeiro & Kimberlin argue that the avoided methane emissions have to be considered in addition to the generally avoided emissions when calculating the annual net CO_2 sequestration.

CO_{2e} from MSW (tons per year)	110,660
CO_{2e} from NG (tons per year)	34,437
Total CO_{2e} emissions (tons per year)	145,097
Specific CO_{2e} emissions (kgCO_{2e}/ton MSW)	501.93

Table II.7: CO_2 emissions of the MSW boiler with OCC configuration. Data source: [Rib10]

II.5 Net present value method

The final decision on whether an investment project will be finally realized or not is confirmed under real conditions by the application of appropriate arrangements. One of these arrangements, more specifically known as capital budgeting, is the discounting based procedure called net present value (NPV) method, which, according to Crastan [Cra09] is especially well-suited to many long term facilities and plants in the energy industry. Presented in the following definition by Crastan, is the main characteristic of the NPV method: that it is bounded by the requirement that capital expenditures such as operating costs, which occur at different moments and thus have different rates, are projected to a joint reference date and then summated.

In his book *Elektrische Energieversorgung 2* Crastan illustrated that all construction expenditures are referred to a reference date, which is generally the year of commissioning, whereby expenditures A_k occurring k years after this point in time are calculated to a present value B_k by using the inflation-adjusted interest rate i, see Equation (1):

$$B_k = \frac{A_k}{(1+i)^k} \tag{1}$$

By the use of Equation (1), we calculate the present values of all investment payments during a plant's life cycle as well as the net costs caused during decommissioning. Respecting the negative sign of k for expenditures that occur before the year zero (0), we receive the present value of the investment B_{inv} (2) by adding all B_k, shown in Figure II.4:

$$B_{inv} = \sum_{k=-m}^{n+p} \frac{A_{k,inv}}{(1+i)^k} \tag{2}$$

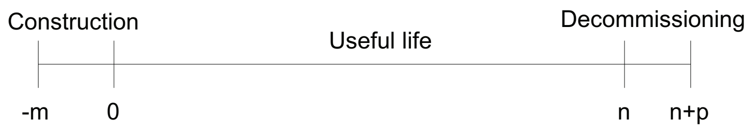

Figure II.4: Schedule of operating and investment costs with year zero (0) as commissioning date. Data source: [Cra09]

The sum of all annual operating costs observed for the useful life of the investment good, also known as the amortization period, converted to the reference year produces the present value of the operating costs B_{ope} (3):

$$B_{ope} = \sum_{k=1}^{n} \frac{A_{k,ope}}{(1+i)^k} \tag{3}$$

According to the NPV method, the total present value (B_{inv} + B_{ope}) of all expenses, or net present value, is a significant valuation basis for the cost appraisal of different investment options. Therefore, Hanafizadeh & Latif [Han11] argue that NPV's characteristics, restricted to be either positive or negative, have to be substantiated for the purpose of robustness against uncertain parameters through approaches like sensitivity or scenario analysis.

III
National trends and traditional waste treatment costs. The case of Rio de Janeiro

This chapter begins with an examination of Brazilian waste trends, followed by an inquiry of traditional MSW treatment costs. Furthermore, the specific case of Rio de Janeiro is characterized by a gravimetric analysis, an explanation of the current state of affairs and an outlook on prospective realities.

III.1 Municipal solid waste in Brazil

With the national policy on solid waste [1] that came into force in August of 2010, the Brazilian government established a national framework action plan on solid waste management directed at individuals or legal entities of private, or public law which are responsible for the generation of solid waste. For this purpose the law implements a solid waste hierarchy in the following order of priority: avoidance of generation, reduction, re-use, recycling, solid waste treatment and the environmentally-sound disposal of waste. Furthermore, the law states that proven technologies for the energetic recuperation of MSW should be used as well.

Nevertheless, the current state of affairs in the Brazilian landscape of MSW treatment is quite disillusioning. For example, a study published in 2000 by the Brazilian Institute of Geography and Statistics (IBGE [2]) [Ins00] noted that dumps accounted for nearly 64% of total MSW disposal compared with 32.2% transferred to suitable landfills (see Figure III.1). However, the study's authors also note that these numbers also represent an historical improvement, considering that in 1989 suitable landfills accounted for only 10.7% of total MSW disposal.

[1] Política Nacional de Resíduos Sólidos - Lei nº12.305, de 2 de aogosto de 2010
[2] In Portuguese: Instituto Brasileiro de Geografia e Estatística - IBGE

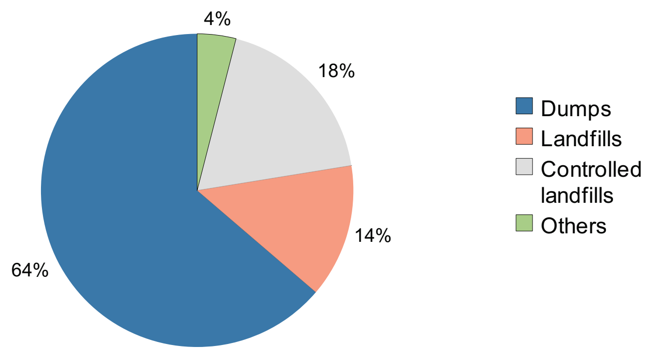

Figure III.1: Final disposal of Brazilian's MSW in 2000. Data source: [Ins00]

From the perspective of MSW generation, the Brazilian representative of the International Solid Waste Association, the ABRELPE [3], published in their most recent 2009-2010 survey of solid waste in Brazil [Ass10] important information. For example, a 6.8% growth in total MSW generation, as well as a 5.3% increase in relative numbers to 378.4 kg/hab/year was noted (see Figure III.2). According to study's authors, this development presents an interesting situation, because both rises are even bigger than the urban population growth rate of approximately 1% in the same period under observation.

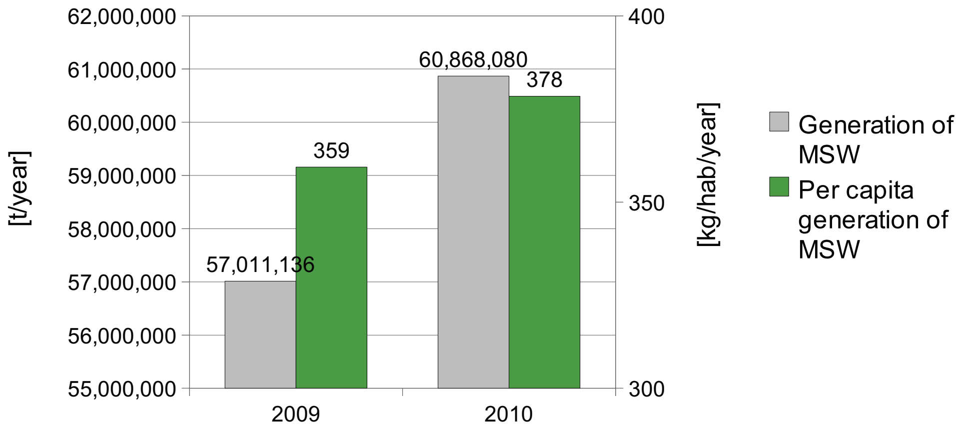

Figure III.2: Evolution of MSW generation in Brazil. Data source: [Ass10]

The comparison of the total waste amount generated in 2010 with the collected amount of MSW shows that some 6.7 million tons of MSW were not collected and, as a consequence of this, were disposed improperly. However, the authors also note several positive tendencies emerging from the study, such as the total amount of MSW collected, which increased by 7.7%, and the related increase in the collection of MSW per capita, which increased by about 6.3%. In general, this reveals the higher growth rate of the collected amount compared

[3]In Portuguese: Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais - ABRELPE

to the generated amount, in accordance with the authors of the survey, an increase in coverage of countrywide waste collection services.

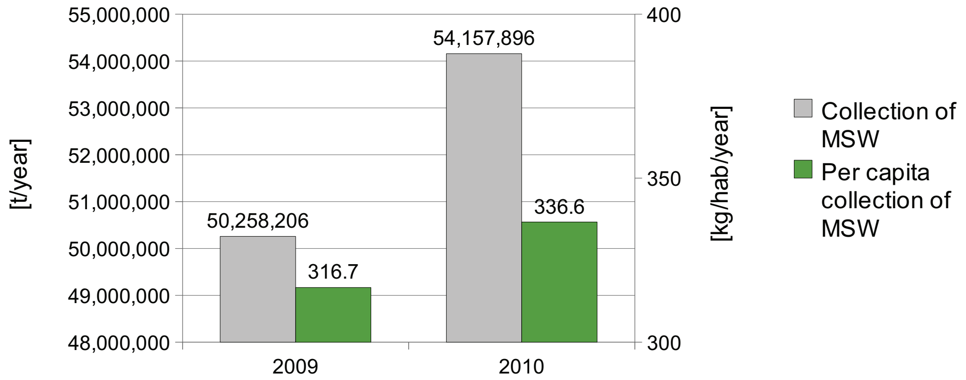

Figure III.3: Evolution of MSW collection in Brazil. Data source: [Ass10]

Finally, Figure III.4 illustrates the important role played by urban cleaning services in the Brazilian economy, with a market capitalization exceeding R$ 19 billion in 2010 and the generation of some 300 thousand jobs, which increased about 5% from the previous year. Indeed, the authors of the ABRELPE survey mention that such jobs are of special importance to the emerging Brazilian economy, as they help fill the need for unspecialized labor, thus contributing positively to social stability.

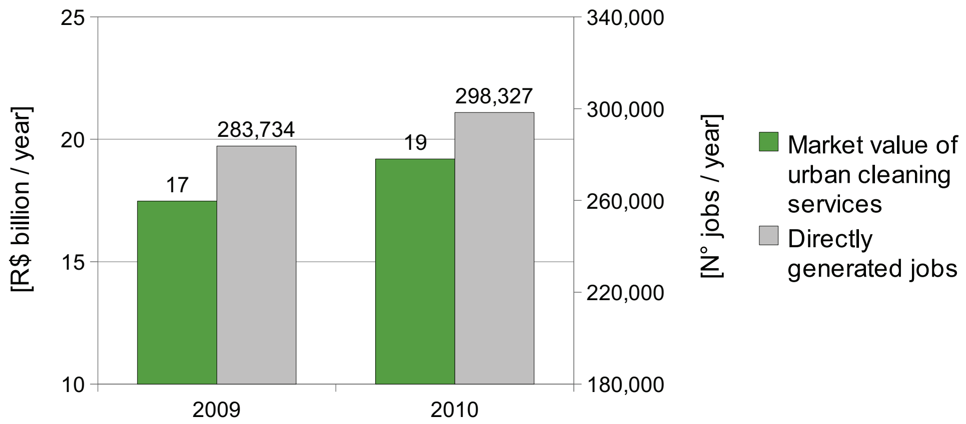

Figure III.4: Market value and job generation by MSW. Data source: [Ass10]

III.2 The case of Rio de Janeiro

In this section, we will examine MSW management in regard to the special, local conditions of the municipal area of Rio de Janeiro, Brazil. For this purpose, COMLURB [4] is chosen as a representative substitute for the urban

[4]In Portuguese: Companhia Municipal de Limpeza Urbana - COMLURB

area. COMLURB is a publicly-traded company controlled by the municipality of Rio de Janeiro. With a collection rate of approximately 9,000 tons/day, out of the total 11,769.30 tonnes per day recorded in 2010 by the ABRELPE, the COMLURB is a good representative for the scope of the present study. For example, the company collects both domestic and publicly generated waste of the whole city, whereas only 40% of this portion is collected by nearly 11,000 street sweepers. [Com11]

(a) Generation and gravimetric characterization

Below, Figure III.5 shows the historical progression of solid waste generation, subdivided according to home and public waste.

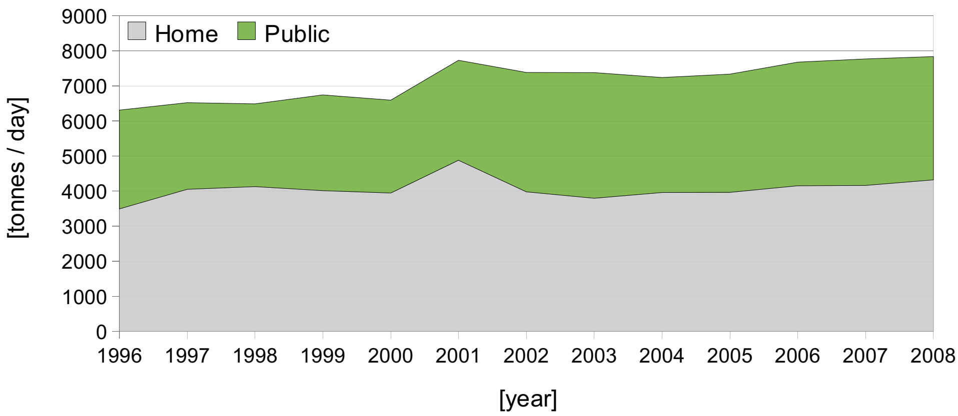

Figure III.5: Home and public waste generation in Rio de Janeiro. Data source: [Com11]

The percentage determination of the fraction of single components, like paper, glass, plastic, organic material, within a representative waste sample is called gravimetric analysis. This analysis serves to outline more specific parameters, such as humidity and specific weight, used to determine the recycling potential of waste products, the feasibility of composting and displays changes in the lifestyle of inhabitants. The course of such a gravimetric analysis for the time frame 1995-2009 is formed in Figure III.6. Specifics for the year 2009, including moisture content, are registered in Table III.1.

The results of such an analysis can be used in the pre-decision process, when different treatment methods are considered, as the fraction of different components (e.g. the 53.63% percentage of organic materials or the 40.26% moisture content) are, in certain circumstances, significant indicators for the feasibility of different strategies.

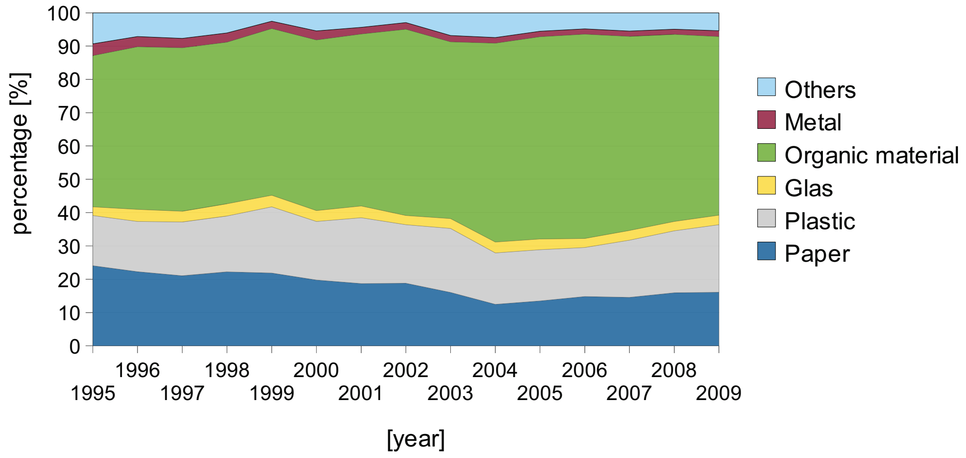

Figure III.6: Gravimetric analysis of Rio de Janeiro's MSW. Data source: [Com09]

Component	Percentage [%]
Others	5.40
Metal	1.74
Organic material	53.63
Glass	2.84
Plastic	20.31
Paper	16.08
Moisture content	40.26

Table III.1: Summary of gravimetric analysis results for 2009. Data source: [Com09]

(b) The waste flow and current state of affairs

The waste flow, which in this case represents an average value in tonnes per day over the period January to June 2009 in the municipal area of Rio de Janeiro, is pictured in Figure III.7 [5]. Simply put, MSW treatment in Brazil begins with the collection of the waste itself. This waste is then carried to four intermediate stations. Two of these, Irajá and Caju, also function as recycling plants, while the latter is also employed as a composting plant, charging R$ 30 per tonne of organic waste [Dia11]. On the other hand, Jacarepaguá and Missões operate as waste transfer stations, known as ETRs [6]. Monthly transferred amounts of MSW are displayed by Figure III.8.

[5] Waste received at stations (In Portuguese: Lixo Recebido nas Estações)
Transfer COMLURB (Transferência COMLURB)
Transfer Large Producers (Transferência Grandes Geradores)
Total amount received at the landfill (Total Recebido nos Aterros)

[6] In Portuguese: Estação de Transbordo de Resíduos - ETR

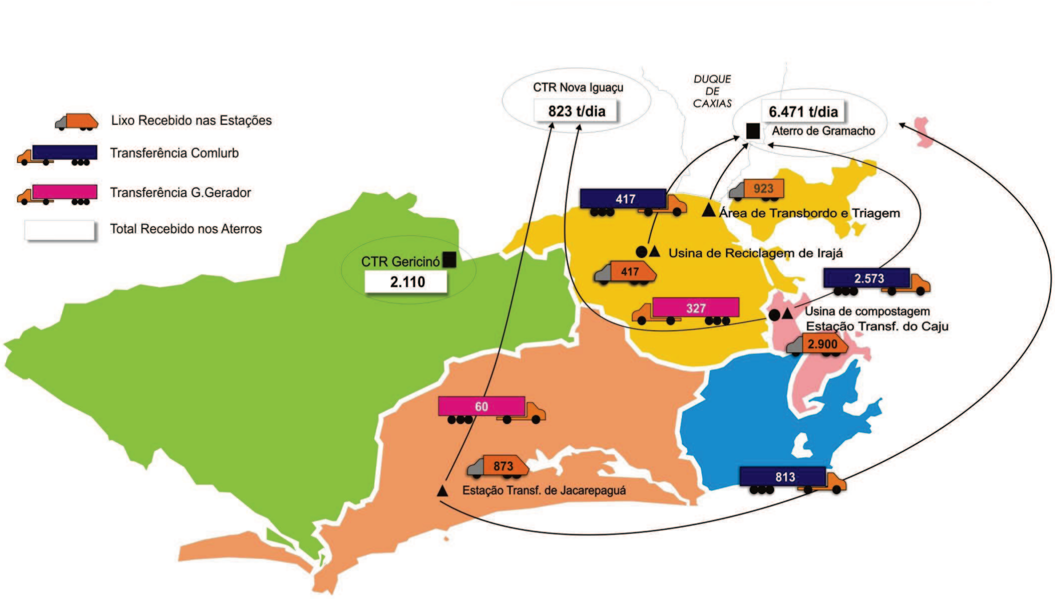

Figure III.7: Waste flow in t/day from January to June 2009. Source: [Fon10]

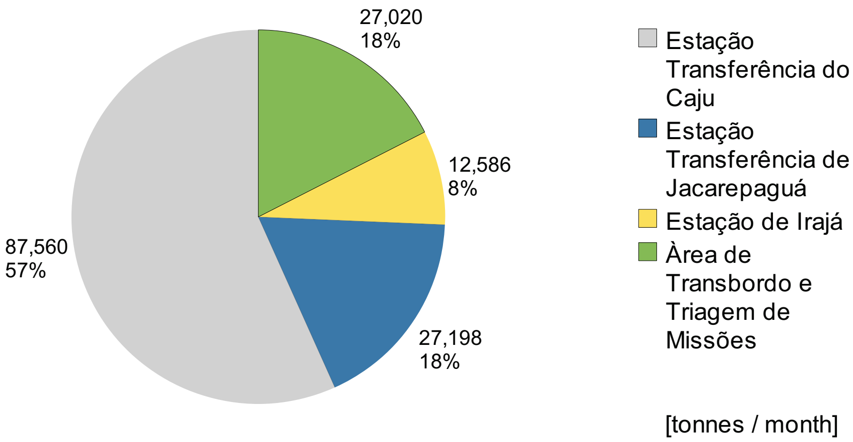

Figure III.8: Monthly transferred amounts in 2009. Data source: [Fon10]

Subsequently, the output of the 4 intermediate stations is carted to permanent waste storage units in the form of waste disposals. Two charted routes, the 60 tonnes per day from ETR Jacarepaguá as well as the 327 t/day from Caju to the CTR [7] Nova Iguaçu landfill, are waste transfers for large producers. These special clients are required to pay R$ 20 per tonne for the first 24 hours of utilizing these ETR's; after this, the ETR's charge the same value, but per hour [Dia11]. COMLURB transfers its collected and pre-treated solid waste to the Gramacho landfill and to the smaller CTR Gericinó, which has similar operating conditions but receives only 23% of Rio's waste. As a result of these transfers, both landfills are already operating over-capacity

[7] In Portuguese: Centro de tratamento de resíduos - CTR

[Lix09, Fon10].

In their 2009 Environmental Impact Report [Ver09] COMLURB makes a note of CTR Gericinó's expired operating life. Commissioned in 1985 and operated since 2002 by a company called Delta Construções, CTR Gericinó, which is located in the district of Gericinó within the metropolitan area of Rio de Janeiro, currently processes about 4,000 tonnes of MSW per day at most. In the first half-year of 2009, Gericinó received 2,110 t/day as well as levied a gate fee for nonhazardous waste in the amount of 17 R$/ton [Fon10, Dia11].

Located in Duque de Caixas within the municipal area of Rio de Janeiro, the Gramacho landfill is the biggest landfill for MSW in Latin America. Commissioned in 1987 as an open dump and managed by COMLURB, Gramacho received in the first half-year of 2009 approximately 77% of Rio de Janeiro's waste, amounting to some 6,500 tonnes a day [Fon10]. Beginning in the 1990's, COMLURB has since sought to convert the open dump into a sanitary landfill, and today Gramacho fulfills many of the formal requirements, such as controlled access, waste compaction by bulldozers and adequate access roads. A pre-feasibility study prepared for the World Bank [Scs05] noted that the landfill is projected to close in 2005, after having landfilled more than 29 million metric tonnes of MSW. However, by the first half-year of 2011, Gramacho still is in service with a gate fee of 14 R$/ton. [Dia11, Gra09]

(c) The prospective waste flow

Given the inadequacies of the current active waste flow system, the prospective system is to be composed of a central final disposal site fed by seven transfer stations (see Figure III.9). The daily and monthly transfer rates, for the new ETR's as well as those of the already existing stations Caju and Jacarepaguá are shown below, in Table III.2 and Figure III.10. In addition, following pre-treatment at destination ETR's, a daily amount of 9,000 tons of waste will be transferred to a privately operated landfill named CTR Santa Rosa, located in the municipality of Seropédica. Covering an area of more than two hectares, this landfill is slated to open in 2011 and is expected to have an operating life of 18 years. [Lan10, Fel10]

For this purpose, COMLURB signed a 15-year contract with the possibility of two further 5-year extensions with the company SERB [8], a subsidiary of Julio Simões Participações S/A. The initial value of this "Contract CTR RIO" amounts to R$ 1,007,628,360 and obligates SERB for the execution and

[8] In Portuguese: Saneamento e Energia Renovável do Brasil S.A. - SERB

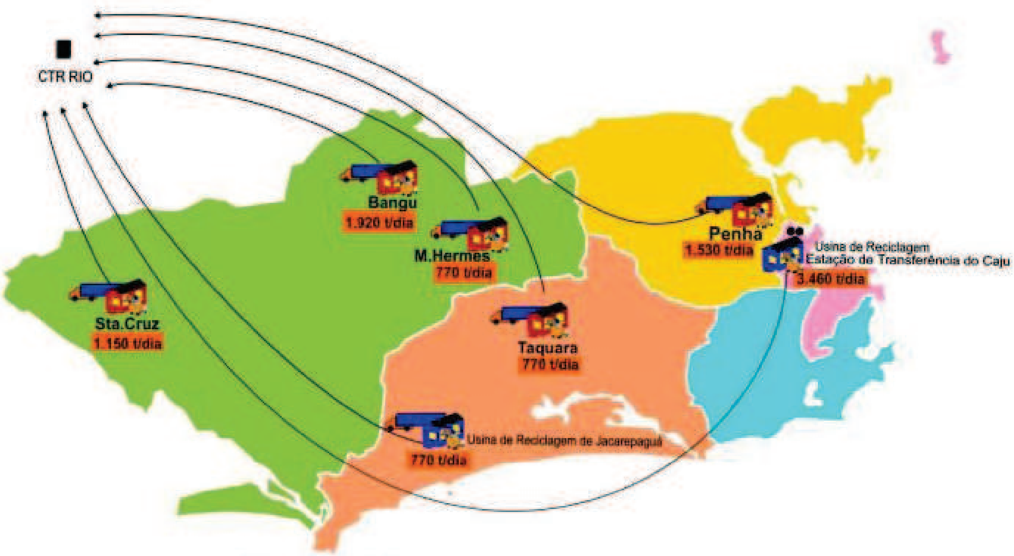

Figure III.9: Future waste flow in t/day. Source: [Fon10]

ETR	Daily waste amount [t/day]
Penha	1,333
Marechal Hermes	667
Taquara	667
Santa Cruz	1,000
Bangu	1,667
Caju	3,000
Jacarepaguà	667
Total	≈ 9,000

Table III.2: Daily future waste transfers. Data source: [Fel10]

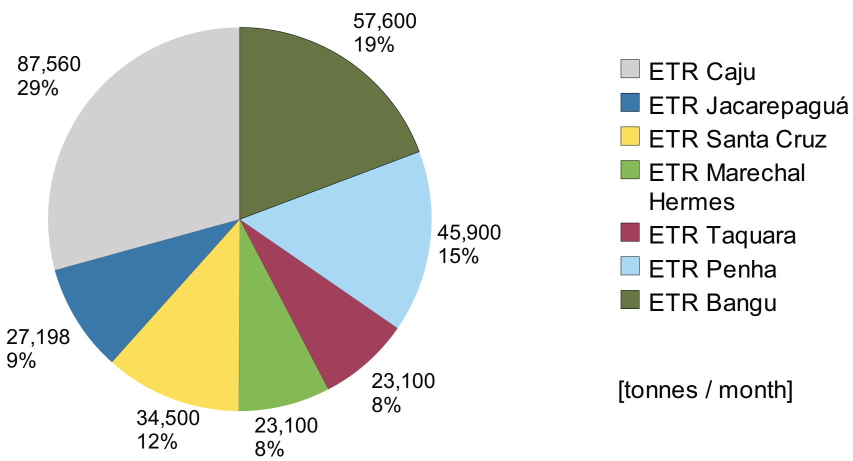

Figure III.10: Expected monthly transferred future amounts. Data source: [Fon10] operation of the waste treatment center of Rio de Janeiro. Moreover, the concession contract between COMLURB and SERB also stipulates the execution of the seven ETR's. The aim of this contract is thus the centralization and optimization of logistics of waste processing in Rio de Janeiro, with the intention of lowering costs for both collection and transportation. According to the value of an executed payment in April of 2011, the gate fee for Seropédica has been estimated at R$ 37.20 per tonne of MSW [9]. Therefore, COMLURB paid R$ 855,607,500 based on a 7-year acquisition period. [Dia11b, Jul10, Fel10]

[9] The lack of public information necessitated an estimation of the gate fee for the new CTR Santa Rosa. In order to do so, the gate fee has been estimated with the above mentioned contract values, a capacity factor of 1, and the knowledge that the daily received amount will be 9,000 t/d:
$Gatefee = \frac{R\$855{,}607{,}500}{365d \cdot 7years \cdot 9{,}000t/d} = 37.20 R\$/t$
The contract conditions contained this value for operation and transportation costs. The transport costs can be estimated by the specific freight charges, the daily waste amount m_i transferred from Table III.2, and the distance x_i between ETR i and the CTR: $c_t = \sum_{i=1}^{7} \left(x_i \cdot m_i\right) \cdot \frac{0.51 R\$/t/km}{9{,}000t/d}$. Using Google Maps (http://maps.google.com.br) to estimate the distances x_i as well as using 0.51 R$/t/km for the specific transport costs gives us for c_t: $c_t = \left(1{,}333 \cdot 56.1 + 667 \cdot 44.8 + 667 \cdot 49.6 + 1{,}000 \cdot 32.5 + 1{,}667 \cdot 36.2 + 3{,}000 \cdot 68.4 + 667 \cdot 54.2\right) \cdot \frac{0.51}{9{,}000} = 26.74 R\$/t$
Consequently, real costs for the waste treatment on-site (i.e. those related to final disposal) can be determined to 10.46 R$/t. This value seems to be exceedingly low for operation and maintenance, especially when compared to gate fees from the ordinary landfills Gericinó and Gramacho, which accounted for 17 and 14 R$/t. Hence, we have to look at this value with a critical eye.

IV
The model for calculating the economic feasibility of municipal solid waste treatment methods

Studies and analyses concerning the economic feasibility of technical facilities are a common and necessary arrangement in the process of decision making. On the other hand, although necessary, the rather abstract, mathematical nature of such processes means that their results tend to focus more on the individual tasks involved than on the system as a whole, with all its possible and thinkable interactions. As such, this chapter seeks to correct this bias, at least in part, by first outlining the parameters of this problem, and by subsequently presenting the methodological approach and description of the mathematical model used later in this study.

IV.1 Description of the problem

A detailed description of the treated problem provides, on the one hand, an identification of the main challenges involved as well as an overview of the topic, while, on the other hand, providing a segregation of primary and secondary objectives. As a result of this process, the importance of first identifying the parameters of the problem and subsequently developing a suitable mathematical model with accurate input values will become clear.

Significant factors of influence to relations with the mathematical model are defined:

- Level of abstraction: For a better understanding of this point it is necessary to distinguish between different points of view and other such interests. Our aim is not the design of a computational model which respects, for example, the whole material life cycle of consumer goods, industrial commodities, or whatever finally ends in waste. To investigate the proposed research field it is important to descend a few more steps to the level of abstraction where the energetic use of MSW is considered.

For example, the energetic use and transformation of primary carrier MSW into useful energy which is identified as electrical energy. Therefore, from the viewpoint of our plant operator, it is crucially important that primary energy is categorized and delivered according to the guidelines established in the existing contract, including its amount, type, delivery date and calorific value, whereby the power plant is able to produce under stipulated terms of contract a predetermined amount of energy to market.

– Valuation method: Before proceeding to the concrete design and formulation of our model we must first distill the suitable valuation methods and find a practicable method to prepare practical, useful results for our research. As noted earlier, the literature associated with this study has already published some useful approaches to make informed investment decisions. Crastan [Cra09], for example, states that dynamic techniques, based on discounting, should be applied to the process of the economical comparison of energy sector constructions, such as NPV, or annuity methods. Similarly, Law [Law04] and Slater [Sla98] noted the favorable impacts of the NPV method for strategic investments, which are especially positive when taking the concept of the time value of money into consideration.

  A special case is given when the discount rate equals the internal-rate-of-return. This means that the NPV goes to zero, or, in other words, the monetary value of all discounted income flows compensates the monetary value of all discounted outgoing cash flows [Hir58]. A NPV equal to zero also implies that an investment creates the originally expected rate of return. However, the more important consideration is to determine which interest rate can be expected, or, more importantly, which rate is representative for this particular investment, rather than simply reflective of shareholder interest? For this reason and due to the fact that the uncertainty of investment projects sometimes plays a major role, NPV method is expanded by applying, firstly, the Capital Asset Pricing Model (CAPM) to estimate the cost of equity capital and, secondly, the Lambda Approach to accommodate possible country risks [Lee98, Dam03].

  Under consideration of the main singularity and characteristic that this feeding demonstrates, including the existence of more or less predictable and varying cash flows over time, such as economic incentives in the form of an acquirable interest rate, and the necessity of providing a clear condition for the waste price for every power plant investment project in a defined period under observation, we apply the NPV method in our model. Especially because of the annually varying cash flows, NPV, with its elementary boundary conditions for decision making, is particularly useful for our purposes.

– Mathematical model: One of the core problems in the decision making process of complex systems, where subareas like energy, markets, technology, and environmental issues intertwine, is the development of a simplified mathematical model. A key role in this connection, model input, output parameters, and the definition of a target function are integral in accounting for all the various factors of influence. Another important aspect of our model is the decision regarding the moment when the information for making our decisions is to be processed, which necessitates that all cash flows have to be adjusted (discounted or accumulated) to that specific moment. Regardless, it must be recognized that such a process will never be exact and will always entail risks - e.g. modeling too much may result in a leakage of the actual aim. Thus the true test remains balancing the need for a sufficient depth of information with the need for timely action. As such, the application of the CAPM in conjunction with the Lambda Approach extension provides a traceable base assumption, which serves to produce a realistic expectation for investor's profits. Below, Figure IV.1 demonstrates the categorical bodywork of the mathematical model.

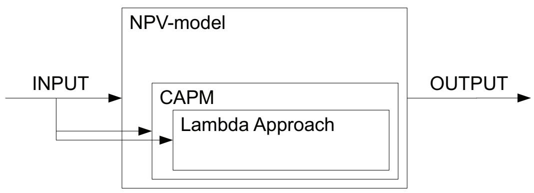

Figure IV.1: Bodywork of mathematical model

– Collection of data: The quality and representativeness of our model output correlates to an extremely high degree with the model input accurateness and completeness thereof. One of our sub goals is to compare the per ton waste treatment price in the specific case of the metropolitan area of Rio de Janeiro when energetic and traditional MSW treatment is considered. In addition to this, an authentic forecast for respective power plant revenues due to the sale of electricity also influences the recurrent cash flows in an important manner.

- Environmental and external impacts: For the purposes of this study, it is understood that at the global, national and regional levels, unpredictable events will inevitably occur which can cause a correspondingly unpredictable modification of the original model's conditions. Examples include mandatory emissions trading, a lawful increase of biomass percentage entering the energy mix, or a modified subsidy policy. This was documented by Pawlina & Kort's [Paw05] study on the impact of policy changes, in the form of investment credit taxes and on the investment behavior of firms. These events, in many cases initiated by policy makers, stakeholders, and other interest groups, are difficult to estimate, and thus equally difficult to take into account mathematically. Consequently, this study shall not consider those impacts in our base model, although the possibility of implementation within different scenarios is, of course, always given.

With the complete description and identification of the problem we are now able to frame abstract model conditions within the methodological approach.

IV.2 Methodological approach

This section contains a methodology to estimate the price paid for a ton of MSW in order to turn this initial investment into a viable power plant. As previously mentioned, the NPV method will be our state of the art tool for decision making within the mathematical model. To meet the requirements of a coherent model and provide a more or less simplified algorithm, we must first limit the ensemble of all possible configurations to a rational level. Consequently, boundary conditions will be defined in the following listing.

- Inflation: Unless otherwise noted, all monetary values in our calculations are implied to be inflation adjusted and purchased to a reference date. Hence inflation is not considered or equal to zero, a nominal rise in price level is caused by a real price increase and can be explained by fundamental data - e.g. higher demand causes higher offer.

- Time span: In reality, the lifetime of the investment varies in accordance with the useful life of the asset, which means that financing adaptation is needed to ensure a complete mathematical model. However, given the need for relative simplicity in our calculations, such cases will not be considered in this work. Also important in our design is the approval and construction time of waste treatment technology, which is defined to be exactly one year and always occurring in year zero of the project start. However, decommissioning is neglected within our research.

- Investment: For the purposes of our work, it is supposed that the same investment conditions apply to every investigated waste treatment technology. More precisely, the same equity and debt capital percentage, interest and taxes, credit period and cash flow moments are presumed to be constant. In addition, plant insurance is not considered within our study.

- TUST and TUSD: According to a resolution of the national energy agency ANEEL [1] special conditions exist for renewables that allow their exclusion of the transmission fee TUST [2] and the distribution fee TUSD [3]. As a result, some requirements have to be fulfilled, such as the requirement of an installed capacity lower than 30 MW, or the 50% minimal percentage of fuel input required to accrue from a renewable energy carrier. It is assumed that all conditions for the application of this exception are fulfilled. [Age04]

- Efficiency: Neither an increasing power plant efficiency as a result of technological improvement, nor an increasing net calorific value (e.g. as a result of varying food patterns) is estimated to modify the efficiency factor.

- Amount of waste: It is presumed that the necessary amount of MSW to run a power plant under its design point is always available.

- Power plant revenues: In general, it is always necessary to evaluate the necessity of generating thermal- and electrical-energy, because of the possible lack of thermal-demand in the observed area. Therefore, possible thermal-energy contributions to the plant revenues will not be considered.

In order to achieve our research objective, to demonstrate a methodology to calculate the price to treat one tonne of waste paid to a treatment plant

[1] In Portuguese: Agência Nacional de Energia Elétrica - ANEEL
[2] In Portuguese: Tarifa de Uso dos Sistemas de Transmissão - TUST
[3] In Portuguese: Tarifa de Uso dos Sistemas de Distribuição - TUSD

operator that results in a value at which investment in such a plant becomes viable, we shall now proceed towards the design of the mathematic model. Of all considered boundary conditions and system relevant variables, the main objective function in our model declares NPV for every investment goes to zero, subject to the break-even waste price. This condition guarantees that investors receive their expected rate of return.

Another fundamental characteristic is represented by the fact that our main aim is to calculate the necessary waste price obtained to a reference date for every capital spending project. In general, cash flows are considered to occur chronologically after the reference date, which is identified as 2010. Therefore, every future cash flow has to be discounted to the year 2010. This conversion is an essential component of a proper decision-making process, considering that we shall examine different investment alternatives with different starting times, and we want a representative waste price valid for the reference date for the future project lifetime. Therefore, a question fitted to a hypothetical power plant project realized in 2015 could be: "We are in 2010 and our intention is to evaluate the possibility of constructing a power plant in 2015. What value paid for MSW to the power plant operator within the time frame 2016 to 2035 is needed in order to achieve a NPV for this investment of zero?"

The following section describes the assembly of the mathematical model for this purpose in syntax, prior to assembling a system of equations in the subsequent section.

IV.3 Description of the mathematical model

In the course of this work a mathematical model to support strategic and sustainable investment decisions favoring the energetic treatment of MSW in urban areas has to be developed. The mathematically formulated NPV method delivers for this an objective function separated into two parts, the first of which presents the investment costs, while the other stands for the annually appearing cash flows. As a result, we are able to use these separated parts to simplify the main functionality and examine the asset financing function, as a kind of precondition for the overlaid waste price function implemented in the base model. In a further step we expand this base model and consider expenditures and revenues pursuant to the reduction of GHG emissions.

(a) Model for investment costs

Our sub model, responsible for calculating the overall investment cost cash flows, is designed to consider a partially external project financing. The part financed by equity capital, a percentage of the total investment costs for the power plant, is considered to be a single cash flow occurring exactly and exclusively in the initial year when the power plant will be build - i.e. year zero in the language of the project time of every investigated investment. Equation (1) describes the cost of equity capital for the investment in the year of construction:

$$\text{Cost of equity capital } (0)_{[R\$]} = \text{Total investment costs}_{[R\$]} \cdot \text{equity ratio}_{[1]} \quad (1)$$

On the other hand, cash flows resulting from the external financing are presumed to occur initiating with the insertion of in- and outgoing payments from year one (i.e. year of commissioning) until the end of contract period. The annual share of the power plant's amortization caused by external finance is calculated when dividing the externally financed investment cost part by the contract period, see Equation (2):

$$\text{Annual amortization}_{[R\$]} = \frac{\text{Total investment costs}_{[R\$]} \cdot (1 \text{ - equity ratio})_{[1]}}{\text{Contract period}_{[1]}} \quad (2)$$

To receive the annual cash flows we have to include the yearly adapted interest payments into our calculation by using the account balance (3),

$$\begin{aligned}\text{Account balance (year)}_{[R\$]} = &\ \text{Account balance (year - 1)}_{[R\$]} \\ &- \text{Annual amortization}_{[R\$]}\end{aligned} \quad (3)$$

The account balance in the initial year exactly corresponds with the external finance need, shown in (4):

$$\text{Account balance } (0)_{[R\$]} = \text{Total investment costs}_{[R\$]} \cdot (1 \text{ - equity ratio})_{[1]} \quad (4)$$

After this intermediate step we are able to calculate the time-discrete interest payments when multiplying the account balance from the year before, because we have to pay the interests for the expired recent treaty year, with the interest rate for external financing, see Equation (5):

$$\text{Interest payment (year)}_{[R\$]} = \text{Account balance (year - 1)}_{[R\$]} \cdot \text{Interest rate}_{[1]} \tag{5}$$

Equation (6) pictures the annual diversifying cost of debt, when adding time-discrete interest payments to constant annual amortization:

$$\text{Cost of debt (year)}_{[R\$]} = \text{Interest payment (year)}_{[R\$]} + \text{Annual amortization}_{[R\$]} \tag{6}$$

Finally the investment sub model output variable, a cash flow presenting function which contains cost of equity capital and cost of debt, defined in (7), will be delivered to the overlaid waste price model.

$$\text{Investment costs}_{[R\$]} = \begin{pmatrix} \text{Cost of equity capital (0)}_{[R\$]} \\ \text{Cost of debt (1)}_{[R\$]} \\ \text{Cost of debt (2)}_{[R\$]} \\ \vdots \\ \text{Cost of debt (Contract period)}_{[R\$]} \end{pmatrix} \tag{7}$$

(b) Base model for waste price

Under consideration of the rendered investment cost function we are able to define an objective function, expressed by Equation (8). NPV stands for the net present value, and is a function of the project initial year and waste price. Furthermore, it must be mentioned that the calculation rule for the whole model is that all occurring outflows are supposed to be mathematically negative, while inflows are determined to be mathematically positive. Furthermore, as with cash flows, investment costs must also be discounted for every single observed investment project to our reference date of 2010.

$$\begin{aligned} \text{NPV}_{[R\$]} = & -\text{Sum of discounted investment costs}_{[R\$]} \\ & + \text{Sum of discounted cash flows}_{[R\$]} \end{aligned} \tag{8}$$

With the calculation of the net cash flow presented in Equation (9):

$$\text{Net cash flow}_{[R\$/yr]} = -\text{Expenditures}_{[R\$/yr]} + \text{Revenues}_{[R\$/yr]} \tag{9}$$

Though general expenditure costs are fixed, variable costs due to used technology tend to be consolidated to the costs for operation and maintenance, while tax payments and revenues have to be seen in terms of energy sale and the payments due to the treatment of waste, (10) and (11):

$$\begin{aligned}\text{Expenditures}_{[R\$/yr]} &= \text{Fixed costs}_{[R\$/yr]}\\ &+ \text{Relative variable costs}_{[R\$/ton]} \cdot \text{Waste amount}_{[ton/yr]}\\ &+ \text{Tax payment}_{[R\$/yr]}\end{aligned} \tag{10}$$

$$\text{Revenues}_{[R\$/yr]} = \text{Energy sale}_{[R\$/yr]} + \text{Waste treatment payment}_{[R\$/yr]} \tag{11}$$

The amount of energy produced annually can be calculated by multiplying the maximum output power with the number of hours in a year and with the capacity factor of the power plant, (12):

$$\begin{aligned}\text{Produced energy}_{[MWh]} &= \text{Maximum output power}_{[MW]}\\ &\cdot \text{Annual hours}_{[h]} \cdot \text{Capacity factor}_{[1]}\end{aligned} \tag{12}$$

Earnings pursuant to the sale of energy and the revenues generated due to the absorption of a certain amount of MSW are calculated by multiplying the energy price with the energy produced in the first case and by multiplying the specific waste price with the waste amount, taking into account the conversion efficiency, in the latter case, (13) and (14):

$$\text{Energy sale}_{[R\$]} = \text{Energy price}_{[R\$/MWh]} \cdot \text{Produced energy}_{[MWh]} \tag{13}$$

$$\text{Waste treatment payment}_{[R\$]} = \text{Waste price}_{[R\$/ton]} \cdot \frac{\text{Produced energy}_{[MWh]}}{\text{Efficiency}_{[MWh/ton]}} \tag{14}$$

Finally, the necessary and sufficient boundary condition (15) delivers the possibility of a transformation of our objective function (8) in order to receive a clear expression for the waste price.

$$\text{NPV (initial year, break-even waste price)}_{[R\$]} = 0 \qquad (15)$$

The calculated break-even waste price is contract based valid for every investment project, respectively, and the dedicated lifetime is determined by NPV presented in Equation (8) goes equivalent to zero and ensures, in addition, power plant revenues in the amount of (14). These formally selected equations and implied conditions are conditioned to be formulated in the mathematical syntax appearing in the following chapter. Prior to this, we expand the already presented approach by a further one, which includes the Clean Development Mechanism (CDM) [4].

(c) Model with carbon credits

An interesting and sustainable expansion of the above described base model for waste price is given when including economical rating of greenhouse gas emission reductions in the form of units, termed Certified Emission Reductions [Fis05]. In conjunction with the designed expression for the net cash flow presented by Equation (9) within the base model, we classify design relevant influences in a similar manner. Expenditures due to the CDM can be described in general as such cash flows which would not occur if the project would not be registered in the CDM project database. These costs are known as CDM-specific project costs [Eco07]. On the other hand, the estimated emission reductions generate carbon credits, which could increase investor's revenues and contribute positively to the overall project financing. First, however, some standards and procedures for the correct registration as a CDM project have to be fulfilled.

Therefore, we apply in our model with carbon credits the "Approved baseline and monitoring methodology AM0025: Avoided emissions from organic waste through alternative waste treatment processes" [Uni10c] and, at the same time, assume that all requirements and conditions for their applica-

[4]The idea of the CDM is to allow emission-reduction projects in developing countries to earn Certified Emission Reduction (CER) credits, each equivalent to one tonne of CO_2. Afterwards, these CERs can be traded and sold, and used by industrialized countries to meet a part of their emission reduction targets under the Kyoto Protocol. One of the main global aims of the mechanism is to stimulate sustainable development in less developed regions and emission reductions, while giving industrialized countries some flexibility in how they meet their emission reduction targets. [Uni11c]

tion are fulfilled. Moreover, our aim is to model qualitative effects according to the CDM registration, rather than model the entire implementation process, i.e. simplifying presumptions of the baseline methodology are additionally applied.

The formulated model for investment costs as a necessary pre-stage for subsequent models can be assembled as one-to-one ex-changes with regards to content. A modification of exogenous nature is given by a changed borrowing requirement, which, however, does not affect the model itself. Additional capital expenditure requirements as a result of charges in the planning and construction phase of a CDM project are designed to be performed in the initial year of a power plant project. The primal total investment costs, already used in Equations (1), (2), and (4), are modeled together with the monetarily increased CDM investment costs pictured in the form of summands, see (16):

$$\begin{aligned}\text{Total investment costs}_{[R\$]} = {} & (\text{Total investment costs})_{[R\$]} \\ & + \text{CDM investment costs}_{[R\$]}\end{aligned} \tag{16}$$

Even so, an extension of the base model to involve supplementary, constant, and variable costs, such as other additional spendings required by the CDM registration is modeled as a modification of the net cash flow (9), and declares for this reason an internal system enhancement. Generally composed of additional expenditures and revenues, the mathematical model with carbon credits adjusts the net cash flow in a well-arranged manner, such as additional outgoing cash flows, in an expansion to Equation (10) caused by required financial resources in the operation phase of a CDM project, (17):

$$\text{Expenditures}_{[R\$/yr]} = (\text{Expenditures})_{[R\$/yr]} + \text{CDM operation phase costs}_{[R\$/yr]} \tag{17}$$

and incoming cash flows generated by the sale of carbon credits increase bracketed power plant revenues, originally modeled out of (11), in Equation (18):

$$\text{Revenues}_{[R\$/yr]} = (\text{Revenues})_{[R\$/yr]} + \text{Carbon credit sale}_{[R\$/yr]} \tag{18}$$

With the composition of revenues in accordance with the sale of carbon credits (19):

$$\text{Carbon credit sale}_{[R\$]} = \text{Estimation of emission reductions}_{[tCO_{2e}]} \cdot \text{Carbon price}_{[R\$/tCO_{2e}]} \quad (19)$$

The estimated emission reductions per year (20) are given by the annual difference of estimated baseline emissions and estimated project emissions, when neglecting a third negative factor which would respect sources of leakage, such as leakage emissions from raised transport, from the residual waste within an incineration process, and from a potential end-use of stabilized biomass [Uni10c].

$$\text{Emission Reductions}_{[tCO_{2e}]} = \text{Baseline emissions}_{[tCO_{2e}]} - \text{Project emissions}_{[tCO_{2e}]} \quad (20)$$

Emissions in the baseline scenario (i.e. in the absence of the project activity) itself are due to the considered methodology composed of several summands (21):

$$\begin{aligned} \text{Baseline emissions}_{[tCO_{2e}]} = {} & \text{Produced landfill methane}_{[tCO_{2e}]} \\ & - \text{Destroyed methane}_{[tCO_{2e}]} \\ & + \text{Baseline of displaced energy production}_{[tCO_{2e}]} \end{aligned} \quad (21)$$

Further steps in this class would be the calculation of the partly complex and single fractions of Equation (21), such as the annually generated amount of methane from a landfill calculated by applying "the approved Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site" [Uni11] and other considerations for the remaining two parts [Uni10c]. Nevertheless, the determination of baseline emissions is one of the most crucial points in the CDM registration process, since they serve as a benchmark against which virtual project emissions are measured and, subsequently, Certified Emissions Reductions (CERs) are issued [Fis05]. Baseline emissions within this research will be adopted from already existing and representative reference projects deemed representative of our specific conditions.

Project emissions, subtrahend in Equation (20) and listed entirely in (22) according to the baseline methodology [Uni10c] for the specific reality, are simplified during this thesis to a product from a global emission coefficient and the amount of waste incinerated. Therefore, we are neglecting the first two summands in Equation (22):

$$\begin{aligned} \text{Project emissions}_{[tCO_{2e}]} = & \text{ electricity consumption on-site due to project}_{[tCO_{2e}]} \\ & + \text{on-site due to fuel consumption on-site}_{[tCO_{2e}]} \\ & + \text{from waste incineration}_{[tCO_{2e}]} \\ & + \text{due to fuel consumption for co-firing}_{[tCO_{2e}]} \end{aligned} \tag{22}$$

V
Mathematical formulation

The mathematical formulation of our model, to calculate the price for one ton of MSW, will be developed in a double-stage procedure. Under consideration of the formal description of the mathematical model (see previous chapter) we institute and describe, to a certain extent, first the necessary variables, needed for the later established system of equations. Subsequently, a sub model to calculate and transfer the annual varying cash flows pursuant to a partial external financing will be designed before we are finally able to deliver an explicit relation between break-even waste price and all considered input values in order to complete this chapter. Finally, the extension of the base model to a model respecting environmental advantages through the application of sophisticated technology in the form of carbon credits will be expounded.

With regard to this matter, it should be noted that these definitions are arbitrary assumptions based upon our current understanding, which serve to protect the complexity, as well as the simplicity of our modeling. Of course, different problems maybe require adaptions and expansions in the form of new, or altered variables supplementing our system of equations. Regardless, all published variables and constants remain satisfactory to describe our present model entirely. A general convention for a better readability is that lowercase letters present relative values, while capitalized characters stand for absolute values.

V.1 Global variables

Global variables are defined to be independent of special model configuration, meaning they will not be modified if we change any input parameters. They exist during a whole model run from beginning to the end, in general with validation and visibility in executable functions and present, more or less, a system's status. As such, all defined variables are of a time-discrete nature, i.e. only integer values will be adopted.

(a) Relative time

The relative time t is used in our model as a runtime index within sum functions in order to discount occurring cash flows during the project lifetime of a credit period, and can be seen in general as a time step index. Therefore relative time t has to be adjusted for every single project in another codomain, which respects the reference to our base year 2010.

(b) Global time

To distinguish between the runtime index t used to discount cash flows, which are composed of project-related expenditures and revenues and the global time index used to define the beginning of an investment project, or, more precisely, their first operating year, we make use of a new variable called σ. For each σ there is a NPV, a respective waste price, as well as a price for energy, which will be explained later on. In general, σ labels the first year of an investment project when cash flows start to occur (i.e. the proximate year after the completion of the treatment plant). As a value range will be considered (1):

$$\sigma \in [2011, 2012, \ldots , 2030\ ] \tag{1}$$

(c) Runtime variable

To meet the needs of incorporating partially external financing in our sub model, a runtime variable, k, is invented. Interest payments give reason for the necessity of this index, because these payments are decreasing in character and vary from year to year. For this reason a variable capable of detecting the corresponding cash flow is needed, which stands for the relative year within the credit lifetime. As a value range will be considered (2):

$$k \in [0, 1, 2, \ldots , \text{Contract period}\ ] \tag{2}$$

V.2 Input variables

Of the utmost significance in this model is the coherent selection of representative input parameters in order to assure legitimate research results. These exogenous variables, some of them constant, others variable, are united by a common ground (as their name suggests), because all of them are supplied from outside and serve the description of extrinsic states just as change in states.

(a) Technology parameters

Conversion technology related variables are assorted and classified in the first procedure towards two aspects; economic and technical instance. Afterwards, it is of particular importance to make sure that all variables are prepared for universal application to power plants through the use of consistent units. The commercial perception is basically dictated by investment costs (I_0) for the power plant building, fixed costs (c_f), and variable costs (c_v), whereupon these last two mentioned cost units, when necessary or unavailable, are sometimes shaped and joined together as costs for operation and maintenance ($c_{O\&M}$). Table V.1 specifies this first group of technological parameters:

Variable	Unit	Description
I_0	R$	Investment costs
c_f	R$	Fixed costs
c_v	R$/tonnes/yr	Variable Costs
$c_{O\&M}$	R$/ton waste	Operation & maintenance costs

Table V.1: Economical technological parameters

In addition to the economical classification of conversion technology we will consider technical parameters in a second step. The maximum power plant's output P stands for the nominally installed capacity in MW available at the exit surface. An exogenous, time-independent value, which combines the concrete plant efficiency and the calorific efficiency of the converted MSW, is defined by Equation (3):

$$\eta_{plant,calorific} = \eta_p \cdot \eta_c \tag{3}$$

where η_p is the percentage efficiency factor based on MSW and η_c is the calorific value in MWh/ton. This value describes the conversion ratio of primary MSW energy to end energy. With the constant overall GHG emission coefficient $COEF_p$, where p represents technology (short for plant), we are defining a specific constant in this subsection. Completed by the capacity factor CF, which takes into account a deviation of the real, annually produced energy from the maximum amount of energy, which could be produced due to the installed capacity of the power plant, Table V.2 lists these technological aspects:

Variable	Unit	Description
P	MW	Output power
$\eta_{plant,calorific}$	MWh/ton	Efficiency
$COEF_p$	tCO_{2e}/ton	Emission coefficient
CF	1	Capacity factor

Table V.2: Technical parameters

(b) External financing parameters

The separately designed model for investment costs is characterized primarily by three significant exogenous variables, where the equity ratio e_r defines the percentage of equity capital to total investment capital, the lend term, or credit period of external financing is modeled by an integer value LT and, subsequently, by an interest rate on debt, where i_{EF} represents the clean part of repayments pursuant to financing costs. Table V.3 identifies this group:

Variable	Unit	Description
e_r	1	Equity ratio
LT	1	Credit period
i_{EF}	1	Interest rate on debt

Table V.3: External financing parameters

(c) Discount rate

To describe the rate of return, which is equivalent to the expected return on an asset, we define risk-free borrowing or lending at a risk-free rate of interest as R_f. The difference between the expected return on market portfolio and risk-free rate is defined as mature market equity risk premium RP, and CR labels an additional risk premium due to country risk. In sum, then, we mean by β and λ the systematic risk of an asset as well as the exposure of a company to country risk [Fam04, Dam03]. Table V.4 shows a summary of the required CAPM parameters:

(d) Tax payment function

Inevitably occurring tax payments, discharged from the operator to the responsible government are in the first instance defined as a return value of an abstract tax-function f_{tax}(“cash flow”), that is, in R\$, with incoming

Variable	Unit	Description
R_f	1	Risk-free rate
RP	1	Mature equity risk premium
CR	1	Country risk premium
β	1	Systematic risk
λ	1	Lambda

Table V.4: CAPM parameters

and outgoing cash flows operating as corresponding, independent variables. However, given the nonlinear input-output relation of f_{tax}, the concrete design and internal coherency of this function cannot be made clear at present; it is a highly progressive matter (e.g. jumping tax rates due to tax progression).

Nevertheless, two important characteristics of our tax-function should be mentioned. They will be required in our later model to simplify the equations and to ensure a formal solution. For this purpose, we can easily insert transient inputs CF_1 and CF_2 as well as multiplicative factors a and b. One characteristic, the named addition theorem, permits the separation of the tax payment function into additive components, such as to separate shares, which are produced by different sources of income (see Equation (4)).

$$f_{tax}(CF_1, CF_2) = f_{tax}(CF_1) + f_{tax}(CF_2) \tag{4}$$

A second theorem is defined to enable a potential linearization of f_{tax}, wherein the property of linearity, from a system theory point of view, is given. The unit of the return value of f_{tax}, more precisely, the unit of a hypothetical, multiplicative product of a and b within f_{tax}, is considered to be in R\$. When withdrawing one factor, in this case a, the new unit of the function return value is defined to accept the unit of the remaining factor, which is in this case that of b (see Equation (5)).

$$f_{tax}(a \cdot b) = a \cdot f_{tax}^{-1}(b) \tag{5}$$

(e) Energy price

Financial inflows compose an important share of revenues due to energy sales. The price $p_{energy}(\sigma)$ for one unit of energy in view of commodities, under the general conditions outlined in R\$/MWh, is a function of global time σ, but is considered to be constant for the whole lifetime of a project. For every power plant investment project which has a different starting time σ, energy prices may vary in a time discrete manner.

(f) Carbon credit price

The variable used to clearly picture the price of carbon credits in R$ for one tonne of CO_{2e} is defined as $p_{carbon}(\sigma)$. An annual variation of this variable depending on the initial year σ may occur, but it must be constant within the period under consideration for a special investment project.

(g) CDM specific parameters

Additional costs generated by the necessity of implementing CDM related peculiarities, are divided into three stages. In the first stage, necessary payments occur in conjunction with the project investment or as payments which consider single CDM-specific characteristics at the beginning of a project, which will be identified as $I_{0,CDM}$. Furthermore, annual outgoing cash flows are labeled as the fixed costs $c_{f,CDM}$, unit R$/year, and variable costs as a percentage of generated CERs are labeled as $c_{v,CDM}$. Below, Table V.5 summarizes the terms presented above.

Variable	Unit	Description
$I_{0,CDM}$	R$	CDM Investment costs
$c_{f,CDM}$	R$/year	CDM fixed costs
$c_{v,CDM}$	1	CDM variable costs

Table V.5: CDM specific costs

The second part of CDM specific parameters handles the definition of an emission related variable, labeled as baseline emissions BE in tCO_{2e} of a project, or, in other words, expected emissions which would occur without the concrete project execution.

V.3 Output variables

Endogenous variables are described by the model as a functional connectivity of input and state variables embedded in a system of equations. Our main objective in this section is the clear definition of not only the variables themselves, but of their function in combinations as state-variables.

(a) Investment cost function

As an output function of the sub model that calculates the annual part of the investment costs - function in a sense that their name corresponds with the delivered function value, while being at the same time an input value representing function for the superposed waste price model - this output variable has to be followed separately. The investment cost function $I_{inv}(k, I_0, e_r, LT, i_{EF})$ features a function name, I_{inv}, independent variables k, I_0, e_r, LT, i_{EF}, and an output function, or a so-called dependent variable, I_{inv}, whose unit is R$.

(b) Produced energy

The yearly generated Energy, E, represents, under consideration of a take-off influenced by any production downtime, the contractually agreed amount of energy in MWh/year delivered from a particular power plant to grid.

(c) Waste amount

To implement the treated amount of waste formulated in our equations, or to calculate the necessary amount of MSW in tons/year, we must check and confirm our previously made assumption, which stated that the amount of MSW to run a power plant under its optimum conditions is available for every analyzed treatment technology, we define the drawn variable as q^w.

(d) Project emissions and emission reductions

The emitted greenhouse gases generated by each project per year will be known as project emissions, or PE (unit tCO_{2e}/year). Annually calculated emission reductions, which can be first estimated, before the actual savings are registered, and subsequently generated by a more GHG neutral conversion technology initiated in the year σ, is defined to ER with the unit tCO_{2e}/year. See Table V.6 below.

Variable	Unit	Description
PE	tCO_{2e}/year	Project emissions
ER	tCO_{2e}/year	Emission reductions

Table V.6: Emission parameters

(e) Expected return

Calculated from an externally developed sub model and designed entirely of linear correlations, $E(R)$ represents an expectable and plausible yield for the investor and thus an expected rate of return under given market conditions. $E(R)$ is also used as a state variable in our model to discount yearly cash flows.

(f) Waste price

One of the main endogenous variables in our model stands for the per ton waste price $p_\sigma{}^{(w,BE)}$, paid to the operator of the incineration plant for taking a certain amount of MSW in such a way that the used technology becomes viable, which from an economic perspective is what is needed in order to achieve a break-even point. It is important to mention that the waste price, also known as the gate fee, is assumed to be constant for the duration of the asset's lifetime secured through contract, but that this can vary for every specific initial year σ of the project.

V.4 Summary of all variables

To sum up all of the discussed variables, Table V.7 lists the entire classification in global, input, and output variables, which are the necessary parameters for our system of equations.

Subsequently we utilize these global, exogenous, and endogenous variables to frame a primary model for the investment cost cash flows and a superordinated model to calculate waste prices for all observed investment project starting times. An assignment of the in Table V.7 summarized variables is presented in Figure V.1, whereas marginal deviation adjustments should be permitted.

V.5 Model for investment costs

Taking into account the above described approach for the investment cost function, we will now proceed to describe in this section the constitution of corresponding function values. As such, our current focus is to display the function value I_{inv}, which corresponds to an investment cash flow, as a function of the defined runtime variable k, which in turn corresponds with any year within our investment time frame.

For the initial year of every investment project in which a power plant

Global variables		
Variable	Unit	Description
t	1	Relative time
σ	1	Global time
k	1	Runtime variable
Input variables		
Variable	Unit	Description
I_0	R$	Investment costs
c_f	R$	Fixed costs
c_v	R$/tonnes/yr	Variable Costs
$c_{O\&M}$	R$/ton waste	Operation & maintenance costs
P	MW	Output power
$\eta_{plant,calorific}$	MWh/ton waste	Efficiency
$COEF_p$	tCO_{2e}/ton waste	Emission coefficient
CF	1	Capacity factor
e_r	1	Equity ratio
LT	1	Credit period
i_{EF}	1	Interest rate on debt
R_f	1	Risk-free rate
RP	1	Mature equity risk premium
CP	1	Country risk premium
β	1	Systematic risk
λ	1	Lambda
f_{tax}("cash flow")	R$	Tax payment function
$p_{energy}(\sigma)$	R$/MWh	Energy price
$p_{carbon}(\sigma)$	R$/$tCO_{2e}$	Carbon credit price
$I_{0,CDM}$	R$	CDM Investment costs
$c_{f,CDM}$	R$/year	CDM fixed costs
$c_{v,CDM}$	1	CDM variable costs
BE	tCO_{2e}/year	Baseline emissions
Output variables		
Variable	Unit	Description
$I_{inv}(k, I_0, e_r, LT, i_{EF})$	R$	Investment cost function
E	MWh/year	Produced energy
q^w	tons/year	Waste amount
PE	tCO_{2e}/year	Project emissions
ER	tCO_{2e}/year	Emission reduction
$E(R)$	1	Expected return on asset
$p_\sigma{}^{(w,BE)}$	R$/ton waste	Waste price

Table V.7: Summary of all defined variables

will be assumed to be constructed, it is assumed that the necessary constraint ($k = 0$) is achieved. Only an elementary calculated cash flow from the product of total investment cost and equity ratio, corresponding to the equity capital

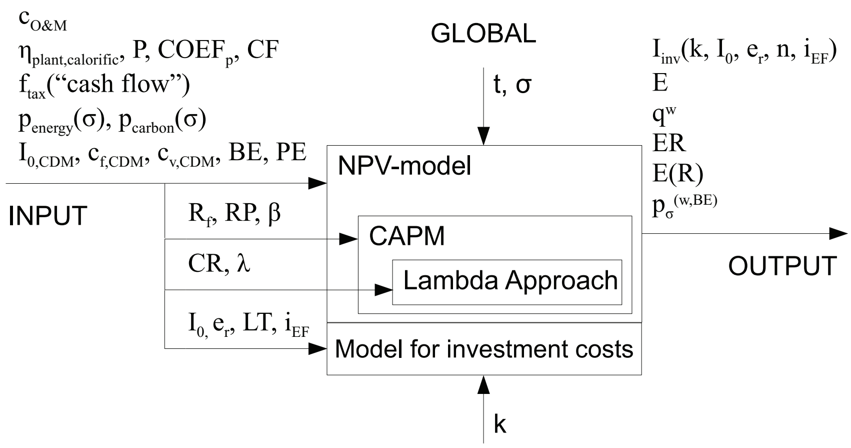

Figure V.1: Bodywork and assignment of variables

contribution, is necessary for this purpose, see (6):

$$I_{inv}(0) = I_0 \cdot e_r \tag{6}$$

From the first year in our external financing period, where $(k = 1)$, until the end of the contract period, equivalent to $(k = LT)$, we define a relation analogous to Equation (7):

$$I_{inv}(k) = \frac{I_0 \cdot (1 - e_r)}{LT} + \left[I_0 \cdot (1 - e_r) - \frac{I_0 \cdot (1 - e_r)}{LT} \cdot (k - 1) \right] \cdot i_{EF} \tag{7}$$

To analyze the mode of operation and to get a better understanding about the main functionality of this designed sub model we must partially separate Equation (7) into its constituent properties. A constant part in every externally financed cash flow, which occurs every year k within the credit period, belongs to the annual amortization, which is simply calculated by dividing the external financing amount by the contract period. Pure interest expenses due to the raising of credit are presented thus by the bracketed term in Equation (7). The squared bracket within the equation stands for the annually decreasing account balance and contains two meaningful expressions: the minuend displays total borrowing costs due to external financing, while the fraction part, or subtrahend, describes the annual share of repayments already made in previous years, and is thus multiplied with $(k-1)$. By multiplying the bracket expression and the interest rate on debt we instantly receive the interest expenses of the relevant year k. The addition of annual amortization and interest expenses provides the investment cash flow in year k where constraint $(0 < k \leq LT)$ is satisfied.

Taken together, Equation (8), given below, thus describes the entire sub model for investment costs cash flows by uniting Equations (6) and (7). These cash flows will be delivered as function or return values to the superordinated waste price model described in the following section.

$$I_{inv}(k) = \begin{cases} I_0 \cdot e_r & \text{if } k = 0 \\ I_0 \cdot (1 - e_r) \cdot \left[\left(1 - \frac{k-1}{LT}\right) \cdot i_{EF} + \frac{1}{LT} \right] & 0 < k \leq LT \end{cases} \tag{8}$$

V.6 Base model for waste price

The skeletal structure of our main model is, of course, dictated by a NPV pattern using investment cost function and other, still uncalculated, output variables. To begin, a chronological order of procedure has to be assured, as not to anticipate still undefined mathematical terms within an equation. Accordingly, the order of necessary output variables definitions will be produced energy, E, waste amount, q^w, expected return on asset, $E(R)$ and, finally, break-even waste price ${p_\sigma}^{(w,BE)}$.

The total produced energy, E, in MWh/year during one operating year is defined by (9), with P being the nominal output power of the plant, 8760 h/year (= 365 day/year · 24 h/day) as maximum number of hours per year and, ultimately, the capacity factor CF.

$$E = P \cdot 8760h \cdot CF \tag{9}$$

Using the calculated total produced energy, or E (9), in combination with the previously defined and constantly estimated input value for efficiency $\eta_{plant,calorific}$ (3), we receive the necessary waste amount to run a power plant under its design point, vide infra Equation (10):

$$q^w = \frac{E}{\eta_{plant,calorific}} \tag{10}$$

For calculating the project based break-even waste price ${p_\sigma}^{(w,BE)}$ for every investigated investment and every year of issue σ we use the NPV approach. The calculation of the NPV method is organized in two components: a negative expression that presents the investment costs and a positive expression that includes discounted cash flows, pictured below by Equation (11):

$$NPV_\sigma\left(p_\sigma{}^{(w,BE)}\right) = -\sum_{t=0}^{LT}\left(\frac{I_{inv}(t)}{(1+E(R))^{t+\sigma-2011}}\right) + \sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{FCFE_\sigma}{(1+E(R))^t}\right) \tag{11}$$

The left side of Equation (11) labels the net present value NPV_σ in the year σ as a function of the waste price. The dependence on global time σ was chosen specifically, as it enunciates a specific project linkage and opens the possibility of an annual alteration. On the other hand, the right side of the equation is composed of two sum functions with important impacts. In the first sum function, negative algebraic sign dates from our previously chosen sign convention, as we can see the investment cost function $I_{inv}(t)$ with t as a independent variable. The codomain of t is fixed by the sum function and guarantees integer values within the range $0 \leq t \leq LT$, whereby t reaches a value only once during a run. However, this should in turn guarantee access to any function value I_{inv}, or investment cash flow, during the credit period. In collaboration with the term in the denominator, each occurring investment cash flow is divided by a corresponding exponential function with the base $(1 + E(R))$ and the exponent $(t + \sigma - 2011)$. The exponent's obligation is to fulfill the necessary condition that each cash flow is discounted to the base year 2010. We can check this immediately when taking under observation the previously mentioned hypothetical case with construction beginning in 2015. Thus for the year of commissioning σ is valid $(\sigma = 2016)$ and for the exponent of the discount rate $(1 + E(R))$ we obtain $(t + 5)$. In combination with the lower bound of the sum function $(t = 0)$ we receive for the denominator of the investment cash with reference to the year of construction $(1 + E(R))^5$. Finally, the corresponding investment cash flow $I_{inv}(0)$ is divided by $(1 + E(R))^5$, and is thereby discounted to the reference year 2010. The chronology for this illustrative example is shown by Figure V.2.

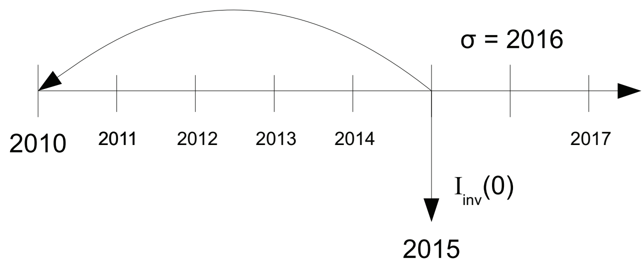

Figure V.2: Investment cash flow discounting with $(\sigma = 2016)$ and $(t = 0)$

Similar in the appearance to the above, the second sum function in

Equation (11) with positive algebraic sign contains the cash flows. The first impression of an approximate layout for the second sum function is not correct, because the indices of the sum function and the fraction term feature slight adjustments. The sum function indices dependent on global time, or σ, start at $(\sigma - 2010)$ and end after a considered project lifetime of 20 years at $(\sigma + 19 - 2010)$, providing the denominator $(1 + E(R))^t$ to discount cash flows correctly. These cash flows, or free cash flows to equity, are included by the variable $FCFE_\sigma$ in the numerator of the fraction, and are in general composed of expenditures and revenues. We are now able to demonstrate the correct operating mode, for this second sum function in the same manner as with the first one by illustrating the case with $(\sigma = 2016)$ as the year of commissioning. Hence the sum function starts with lower bound $(t = 6)$ and the belonging cash flow $FCFE_{2016}$ corresponds with the discount rate $(1 + E(R))^6$. Ultimately, discounting the observed free cash flow to equity at the presumed base year 2010 is achieved when multiplying $FCFE_{2016}$ with $(1 + E(R))^{-6}$, adjusted chronology illustrated below in Figure V.3.

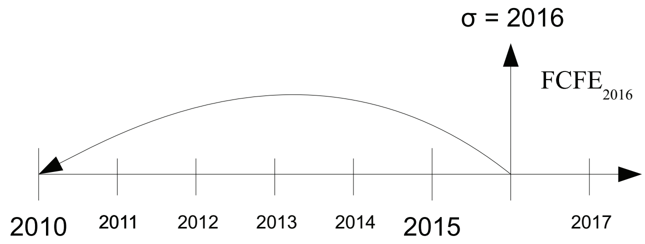

Figure V.3: FCFE discounting with $(\sigma = 2016)$ and $(t = 6)$

Cash flow variable $FCFE_\sigma$ itself is structured through the same sign convention discussed earlier. Negatively valued expenditures contain fixed costs c_f, variable costs c_v, and taxes represented by f_{tax}, wherein in some cases we replace c_v by $c_{O\&M}$ and distort c_f from our equation, because we understand that $c_{O\&M}$ has the capacity to substitute technological parameters in an identical manner. On the other hand, positively valued revenues are from the sale of energy and the contract based treatment of a determined amount of MSW. Equation (12) shows the free cash flow to equity $FCFE_\sigma$ with the independent variable σ:

$$\begin{aligned} FCFE_\sigma = &-c_f + p_{energy}(\sigma) \cdot E + \Big(- c_v + {p_\sigma}^{(w,BE)} \Big) \cdot q^w \\ &- f_{tax}(c_{O\&M}, p_{energy}, E, {p_\sigma}^{(w,BE)}, q^w) \end{aligned} \tag{12}$$

As the uncertainty of investments often plays an important role, we apply the Capital Asset Pricing Model (13) with the Lambda Approach extension [Dam03] in order to describe the expected return on our asset $E(R)$ due to the possibility of interactive country risks [Bru98]. This approach contains a linear function of dependent variables β and λ, which label the systematic risk of the asset respectively measure the company's exposure to country risk, and the constant inputs risk-free rate R_f, mature equity risk premium RP, and country risk premium CP:

$$E(R) = R_f + \beta \cdot \big(RP\big) + \lambda \cdot \big(CP\big) \tag{13}$$

Finally, the advisement is to calculate for every power plant project the minimal waste treatment price $p_\sigma^{w,BE}$ per ton when the condition of our target function, where net present value NPV_σ equals zero (14), is met.

$$\min_{p_\sigma{}^{(w,BE)}} \left\{ p_\sigma{}^{(w,BE)} \middle| NPV_\sigma\Big(p_\sigma{}^{(w,BE)}\Big) = 0 \right\} \qquad \forall \sigma \in [2011 \ldots 2030] \tag{14}$$

If we set Equation (12) and constraint (14) into Equation (11), we receive term (15) with one unknown:

$$\begin{aligned} 0 = &- \sum_{t=0}^{LT} \left(\frac{I_{inv}(t)}{(1+E(R))^{t+\sigma-2011}} \right) \\ &+ \sum_{t=\sigma-2010}^{\sigma+19-2010} \left(\frac{\Big(-c_{O\&M} + p_\sigma{}^{(w,BE)}\Big) \cdot q^w + p_{energy}(\sigma) \cdot E}{\Big(1+E(R)\Big)^t} \right) \\ &+ \sum_{t=\sigma-2010}^{\sigma+19-2010} \left(\frac{-f_{tax}(c_{O\&M}, p_{energy}, E, p_\sigma{}^{(w,BE)}, q^w)}{\Big(1+E(R)\Big)^t} \right) \end{aligned} \tag{15}$$

For the tax payment function f_{tax}, originally implemented in (12), we are using the particular defined calculation rules (4) and (5), wherein we are able to simplify the f_{tax} expression in Equation (15) to the more useful term (16):

$$\begin{aligned} f_{tax}(c_{O\&M}, p_{energy}, E, p_\sigma{}^{(w,BE)}, q^w) = &\, f_{tax}(c_{O\&M}, p_{energy}, E, q^w) \\ &+ p_\sigma{}^{(w,BE)} \cdot f_{tax}^{-1}(q^w) \end{aligned} \tag{16}$$

As (15) is a linear equation with one unknown variable $p_\sigma{}^{(w,BE)}$, we are easily able to solve this, and instantly receive the equation below, where ${p_\sigma}^{(w,BE)}$ is on the left side of the equal sign, as in (17):

$$p_\sigma^{w,BE} = \frac{\sum_{t=0}^{LT}\left(\frac{I_{inv}(t)}{(1+E(R))^{t+\sigma-2011}}\right) + \sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{-p_{energy}(\sigma)\cdot E}{(1+E(R))^t}\right)}{\sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{-f_{tax}^{-1}(q^w)+q^w}{(1+E(R))^t}\right)} + \frac{\sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{c_{O\&M}\cdot q^w + f_{tax}(c_{O\&M}, p_{energy}, E, q^w)}{(1+E(R))^t}\right)}{\sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{-f_{tax}^{-1}(q^w)+q^w}{(1+E(R))^t}\right)} \tag{17}$$

V.7 Model with carbon credits

Building upon our established base model for calculating break-even waste prices, our next goal is to establish an extended model for a power plant according to CDM guidelines. Using the description of our model with carbon credits elaborated earlier, we can now expand the sub model used to calculate the investment costs simply by adding investment costs $I_{O,CDM}$. In other words, the extension of Equation (8) immediately delivers the equation for the updated investment cost function (18):

$$I_{inv}(k) = \begin{cases} (I_0 + I_{0,CDM}) \cdot e_r & \text{if } k = 0 \\ (I_0 + I_{0,CDM}) \cdot (1 - e_r) \cdot \left[\left(1 - \frac{k-1}{LT}\right) \cdot i_{EF} + \frac{1}{LT}\right] & 0 < k \leq LT \end{cases} \tag{18}$$

In the same manner, we can then begin to adapt our processed base model for the waste price and modify our processed $FCFE_\sigma$, with the project initial year σ, based on Equation (12) according to the sign convention for additional expenditures and revenues, see Equation (19):

$$\begin{aligned} FCFE_\sigma = &\left(-c_{O\&M} + {p_\sigma}^{(w,BE)}\right) \cdot q^w + p_{energy}(\sigma) \cdot E \\ &- c_{f,CDM} + \left(1 - c_{v,CDM}\right) \cdot ER \cdot p_{carbon}(\sigma) \\ &- f_{tax}(c_{O\&M}, p_{energy}, E, {p_\sigma}^{(w,BE)}, q^w, c_{f,CDM}, c_{v,CDM}, ER, p_{carbon}) \end{aligned} \tag{19}$$

The estimation of yearly recorded emission reduction ER is simply calculated by the difference between baseline emissions BE and project emissions PE in Equation (20),

$$ER = BE - PE \tag{20}$$

while the estimation of yearly project emissions PE in (21) is determined by multiplying CO_2 emission coefficient $COEF_p$ by waste amount q^w.

$$PE = COEF_p \cdot q^w \tag{21}$$

When putting Equation (20) and (21) in the free cash flow to equity shown in Equation (19) we receive the complete expression in (22):

$$\begin{aligned} FCFE_\sigma = & \Big(- c_{O\&M} + p_{energy}(\sigma)\Big) \cdot E + {p_\sigma}^{(w,BE)} \cdot q^w - c_{f,CDM} \\ & + \Big(1 - c_{v,CDM}\Big) \cdot \Big(BE - COEF_p \cdot q^w\Big) \cdot p_{carbon}(\sigma) \\ & - f_{tax}(c_{O\&M}, p_{energy}, E, {p_\sigma}^{(w,BE)}, q^w, c_{f,CDM}, c_{v,CDM}, \\ & \quad BE, COEF_p, p_{carbon}) \end{aligned} \tag{22}$$

Finally, using Condition (14) and Equation (22) we can determine the expression for the waste price $p_\sigma^{w,BE}$ corresponding to the initial year σ of an investment project in (23). In order to simplify the f_{tax} term in Equation (22) a similar adaption to that used in (16) is applied. The tagging of this correlation finds the necessary modification in the form of additional outgoing and incoming cash flows, explicitly represented in the denominator of the second fraction term.

$$\begin{aligned} p_\sigma^{w,BE} = & \frac{\sum_{t=0}^{LT}\left(\frac{I_{inv}(t)}{(1+E(R))^{t+\sigma-2011}}\right) + \sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{(c_{O\&M}-p_{energy}(\sigma))\cdot E}{(1+E(R))^t}\right)}{\sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{-f_{tax}^{-1}(q^w)+q^w}{(1+E(R))^t}\right)} \\ & + \frac{\sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{c_{f,CDM}-(1-c_{v,CDM})\cdot(BE-COEF_w\cdot q^w)\cdot p_{carbon}(\sigma)}{(1+E(R))^t}\right)}{\sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{-f_{tax}^{-1}(q^w)+q^w}{(1+E(R))^t}\right)} \\ & + \frac{\sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{f_{tax}(c_{O\&M},p_{energy},E,q^w,c_{f,CDM},c_{v,CDM},BE,COEF_p,p_{carbon})}{(1+E(R))^t}\right)}{\sum_{t=\sigma-2010}^{\sigma+19-2010}\left(\frac{-f_{tax}^{-1}(q^w)+q^w}{(1+E(R))^t}\right)} \end{aligned} \tag{23}$$

VI
Results

In this chapter, our mathematical model for calculating the necessary price for one tonne MSW needed to create an economically viable WTE plant will be applied to the country-specific conditions of Brazil. Therefore, both designed models, the base model as well as the extended model which includes emission reductions in the form of carbon credits, will be considered. Further, this chapter presents a description of the investigated cases as well as relevant information about the origin of the data utilized as part of the most likely initial situation, scenarios, and sensitivity analyses.

VI.1 Input values for the base model

This section includes a complete specification of the origin and determination of the required values for the base model variables. These have been sub classified into technological parameters, external financing parameters, expected rate of return, tax payment function, energy price, and finally summarized in Table V.7. We will begin with the consideration of a typical business containing all input values in a representative manner as a reference model, on which the simulated scenarios and sensitivity analysis will be built.

(a) Initial situation B1

The initial situation is based on the assumption that all input values are constant for all 20 observed future projects ($\sigma = 2011 \ldots 2030$). In our first group of inputs we will treat the determination of technological parameters:

Technological parameters: Likely the most crucial of the following parameters, technological parameters must be regarded with caution, because as of yet no state of the art WTE plant exists in Brazil [Emp08]. In the same fashion, no experienced data or comparison values are available for this purpose. Nevertheless, both Oliveira & Rosa [Oli03] in 2003 and Rovere et al. [Rov10] in 2010 published data for electricity generation by MSW incineration. Oliveira & Rosa, for example, use a 500 tonnes per day (tpd) incineration plant with an installed capacity of 16 MW by specific investment costs of 1,563 US$/kW, operation and maintenance costs of 7.67 US$/MWh, and avoided emissions of 2.23 $tCO2_e/MWh$. Later, Rovere et al. characterized MSW optimized combustion by specific investment costs of 4,164 US$/kW, a net generation efficiency of 40%, and an average annual availability of 80%.

A fundamental correlation between the characteristics of the Brazilian MSW and the costs for a WTE plant was pointed out by Ribeiro [Rib10b], when he argued that MSW in Brazil, characterized by a lower heating value (LHV) of some 8 kJ/kg and a dry percentage of 52%, requires 22% less air to burn than typical MSW in the United States, which holds a dry percentage of 67% and a LHV of approximately 11 kJ/kg. Taken together with the fact that Brazilian waste contains 83% more water than that of the United States, such circumstances mean that less air is needed for cooling, so Ribeiro argues that a WTE plant in Brazil should cost about 20-30% less per ton than in the USA. Indeed, an Austrian study [Stu02] from 2002 states that the thermal output required determines the size of the flue gas cleaning device, the size of the boiler, and, ultimately, the investment and operating costs.

As noted earlier, we consider in this study an approach for WTE plants named Optimized Combined Cycle (OCC). However, this approach has yet to be proven in reality in the unique conditions for Brazil. The OCC configuration is generally characterized by a high MSW share in the fuel input and a relatively high efficiency based on natural gas and MSW. For this reason, Ribeiro [Rib10c] registers different examples for plant specifications, such as an 850 tpd OCC WTE plant with specific investment costs of 134,500 US$/tpd and specific operation and maintenance costs of 21 US$/ton, or the possible configuration of a 792 tpd plant with investment costs of R$ 180,000,000 and O&M costs of between 40-50 R$/ton. One set-up especially highlighted by Ribeiro due to its low tax to income ratio while having an installed capacity of 28.73 MW, which is stated to be a local maximum under the mentioned 30 MW restriction for avoiding transmission and distribution tax, is considered to be the reference technology applied in our initial situation. Summarized by Table VI.1 presents this setting a recommendable initial situation for further investigations.

The expenditures for the additional natural gas used as fuel input for the gas turbine are included for this purpose in the variable costs c_v. For this purpose we go along with Ribeiro's [Rib10c] presumption as well as with prices from Ribeiro's [Rib09] MSc Thesis and utilize 9 US$/MMBTU

Variable	Unit	Value
I_0	R$	$174 \cdot 10^6$
c_v	R$/tonnes/yr	27.65
$c_{O\&M}$	R$/ton waste	50
P	MW	28.73
$\eta_{plant,calorific}$	MWh/ton waste	0.95767
$COEF_p$	tCO_{2e}/ton waste	0.53539
CF	1	0.9123

Table VI.1: Technological parameters for a 720 tpd OCC WTE plant. Data source: [Rib10c] and own calculation

(= 52.20 R$/MWht [1]) as NG price and 15.89 MWt for the consumption of the gas turbine to determine c_v to be 27.65 R$/tonnes/yr [2]. To calculate the GHG emissions coefficient $COEF_p$ we determine primarily the project emissions and divide them subsequently by the yearly consumed amount of waste. For the calculation of project emissions we already marked parts which are being neglecting, such as emissions from on-site electricity consumption due to project activity, and on-site emissions due to fuel consumption. However, on-site encroachments on our calculation as summands in the project emission equation [Uni10c] are irrelevant, and only emissions from waste incineration and emissions from electricity generation from on-site fossil fuel consumption during co-firing play decisive roles [3].

External financing parameters: While reflecting on the financial investment process implemented recently by the investment function $I_{inv}(k, I_0, e_r, LT, i_{EF})$, it shall be remembered that a partial external financing was considered, where equity ratio e_r, contract period LT, and interest rate i_{EF} have to be appointed. In this context, the Brazilian development bank BNDES [4] provides with their program *Project Finance* a structural mechanism of funding sources for a project where implementation and operational risks

[1] 1 US$= 1.70 R$

[2] $c_v = \frac{52.20 R\$/MWht \cdot 15.89 MWt \cdot 8760 h/yr}{720 t/d \cdot 365 d/yr} = 27.65 R\$/tonnes/yr$

[3] $PE = A_{MSW} \cdot FCF_{MSW} \cdot EF \cdot \frac{44}{12} + Q_{biomass} \cdot (EF_{N2O} \cdot GWP_{N2O} + EF_{CH4} \cdot GWP_{CH4}) \cdot 10^{-3} + F_{co-firing} \cdot NCV_{co-firing} \cdot EF_{co-firing} = 128,362 tCO_{2e}/yr$
$A_{MSW} = 239,752 t/yr$ ... amount of MSW fed into incinerator
$FCF_{MSW} = 0.116$ ... fraction of fossil carbon in MSW [Con05, Rib10]
$EF = 1$ ... combustion efficiency for waste [Rib10]
$Q_{biomass} = A_{MSW}$
$EF_{N2O} = 0.043 kgN_2O/t$ ... aggregate N2O emission factor [Lix09]
$GWP_{N20} = 298$ ... see Table II.1
$EF_{CH4} = 0$ ... aggregate CH4 emission factor [Hir00]
$F_{co-firing} \cdot NCV_{co-firing} = 126,988.88 MWh$ ... generated energy content of NG
$EF_{co-firing} = 0.1836 tCO_{2e}/MWh$ ... CO2 emissions factor of the fossil fuel [Han07]

[4] In Portuguese: Banco Nacional do Desenvolvimento Econômico e Social - BNDES

are distributed to several stakeholders. For example, between 2003 and June of 2008 210 projects with a total investment volume of R$ 54.5 billions have been backed up by BNDES fundings in the amount of R$ 32.2 billions [Fil02].

In particular, the biomass segment within the renewable energy sector of the BNDES program documents that between 2003 and 2009 34 projects of an installed capacity of at least 1,517 MW were supported, with BNDES owning a 75% financing share of the total R$ 3,128,693 invested. This offers us an interesting opportunity to consider actual management policy in Brazil by establishing a 14-year cash recovery period based upon an 80% BNDES percentage on capital cost [Fis10]. Table VI.2 shows the chosen external financing parameters for our initial situation [5].

Variable	Unit	Value
e_r	1	20%
LT	1	14
i_{EF}	1	11%

Table VI.2: External financing parameters. Data source: [Fis10]

Discount rate: The discount rate in our model reflects the expected rate of return when CAPM and country risk are respected. For estimating the risk-free rate R_f we follow Damodaran [Dam08] by choosing a long term government bond, while neglecting the usual necessity of adapting a discount rate due to inflation, given our stated pre-condition which declares cash flows are noninflationary. The twenty-year US treasury bond rate, identifying the highest appearing value in 2010 exactly as of the 4th of May, thus gives us the risk-free rate is 4.69% [Uni11b]. According to Damodaran [Dam11], who recommends an equity risk premium RP of 4.5% for 2010, it is calculated that Brazil's Country Risk Premium in February 2011 is 4.82% [6], when using the 100 trading days prior to this for determining CR. The company's exposure to market risk β is designated to 1.54 when using a 60 months sector related value for engineering companies noted on the Sao Paulo Stock Exchange BOVESPA

[5] Total financing costs = TJLP + basic spread + risk spread ≈ 11%
TJLP = 6% … long term interest rate (In Portuguese: Taxa de Juros de Longo Prazo - TJLP) [Ban11]
basic spread = 0.9% … standard value [Fis10]
risk spread = 3.57% … conservative value [Fis10]

[6] Brazil's Country Risk Premium = Country Default Spread $\cdot \frac{\sigma_{\text{Equity}}}{\sigma_{\text{Country Bond}}} = 2\% \cdot \frac{17.65\%}{7.32\%} = 4.82\%$ … [Dam11]

[7] [8]. Despite the fact that Samanez's [Sam07] procedure to calculate an adjusted β is correct, our systematic risk results from the leveraged β, because of the lack of a specific and company related debt to equity ratio. Finally, λ is estimated to 1, representing an arbitrary company with an average exposure to country risk [Dam03]. These chosen values result in an expected rate of return in the amount of 16.44%.

Variable	Unit	Value
R_f	1	4.69%
RP	1	4.5%
CR	1	4.82%
β	1	1.54
λ	1	1
E(R)	1	16.44%

Table VI.3: Chosen CAPM and Lambda Approach values

Tax payment function: As we have not specified the internal bodywork of our tax payment function f_{tax}, we will now outline the relevant aspects of the Brazilian taxation system. Following Rachid's et al.'s [Rac05] recommendations, the Brazilian government knows four different tax schemes for the purpose of calculating relevant taxes:

- IRPJ: Corporate Income Tax [9]
- CSLL: Social Tax on Net Profit [10]
- PIS: Social Integration Program [11]
- COFINS: Social Security Contribution [12]

However, we are neglecting a priori both tax schemes called "Lucro Arbitrado", such as "Simples", and, subsequently, brings into focus "Lucro Real", which is accessible to all taxpayers, as well as "Lucro Presumido", optional when yearly total revenues are equal or below R$ 48 millions.

According to Rullo's [Rul08] study on developing a decision model for the application of the *Lucro Real* and *Lucro Presumido* tax scheme, in both

[7] In Portuguese: Bolsa de Valores de São Paulo - BOVESPA

[8] *Economatica* accessed on 03.05.2011: $\beta_{leveraged} = 1.54$, correlation = 0.63, D/(D+E) = 26.4% and $\beta_{unleveraged} = 1.19$

[9] In Portuguese: Imposto de Renda da Pessoa Jurídica - IRPJ

[10] In Portuguese: Contribuição Social sobre o Lucro Líquido - CSLL

[11] In Portuguese: Programa de Integração Social - PIS

[12] In Portuguese: Contribuição para Financiamento da Seguridade Social - COFINS

cases the contributions PIS and COFINS are calculated on total revenues, though with differences in percentages as well as exceptional rules in the case of *Lucro Real*, while IRPJ and CSLL both require pre-treatment before the actual determination takes place - like the *Lucro Presumido* case they are determined on a calculation base applied on gross revenues. In the *Lucro Real* alternative, they are directly calculated as a percentage of the earning before taxes (EBT) indicator. Below, Table VI.5 sums up our tax parameters, which respects the calculation base for the *Lucro Presumido* alternative shown in Table VI.4.

Activity	Percentage	
	IRPJ	CSLL
Energy & Carbon credit sales	8%	12%
MSW gate fee	32%	32%

Table VI.4: Calculation base for *Lucro Presumido*. Data source: [Sec11, Rul08]

Type of tax	Aliquot	
	Lucro Presumido	*Lucro Real*
PIS	0.65%	1.65%
COFINS	3%	7.6%
IRPJ	15(25)%	15(25)%
CSLL	9%	9%

Table VI.5: Difference between *Lucro Presumido* and *Lucro Real*. Increased values are shown in brackets. Data source: [Rac05]

In conclusion, Equations (1),(2),(3) and (4) describe fully the adapted tax payment function $f_{tax}\left(p_{\sigma}{}^{(w,BE)}\right)$ under consideration of relevant input factors.

$$f_{tax}\big({p_\sigma}^{(w,BE)}\big) = \begin{cases} \begin{cases} PIS_{R\$} + COFINS_{R\$} = (0.65\% + 3\%) \cdot R\big({p_\sigma}^{(w,BE)}\big) \\ IRPJ_{R\$} = \begin{cases} B_{IRPJ} \cdot 15\% & \text{if } B_{IRPJ} \leq \text{R\$ 240,000} \\ R\$240,000 \cdot 15\% + (B_{IRPJ} - R\$240,000) \cdot 25\% & \text{otherwise} \end{cases} \\ CSLL_{R\$} = B_{CSLL} \cdot 9\% \end{cases} & \text{if } R\big({p_\sigma}^{(w,BE)}\big) \leq R\$48 \cdot 10^6 \\ \begin{cases} PIS_{R\$} + COFINS_{R\$} = (7.6\% + 1.65\%) \cdot \Big(R\big({p_\sigma}^{(w,BE)}\big) - c_v \cdot {p_\sigma}^{(w,BE)}\Big) \\ IRPJ_{R\$} = \begin{cases} EBT \cdot 15\% & \text{if } EBT \leq \text{R\$ 240,000} \\ R\$240,000 \cdot 15\% + (EBT - R\$240,000) \cdot 25\% & \text{otherwise} \end{cases} \\ CSLL_{R\$} = EBT \cdot 9\% \end{cases} & \text{otherwise} \end{cases} \tag{1}$$

$$R\big({p_\sigma}^{(w,BE)}\big) = p_{energy}(\sigma) \cdot E + {p_\sigma}^{(w,BE)} \cdot q^w + p_{carbon} \cdot ER \tag{2}$$

$$B_{IRPJ,R\$} = (p_{energy}(\sigma) \cdot E + p_{carbon} \cdot ER) \cdot 8\% + ({p_\sigma}^{(w,BE)} \cdot q^w) \cdot 32\% \tag{3}$$

$$B_{CSLL,R\$} = (p_{energy}(\sigma) \cdot E + p_{carbon} \cdot ER) \cdot 12\% + ({p_\sigma}^{(w,BE)} \cdot q^w) \cdot 32\% \tag{4}$$

Energy price: Depending on the type, there exist several possibilities for the commercialization of the annually generated energy, or E, in the Brazilian energy sector, the risks of which are dependent upon the uncertainty of determination. For our purposes, we shall examine Machado [Mac10], Bassi [Bas08] and Melo's [Mel10] recommendation's for the consideration of price determination:

– an incentive program known as PROINFA [13]
– the free market environment ACL [14]
– the regulated market environment ACR [15]

The regulated market environment, or ACR, is a market segment, in which the buying and selling operations of electricity are realized between distribution and selling agents through standardized auctions based upon the principle of lowest bidder benefits [Bas08]. Characteristics of this scheme are long term contracts, low risks, and an alignment of auction prices to the consumer price index IPCA [16] [Mel10]. For example, an auction for renewable energy sources in 2010 in the biomass sector for an auctioned installed capacity of 712.9 MW yielded an average price of 144.20 R$/MWh [Mac10b].

In contrast, the free market environment, or ACL, allows the buying and selling operations of electrical energy covered by freely and bilaterally negotiated contracts, while following the specific rules and procedures of commercialization [Bas08]. What is notable about this variant is that prices are freely negotiated and contracts are concluded on the short, middle, and long run, while supplying approximately 26.5% of all energy fed into the national grid SIN [17] in the June of 2010 [Mac10]. Of course, this means that this strategy also incurs moderate to high risks on price, as their is no fixed price [Cam08].

Finally, launched in 2004 by the Ministry of Mines and Energy (MME) and Eletrobrás, PROINFA's [Coo09] incentive based program is aimed at creating greater diversification in the Brazilian energy sector through the exploration of regional and local potential, with the intent of improving social welfare and the reduction of GHG emissions. Characteristics of this strategy are low risks due to a minimum refund of 70% of the contractually stipulated

[13] In Portuguese: Programa de Incentivo às Fontes Alternativas de Energia Elétrica - PROINFA
[14] In Portuguese: Ambiente de Contratação Livre - ACL
[15] In Portuguese: Ambiente de Contratação Regulada - ACR
[16] In Portuguese: Ìndice de Preços ao Consumidor Amplo
[17] In Portuguese: Sistema Interligado Nacional - SIN

value, a Power Purchase Agreement (PPA) with a duration of 20 years, and annually adjusted prices regulated by the Ministry to the general index of market prices IGP-M [18] [Mac10]. As a result, though representing a mere 3.59% of the total energy share supplied to the national grid SIN in 2009, the average cost of PROINFA is 159 R$/MWh, which is slightly superior to the 130.01 R$/MWh paid to biomass plants [Coo09, Age09]. Moreover, as Barroso et al. [Bar05, Bar08] note, long-term PPA's are historically a well approved mechanism for the sale of electrical energy in the Brazilian power system.

Indeed, by employing 159 R$/MWh in the calculations for our own reference situation for $p_{energy}(\sigma)$ (5), PROINFA's balanced strategy appears quite similar to the values Ribeiro [Rib10c, Rib10d] used in his studies, as we notice that he calculated with 150 R$/MWh and 170 R$/MWh. This value seems to be reasonable, when compared to the more or less risk-free and recently in an ACR auction yielded energy price of 144.20 R$/MWh.

$$p_{energy}(\sigma) = 159 \text{ R\$/MWh} \qquad \forall \sigma \in [2011 \ldots 2030] \tag{5}$$

(b) Scenario: Learning effects B2

Especially during the construction phase of a new plant, higher than estimated costs must be anticipated in the early stages and development of immature technologies and new plant designs. This is what is known in technical literature as the "experience curve", in which most technologies incur high costs due to unanticipated problems, while subsequent projects learn from these mistakes to achieve higher degrees of proficiency [Int10]. These estimated learning rates can vary significantly not only between technologies, but between capital and O&M based estimations [Tor10].

Further, in order to apply the logarithmic experience curve correctly we also need to know the cumulative installed capacity of the desired technology, which allows us to calculate their prospective costs. However, given the lack of information about the cumulative installed capacity of WTE plants during the next 20 years, we have to apply a simplified constraint in order to achieve a linear approach. For this purpose we are going to apply the results from a study [Eae08] prepared for the IEA's Implementing Agreement on Renewable Energy Technology Deployment, which aims at a total reduction in investment costs of 7.93% and in O&M costs of 8.31% between 2010 and 2025. Using the values from that study within a linear approach and extending the timeframe

[18] In Portuguese: Ìndice Geral de Preços do Mercado - IGP-M

to 2030 delivers an adjusted course of the function presented in Equation (6) and (7):

$$I_0(\sigma) = \begin{cases} I_0 & \text{if } \sigma = 2011 \\ \left(I_0 \cdot \frac{1-0.9207}{2011-2025}\right) \cdot \sigma + I_0 \cdot \left(1 - \frac{1-0.9207}{2011-2025} \cdot 2011\right) & 2011 < \sigma \leq 2030 \end{cases} \tag{6}$$

$$c_{O\&M}(\sigma) = \begin{cases} c_{O\&M} & \text{if } \sigma = 2011 \\ \left(c_{O\&M} \cdot \frac{1-0.9169}{2011-2025}\right) \cdot \sigma + c_{O\&M} \cdot \left(1 - \frac{1-0.9169}{2011-2025} \cdot 2011\right) & 2011 < \sigma \leq 2030 \end{cases} \tag{7}$$

(c) Scenario: Tax harmonization B3

Given that the determinant (annual income of R$ 48 million/year) of whether our model will follow the *lucro real* or the *lucro presumido* tax regime, we must account for the influence of a hypothetical government's tax liberalization scheme on the gate fee of WTE plants slated to begin in 2020. As a result, only the *lucro presumido* tax regime will be applied to compute annual tax payments after 2020. A practical implementation of such a tax harmonization could be to implement an exception for incineration plants as an incentive, much like the transmission and distribution fee exception implemented by the national energy agency ANEEL.

(d) Sensitivity analysis B4

This sensitivity analysis is aimed at identifying the influential factors in our base model input variables. In order to do so, the best practice is to take several input values, in our case from initial situation B1, and modify them within an arguable codomain to see how this alteration effects the system output, or waste price $p_\sigma{}^{(w,BE)}$. Below, Table VI.6 shows the selected representatives energy price $p_{energy}(\sigma)$, investment costs I_0, expected rate of return $E(R)$, and variable costs c_v of our base model according to the selected modifications.

More than this, from now on it is assumed that all projects are calculated by the *lucro presumido* regime.

Parameter drift	$p_{energy}(\sigma)$	I_0	$E(R)$	c_v
%	R$/MWh	10^6 R$	%	R$/tonnes/yr
-20	127.2	139.2	13.15	22.12
-15	135.15	147.9	13.97	23.50
-10	143.10	156.6	14.80	24.88
-5	151.05	165.3	15.62	26.27
0	159.00	174.0	16.44	27.65
5	166.95	182.7	17.26	29.03
10	174.9	191.4	18.08	30.41
15	182.85	200.1	18.91	31.80
20	190.80	208.8	19.73	33.18

Table VI.6: Input values for sensitivity analysis B4

VI.2 Input values for the model with carbon credits

Much like our earlier description of our base model, this section includes a complete specification of the origin and determination of the required values for the model with carbon credits. As such, after first having built upon the initial situation presented in our base model, we shall define the carbon credit price and the CDM specific parameters, beginning with the consideration of a typical business containing all the representative fixed input values as a reference model on which the simulated scenarios and sensitivity analysis will later be built.

(a) Initial situation C1

As before, the initial situation is characterized by the fact that all input values are supposed to be constant for all 20 observed future projects ($\sigma = 2011 \ldots 2030$).

Carbon credit price: Like all energy commodities traded in volatile markets, the determination of $p_{carbon}(\sigma)$, which stands for the price of a Certified Emission Reduction (CER) and represents a reduction in GHG emissions of one metric ton of carbon dioxide equivalent (CO_{2e}), is in generally dependent on the status of worldwide economic development [Cap09]. The reason to this is that market players tend to maintain a long run view, which necessarily effects their economic decisions, meaning that carbon markets should not be treated any different than other markets.

Figure VI.1 shows the development of carbon prices from April 2008 to April 2010. As Kossoy & Ambrosi [Kos10] noted, the widening of the recent financial crisis of 2008 was largely responsible for the exceptional market volatility of carbon indices since the second half of 2008. Fixed prices for pre-2013 pCERs averaged €8-10 across most regions and sectors [Lin11]. Despite low average prices, the World Bank completed in May 2011 an auction of 200,000 tons of CERs at a price per ton of €12.52 (R$ 28.792 [19]) [The11b].

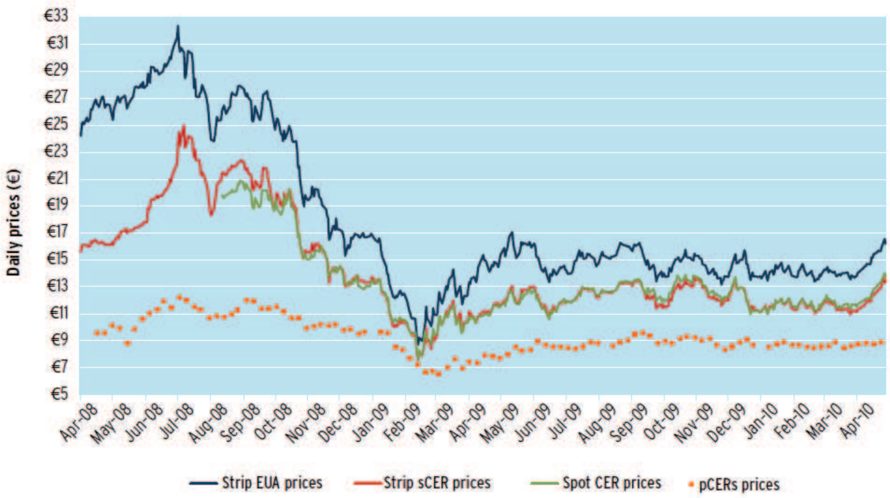

Figure VI.1: Carbon prices, 2008 - 2009. Source: [Kos10]

For our initial situation we will consider transactions using an emissions reduction purchase agreement (ERPA) with the World Bank Carbon Finance Unit as project participant, such as implemented in the "Brazil NovaGerar Landfill Gas to Energy Project" [Bra04]. Such a 20-year contract offers several advantages, such as more reliable economic forecasts and a clear definition of key legal issues [Kos09]. The carbon price $p_{carbon}(\sigma)$ chosen in this first initial case, which is constant for all investigated projects, is determined as R$ 20.70 (€9) per ton of CO_{2e} (8).

$$p_{carbon}(\sigma) = 20.70 \text{ R\$/CER} \qquad \forall \sigma \in [2011 \ldots 2030] \tag{8}$$

CDM specific parameters: This paragraph contains the determination of additional costs due to the CDM registration sub-divided into investment, fixed and variable costs. Additional costs caused by higher than expected plant construction expenditures and installation costs are neglected. The Guidebook to Financing CDM Projects developed by EcoSecurities under the UNEP's Capacity Development for CDM (CD4CDM) [Eco07] distinguishes between specific costs for large- and small-scale projects. According to their guidebook,

[19] 1.0 € = 2.3 R$

total CDM-specific costs in the planning phase amount to a total of US$ 38,500-610,000 and in the operation phase to a total of annually US$ 5,000-25,000 when annualizing initial verification costs. In addition, the UN Adaption fund fee requires 2% of CERs per year. In order to simplify matters, and considering that the development of a new methodology is not necessary for this large-scale CDM project, we are going to apply a low cost implementation, the costs of which are summarized in Table VI.7 [20].

Variable	Unit	Value
$I_{0,CDM}$	R$	65,450
$c_{f,CDM}$	R$/year	8,500
$c_{v,CDM}$	1	2%

Table VI.7: CDM specific costs. Data source: [Eco07]

Ideally, the estimation of baseline emissions BE should be based on the Lixo Zero Composting project [Lix09], a composting project in the State of Rio de Janeiro, Brazil, which has been until now the only CDM project in Brazil applying the AM0025 methodology. However, the type of waste this project treats is not adequate to determine the BE, as its composition (percentages: 5% Pulp and paper, 15% garden waste, 65% food waste, 5% wood waste, and 10% others) is not representative of the type of waste a state-of-the-art incinerator would normally use as fuel.

Another registered project in the state of Rio de Janeiro is the Brazil NovaGerar Landfill Gas to Energy Project [Bra04], which is applying the AM0003 baseline methodology, and began its first 7-year crediting period from 2004 to 2011. As a result of the capacities of this site, as well as those of the Adrianopolis site contained within this project, the emission baseline of 16,659,501 tCO_{2e} based on a 21-year horizon seems to be a good compromise when compared with the annual emission reduction of 265,000 tCO_2 published by Ribeiro & Kimberlin [Rib10]. As a result, baseline emissions, or BE, can be simplistically determined by respecting the lower amount of 720 tpd treated by the WTE plant, in comparison to the 2000 tpd treated by the Adrianopolis site, see Equation (9) [21]:

$$BE = 260,545\ tCO_{2e}/yr \tag{9}$$

[20] 1 US$= 1.70 R$

[21]
$$BE = \frac{16,659,501\ tCO_{2e}}{21 years} \cdot \frac{720 tpd \cdot 0.9123}{2,000 tpd} = 260,545 tCO_{2e}/yr$$

(b) Scenario: Baseline adjustment C2

The baseline emissions in the initial situation C1 have been determined according to a 21 years time horizon. As a result, throughout the 21 years of the landfill's operation, the resulting emissions are summated and then divided by 21 to get the constant, annual baseline emission. Of course, the annual production of GHG emissions of a landfill is not constant, and thus normally cannot be calculated by a linear equation that would allow an ordinary interpolation between different time bases. Taking a 14 years baseline instead of a 21 years baseline results immediately in new emission reductions ER and thus different CER revenues. Given the above, it is useful to ask how a variation in baseline emissions BE affects the gate fee $p_{\sigma}{}^{(w,BE)}$, as compared with the most beneficial baseline of situation C1. Table VI.8 demonstrates adapted baselines from the Adrianopolis landfill site [Bra04], registered as Brazil NovaGerar Landfill Gas to Energy Project in the CDM mechanism.

Time frame	BE
years	tCO_{2e}
7	85,808
10	123,107
14	175,259

Table VI.8: Adapted baseline emissions BE

(c) Scenario: Post-Kyoto C3

The scenario C3 applies a combined approach as a reference pathway by simulating a scenario with learning effects B2 from the base model together with the initial situation C1 from the model with carbon credits. This is, of course, an ideal situation in the sense of having a low gate fee. Subsequently, the CER price $p_{carbon}(\sigma)$ will then be changed to include the changed framework requirements due to the expiry of the Kyoto contract. The post-2012 CER prices will thus be modeled in the €6-8 range (R$ 13.8-18.4) (see Equations (10) and (11)) [Lin11].

$$p_{carbonLOW}(\sigma) = \begin{cases} 20.7 \text{ R\$/CER} & \text{if } \sigma < 2013 \\ 13.8 \text{ R\$/CER} & 2013 \leq \sigma \leq 2030 \end{cases} \tag{10}$$

$$p_{carbonHIGH}(\sigma) = \begin{cases} 20.7 \text{ R\$/CER} & \text{if } \sigma < 2013 \\ 18.4 \text{ R\$/CER} & 2013 \leq \sigma \leq 2030 \end{cases} \tag{11}$$

(d) Scenario: Reduced output C4

This last scenario for the model with carbon credits investigates the impacts of a reduced output. Below, Table VI.9 illustrates the chosen values for this situation, where the initial situation's investment costs I_0 and costs for operation and maintenance $c_{O\&M}$ remain the same, as they correlate with the amount of waste incinerated, which remains at 720 tonnes per day. On the other hand, variable costs c_v are dropped to R$/ton 20.01, because of the lower demand for thermal power generated by natural gas [22]. The performance of all other parameters also drop, such as the installed capacity P by nearly 8% to 26.51 MW, the caloric efficiency $\eta_{plant,calorific}$, the emission coefficient $COEF_p$ [23] some 5%, and capacity factor CF about 0.8%.

Variable	Unit	Value
I_0	R$	$174 \cdot 10^6$
c_v	R$/tonnes/yr	20.01
$c_{O\&M}$	R$/ton waste	50
P	MW	26.51
$\eta_{plant,calorific}$	MWh/ton waste	0.88367
$COEF_p$	tCO_{2e}/ton waste	0.50853
CF	1	0.905

Table VI.9: Technological parameters for a 720 tpd OCC WTE plant with reduced output. Data source: [Rib10c] and own calculation

For the costs evolution of investment and O&M costs, the same conditions as in learning effect scenario B2 are employed. As such, the baseline emissions BE are modified in the same way as expressed for carbon model initial situation C1. Observing a 21-year horizon and applying the reduced capacity factor CF of 0.905 gives for BE Equation (12) [24] , shown below.

$$BE = 258,460\ tCO_{2e}/yr \tag{12}$$

[22] $c_v = \frac{52.20\text{R\$/MWht} \cdot 11.50\text{MWt} \cdot 8760\text{h/yr}}{720t/d \cdot 365d/yr} = 20.01\text{R\$/tonnes/yr}$

[23] The calculation of the project emission took place under the same conditions as presented in the footline of the base model initial situation B1, but with respect to the new values from Table VI.9, $PE = 120,945tCO_{2e}/yr$

[24]

$$BE = \frac{16,659,501\ tCO_{2e}}{21years} \cdot \frac{720tpd \cdot 0.905}{2,000tpd} = 258,460tCO_{2e}/yr$$

VI.3 Numerical simulation

The numerical simulation of the waste prices ${p_\sigma}^{(w,BE)}$ with the equations presented in (17) and (23), in particular the mathematically solvability in practical applications, will depend a lot on the structure of the implemented tax payment function, or f_{tax}. As Damodaran [Dam02] and Samanez [Sam07] have noted, due to the necessity of calculating for different tax bases, the Brazilian legal framework makes the resolution of the highly nonlinear tax-function (1) disproportionate and unprofitable. The Annex to this work illustrates the cash flow analysis for the Post-Kyoto scenario C3, for a project where σ=2011.

VI.4 Analysis of results

The simulation for both the base model and the model with carbon credits and their relative tasks are presented within the following section.

(a) Base model

B1: When starting with the first case considered within the base model configuration, we can see that the initial situation B1 is clearly influenced by the fact that all output values are constant, which is quickly confirmed when looking at the resulting Equation (17) for the waste price ${p_\sigma}^{(w,BE)}$. Fixed through the constraint $NPV = 0$, we can distinguish one project from another by the different exponent in the denominator expression. Indeed, a simple multiplication with a fitting term is able to compensate for this difference and demonstrates the properness for this case.

Given the assumptions outlined earlier, each 720 tpd WTE plant thus generates a tradable amount of electrical energy of some 229.6 GWh per year and treats some 239,752 tonnes of MSW yearly, while offering an expected rate of return of 16.44% calculated in Equation (13) with values from Table VI.3. To ensure this, a constant waste price of 64.22 R$/ton (see Figure VI.2) for all 20 investigated future projects is required, which, according to prognosticated energy sales, thus generates annual revenues of virtually R$ 51.9 million. Of this total, MSW accounts for nearly 30% of the total income. However, this also means that, because annual sale revenues top the critical R$ 48 million threshold, the *lucro real* tax scheme must then be applied to determine PIS, COFINS, CSLL and IRPJ. This results in a tax share of total revenues that increases from 11.36% in the first year to 21.39% in the last year of each observed investment project, because of the rising IRPJ and CSLL share.

Figure VI.3 shows the course of tax payments for a WTE plant that has a construction start in 2010, i.e. $\sigma = 2011$.

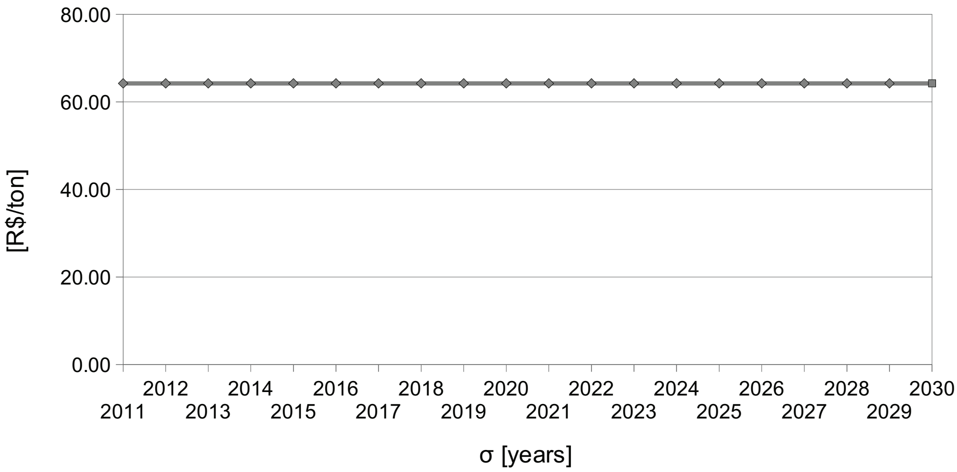

Figure VI.2: Gate fee $p_{\sigma}{}^{(w,BE)}$ in base model initial situation B1

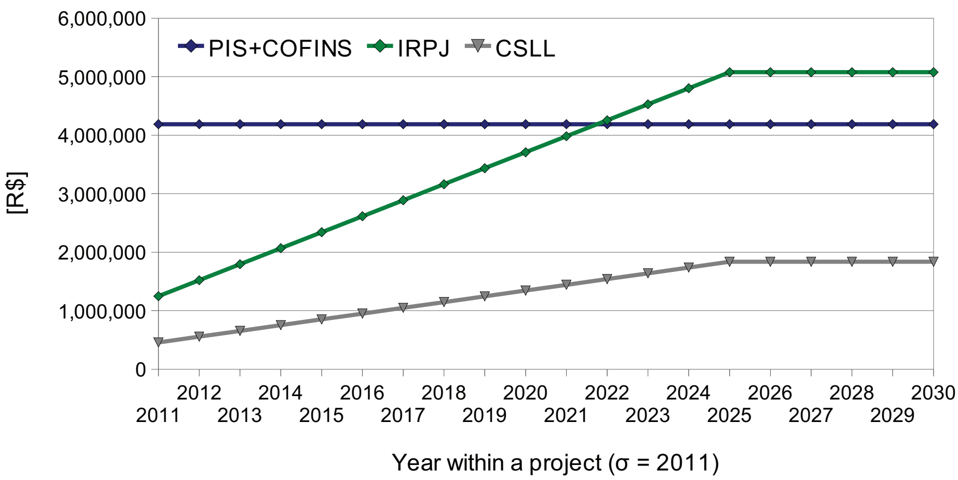

Figure VI.3: Output response of tax payment function f_{tax} in B1

Even more interesting is a function that shows how the NPV varies with the waste price $p_{\sigma}{}^{w}$, as Figure VI.4 shows for a project with σ=2015 [25]. The part of function $NPV(p_{2015}{}^{w})$ located on the left side of the vertical boundary line at a waste price of 47.93 R$/ton is calculated within the *lucro presumido* regime. When compared with the right part of the NPV function, calculated by *lucro real* taxes, we notice that there is no waste price within the *lucro presumido* calculation where NPV equals zero. In general, a feasible region can be defined by the solution set $\mathcal{C}$ of waste prices $p_{\sigma}{}^{w}$, which all correspond with

[25] $$NPV(p_{2015}{}^{w}) = \begin{cases} 1,167,229 \cdot p_{2015}{}^{w} - 57,452,378 & 0 \leq p_{2015}{}^{(w)} < 47.93 \\ 813,178 \cdot p_{2015}{}^{w} - 52,222,924 & 47.93 < p_{2015}{}^{(w)} \leq 80 \end{cases}$$

a NPV greater than zero (see Equation (13)). Therefore, we receive Equation (14) for the solution set $\mathcal{C}$ applied to our specific situation.

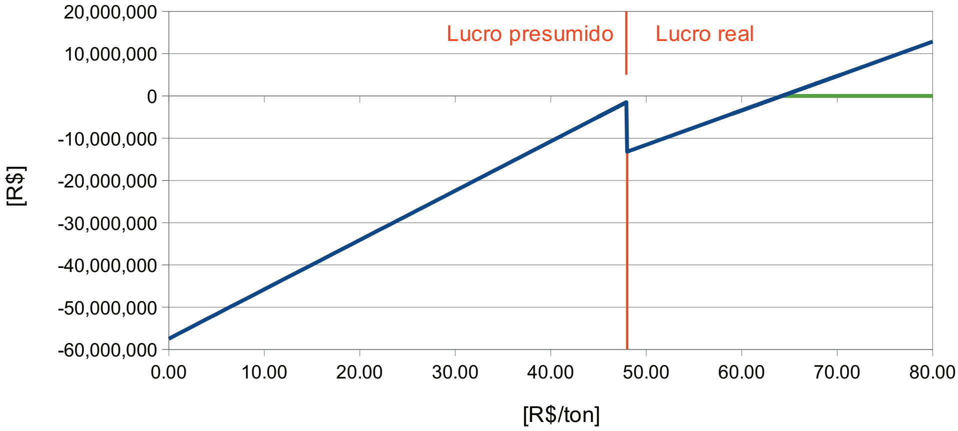

Figure VI.4: Course of the function $NPV(p_{2015}{}^{(w)})$ in the B1 situation

$$\mathcal{C} = \left\{ p_\sigma{}^w \middle| NPV_\sigma\left(p_\sigma{}^w\right) \geq 0 \right\} \tag{13}$$

$$\mathcal{C} = \{[64.22\ ,\ \infty)\} \tag{14}$$

Of course, in reality, rational decision-makers will always choose the lowest price for the treatment of a tonne of MSW in order to maximize their competitiveness in the market as lowest price tender. Considering this, we thus receive for the break-even waste price the already known value of 64.22 R$/ton, see Equation (15):

$$p_{2015}{}^{(w,BE)} = \min_{p_\sigma{}^w} \left\{ p_{2015}{}^w \middle| p_{2015}{}^w \in \mathcal{C} \right\} = 64.22 R\$/ton \tag{15}$$

With external financing through BNDES Project Finance our designed investment cost function I_{inv} results in a 20% equity share and 11% total financing costs, with a 14-year credit period. Figure VI.5 shows the course of the function valid in the initial situation. Year zero exclusively presents the 20% equity share of total investment costs I_0, equal to almost R$ 35 million. The debt portion is composed of, first, a constant, annual amortization of some R$ 10 million and, second, of declining interests depending on the debt levels of prior years.

B2: Considering our definition of the experience rate influence noted earlier, the linear, declining investment and O&M costs between 2010 and 2030 will clearly follow the near-linear character for waste price evolution. Therefore, keeping in mind that NPV must equal zero, total revenues must

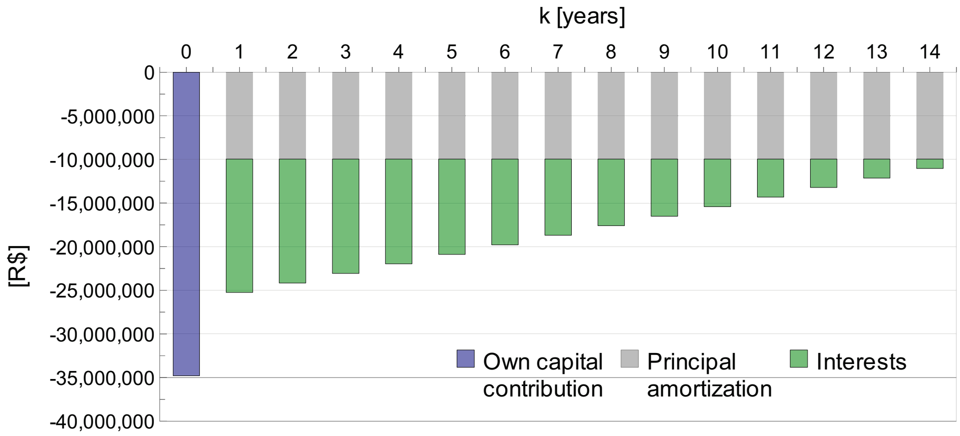

Figure VI.5: Investment cost function $I_{inv}(k, 174 \cdot 10^6, 20\%, 14, 11\%)$ for the base model B1 situation

also be allowed to decline in a similar manner. Below, Figure VI.6 shows both simulated trends: one track recorded with a low initial value of 0 R$/ton, named to B2_L, and the other with a relatively high initial value of R$/ton 100, B2_H. Thus the determination of whether the initial price is high or low must be seen in relation to the specific waste price, which in our calculation would amount to a total income of about R$ 48 million [26]. Also illustrated are the corresponding trends of total annual receipts referred to as Total receipts_L and Total receipts_H, for low and high starting values, respectively.

For the first two projected years $((\sigma = 2011) \wedge (\sigma = 2012))$ a single waste price $p_\sigma{}^{(w,BE)}$ exists for each project. Given our constraint for the NPV, the level of annual expenditures required during these two years results in annual revenues exceeding the 48 million R$ threshold, meaning that the *lucro real* tax scheme must be applied. Consequently, annual revenues are allowed to decrease in proportion to decreasing expenditures, which is justified as long as NPV remains at zero in each case. As a result of this cash flow decline, between 2013 and 2025 accountants may thus choose between either of two waste prices $p_\sigma{}^{(w,BE)}$ to achieve an NPV of zero, both of which are local minimums. On the one hand, the B2_H course achieves this by requiring a high waste price to compensate for the *lucro real* regime's additional tax expenses. On the other hand, the B2_L gradient may only achieve an NPV of zero by charging a gate fee between 24% to 30% lower than in the case of the B2_H. In fact, our calculations show that by 2026 the B2_H situation no longer falls under the jurisdiction of the *lucro real* regime, as they are then below the R$ 48 million threshold. As a result, between 2026-2030 the waste price begins to decline

[26]corresponding with 47.94 R$/ton

under the *lucro presumido* regime [27].

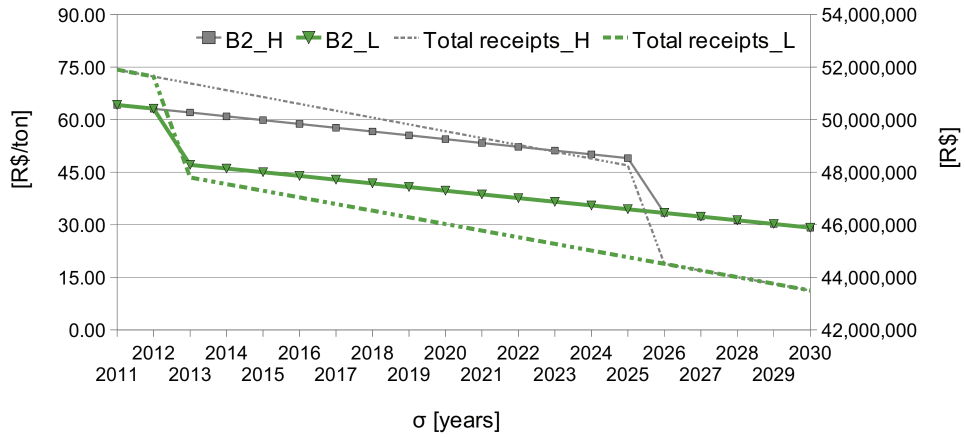

Figure VI.6: Waste price ${p_\sigma}^{(w,BE)}$ distribution with learning effects B2

Finally, the chosen waste price ${p_\sigma}^{(w,BE)}$ has to be a global minimum for every investigated power plant project σ according to our target function. Seen in the course of the function VI.6, B2_L has to be picked according to the minimization of the waste price, which is in keeping with our overall goal of ensuring that NPV equals zero and equivalent to the B2_H case's higher waste price. The reason for these two different gate fees is the nonlinear character of the tax-function f_{tax}, with its progressive discontinuities.

An explanation for the resulting gate fee for a specific project is given when observing the NPV variation as a function of the waste price ${p_\sigma}^w$, pictured in Figure VI.7 [28]. In comparison with the initial situation B1, there now exists a feasible region within the *lucro presumido* regime. Therefore, we receive two subsets for the solution set $\mathcal{C}$ shown in Equation (16), as well as for the break-even waste price ${p_{2015}}^{(w,BE)}$ shown in Equation (17):

$$\mathcal{C} = \{[45\ ,\ 47.93]\ \cup\ [59.88\ ,\ +\infty)\} \tag{16}$$

[27] However, we recognize that the course of ${p_\sigma}^{(w,BE)}$ has two linear parts: the first one, between 2011 to 2025, where *luco real* is applied and the second period, between 2013-2030, where *lucro presumido* is applied. A linear regression for these two parts gives us for the waste price function:

$$p_\sigma^{(w,BE)} = \begin{cases} -1.08612 \cdot (\sigma - 2011) + 64.22076 & \text{if } 2011 \le \sigma < 2013 \\ \begin{cases} -1.08612 \cdot (\sigma - 2013) + 62.04852 & \text{if B2\_H} \\ -1.05488 \cdot (\sigma - 2013) + 47.11143 & \text{B2\_L} \end{cases} & 2013 \le \sigma < 2026 \\ -1.05488 \cdot (\sigma - 2026) + 33.39802 & 2026 \le \sigma \le 2030 \end{cases}$$

We can detect that the annual decrease of the gate fee is higher when *lucro real* is applied in comparison to the *lucro presumido* part.

[28] $$NPV({p_{2015}}^w) = \begin{cases} 1,167,229 \cdot {p_{2015}}^w - 52,527,244 & 0 \le {p_{2015}}^{(w)} < 47.93 \\ 813,178 \cdot {p_{2015}}^w - 48,690,081 & 47.93 < {p_{2015}}^{(w)} \le 80 \end{cases}$$

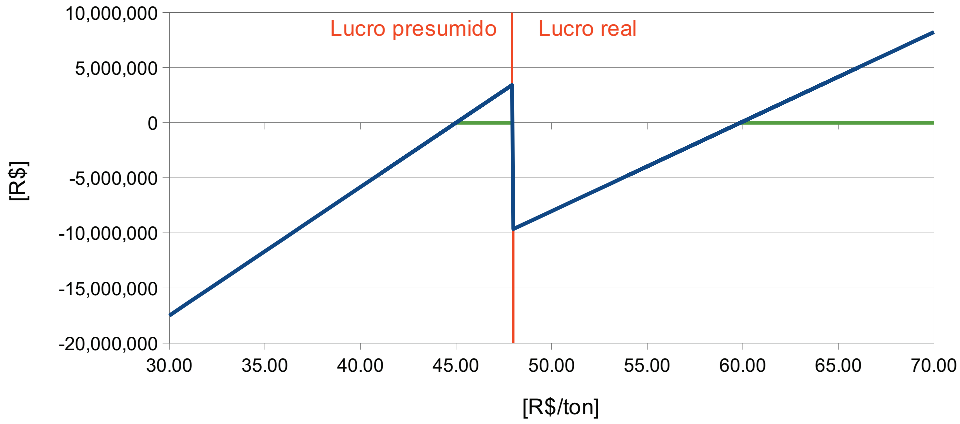

Figure VI.7: Course of the function $NPV(p_{2015}{}^{(w)})$ in the B2 situation

$$p_{2015}{}^{(w,BE)} = \min_{p_\sigma{}^w} \left\{ p_{2015}{}^w \middle| p_{2015}{}^w \in \mathcal{C} \right\} = 45R\$/ton \quad (17)$$

B3: The results of the tax harmonization scenario B3, where we modeled a *lucro real* exception for WTE plants coming into force 2020, is illustrated by Figure VI.8. In comparison with B1, where $p_\sigma{}^{(w,BE)}$ is calculated to be constant at R$/ton 64.22, our calculations result in a break-even gate fee of R$/ton 56.34 for a project initiated in 2011 and R$/ton 49.22 from 2020 on, with an average tax to income ratio of 8.59%. The decline in the period 2011-2019 is interesting, because even in the worst case scenario of tax liberalization starting several years after revenues begin, accountants are already able to take advantage of the new conditions within the project duration and apply *lucro presumido* to calculate annual taxes. Seen in this light, the predicted tax liberalization scheme has positive effects for both, present and future WTE plants.

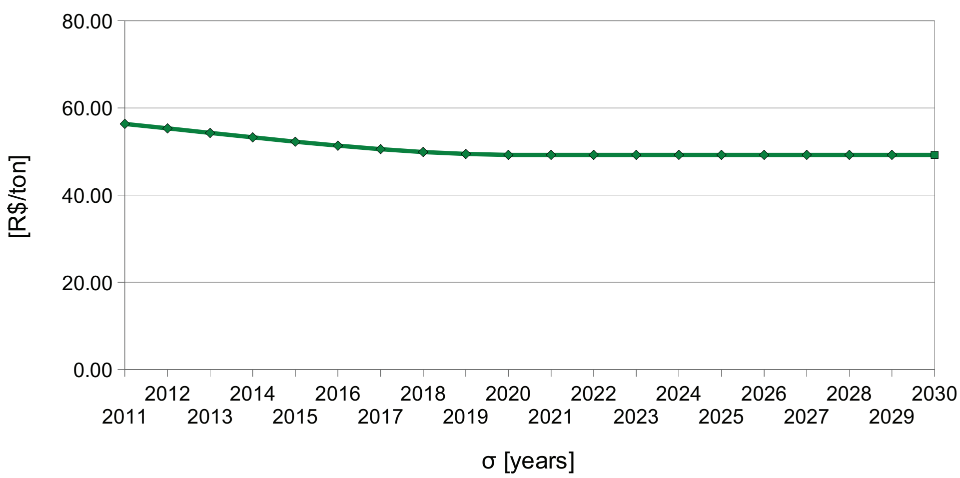

Figure VI.8: Waste price $p_\sigma{}^{(w,BE)}$ distribution with tax harmonization B3

From now on, it is assumed for all investigated projects that they always achieve tax payments according to the *lucro presumido* regime; no project will use *lucro real*.

B4: A change in waste price ${p_\sigma}^{(w,BE)}$ subject to a variation of selected input parameters is illustrated by Figure VI.9. The highest degree of sensitivity of a change in output is reached when varying either the energy price $p_{energy}(\sigma)$ or the investment costs I_0. The bandwidth of the waste price change caused by a change of the energy price in the range -20% to +20% is from +67.61% to -67.61%. For example, an energy price of R$/MWh 190.8 would result in R$/ton 15.94 for the waste price, or more than 67% lower when compared with the initial situation. In addition, Figure VI.10 shows the waste price ${p_\sigma}^{(w,BE)}$ in real values subject to the energy price $p_{energy}(\sigma)$. A lower degree of sensitivity is given when varying the investment costs I_0. For example, the same percentage change (-20% to +20%) would result in a range of $\mp$50.68% for the proper gate fee. On the other hand, a variation in the variable costs c_v and the expected rate of return $E(R)$, such as the price of the natural gas or the interest sub model parameters, results in relatively little impact on the waste price.

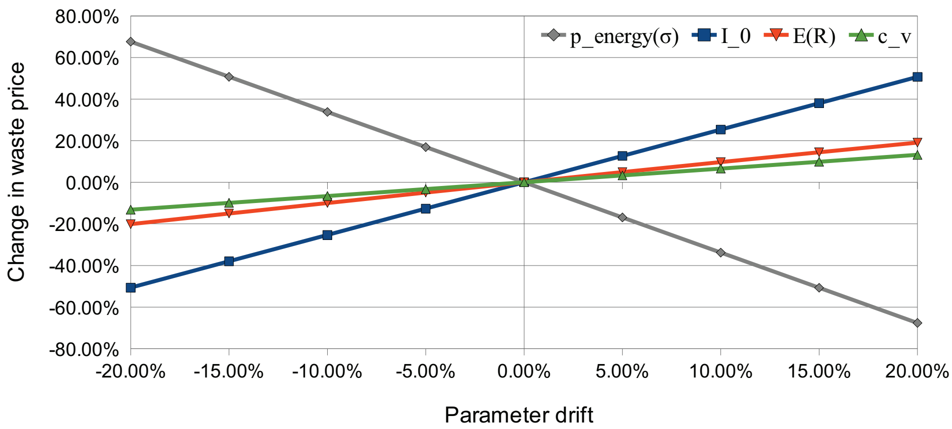

Figure VI.9: Sensitivity analysis B4

(b) Model with carbon credits

C1: Generally speaking, initial situation C1 for the model with carbon credits is an easy expansion of base model B1, but with the addition of the *lucro real* exception. All input values are supposed to be constant, including the newly determined variables for project emissions PE, baseline emissions BE, emission reductions ER, and carbon price $p_{energy}(\sigma)$. In short, the gate fee ${p_\sigma}^{(w,BE)}$ should also be constant for all projects. The WTE plant still produces almost 230 GWh of energy per year through the incineration of some 240,000 tonnes of MSW yearly. In addition, revenues are generated through the

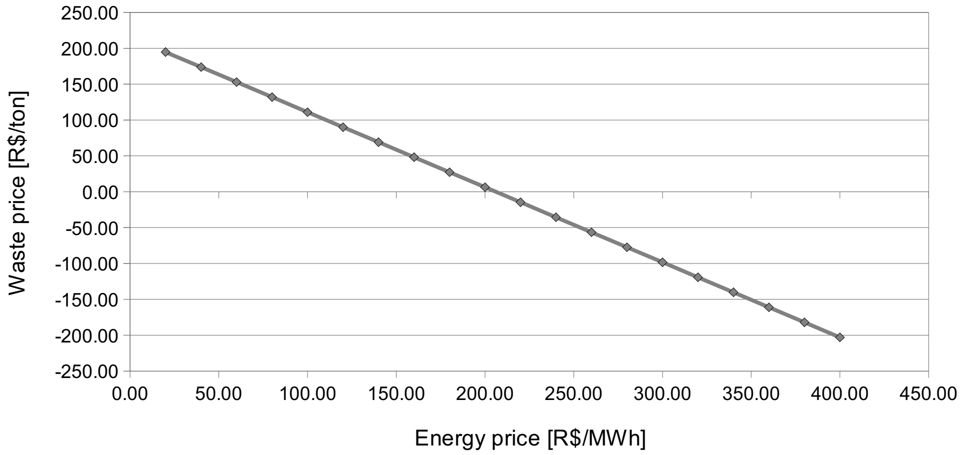

Figure VI.10: Waste price as a function of energy price in B4

mitigation of 132,183 tons of CO_2 equivalent, or tCO_{2e}, positively contributing to the annual balance.

Despite of requiring additional variable and fixed costs in the amount of R$ 63,224 per year and one-time investment costs of R$ 65,450, the CDM project registration with the lucro real exception results in a waste price more than 42% lower than in the case lacking carbon revenues and fiscal benefits. The course for the achieved gate fee in the amount of R$ 37.11 per ton of MSW is shown in Figure (VI.11).

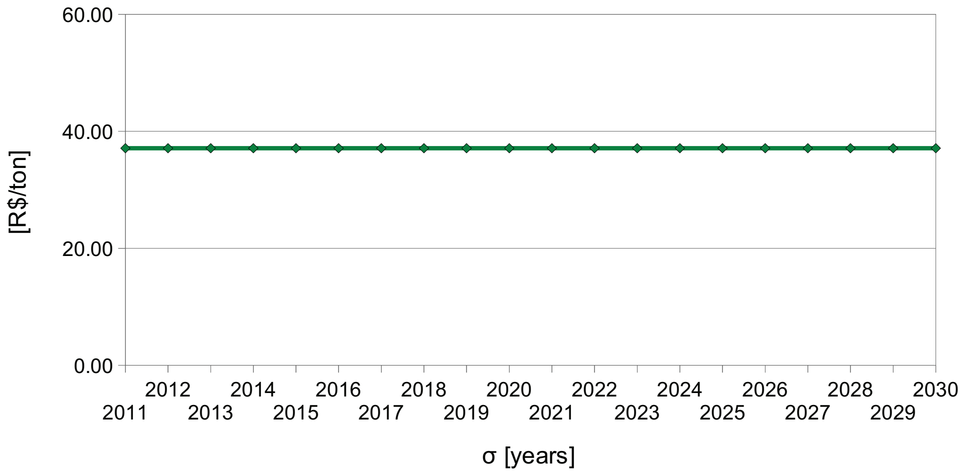

Figure VI.11: Waste price $p_{\sigma}{}^{(w,BE)}$ for initial situation C1 of the model with carbon credits

The 42% reduction is driven primarily by the additional revenues generated by the sale of registered CERs, equaling somewhere the region of R$ 2.7 million yearly, or 5.68% of total income. Below, Figure VI.12 demonstrates how carbon credit revenues squeeze the MSW revenues out of the balance sheet, while failing to boost total sales revenues, due to our fundamental condition that ties down NPV to ensure a stable expenditures/revenues relation. As a result, the R$ 48.2 million in revenues are almost 7.20% lower than in the equivalent base model situation B1 without the noted benefits, while waste revenues as a percentage of total income also drop from 32.33% in situation B1 to 24.37% in situation C1.

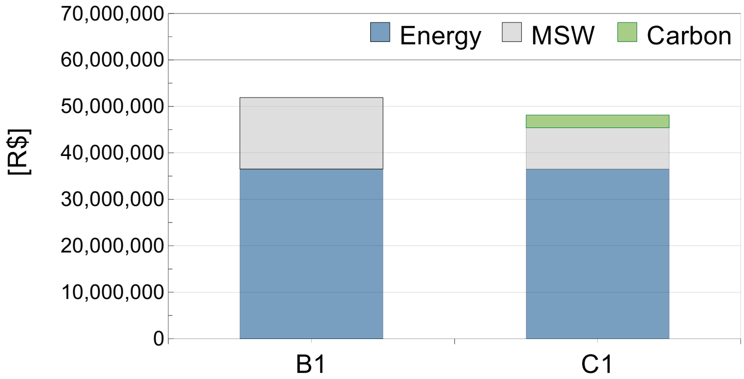

Figure VI.12: Composition of total revenues in B1 and C1 case

C2: The selection of a base year to determine baseline emissions BE depends on several motives, including the particular intention of the modeler. Due to the fact that in our case 7- and 10-year adapted baselines valued at 85,808 tCO_{2e} and 123,107 tCO_{2e} respectively, are lower than the calculated project emissions PE of 128,362 tCO_{2e}, we do not, therefore, need to apply a CDM registration. From an economic point of view this is correct, as it would not make sense to spend money when there is no adequate return. Compared to the gate free from the initial situation C1 of 37.11 R$/ton in Figure VI.13, the achieved gate fee in case C2 in the amount of 45 R$/ton is still 30% lower than case B1 without using the carbon credit sale option and without the *lucro real* exception, which resulted in 64.22 R$/ton.

C3: Figure VI.14 presents the results for the Post-Kyoto scenario in situation C3 [29]. On the one hand is pictured a reference situation that builds up-on the learning effect scenario B2 together with the consideration of carbon credit revenues ($R\$/tCO_{2e}$ 20.70) of C1. The other two pictured characteristics expand the C3 approach while integrating a price trend for post-2012 CERs. Earlier, we defined a low value of 13.8 R$/CER and a high value to 18.4 R$/CER, both assumed to take effect in 2013. The real break-even waste price is expected to reside within this calculated band. In general, the post-Kyoto Era will have a negative effect on CER prices, thus on waste prices, but this is

[29] A linear regression for the displayed C3 case gives us for the waste price function: $p_{\sigma}^{(w,BE)} = -1.05488 \cdot \sigma + 37.10539$

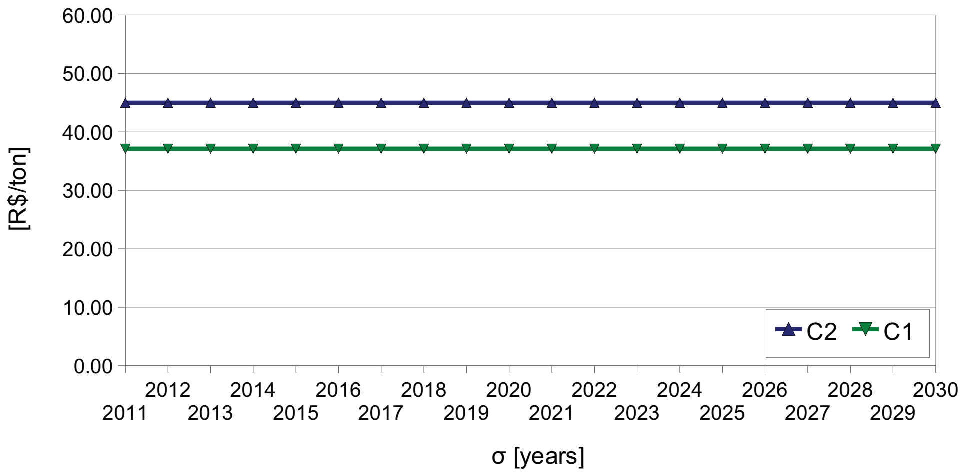

Figure VI.13: Waste price $p_\sigma{}^{(w,BE)}$ for a 14-year baseline in C2

compensated for by the fact that additional charges due to CDM registration appear advantageous in an overall system view. Moreover, the course of the waste price function in this case also demonstrates that the level of income is purely governed by the necessity to compensate for expenditures, which contain the *lucro presumido* regime's tax expenses. Taken together with Figure VI.15 below, this case shows that although waste price $p_\sigma{}^{(w,BE)}$ and total revenues are allowed to decrease, our NPV constraint is still fulfilled.

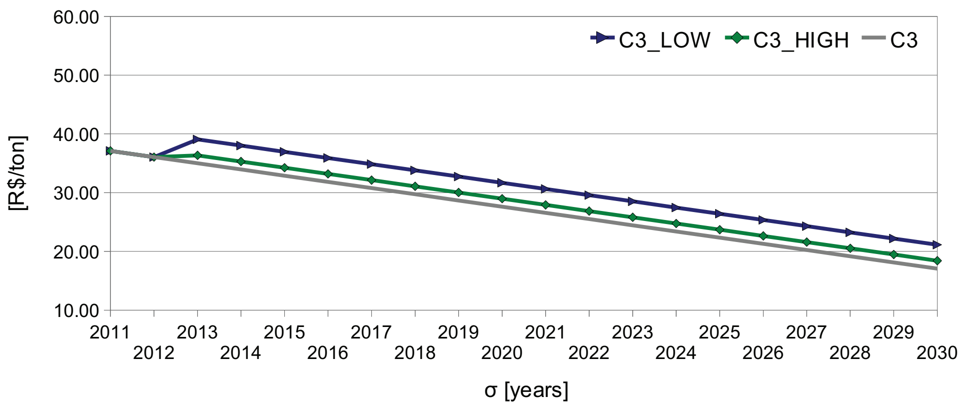

Figure VI.14: Waste price $p_\sigma{}^{(w,BE)}$ for two different post-2012 CER prices in scenario C3

C4: Finally, the effects of downgrading the WTE plant output power on the course of the waste price function $p_\sigma{}^{(w,BE)}$ will now be investigated. Therefore, the total produced energy is dropped by about 8.5% to 210,166 MWh per year, while maintaining an incineration rate approximately the same as in our initial situation C1, which used an installed capacity of 28.73 MW. Next, Figure VI.16 shows the course of the gate fee when the known carbon prices $p_{carbon}(\sigma)$ from scenario C3 are applied. The simple C4 graph uses a

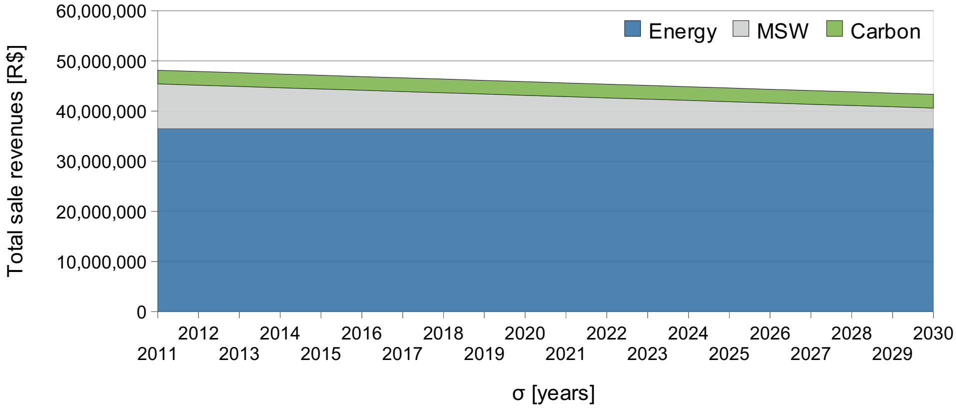

Figure VI.15: Total sale revenues in the C3 case

constant CER price of $R\$/tCO_{2e}$ 20.70 for the whole period, whereas the courses C4_LOW and C4_HIGH respect an alteration regarding the Post-Kyoto conditions at R$ 13.80 and R$ 18.40 per CER respectively, and effective from 2013 [30].

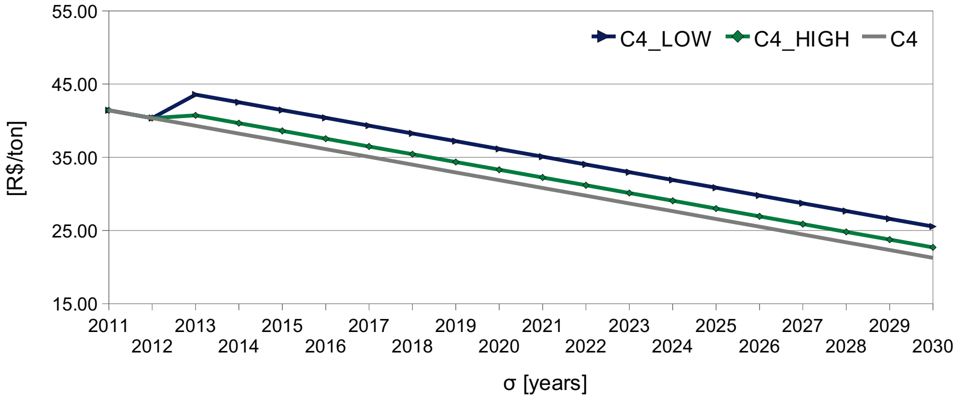

Figure VI.16: Waste price ${p_\sigma}^{(w,BE)}$ for the reduced output scenario C4

Upon comparing the gradients of scenario C4 with the corresponding equivalents from the C3 case, we recognize an economic degradation for each starting year σ. Even the C4 case with a constant carbon price of R$ 20.70 per CER results in a slightly higher gate fee than the most disadvantageous C3_LOW case within the initial power plant configuration. This is because we downsized the output power by decreasing the gas share in the fuel input, resulting in lower variable costs c_v, but plant investment costs I_0 remain the same and efficiency $\eta_{plant,calorific}$ drops some 8% to 0.88367 MWh/tonne of waste.

[30]The linear course of ${p_\sigma}^{(w,BE)}$ in the C4 case is determined by a linear regression to: $p_\sigma^{(w,BE)} = -1.0606 \cdot (\sigma - 2011) + 41.4202$

VI.5 Summary of results

This section presents the results for both the base model and the model with carbon credits and their respective configurations. We started the base model simulation with initial situation B1, where all input values are supposed to be constant for each project σ. After applying the learning curves in B2 we saw that the waste price function ${p_\sigma}^{(w,BE)}$ has two different solution curves, one for *lucro real* and one for *lucro presumido*. Subsequently, scenario B3 demonstrated the beneficial effects of a predicted tax liberalization on present and on prospective WTE plants. From then on we assumed a *lucro real* exception for our investigated WTE plants and calculated the break-even waste prices by applying only the *lucro presumido* characteristics. Finally, sensitivity analysis B4 highlighted the positive impacts of rising energy prices and lowered investment costs on the price of the gate fees, which inevitably lowered over time. The results from the model run B1, B2, and B3 are summarized in Figure VI.17.

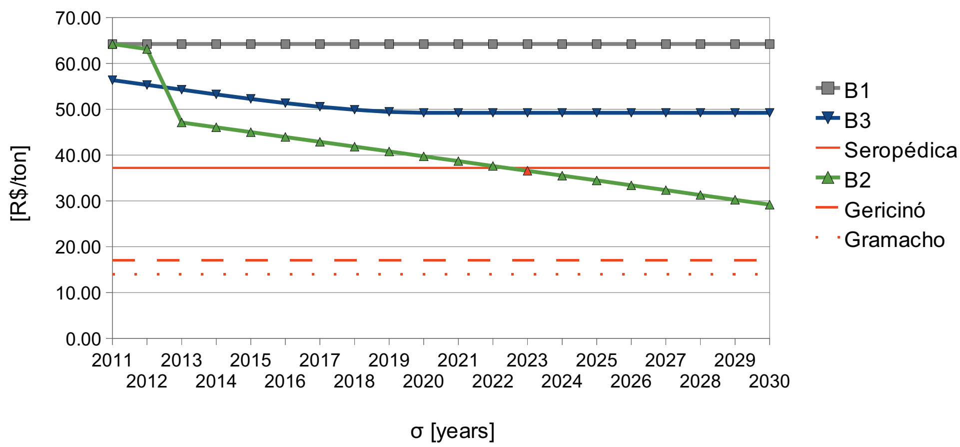

Figure VI.17: Solution curves of the base model simulation

We then expanded upon our base model by simulating a model with carbon credits. In our initial situation C1, we first added the CDM variables assumed to constant, followed by the configuration of baseline emissions in scenario C2. Next, scenario C3 accounted for the expected changes in the global carbon markets after 2012 caused by the expiry of the Kyoto Protocol by applying a high and a low boundary line for prospective carbon credit prices. This scenario was then modified by using a WTE plant with reduced output power in order to simulate a situation, where a project σ achieves accounting within the *lucro presumido* regime without the consideration of a tax liberalization. The results of these simulations are shown below in Figure VI.18.

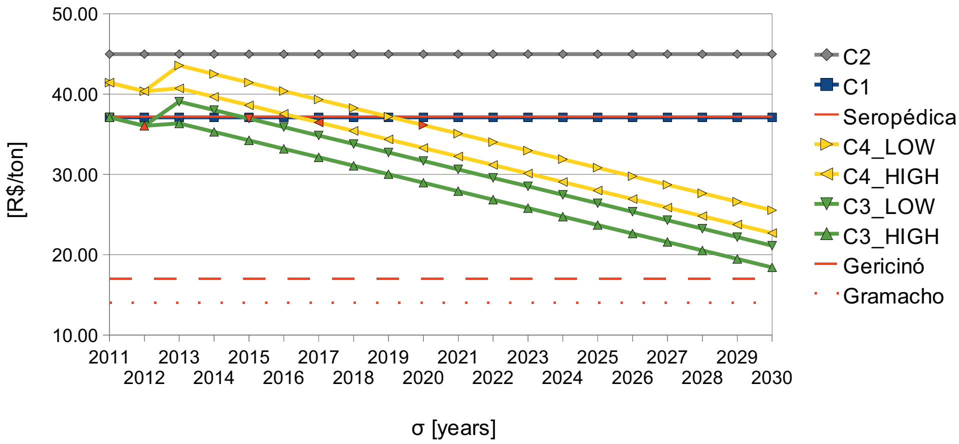

Figure VI.18: Solution curves of the model with carbon credits

Above Figures VI.17 and VI.18 also include the gate fees from the traditional waste treatment case of Rio de Janeiro. However, given that the final gate fee of 37.20 R\$/t estimated for Seropédica's site seemed rather high when compared to the far older Gericinó and Gramacho sites, we then applied a simple approach to account for this discrepancy. By comparing the lower 17 and 14 R\$/t rates of the Gericinó and Gramacho landfills respectively with that of the anticipated Seropédica plant, it was found that only the dynamic B2 scenario led to an economic benefit of the investigated WTE conversion technology. Therefore, waste price ${p_{2023}}^{(w,BE)}$ of 36.56 R\$/ton would underrun Seropédica's costs of 37.20 R\$/ton in 2023.

Moreover, the consideration of additional revenues due to the CDM registration and the *lucro real* exclusion showed clear benefits in the sense of lowering the necessary gate fees for WTE plants. In our first investigated model run, initial situation C1, we received a constant gate fee of 37.11 R\$/ton, which is marginally lower than the gate fee for the Seropédica landfill, putting it in direct competition with the landfill. Indeed, the post-2012 scenario C3 showed improvements in both presented categories, when compared with the B2 scenario, with relatively high CER prices turning both our considered configurations viable as early as 2011 and 2012 respectively, whereas the lower projected scenario C3_LOW achieves stability after 4 years in 2015. Of course, reducing the output of our incineration plant in scenario C4 resulted in higher waste prices when compared with scenario C3's initial technological values. However, by 2017 the high carbon price course considered in C4_HIGH achieved a commissioning date already preferable in terms of a lower gate fee. Thus, a lower price for CERs would result in an economically viable WTE plant realization in 2020, at the earliest.

Nevertheless, it must be remembered that we excluded Gericinó and Gramacho from our economical comparison. Originally installed as open dumps and today charging gate fees of 17 R$/ton and 14 R$ per tonne of MSW respectively, both are far more economical than the price required of a modern WTE plant to be economical. Table VI.10 lists the specific instant of time σ^* when a considered OCC WTE plant configuration where price ${p_{\sigma^*}}^{(w,BE)}$ underruns the 37.20 R$/ton gate fee of the Seropédica landfill would be preferable in competition to the considered landfill.

Scenario	σ^* [year]	${p_{\sigma^*}}^{(w,BE)}$ [R$/ton]
Learning effects B2	2023	36.56
Initial situation C1	2011	37.11
Post-Kyoto C3_HIGH	2011	37.11
Post-Kyoto C3_LOW	2011/2015	37.11/36.95
Reduced output C4_HIGH	2017	36.48
Reduced output C4_LOW	2020	36.14

Table VI.10: Break-even conditions for WTE plant utilization

VII
Conclusion

This conclusion summarizes some of the important findings of this thesis and describes the specific characteristics met on the way. In the introduction, in particular the motivation, the main aim and objective of this thesis were somewhat vague. Interestingly urbanization turned out to be exactly one of the main driving forces in the generation of municipal solid waste (MSW), which has been the investigated energy source of this research. It can be expected that in the future even more solid waste will be generated, which demands smarter and more sustainable solutions. In this sense, the terminology showed some interdisciplinary insights and moreover defined the Optimized Combined Cycle (OCC) as well as the net present value (NPV) method as our fundamental terms. Given the specific MSW characteristics of the Brazilian economy (i.e. a high moisture content in combination with a low calorific value) the OCC has been shown to be the best suited waste-to-energy (WTE) plant configuration.

To analyze the traditional MSW treatment costs, we took a look at the Brazilian situation as a whole. The final disposal of Brazilian's MSW is dominated by open dumps, which in 2000 accounted for almost two thirds of all disposals. As the year to year increase in collection percentage is higher than the growth rate of solid waste in the same period, collection coverage seems to be increasing in efficiency. Next the particular case of Rio de Janeiro was investigated. We began with a gravimetric characterization of the waste and found the already mentioned high moisture content as a fraction of organic material. Separately considering the waste flow first in its current state of affairs then second in an optimized prospective scenario helped to simplify the analysis of the general structure. Traditional waste treatment costs for the Gericinó and Gramacho landfills were found through a public announcement. It is interesting to note that the literature itself mentioned, their operating lives have already been exceeded, and they should have been closed. For the prospective final disposal in Santa Rosa, Seropédica, no sound value for the gate fee is available due to the lack of public transparency and thus had to be estimated.

On the other hand, as our research has shown, the methodology of calculating the price per ton of waste at which investment in a treatment technology becomes viable leads to a completely new trajectory of research. The existing literature shows examples of similar studies, but these publications tend to focus more on economic goals rather than the perspective of a public body's requirements and the economic realities of waste management. With the break-even price per ton of waste from our calculation, we guarantee investors an expected return. This waste price can be seen under this circumstance as a negative fuel price and presents exactly the value necessary to fulfill the target function that the investment's NPV goes to zero. With this methodology, a base model and an extended model with carbon credits were developed.

Finally, these two models were used for a representative simulation. The input values for the simulation were chosen from a careful consideration of the Brazilian case. The results for the base model as well as for the model with carbon credits showed some interesting common ground. On the one hand, the static simulations in both model configurations clearly showed the wide influence of the Brazilian tax structure on the gate fee. Exorbitant tax payments in the *lucro real* situation proved to be a serious competitive disadvantage for this biomass technology. Therefore, a tax harmonization, which could be implemented similar to the transmission and distribution tax exclusion for renewables, could be a logical step forward to ensure best available technology for the purpose of MSW treatment.

On the other hand, taking into consideration global as well as local advances in technology, the dynamic simulation offered valuable clues to the interpretation of the waste price function. Moreover, under special conditions there exist two solution sets for the waste price function, as expressed by different solution curves. Both solution sets meet the requirements of our target function. One of these solution sets corresponds to a relatively high waste price, which is in fact necessary to compensate for the increased expenditures resulting from falling into the classification of the *lucro real* tax regime. On the other hand, the second solution curve for each investigated project results in lower waste prices. This is possible because of the nonlinear course of the tax structure and in particular, because of the more beneficial conditions of the *lucro presumido* regime. On the whole, these findings provide interesting insights into the conditions under which state of the art MSW incineration plants with energy recovery using the Clean Development Mechanism (CDM) are competitive with low cost landfills.

VII.1 Future works

An important extension of this work could include an overall system approach. The consideration of a single WTE plant for final waste treatment limits our model's results. Moreover, we presumed that there is no correlation between the 20 regarded future projects, which is clearly a simplification to the assumption that all 20 future projects would, in fact, be realized. There is also a strong need for a model design that respects the whole waste cycle and its needs. This can be accomplished with a design approach starting at the beginning of the waste cycle, where the MSW is originally generated, up to the end of the waste cycle, where the waste is ultimately disposed of.

A linear optimization model could give this subject the necessary flexibility. For this purpose, one possible expansion could be a target function aimed at minimizing the total costs of the waste treatment cycle with the additional constraint that environmental impacts are restricted. Some important considerations could be:

- All stations of the waste cycle must consider the state of the waste from a gravimetric point of view. Because the economical worth of MSW varies from step to step effective waste treatment should begin with the application of techniques at the top of the waste management hierarchy, where these methods have a far more positive influence.
- The planning of applications depending on the locality where the waste is generated should be considered in order to ensure that conversion stations are implemented close to the points of generation to avoid transport related charges.
- The whole bandwidth of available waste disposal technologies should be included in the simulation, independent of their qualities or chances of implementation.
- The realization that single technologies are fundamentally interconnected with each other, such as the reality that the implementation of an incineration plant will effect next year's available waste amount.
- Total waste generation should be forecasted in order to ensure adequate resource planning. For example, we know that the minimum amount of waste needed to run a new waste treatment plant should be available three years from now.

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[Ver09] E. W. Veríssimo et al. **Relatório de Impacto Ambiental: Ampliação do Centro de Tratamento de Resíduos de Gericinó - RJ**. Companhia Municipal de Limpeza Urbana - COMLURB, Rio de Janeiro, 2009. III.2(b)

A
Numerical simulation

Carbon model - Scenario post kyoto C3										
Variable	**Unit**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
I0	R$	174.000.000	173.013.906	172.027.812	171.041.718	170.055.624	169.069.530	168.083.436	167.097.341	166.111.247
cv	R$/tonnes/waste	27,65	27,65	27,65	27,65	27,65	27,65	27,65	27,65	27,65
cO&M	R$/tonnes/waste	50,00	49,70	49,41	49,11	48,81	48,52	48,22	47,92	47,62
P	MW	28,73	28,73	28,73	28,73	28,73	28,73	28,73	28,73	28,73
ηplant,calorific	MWh/tonne waste	0,958	0,958	0,958	0,958	0,958	0,958	0,958	0,958	0,958
COEFp	tCO2e/tonne waste	0,535	0,535	0,535	0,535	0,535	0,535	0,535	0,535	0,535
CF	1	0,91	0,91	0,91	0,91	0,91	0,91	0,91	0,91	0,91
er	1	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%
LT	1	14	14	14	14	14	14	14	14	14
iEF	1	11,00%	11,00%	11,00%	11,00%	11,00%	11,00%	11,00%	11,00%	11,00%
Rf	1	4,69%	4,69%	4,69%	4,69%	4,69%	4,69%	4,69%	4,69%	4,69%
RP	1	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%
CR	1	4,82%	4,82%	4,82%	4,82%	4,82%	4,82%	4,82%	4,82%	4,82%
β	1	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54
λ	1	1	1	1	1	1	1	1	1	1
ftax("cash flow")	R$	*see below*	*see below*	*see below*	*see below*	*see below*	*see below*	*see below*	*see below*	*see below*
penergy(σ)	R$/MWh	159,00	159,00	159,00	159,00	159,00	159,00	159,00	159,00	159,00
pcarbon(σ)	R$/tCO2e	20,70	20,70	20,70	20,70	20,70	20,70	20,70	20,70	20,70
I0,CDM	R$	65.450	65.450	65.450	65.450	65.450	65.450	65.450	65.450	65.450
cf,CDM	R$/yr	8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500
cv,CDM	1	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%
BE	tCO2e/yr	260.545	260.545	260.545	260.545	260.545	260.545	260.545	260.545	260.545
Lucro Real										
IRPJ	1	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%
CSLL	1	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%
PIS+COFINS	1	9,25%	9,25%	9,25%	9,25%	9,25%	9,25%	9,25%	9,25%	9,25%
Lucro Presumido										
IRPJ	1	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%
BaseIRPJ_1	1	8,00%	8,00%	8,00%	8,00%	8,00%	8,00%	8,00%	8,00%	8,00%
BaseIRPJ_2	1	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%
CSLL	1	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%
BaseCSLL_1	1	12,00%	12,00%	12,00%	12,00%	12,00%	12,00%	12,00%	12,00%	12,00%
BaseCSLL_2	1	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%
PIS+COFINS	1	3,65%	3,65%	3,65%	3,65%	3,65%	3,65%	3,65%	3,65%	3,65%

Figure A.1: Inputs for scenario C3, part 1

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
165.125.153	164.139.059	163.152.965	162.166.871	161.180.777	160.194.683	159.208.589	158.222.495	157.236.401	156.250.307	155.264.213
27,65	27,65	27,65	27,65	27,65	27,65	27,65	27,65	27,65	27,65	27,65
47,33	47,03	46,73	46,44	46,14	45,84	45,55	45,25	44,95	44,66	44,36
28,73	28,73	28,73	28,73	28,73	28,73	28,73	28,73	28,73	28,73	28,73
0,958	0,958	0,958	0,958	0,958	0,958	0,958	0,958	0,958	0,958	0,958
0,535	0,535	0,535	0,535	0,535	0,535	0,535	0,535	0,535	0,535	0,535
0,91	0,91	0,91	0,91	0,91	0,91	0,91	0,91	0,91	0,91	0,91
20,00%	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%	20,00%
14	14	14	14	14	14	14	14	14	14	14
11,00%	11,00%	11,00%	11,00%	11,00%	11,00%	11,00%	11,00%	11,00%	11,00%	11,00%
4,69%	4,69%	4,69%	4,69%	4,69%	4,69%	4,69%	4,69%	4,69%	4,69%	4,69%
4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%
4,82%	4,82%	4,82%	4,82%	4,82%	4,82%	4,82%	4,82%	4,82%	4,82%	4,82%
1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54
1	1	1	1	1	1	1	1	1	1	1
see below	*see below*	*see below*	*see below*	*see below*	*see below*	*see below*	*see below*	*see below*	*see below*	*see below*
159,00	159,00	159,00	159,00	159,00	159,00	159,00	159,00	159,00	159,00	159,00
20,70	20,70	20,70	20,70	20,70	20,70	20,70	20,70	20,70	20,70	20,70
65.450	65.450	65.450	65.450	65.450	65.450	65.450	65.450	65.450	65.450	65.450
8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500
2,00%	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%
260.545	260.545	260.545	260.545	260.545	260.545	260.545	260.545	260.545	260.545	260.545
15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%
9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%
9,25%	9,25%	9,25%	9,25%	9,25%	9,25%	9,25%	9,25%	9,25%	9,25%	9,25%
15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%	15,00%
8,00%	8,00%	8,00%	8,00%	8,00%	8,00%	8,00%	8,00%	8,00%	8,00%	8,00%
32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%
9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%	9,00%
12,00%	12,00%	12,00%	12,00%	12,00%	12,00%	12,00%	12,00%	12,00%	12,00%	12,00%
32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%	32,00%
3,65%	3,65%	3,65%	3,65%	3,65%	3,65%	3,65%	3,65%	3,65%	3,65%	3,65%

Figure A.2: Inputs for scenario C3, part 2

year	0	1	2	3	4	5	6	7	8
2011									
+ Energy		36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864
+ MSW		8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077
+ Carbon		2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193
Sale revenues - TOTAL		**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**
- Indirect taxes (PIS+COFINS)		1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078
Net revenue		**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**
Costs - TOTAL		**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**
+ Operation & Maintenance		11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580
+ Natural Gas (NG)		6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819
+ Fixed costs CDM		8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500
+ Variable costs CDM		54.724	54.724	54.724	54.724	54.724	54.724	54.724	54.724
EBITDA		**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**
- Depreciation&Amortization		8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000
EBIT		**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**
- Interest expense		15.317.760	14.223.634	13.129.508	12.035.383	10.941.257	9.847.131	8.753.005	7.658.880
EBT		**3.684.673**	**4.778.799**	**5.872.924**	**6.967.050**	**8.061.176**	**9.155.301**	**10.249.427**	**11.343.553**
- Tax expense (IRPJ+CSLL)		2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579
Net income		**1.532.094**	**2.626.219**	**3.720.345**	**4.814.471**	**5.908.596**	**7.002.722**	**8.096.848**	**9.190.973**
+ Depreciation&Amortization		8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000
- Changes in Working Capital (10%)		2.770.243	0	0	0	0	0	0	0
- Capital expenditure		9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	9.946.597
FCFE	**-34.813.090**	**-2.484.747**	**1.379.622**	**2.473.748**	**3.567.873**	**4.661.999**	**5.756.125**	**6.850.250**	**7.944.376**
NPV	**0**								
External financing									
Initial balance	139.252.360	129.305.763	119.359.166	109.412.569	99.465.971	89.519.374	79.572.777	69.626.180	59.679.583
Principal amortization		9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	9.946.597
Interests		15.317.760	14.223.634	13.129.508	12.035.383	10.941.257	9.847.131	8.753.005	7.658.880
Tax expense									
PIS+COFINS		1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078
IRPJ		1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547
CSLL		680.032	680.032	680.032	680.032	680.032	680.032	680.032	680.032

Figure A.3: Cash flow analysis for a project (σ=2011), part 1

9	10	11	12	13	14	15	16	17	18	19	20
36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864	36.506.864
8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077	8.896.077
2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193	2.736.193
48.139.134	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**	**48.139.134**
1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078
46.382.056	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**	**46.382.056**
18.679.623	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**	**18.679.623**
11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580	11.987.580
6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819	6.628.819
8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500	8.500
54.724	54.724	54.724	54.724	54.724	54.724	54.724	54.724	54.724	54.724	54.724	54.724
27.702.432	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**	**27.702.432**
8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000
19.002.432	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**
6.564.754	5.470.628	4.376.503	3.282.377	2.188.251	1.094.126	0	0	0	0	0	0
12.437.678	**13.531.804**	**14.625.930**	**15.720.055**	**16.814.181**	**17.908.307**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**	**19.002.432**
2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579	2.152.579
10.285.099	**11.379.225**	**12.473.350**	**13.567.476**	**14.661.602**	**15.755.727**	**16.849.853**	**16.849.853**	**16.849.853**	**16.849.853**	**16.849.853**	**16.849.853**
8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000	8.700.000
0	0	0	0	0	0	0	0	0	0	0	0
9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	0	0	0	0	0	0
9.038.502	**10.132.628**	**11.226.753**	**12.320.879**	**13.415.005**	**14.509.130**	**25.549.853**	**25.549.853**	**25.549.853**	**25.549.853**	**25.549.853**	**25.549.853**
49.732.986	39.786.389	29.839.791	19.893.194	9.946.597	0	0	0	0	0	0	0
9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	9.946.597	0	0	0	0	0	0
6.564.754	5.470.628	4.376.503	3.282.377	2.188.251	1.094.126	0	0	0	0	0	0
1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078	1.757.078
1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547	1.472.547
680.032	680.032	680.032	680.032	680.032	680.032	680.032	680.032	680.032	680.032	680.032	680.032

Figure A.4: Cash flow analysis for a project (σ=2011), part 2

Variable	Unit	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Iinv(k,I0,er,LT,iEF)	R$	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*
E	MWh/yr	229.603	229.603	229.603	229.603	229.603	229.603	229.603	229.603	229.603	229.603
qw	tonnes/year	239.752	239.752	239.752	239.752	239.752	239.752	239.752	239.752	239.752	239.752
E(R)	1	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%
PE	tCO2e/yr	128.362	128.362	128.362	128.362	128.362	128.362	128.362	128.362	128.362	128.362
ER	tCO2e/yr	132.183	132.183	132.183	132.183	132.183	132.183	132.183	132.183	132.183	132.183
pσ(w,BE)	R$/tonne waste	37,11	36,05	35,00	33,94	32,89	31,83	30,78	29,72	28,67	27,61

Variable	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Iinv(k,I0,er,LT,iEF)	R$	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*	*internal*
E	MWh/yr	229.603	229.603	229.603	229.603	229.603	229.603	229.603	229.603	229.603	229.603
qw	tonnes/year	239.752	239.752	239.752	239.752	239.752	239.752	239.752	239.752	239.752	239.752
E(R)	1	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%	16,44%
PE	tCO2e/yr	128.362	128.362	128.362	128.362	128.362	128.362	128.362	128.362	128.362	128.362
ER	tCO2e/yr	132.183	132.183	132.183	132.183	132.183	132.183	132.183	132.183	132.183	132.183
pσ(w,BE)	R$/tonne waste	26,56	25,50	24,45	23,39	22,34	21,28	20,23	19,17	18,12	17,06

Figure A.5: Outputs for scenario for C3