Production of electricity from Municipal Solid Waste (MSW)

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Abstract

This dissertation was written as a part of the MSc in Energy Systems of the International Hellenic University. Nowadays a more rational waste management stream is considered necessary due to the environmental, economic and social demand. The willingness for the minimization of the accumulated waste and the increased energy demand led to the development of the third generation waste management systems. Such systems are the Waste to Energy facilities which are considered friendly for the environment and the society.

This dissertation studies the transformation of two Greek islands Skopelos and Kos in a third generation waste management stream with recovery of energy. Moreover, it is included a detailed research on which is the optimum waste to energy technology between combustion, gasification and anaerobic digestion. The effort of comparison between the pre mentioned alternatives created a software program helping the decision makers and engineers to select the optimum technology in mechanical, financing and environmental terms.

In the end of this dissertation a parametric analysis and some conclusions, extracted from the software program, concerning the financing viability of the waste to energy facilities in the two case studies and in general, are presented.

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Introduction

Background

Opening this dissertation a short description of the interaction between people and waste in urban areas will take place to illustrate the development of the processes through the years.

Initially, a historical background shows the willingness of urban society to solve the problem of the waste accumulation. Since man left nomadic life behind to create settlements some 10,000 years ago he started creating waste. The accumulation of this waste appears to have troubled early communities as there is evidence of waste management measures in a number of ancient towns in Asia and southern Europe. For the most part however, people in urban areas lived among their waste.

This led to dangerous situations for the inhabitants and in many cases laws were passed to enforce urban waste to be deposited at specific locations far from the city.

During the middle ages and the on-going rise in urban population these waste management mechanisms were lost and city dwellers endured unimaginable filth. After the Black Death urban populations plummeted, alleviating the problem until the rise of the industrial revolution created a new wave of urbanization.

Through this time period it was customary to throw waste in the streets where ragmen would salvage what was useful. An early form of recycling was attempted in Baltimore in 1874 but was not very successful for reasons similar to today's recycling programs [1][2].

As early as 1657 throwing garbage into the street was illegal in New York. The first incinerator was built in 1887 to dispose garbage, however the first municipal collection system was created in 1895. At the time the method of disposal was executed by loading all the waste on a barge and dumping it into the water outside the city. A comprehensive materials recovery was initiated to recycle usable materials and sell them but it was quickly abandoned due to public opposition.

The eventual fouling of beaches forced legislation in 1934 and dumping of municipal waste in the sea became illegal. The first hole in the ground that served as a dumping
site similar to today's modern landfills was constructed in California in 1934. The American Society of Civil Engineers published the first guide to sanitary landfills in 1959 [2].

Problem definition

The accumulation of the waste is a major problem and the creation of a sustainable waste management stream is vital for every region. The existing waste management streams could be classified/ categorized into three generations which are still exists. The first generation deals with the uncontrolled waste disposal site the second one with the sanitary landfills and the third generation with an integrated waste management stream with energy recovery.

The uncontrolled waste disposal is nothing more than open-air dump sites, similar to dumping waste in the ocean for communities near the sea. However this leads to a large number of pollution and health problems and has led to the development of sanitary landfilling. These consist of engineered operations, designed and operated with acceptable standards.

The basic characteristics of these landfills is the lining of the landfill prior to waste disposal to prevent ground contamination, the depositing of the waste, the compacting with heavy machinery and the covering with earth to deter the attraction of animals and insects, as showing in Figure 1[1][3].

![Section of a sanitary landfill](image)

Figure 1: Section of a sanitary landfill [1].

After the waste is buried in landfills the organic material decomposes anaerobically, producing various gases (primarily methane and carbon dioxide) and liquids that have
extremely high pollutional capacity when they enter the groundwater. This leachate is blocked by liners, made of either impervious clay or plastic, from moving into the groundwater.

Figure 2: Comprehensive cross section of an environmentally safe landfill design [1].

Synthetic landfill captures most of the leachate, but they are never perfect. No landfill is sufficiently tight so that groundwater contamination could be totally avoided. Wells have to be drilled around the landfill to check for groundwater contamination from leaking liners, and if such contamination is found, remedial action is necessary. The landfill never disappears limiting the use of the land for other purposes.

Modern landfills, such the one showing in Figure 2, also require the gases generated by the decomposition of the organic materials to be collected and burned or vented to the atmosphere. The gases are mostly carbon dioxide and methane which are greenhouse gases. Larger landfills use the gases for running turbines for the production of electricity, as showing in Figure 3, also known as landfill gas.

The fact that landfills produce methane gas has been known for a long time, and many accidental explosions have occurred when the gas has seeped into basements and
other enclosed areas where it could form explosive mixtures with oxygen. Modern landfills are required to collect the gases produced in a landfill and either flare them or collect them for subsequent beneficial use[1] [4].

The third generation waste management stream comes to solve the problems of the previous generation streams with the most effective way. The philosophy of an integrated waste management stream starts with the separation of the waste. The last one can be done with a sorting in the source system or with a municipal recovery facility. The first alternative is more effective in financing terms. However, cooperation of the local population is required. After that the Municipal Solid Waste is separated in various fractions. The recyclable fractions proceed in recycling facilities and the biodegradable fraction of the waste proceeds to energy recovery facilities or for aerobic digestion.

The pre mentioned procedures before the final deposition of the MSW have a direct impact in the existing landfills, where only residues from the recycling procedure and some residues from the waste to energy facilities, if the selected route is not able to convert the residues of the procedure into useful fertilizer (compost), end there.
Therefore a new generation of landfills is arisen. This third generation includes only Landfills for residues which are much more environmental friendly, easier to handle them, less required space, no ground or water pollution, economic benefits both from the recycling materials and from the production of useful renewable energy. Furthermore, the expansion of the life cycle of the existing landfills is a side benefit.

Aim of thesis

The current dissertation deals with the relative new concept of an integrated waste management stream. More specifically, the aim of the thesis is to indicate the development of a 3rd generation waste management stream.

For this purpose two real case studies are selected. Both case studies, Skopelos and Kos, are Greek islands. However these islands, which are under investigation, display two main differences. The first one is the fact that Skopelos is an interconnected island while Kos is not. The second deals with the intensity of the touristic period during the summer months, which is much higher in Kos, resulting in higher accumulation of MSW.

Although, an integrated and sustainable waste management stream is indicated, the research focuses in the recovery of energy trough the waste. For that reason a self-developed software tool is constructed to illustrate which is the optimum technology in financing and environmental terms for each case study between combustion, gasification and anaerobic digestion.

Structure of thesis

The content of this dissertation is structured in the introduction and in the 8 chapters which are presented below.

The first section of the thesis is introductory, in which a historical background is presented along with the problem definition, the aim and the structure of the thesis.

Chapter 1 contains a theoretical background, regarding the thermochemical conversion routes which are combustion, pyrolysis, and gasification and the biochemical conversion routes which are anaerobic and aerobic digestion. The basic operation principles with advantages and disadvantages of each technology are also presented to this chapter.
Chapter 2 is formed of three SWOT analyses which present existing waste to energy facilities, indicative for each technology.

Chapter 3 explains the recommended scenarios for recovery energy from waste in the two case studies.

After that the estimation of the available feedstock for the waste to energy facilities in the two islands is taking place in Chapter 4.

Chapter 5 includes the methodology and the steps for the construction of the standalone program which developed in Matlab to illustrate which is the most appropriate technology to convert the MSW to useful renewable energy.

Chapter 6, which is the core of the thesis, illustrates the results of the stand-alone program for the two case studies. Based on these results the most sustainable waste to energy facility can be identified.

Chapter 7 contains the parametric analysis. The parametric analysis is mainly conducted examining the influence of some parameters in the viability of the projects, using as indicator the NPV.

Chapter 8 includes the conclusions of the dissertation for the two case studies and some more general conclusion for the usage of MSW as biomass for renewable energy production.

Finally, Chapter 9 is only a personal opinion about the future development on the sector.
Chapter 1: Recovering energy from waste

The production of municipal solid waste has been increased significantly the last decades, due to the consumerism that characterized the western world during the second half of the 20th century. It is a phenomenon expected to expand rapidly in the future, making the problems of waste disposal and waste management, key issues for the future and present generations.

In the same direction, agricultural waste has been increased due to the novel technologies in the cultivation of land and the increased demand of goods, which is the natural result of the ongoing growth of the world population.

The accumulation of waste is a major problem, difficult to solve. The solution of that problem is strictly connected with a lot of different and complex parameters; economic parameters such as the possible benefits that can occur from a recycle program instead of simplified methods of land filling; energy parameters, such as the energy required for the transportation, treatment and disposal of waste and the benefits that could be generated from a possible energy recovery project; environmental parameters, such as the pollution of the atmosphere, the ground and the aquifers; social parameters, such as the degradation of areas in which the waste disposal takes place. Granted that all the previous parameters should be considered, emphasis should be given on the methods of waste treatment and disposal and also, the energy and the materials that can be recovered from waste.

1.1 Methods and Technologies

Renewable biomass deposits are classified into three categories. The first one is wastes coming from plant crops, animal production, the processing of agricultural products, crop residues, wood industry and the biodegradable fraction of the municipal waste. The second one is forest biomass such as wood, forest wood residues, trees, bushes and forest cycle residues. The last one is energy crops such as short cycle forest crops, leafy forest crops, annual non-woody crops, cereals, sugar crops, forage crops, oilseed crops, and aquatic plants [5].

The ongoing project will deal only with the waste fraction of biomass, as the target is not only to recover energy from waste but to introduce an integrated waste
management stream. The municipal waste particularly, constitutes a major problem and has a steady production instead of the seasonally production that the agricultural wastes have.

1.1.1 Thermochemical conversion

The Thermochemical conversion of biomass is taking place through 3 main processes. These processes are combustion, gasification and pyrolysis. Through these processes the initial biomass feedstock is converted to the end product which can be power, heat, transportation fuel or chemical feedstock. The optimum solution depends on the economics of biomass availability and the preferable end product [6].

1.1.1.1 Biomass Combustion

The thermal conversion of biomass, using air, into heat and electricity is the most established process worldwide. This is happening with the rapid oxidation of the biomass which is used as a fuel (after the required drying) to produce heat. The main products of the combustion of biomass are carbon dioxide and water, because the components with the biggest concentration in the initial feedstock are carbon, hydrogen and oxygen and the procedure is made with excess air.

The combustion is takes place in a boiler, furnace or stove, where the fuel is burned directly to produce heat. Different types of biomass, such as wood, agricultural waste, wood pulping liquor, municipal solid waste (MSW), and refuse derived fuel, can be burned in industrial facilities like. The main target of the combustion procedure is to release all of the chemical energy stored in the biomass. Also in the same direction the losses should be minimized due to incomplete combustion.

The combustion should be complied with three requirements in order to be proper and sufficient. These are high temperatures for ignition, sufficient turbulence for the mix of the oxygen with the rest of the components, and the required time for the oxidation reaction to be completed.

Combustion can be divided into four phases. Initially the biomass is heated up for the removal of the water, so the drying procedure displays a small volume reduction of the biomass. Then the second phase is consisted of the pyrolysis or de-volatilization which is the chemical decomposition of biomass in the absence of oxygen in order to
get the volatile matter. The last one is composed mainly of HC, CO, CO₂, H₂, and CH₄. The remaining of this phase is called char or fixed carbon and the volume of biomass decreases significantly as most of the biomass leaves as removal gasses. The third phase is the gasification (flame combustion) of the previous gasses that are emitted from the pyrolysis with mixed air and are combusted at high temperature to CO₂ and H₂O. The last phase is the combustion of the residue that remains (char) which is made slower in lower temperature and has a lower reduction ratio of the biomass. The residue of the previous procedure is the ash.

Combustion is more commonly performed in boilers where heat is adsorbed by water to produce either lower pressure steam for heating or high pressure steam for power generation. Combustion efficiency is higher than the boiler efficiency, because it also depends on the efficiency of the transmittance of heat in the water for steam production.

The losses that appears in the combustion are the heat that is lost to the exiting flue gasses (the heat leaves the chimney), the heat which is trapped in the ash. Then the heat which is used for the evaporation of the water doesn’t offer useful heat. Also useful heat is lost from the incomplete combustion. Moreover losses can occur through radiation in the boiler [7].

Biomass with low percentage of moisture is preferable due to the step of ignition. If the percentage of moisture is above 50%, a pre-dry of biomass is required. However, if the moisture appears in high concentrations, a biochemical conversion process could be a nice alternative solution instead of the thermochemical route.

The combustion is the simplest thermochemical process and can be easily installed in the existing production and distribution networks, compared with the gasification and pyrolysis. Nevertheless, some steps are required so that it can remain competitive with the other two technologies. These steps have to do with the development of the existing technology, the increase in the efficiency, the reduction in the capital and operational cost, and the reduction of greenhouse gas emissions. Co-combustion of biomass with coal or natural gas is an efficient way to achieve high yields and to reduce the emissions.
High temperatures up to 2000° C are required, depending on the moisture of the fuel for the combustion of biomass. This procedure produces hot gases at temperatures between 800° C and 1000° C, which can be used for heat production in the household and industrial sector or in the cogeneration of electricity and thermal power in a steam turbine like in a Rankine cycle [5], [6], and [7].

**Combustion technologies**

The basic aim of a combustor is the conversion of the chemical energy included in fuels, into high temperature exhaust gases. The most common unit is called boiler and it is used for the production of steam. The latter can be used for process heat, or power generation, in case that the steam is in low-pressure and high-pressure respectively. Apparently, all the energy provided with the fuel, cannot be available for the steam production. This can be explained by the occurrence of various losses, such as heat losses to the exiting flue gas and ash, evaporation of the water from the biomass due to its moisture, incomplete combustion and radiation losses. Boiler efficiencies range from 50% to 80%, in favor of large scale boilers [6].

Combustion technologies can be classified as fixed bed, fluidized bed, and dust combustors.

In fixed bed combustors, processes such as drying of raw material, gasification and combustion of charcoal (solid residue) take place at a fixed bed, through which the primary air stream flows. Secondary air is stoked from the top of the bed, in order to oxidize the flue gases from the gasification. An appropriate design should avoid the bad interaction of biomass with air, the production of flying ash, which is harmful for the environment and the human health and the supplementary need for excess air. Fixed bed combustors are more suitable for fuels with low ash concentration and they can function effectively under low feed conditions [5].

In fluidized bed combustors, solid fuels are suspended in jets of air during the combustion, resulting in the mixing of solids and gas. The installation cost is relatively high, making the fluidized bed combustors suitable for plants with power capacity over 20 MWth. A smaller feedstock of biomass requires the removal of one part of the bed. Thus, the operation under low feed conditions is less effective. The recirculation combustor, which is a kind of fluidized bed combustor, increases the
fluidization speed with a usage of smaller particles and displays higher turbulence, which has as a result the uniformity of temperature distribution. The disadvantage appears to be the high cost, which makes this type of plant economically feasible for power units over 30 MWth [5].

When the fuels are in powder form, an appropriate option is the usage of dust burners. In dust burners the fuels are atomized into the primary air stream, achieving a high rate of heat release. They are suitable for units with power capacity between 2 and 8 MW [5].

1.1.1.2 Biomass Gasification

Gasification is a thermochemical process that converts biomass into gaseous biofuel by partial oxidation. The temperatures needed for the procedure range from 650 °C to 1200 °C. Besides the conversion of organic materials, gasification can be used for the conversion of coal into gas, a method which was used two centuries ago. After the energy crisis, circa 1973, the attention paid in gasification techniques started to grow in the direction of energy production from small-scale industrial generators and in the decrease of the dependence on fossil fuels.

In gasification, a lot of different processes occur, till the emergence of the final product, a gas mixture that is called syngas (synthetic gas) and consists mainly of H₂ and CO. The basic stages that raw materials undergo since their entrance into the gasifier are the following: a) dehydration of biomass, b) dry biomass pyrolysis, c) combustion of the products of pyrolysis, d) gasification and e) reforming of hydrocarbons towards CO and H₂.

Using biomass for gasification leads to a lower carbon footprint. Additionally, using biomass for gasification can contribute to a wiser waste management [6].

Compared to the gasification of coal, the gasification of biomass is considered to be easier, due to the high amount of volatile substances. The latter contributes to a higher production of gas and lower amounts of solid residues. On the other hand, drawbacks appear, caused by the lower energy density, the higher transportation cost and the more complex gas clean up. In addition, in the case of a large scale gasifier, a big area may be needed in order to supply the necessary amounts of feed stock [6].
Compared to combustion, gasification can display some advantages such as the potential for use in fuel cells or to produce chemicals, lower emissions of NOx and S and the purging from dioxins and furans. Furthermore, gases produced from combustion are fully oxidized while syngas is partially oxidized. In combustion the amount of excess air supplied varies from 6 to 7 kg of air per kg of biomass, while in gasification the same analogy is 1.5 to 1.8 kg of air per kg of biomass. Also a difference appears in the solid byproducts of gasification and combustion. In low pressure gasification the solid residue could be a source of activated carbon and in high pressure gasification the remaining slag can be rejected as a non-hazardous waste [6].

In contrast to combustion, which is an exothermic process, gasification is an endothermic one, meaning that in order to operate, additional energy is needed. The source of this energy needed, could be external or internal, in the case that a part of the biomass is burning to heat the gasifier [6].

Gasification technologies

Gasifiers can be classified into different categories, depending on the gasification agent used, the direction of the gasification agent and the resulting gas, the material of which the gasifier is heated and the technology in use. Therefore, gasifiers can be divided into co-current or counter-current, updraft or downdraft and finally into fixed bed, bubbling fluidized bed or recycling fluidized bed, while the most commonly used agents are air, oxygen and steam [5].

Each gasification agent has its pros and cons. For example, using air can lead to lower operating costs although the produced gas appears to have a lower heating value. Using oxygen creates a syngas with high heating value, which can contribute to the formation of chemicals and fuel cells. Catalytic gasification uses steam along with feedstock and leads to the production of CO and H\textsubscript{2}. In advanced gasification technologies the gasification agent can be hydrogen for the production of syngas with higher heating value [6].

In co-current gasifiers, the direction of the solid biomass and the direction of the gas are the same, while in counter-current are the opposite [5].
Fixed bed gasifiers are the most commonly ones, due to their simplicity. It is the simplest type of gasifier consisting of usually a cylindrical space for fuel feeding unit, an ash removal unit and a gas exit [8].

Updraft gasifiers are heated by the combustion of the char, while downdraft gasifiers are heated by the combustion of the volatiles. Updraft gasifiers are simple and have low capital cost, they are suitable for operation with high moisture and high inorganic percent, such as municipal solid waste, and they are considered as a proven technology. On the other hand, updraft gasifiers exhibit certain disadvantages, including the high amount of tar contained in the syngas, which constrains an extensive cleanup of the syngas. For that particular reason, the syngas produced from updraft gasifiers, is most commonly burned in combustion devices, where possible high amounts of tar do not cause notable problems [6].

Another type of fixed bed gasifier is the downdraft gasifier, which has a more complex design. Compared to updraft gasifiers, downdraft ones require a more stringent fuel size, and biomass with low moisture content. Also, the temperatures of the exiting gas are a lot higher, in comparison with the gas exit temperatures from updraft gasifiers, a characteristic that leads to the utilization of a secondary heat recovery system and flue gas cleanup. Nevertheless, downdraft gasifiers are a proven technology, relatively simple, with a low cost overall process and most importantly, they do not need a tar cleanup, as the produced gas has low tar content, making it useable in engines [6].

Increasing the size of the gasifier could lead to several problems according to the contact between the fuel and the source which provides the heat. The basic aim of fluidized bed gasifiers is to eliminate these problems by allowing the continuity of uniform temperatures between gases and solids and to avoid the hot spots formation. In fluidized bed gasifiers, temperatures varies between 750 °C and 900 °C, while in fixed bed, varies from 1000 °C to 1200 °C. Most of the large scaled gasifiers that have been constructed during the recent past are fluidized bed gasifiers [6].

Inside bubbling fluidized bed gasifiers there are inactive particles of sand or alumina. The biomass fed into the bed is broken up by the fluidized particles, resulting in a more appropriate heat transfer. Except the uniformity of the product gas and of the temperature distribution, bubbling fluidized bed gasifiers have also the advantage of
being able to use as a feedstock various biomass particle sizes, including fines and also to provide efficient heat transfer between inert materials, biomass and gas. Last but not least, the residue is formed of low amounts of tar and unconverted carbon. The main disadvantage of this technology is that the large bubbles lead to gas bypassing through the bed [6].

Inside circulating fluidized-bed gasifier, some particles are entrained due to high gas velocities and then returned to the reactor through the separation in a cyclone as they had escaped earlier from the top of the gasifier vessel. They are proper for rapid reactions and efficient heat transfer as bed materials are designed to maintain high heat capacity. Furthermore, the residue is formed of low amounts of tar and unconverted carbon. However, in the path of solid flow temperature variations occur. Moreover, the size of biomass particles may result in the corrosion of the equipment in high transport velocities. Besides, circulating fluidized-bed gasifier has less efficient heat exchange than bubbling fluidized bed gasifier [6].

Another option is the usage of two fluidized bed reactors; the first one for the pyrolysis and the second one for the combustion of the solid residue. The heat released during combustion of the solid residue can be used to provide energy for the pyrolysis in the first reactor. The main advantage arises from the separation of the combustion and pyrolysis which lead to a syngas with much higher BTU content because of the low percentage of nitrogen and carbon dioxide. Through catalytic reaction the advanced syngas can be used for the formation of other chemicals and fuels or the power production with a less capital intensive and lower operating costs installation.

After the gasification of the biomass feedstock the produced syngas can be used for the formation of hydrogen, or methanol, or ethanol, or the production of wax, diesel, gasoline, and naptha with the Fischer-Tropsch approach, or the power production. The power production can be occurred in a gas turbine, or in a steam turbine, or in fuel cells. The overall efficiency can be increased with a combined cycle power plant. In this approach both a gas and a steam turbine are used. The gas turbine operates on the Brayton cycle and the steam turbine on the Rankine cycle.
1.1.1.3 Pyrolysis

Pyrolysis is the thermochemical decomposition of biomass at high temperatures in the absence of oxygen, having as products gases, bio oil and char. The bio oil and the gases, come from the volatile part of the organic raw material. On the other hand, char comes from the fixed carbon component [6].

The duration of the process can play a significant role, thus pyrolysis is divided into slow pyrolysis and fast pyrolysis. Slow or conventional pyrolysis, is a well-known procedure, during which biomass is heated for a number of minutes to about 500 °C, producing in the end charcoal or char. As a matter of fact, when simple organic matter, such as wood, paper, or cloth, is being burned, pyrolysis is usually the first chemical reaction that takes place. In fast pyrolysis, biomass is heated in the absence of oxygen during only few seconds. This results to the creation of vapors, aerosols and char. Vapors do not stay for long into the reactor (less than 2s), minimizing in that way the reactions between the char and the volatiles.

Cooling and condensation of the vapors and the aerosol particles lead to the formation of bio oil, a dark colored liquid which has half the heating value of fuel oil. Bio oil can reach up to three quarters of all the products of fast pyrolysis, making fast pyrolysis an ideal method for the production of bio oils. In order to use bio oil for an application, some of its characteristics may need to be upgraded. For example, bio oil’s low pH and the alkali metals that it contains, may lead to corrosion, or to cause damage to the blades of the turbine. Also, its high viscosity makes the transportation of the bio oil through pipes quite difficult, while its water content leads to a less homogenous state. Moreover, high oxygen conciseness of bio oil results in a lower heat value and stability. Therefore, some methods including the installation of filters, hydrogenation, or catalytic cracking may be indispensable. Another point worth mentioning is that, bio oils can be used as fuels into combustion boilers or to be transformed to transportation fuels through a petroleum refinery.

Pyrolysis is not the appropriate technology to produce electricity. It is mostly used to produce bio-oil through the fast pyrolysis procedure. It is cheap and much simpler technology than gasification. When biomass is distributed in an area and it is necessary to collect it in a central power plant, pyrolysis could be a nice solution as the bio-oil is much more transferable than biomass [7].
1.1.2 Biochemical conversion

1.1.2.1 Anaerobic digestion

Anaerobic digestion consists of several biochemical reactions, triggered by microorganisms with the ability to live without oxygen. These microorganisms convert the organic biomass molecules into less complicated chemical molecules. The final products of the previous conversion are mostly molecules of methane and carbon oxides and in a much lesser degree (less than 1% of the gas volume), ammonia hydrogen and hydrogen sulfide [5] [9].

The process of anaerobic digestion is divided into the following four basic steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The procedure starts with hydrolysis, which takes place after the decomposition of the organic polymers (carbohydrates, proteins, lipids and nucleic acids). During hydrolysis, organic polymers are depolymerized into monomers. Different micro-organisms produce enzymes which play a catalytic role in order to achieve a relatively fast decomposition of the organic polymers. Afterwards, the most important stage of acidogenesis starts, by converting the simple monomers, into the main product, called acetate, along with volatile fatty acids, alcohols, carbon dioxide, hydrogen sulfide and other byproducts. Acetogenesis is the transformation into acetic acid, of the VFAs produced from the previous process of acidogenesis. [alternative: Acetogenesis is the transformation of volatile acids to acetate and hydrogen.] In this stage, carbon dioxide and hydrogen are also produced. The terminal stage is called methanogenesis during which the products of the previous phase (acetate and hydrogen) are converted into methane and carbon dioxide, by the methanogenic bacteria. In normal conditions, approximately 70% of the produced methane derives from the degradation of acetic acid, while the rest derives from the reaction of carbon dioxide with hydrogen. Noting that methanogenic bacteria have the slowest rate of growth from all the anaerobic micro-organisms, they play a significant role to the speed and the efficiency of the whole process [5], [7], [10], [11], and [12].

Although anaerobic digestion can be functional in a wide range of temperatures, there are two separate ranges, where the performance is optimized: mesophilic process (between 30 °C and 40 °C) and thermophilic process (between 50 °C and 65 °C).
Thermophilic processes can achieve higher conversions in less time than mesophilic processes. Nevertheless the energy costs are higher in thermophilic processes. In fact, mesophilic processes are preferable to thermophilic ones, due to the increased financial costs of the latter.

Anaerobic processes are not highly exothermic and do not produce large amounts of heat. Even for the mesophilic process the biologically produced heat is not at the required level for the optimum temperatures to be reached. Thus, additional, external heat is needed to be provided. The extra amount of heat needed can be generated by burning the produced biogas, which is sufficient to maintain the required temperature and to produce excess energy.

Critical factors for the anaerobic digestion are the load rate of the feedstock, temperature and pH. The load rate of feedstock tend to be lower in low temperatures locations, whereas is higher in warmer regions (the variations is 48 gr VS/m^3-d in the north to 96 VS/m^3-d TO in the south of the U.S.A) due to the fact that the variation of temperature is crucial for the bacterial activity. The dilution of the waste by water is an efficient method used for keeping the Ph. from 7 to 8 in order to contribute to the maximization of the degradation of the waste.

Another critical factor has to do with the stages of fermentation, which can be single or multiple. There are digesters where the steps are separated with the different bacteria in each step and digesters where all steps are in the same phase. The first alternative appears to be more capital intensive and yields of higher amount of biogas, while the second one is more economical but yields in lower amount of biogas [7].

There is a great number of different types of anaerobic digesters. The selection of the most appropriate solution depends on several issues, such as the composition of the biomass used, the amount of the biomass needed, the operating conditions etc.

In general, anaerobic digestion has a high processing efficiency, which leads to the reduction of the pollution load of waste along with the production of biogas and high quality compost. Another advantage is the low initial capital cost and the low operating cost, in compare with some thermochemical processes such as combustion and gasification. On the other hand, the first activation of a wastewater treatment plant, without the presence of the appropriate activated sludge, requires a lot of time
(several months) due to the low growth rate of anaerobic bacteria. Anaerobic digestion for municipal solid waste requires great amounts of water so that the percentage of moisture will reach the desired level, something that could be avoided by using sludge with high moisture content. Also, when the treated biomass contains sulfur compounds, the anaerobic treatment can be accompanied by evolution of odor due to the formation of hydrogen sulfide [5], [10], [11], and [12].

Other advantages of anaerobic digestion are the ability to use wet and dry biomass and high variety of feedstock. Such as waste of animals, harvest surplus, vegetable oil residues, waste water sludge, municipal solid waste, and dedicated energy crops.

1.1.2.2 Aerobic digestion

Another alternative option for the exploitation of the waste is aerobic digestion. In this option the recovery of energy is not possible. However, significant amounts of high quality compost can be produced.

Aerobic digestion is the regulated decomposition of the organic compounds of the waste. The final results of the decomposition with the contribution of microorganisms are humus (compost) which is used as soil improver and CO₂ and H₂O [13].
Chapter 2: Existing projects

In Chapter 2 an investigation of existing WtE facilities takes place. The investigation focuses in Europe. The existing projects are located in United Kingdom, Spain and Germany. The gathered information is presented in 3 SWOT analyses.

Table 1: SWOT Analyses – Gasification.

<table>
<thead>
<tr>
<th>Gasification power plant</th>
<th>Location: Isle of Wight, United Kingdom</th>
<th>Commissioned: October 2008</th>
<th>Fuel capacity: 30,000 tones/year</th>
<th>Energy production (electrical)/year: 2.3MW</th>
<th>Installation cost: 10,000,000 € (4,348 €/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strengths</td>
<td>Powers 2000 homes producing 2.3 MWe.</td>
<td>Diverts 15,000 tons of waste from landfill.</td>
<td>Localized production, less wastage during transmission.</td>
<td>Lower cost due to retrofitting to existing incineration plant (The cost of building a new facility would have been 15 million euros to 18.5 million euros)</td>
<td></td>
</tr>
<tr>
<td>Weaknesses</td>
<td>Suspended operation in 2010 (opened again in October of the same year), due to increased dioxin emissions (8 times the legal limit).</td>
<td>Retrofitting the plant into the older incinerator plant may cause several additional problems.</td>
<td>Failure of protection against the effects on increases in landfill tax and LATS (Landfill Allowance Trading Scheme) penalties.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opportunities</td>
<td>People in the island should accept that the power plant is safe for their health and the environment.</td>
<td>The business to be successful both in financing, operation terms and to be an experiment for the development of similar gasification plant.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threats</td>
<td>The people of the island may become conscious about the emissions of the power plant.</td>
<td>Isle of Wight council decided to reduce its dependence on the gasification plant, due to its history of</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>facilities.</td>
<td>limited reliability (increased dioxin emissions incident).</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• The dependence of landfills is reduced while useful renewable energy is produced.</td>
<td>• A poor managing in financing and operation terms could lead to an example to be avoided.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[14], [15], [16], and [17].
Table 2: SWOT Analyses –Combustion.

<table>
<thead>
<tr>
<th>Combustion power plant</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location:</strong> Melilla Spain (Morocco)</td>
</tr>
<tr>
<td><strong>Commissioned:</strong> 1996</td>
</tr>
<tr>
<td><strong>Fuel capacity:</strong> 30,000 tones/year</td>
</tr>
<tr>
<td><strong>Energy production (electrical)/year:</strong> 2.5MW</td>
</tr>
<tr>
<td><strong>Installation cost:</strong> 12,500,000 € (5,000 €/kW)</td>
</tr>
</tbody>
</table>

**Strengths**
- Provides 2.5 MWe, covering 10% of the city’s total power consumption.
- Diverts almost 90% of all the waste produced by the city from landfill.
- Localizes electricity production, important element for an autonomous city such as Melilla.
- Along with MSW, the facility accepts clinical wastes, tires, used oils and hydrocarbon sludge.

**Weaknesses**
- Sacks of incineration residue build up on a site, very close to the coast.
- Discharge of waste products without the appropriate treatment.

**Opportunities**
- People should accept that the power plant is safe for their health and the environment.
- Due to its geographical and political situation, Melilla acts like an island, making electricity production and waste management vital issues.
- The dependence of landfills is reduced while useful renewable energy is produced.

**Threats**
- The usage of clinical wastes along with tires is a risk factor for potential environmental pollution.
- Environmental activist groups are opposed to incineration.

[18], [19], [20], and [21].
### Table 3: SWOT Analyses – Anaerobic Digestion.

<table>
<thead>
<tr>
<th>Anaerobic digestion power plan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location:</strong> Kirchstockach, Germany</td>
</tr>
<tr>
<td><strong>Commissioned:</strong> 1997</td>
</tr>
<tr>
<td><strong>Fuel capacity:</strong> 30,000 tones/year</td>
</tr>
<tr>
<td><strong>Energy production (electrical)/year:</strong> 1MW</td>
</tr>
<tr>
<td><strong>Installation cost:</strong> 8,000,000 € (8,000 €/kW)</td>
</tr>
</tbody>
</table>

#### Strengths
- Supplying of heat to nearby industrial premises along with electricity production.
- Digestion process is more stable on account of the hydrolysis which takes place.
- Production of compost and substrate.

#### Weaknesses
- The installation cost for the anaerobic digestion of municipal solid waste is higher compared to the agricultural and animal waste.
- Attempts to store energy via silicum silicate failed.
- The plant is very complicated. Today digestion plants are built easier and cheaper. *

#### Opportunities
- The dependence of landfills is reduced while useful renewable energy is produced.

#### Threats
- Small possibility of bad odor nearby.

* Information came by personal contact with the operation manager (by e-mail) [22], [23], and [24].

The general conclusions, derived from the investigation of existing WtE facilities, are that there is a new innovative concept that is in the stage of development and that
there are not many installations in the European region. The next inference is that these installations can effectively reduce the volume of the waste and improve the waste management scheme. However whatever includes incineration of any type of waste is treated with caution by residents.
Chapter 3: Waste management

The scope of the current thesis is to illustrate the appropriate technology for recovery energy from waste in two case studies. The first case study takes place in Skopelos, an interconnected island in the region of Sporades. The second takes place in the island of Kos, a not interconnected island in the region of Dodekanisa.

The purpose of both projects is to bring out the final stage of an integrated waste management stream. Every region which adopts this strategic plan could solve the waste problem while contributing in the production of renewable energy from the biodegradable fraction of the municipal solid waste, the animal waste and the agricultural waste.

After the existing Landfills, which succeeded the uncontrolled waste disposal, the third generation of the waste management is being under development. In this direction all the recyclable fraction of the waste is being recycled, while the biodegradable fraction of the waste is used from the previous described technologies to produce energy. In the end, only the residues of the recycling system and from waste to energy technologies are disposed to new smaller scale Landfills. Therefore, the life cycle of existing Landfills is expanding and after that new small scale and more efficient in economic terms Landfills, only for residues are needed.

In both case studies the first scenario which is also proposed is that the integrated waste management should start with a sorting in the source system, where the biodegradable fraction of the municipal solid waste (MSW) should be separated from the rest of the waste. Moreover, the blue bins which collect all the recycled segments should be separated in more bins, for plastic, glass, paper, aluminum, and other metals. Only the residues from the recycle will be disposed to the Landfills residues. At this point an investigation could take place about the possibility of combining the agricultural waste (residues from the oils and gardens), the manure, and the sludge from the biological treatment with the biodegradable fraction of the MSW. However, in the current study, the waste that is disposed in the existing Landfills is taken into account. In this scenario households should separate their waste in certain bins. A separate investigation should take place, regarding the economic feasibility, for the investor of the whole process (state, municipality, individual investor or an
organization), of giving incentives to people, in the form of real finance support or reduction of municipal taxes. Moreover, in this scenario the information of citizens is required, because they are the bottom of the pyramid of the integrated waste management stream and nothing could work without their contribution.

An alternative solution which does not require the contribution of the citizens, the sorting in the source system, is the installation of a central collection facility. In this center the sorting of the waste will take place where the recycled segment will be separated from the biodegradable fraction. The latter will be transferred in the waste to energy facility and it will be used as feedstock.

In the island of Skopelos the municipality is under negotiations with a private company which is willing to install an aerobic digestion facility. All the sorting of the waste will remain to the local municipality which will install separate bins for the biodegradable fraction of the MSW and for the recycled materials (the existing blue bins). The agreement is that the private company will have a place where the garbage trucks of the municipality will transfer all the recycle segments and the private company will sell the recycled materials as raw materials to other companies. However, there will be a small percentage of the sales of the recycle products which will be given to the municipality (a percentage from the sales of the plastic bottles for the example). Moreover the garbage trucks of the municipality will transfer the biodegradable fraction of the (MSW) to the aerobic digestion facility. Then the produced compost will be available for sale as a soil improver.

In the Current thesis, it is assumed that all the sorting system will remain to the municipality which is responsible to transfer the biodegradable fraction of the MSW to the waste to energy facility (WtE) adopting the first or the second scenario of sorting. However the investment could be made by the state, the municipality, individual investors or an organization. Therefore, each of these interested possible investors could invest in the whole process of the waste management.

In the case of Skopelos the results of this thesis could be an alternative solution where an integrated waste management stream could include the production of energy from RES. Moreover, it is an alternative solution for the investors which on the one hand face higher installation cost but on the other hand, they will have stable annual cash flows. This is a result of the dependence of revenues on the fixed tariff of RES and the
energy production which can be handled smoothly with the right waste management stream. In contrast, in the aerobic digestion option, they will have to face the volatile market of soil improvers.

In the case of Kos, the integration of a waste management option which will produce renewable energy too could be even more sustainable. Because Kos is not an interconnected island, it is fully dependent on petroleum. Therefore, it is a vital issue for the local community to be less dependent on an expensive and not environmental friendly source of electricity. Moreover, it will have positive effects to the citizens of the whole country, as they pay extra taxes for the electrification of the not interconnected islands.
Chapter 4: Estimation of the feedstock

The feedstock of the waste to energy power plants will be the biodegradable fraction of the (MSW). Using the total amount of the waste, for the thermochemical conversion processes, on the one hand provides with higher installed capacity on the other hand it does not provide the recycle stream and will probably have dangerous emissions. For the biochemical procedures only the biodegradable fraction could be digested.

4.1 Feedstock estimation in Skopelos

After a research made in the municipality of Skopelos data for the waste disposal in the existing Landfill for the years 2011, 2012 and 2013 was collected. Table 4 illustrates the final data which shows the average of the total amount of waste per month for the years 2011, 2012, 2013 in tons.

Table 4: Average of the total amount of waste per month for the years 2011, 2012, 2013 in tons[25].

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>155</td>
</tr>
<tr>
<td>February</td>
<td>159</td>
</tr>
<tr>
<td>March</td>
<td>173</td>
</tr>
<tr>
<td>April</td>
<td>223</td>
</tr>
<tr>
<td>May</td>
<td>219</td>
</tr>
<tr>
<td>June</td>
<td>318</td>
</tr>
<tr>
<td>July</td>
<td>441</td>
</tr>
<tr>
<td>August</td>
<td>537</td>
</tr>
<tr>
<td>September</td>
<td>307</td>
</tr>
<tr>
<td>October</td>
<td>188</td>
</tr>
<tr>
<td>November</td>
<td>134</td>
</tr>
<tr>
<td>December</td>
<td>139</td>
</tr>
</tbody>
</table>

Therefore, the total amount of waste for one year according to the average amount of the 3 years is 2,993,450 kg (2993.45 tons). Figure 4 is constructed by the data of Table 4. Figure 4 illustrates the seasonal distribution of the waste in Skopelos, which is mainly related to the high increase of population during the summer period caused by tourists. Even the small increase in April is related to Easter, during which the population is increased.
Figure 4: Average of the total amount of waste per month for the years 2011, 2012, 2013.

From a document containing waste management data for each region of Greece, table 5 was constructed. From this table, by using the percentage of the biodegradable fraction of (MSW) for the region of Thessaly, the total amount of biodegradable waste for Skopelos is found to be 1,407 tones.

Table 5: Qualitative composition of solid waste in Thessaly region. [26]

<table>
<thead>
<tr>
<th>Composition</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodegradable</td>
<td>47</td>
</tr>
<tr>
<td>Paper</td>
<td>20</td>
</tr>
<tr>
<td>Plastic</td>
<td>8.5</td>
</tr>
<tr>
<td>Metal</td>
<td>4.5</td>
</tr>
<tr>
<td>Glass</td>
<td>4.5</td>
</tr>
<tr>
<td>The rest</td>
<td>15.5</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

4.2 Feedstock estimation in Kos

After a research made in the municipality of Kos, data for the waste disposal in the existing Landfill for the year 2012 was collected. Table 6 illustrates the final data which shows the average of the total amount of waste per month for the years 2011, 2012, 2013 in tons.
Table 6: Total amount of waste in Kos per month for the year 2012 (tons) [27]

<table>
<thead>
<tr>
<th>Month</th>
<th>Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1,183</td>
</tr>
<tr>
<td>February</td>
<td>1,288</td>
</tr>
<tr>
<td>March</td>
<td>1,607</td>
</tr>
<tr>
<td>April</td>
<td>1,869</td>
</tr>
<tr>
<td>May</td>
<td>2,899</td>
</tr>
<tr>
<td>June</td>
<td>3,697</td>
</tr>
<tr>
<td>July</td>
<td>4,293</td>
</tr>
<tr>
<td>August</td>
<td>4,650</td>
</tr>
<tr>
<td>September</td>
<td>3,653</td>
</tr>
<tr>
<td>October</td>
<td>3,047</td>
</tr>
<tr>
<td>November</td>
<td>1,685</td>
</tr>
<tr>
<td>December</td>
<td>1,421</td>
</tr>
</tbody>
</table>

Therefore, the total amount of waste for the year 2012 is 31,291.314 kg (31.291 tons).

The percentage of the biodegradable fraction of the (MSW) in Kos is 45.1 %[26]. Therefore, the biodegradable fraction of the (MSW) is 14.112 tons.

Figure 5 illustrates the seasonal distribution of the waste in Kos, which is mainly related to the high increase of population during the summer period caused by tourists.

Figure 5: Total amount of waste in Kos per month (2012).
Comparison between Figures 4 and 5 clarifies the longer touristic period in Kos. Moreover, from the distribution of the waste several factors can be examined with high accuracy. For example both of the Figures show the months during which the islands have only their permanent population: the three winter months in Kos and from November to March in Skopelos. Furthermore, the distribution of tourists in the island of Kos the three summer months is smoothly in contrast with Skopelos where a sudden increase happens in August.
Chapter 5: Construction of the program

The scope of the study is to examine which is the appropriate waste to energy technology to install in two case studies, in Skopelos and Kos. The basic elements that the decision maker has to examine are: the installed capacity (related to the volume of the feedstock), economic and financing variables and the emissions of each technology. For this estimation a program is needed. After research, the only tool that had been found was system advisor model. However, that was not enough because it contained estimations only for the combustion. Thus, a new program was constructed, containing information for gasification and anaerobic digestion too. Initially all the calculations were made in EXCEL. After this all the logic of the calculations was coded in MATLAB, forming a new stand-alone program.

5.1 Biomass Combustion

In the combustion example, the technology simulated, is that of the fluidized bed combustor. Although most combustion technologies follow the same basic principles, there are same differences that should be taken into account, considering the fact that the simulation is based on the fluidized bed combustor.

Initially the user of the program has to import the feedstock (biodegradable fraction of the municipal solid waste), the composition of the biomass, the percentage of the moisture and ash, the temperature of exhaust gases (°C), and the percentage of excess air and of CO. Figure 6 shows the above mentioned inputs from the program.

In the computational procedure, only the basic elemental composition of the biomass that will be fed into the combustor is used. That means that the user has to type the percentage of weight that each of the three basic elements (C, O, H) corresponds to the total weight of the dry and ash free biomass. By assuming that the dry and ash free biomass contains no other element except the previous three (obviously, the sum of the percentage of C, O and H should be 100%), we have to keep in mind that the actual products from the combustion will be slightly different from the products of this specific simulation. This mainly has to do with the other elements that the feedstock could have, like N, CL, F and S.
Despite the fact that complete combustion of biomass or other carbon based fuels, produces solely CO$_2$ and H$_2$O, in reality we do not have a complete combustion, no matter how much excess oxygen will be used. Therefore the final products of the combustion are CO$_2$ and H$_2$O, but also CO and N$_2$. Following the assumption that the dry and ash free biomass contains only the elements of C, O, and H, we do not expect the appearance of sulfur or nitrogen oxides, contrary to what we may notice in practice. Along with the elemental composition, the user will have to type the
percentage of moisture and ash contained in the biomass. High values of moisture and ash are considered to be a drawback in combustion procedures, leading to lower efficiencies.

Figure 7 illustrates the effect of moisture in the total efficiency (electric) and the different values of the total efficiency was estimated with stable feedstock equals to 14,112,427 kg (the feedstock in the case of Kos).

![Figure 7: Effect of moisture in total efficiency.](image)

Other variables that can influence the final results are the percentage of CO existing in the exhaust gases, the temperature of the exhaust gases and the percentage of the excess air feed.

Figure 8 illustrates the effect of excess air in total efficiency. Similarly, Figure 9 illustrates the effect of percent of content of CO in total efficiency and Figure 10 the effect of ash in the total efficiency. All of them when are increased are drawbacks for the overall efficiency. Moreover, these three Figures are formed with stable feedstock that equals 14,112,427.26 kg (the feedstock in case of Kos) and stable all the other parameters that user could change.
Figure 8: Effect of excess air in total efficiency

Figure 9: Effect of percent of content of CO in total efficiency
High Heating Value derives from the known formula:

\[ HHV = 33,890.4 \times C + 144,180.6 \times (H - 0.8) \text{ (kJ/kg)} \] (1)

Afterwards, the amount of the air fed in the combustion is calculated, taking into the account the percentage of the excess air and the ratio of N\(_2\) and O\(_2\) existing in the air which is 79/21.

Then the composition of the products of the reaction is computed, considering the percentage of the CO existing in the exhaust gases. By using the enthalpy of formation of each product, the amount of heat generated by the reaction is calculated.

The heat removed with waste gas is given by the equation:

\[ \text{Losses} = \Sigma n_i \times c_p(T_e - T_{25}) \] (2)

\(T_e\) corresponds to the temperature of the exhaust gases.

Finally:

\[ \text{useful heat} = \frac{\text{heat generated during combustion}}{\text{latent heat} - \text{losses}} \] (3)

In order to produce electricity, a Rankine heat engine is used to provide the needed power to the generator.
Figure 11: Rankine cycle.

![Rankine cycle](image)

Figure 11 shows the inputs that the user can put for pump efficiency and turbine efficiency.

In the simulation that takes place, the following assumptions take part:

- The superheated steam leaves the boiler at 600°C, just before entering the steam turbine.
- The operating pressure of steam turbine is 30MPa.
- Heat rejection takes place at ambient temperature of 25°C.
- The vapor fraction after the turbine is 90%.

Figure 12: View more results, combustion.

![Fluidized bed combustor](image)

Taking into account the previous assumptions plus the turbine and pump efficiencies, we can calculate the work that the turbine delivers (W_{out}), the work that the pump
consumes (Win) and finally the net power output from the steam turbine (Wel). All of them are shown in the following table.

The window from the program (Figure 12) shows the detailed results which appears when the user push the view more results button.

5.2 Biomass Gasification

Regarding the gasification simulation, the technology used was that of the recycled fluidized bed gasifier. The basic characteristic of the recycled fluidized bed gasifier, in comparison with other gasification technologies such as fixed bed gasifiers or fluidized bed gasifiers, is that they are more efficient in the conversion of solids, although that they are expensive in manufacture, an element that makes them more suitable for capacities of 15 tons of dry biomass per hour, or more.

The variables related to the chemical composition of the biomass, that the user has to define are the same as the ones in the combustion simulation. The differences occur in the variables that describe the percentage of air required for complete combustion, which is the air that enters the gasifier, the extent by weight of the combustion and the percentage by volume of the methane contained in the resulting gas. Another important set of variables is the chemical composition of the organic portion of the solid residue, given by the percentage of C, H and O that form it.

The amount of oxygen required for the complete combustion of the biomass that enters the gasifier in one second is calculated in order to define the amount of air that enters the gasifier, by using also the percentage of excess air, which is one of the variables mentioned above. Taking into account the chemical composition of the organic portion of the solid residue, along with the by weight extent of the complete combustion and the percentage of methane that exists in the produced gas, the final composition of the resulting gas is determined.

The energy balance of the gasification is given by the following equation (4):

\[
\text{sensible heat exiting with product gas} = \text{sensible heat entering with reactants} + \text{heat produced through reaction} + \text{heat from solid residue} - \text{latent heat of incoming moisture}
\]
We presume the sensible heat entering with the reactants to be equal to zero, by assuming that the biomass and the air entering in gasifier are both at ambient temperature.

Figure 13: Brayton and Rankine cycles efficiencies.

Figure 14: View more results, gasification.

Taking into account the previous assumptions, along with the compressor and turbine efficiencies for the brayton cycle and the pump and turbine efficiencies of the rankine cycle (Figure 13), the total electricity and thermal generation of the whole procedure can be calculated, as well as its efficiency. Figure 14 shows the detailed information that the user is able to extract by pressing the view more results button.
5.3 Anaerobic digestion

For the simulation of the anaerobic digestion, the chosen process is that of the mesophilic process. In contrast to the thermophilic process, where the digestion takes place in a region of temperatures between 50°C and 65°C, mesophilic process takes place in a region of temperatures around 35°C. Despite the fact that thermophilic process requires less time to convert the same amount of solids, than mesophilic process, the latter has a significantly lower energy cost, a characteristic that makes mesophilic process more desirable in most of the situations.

The variables that describe the composition of the biomass feedstock, are the same as in the two previous technologies, and are the percentages of C, O and H existing in the dry ash free biomass, along with the percentage of moisture and ash concentration. The difference occurs in the variables that describe the percentage of the total solid biomass that is converted and the percentage of the volatile part, which corresponds to the dry biomass without the inorganic part and the fixed carbon, by weight of total solids (Figure 15).

The hydraulic retention time (in days) required for the conversion of x % of the volatile solids to biogas, in the mesophilic process, is given by the empirical formula:

\[ HRT = e^{\frac{(x+3.9)}{17.9}} \]  

The total volume of the digester (in m³) is:

\[ V = \frac{4}{3} \times HRT \times VFR \]  

VFR stands for volumetric flow rate (in m³/day) at the entrance of the digester.

Afterwards, the amount of biogas produced in a year is calculated, along with its composition in methane and carbon dioxide. The calorific value of the biogas can be calculated by using the lower calorific value of methane, which is 802.6 kJ/mol CH₄.

In contrast to the technologies of combustion and gasification, in order to produce electrical or/and thermal power, in anaerobic digestion, an internal combustion engine, such one described by the Diesel cycle, is used. For this specific simulation, the compression ignition engine in use is assumed to operate at a compression ratio of 20, a cutoff ratio of 2.2 and with an ideal efficiency of 90%. Along with the previous
variables, the electrical efficiency of the real engine can be defined (Figure 16), so that the amount of the generated electrical and thermal power can be calculated, as well as the overall efficiency of the engine.

Figure 15: Mesophillic process.

![Mesophillic process](image)

Figure 16: Diesel engine.

![Diesel Engine](image)

The percentage of the thermal power that must be fed back into the process in order to keep the temperature of the digester up to the operating temperature of the mesophilic process, which is 35°C, is also calculated in relation to the average ambient temperature of the year. Subsequently, the electric efficiency of the integrated digestion process is calculated, via the LHV of the biomass. Figure 17 shows the detailed information that the user is able to extract by pressing the view more results button in the anaerobic digestion section of the program.
5.4 Economics

The procedure is followed for the estimation of the economic data is the same for all the technologies. The user has to import some variables and some others are calculated by functions.

The cost of installing an integrated biomass combustion and cogeneration unit for thermal energy and electricity in a steam turbine is given by the following relation:

Capital investment: \( CI = 4029 - 643\ln C \) [€ / kWe] (7). The corresponding cost of installing an integrated biomass gasification and cogeneration unit in a combined gas-steam turbine cycle (Biomass Gasification Combined Cycle - BIGCC) is given by the following equation: Capital investment: \( CI = 7,675 - 1,235 \ln C \) [€ /kWe] (8). And the cost of installing an anaerobic digestion plant in a diesel engine is given by the following relation: \( 15,35-2,256*\ln C \) (9), when the installed capacity is lower than 500 kW and 1.25 million euros for each 500 kW when the installed capacity is higher than 500 kW.

Where in C is the nominal capacity of the plant in MWe, while the jobs created are
estimated at 3 employees/MWe. The user can import the average annual cost per employee (including social security contributions). At this way the total annually labor costs are estimated. Similarly, the costs of maintenance, management, security, utilities, etc. are estimated at 2/3 of the total cost of labor.

The formula $15.35 - 2.256 \cdot \ln C$ had to be created due to the high divergence of the results between the formula used for installed capacities over 0.5 MWe and real case studies, when their installed capacities were below 0.5 MWe. For the construction of the current formula used for installed capacities of less than 0.5 MWe, the installation costs of real anaerobic digestion facilities were taken into account. [11], [28], [29], [30], [31], and [32].

However, for the two case studies of this thesis (skopelos and kos) the thermal energy isn’t used, mainly because of the lack of the appropriate infrastructures and especially in case of Kos is difficult such an investment to be economically feasible due to environmental conditions. However parametric analysis will take place in a next chapter to illustrate the results when the thermal power is also taken into account.

After that the user could import a government grant of capital investment funding and a price of biomass per ton. In the case of the biodegradable fraction of the municipal solid waste the price of the feedstock could be considered zero or it could be examined the possible price that will be given to the citizens (in order to have incentive for the collection of the biodegradable fraction of the waste) keeping the investment economically feasible. Also the costs of transportation could remain to the local municipality as they have to transfer the waste in the Landfill in any case or it could be examined the possibility of the investors to adopt this cost.

The annual electricity in MWh/year is estimated by the formula:

\[
\text{Installed capacity} \times 24 \text{ h/day} \times 365 \text{ days/year} \quad (10)
\]

The installation cost is estimated by the formula:

\[
\text{Installed capacity} \times \text{ capital investment (€/KW)} \quad (11)
\]

Then the user has to import the depreciation, the sale price of electricity (€/MWh) and the tax rate.

Afterwards, the following calculations are taking place:
Subsidy: Capital investment funding x Installation cost (12)

Equity capitals: Installation cost- Subsidy (13)

Electricity Income: Sale price electricity x Annual Electricity (14)

Total operating costs: Total cost of labor + Cost of maintenance (15)

Total finance costs: Equity capitals x depreciation (16)

Earnings before taxes and depreciation (EBTD): Electricity Income- Total operating costs (17)

Profit before tax: Earnings before taxes and depreciation (EBTD) - Total finance costs (18)

Net profit: Profit before tax- Profit before tax x tax rate (19)

5.5 Financing

The aim of the previous part of the program is the extraction of a detailed finance table in incremental cash flows for each year of the plant operation. Table 6 has the following elements:

Table 6: Elements of the finance table.

<table>
<thead>
<tr>
<th>Revenues(+)</th>
<th>Total cost for labor:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of maintenance*</td>
<td></td>
</tr>
<tr>
<td>Total operating costs(-):</td>
<td></td>
</tr>
<tr>
<td>Installation Cost(-):</td>
<td></td>
</tr>
<tr>
<td>Earnings before taxes and depreciation(EBTD):</td>
<td></td>
</tr>
<tr>
<td>Finance cost (Depreciation)(-):</td>
<td></td>
</tr>
<tr>
<td>Profit before tax:</td>
<td></td>
</tr>
<tr>
<td>Taxes(-):</td>
<td></td>
</tr>
<tr>
<td>Net profit (after taxes):</td>
<td></td>
</tr>
<tr>
<td>Depreciation(+)</td>
<td></td>
</tr>
<tr>
<td>Cash flows:</td>
<td></td>
</tr>
<tr>
<td>Discount Rate:</td>
<td></td>
</tr>
<tr>
<td>NPV (for each year):</td>
<td></td>
</tr>
<tr>
<td>NPV(sum of 25 years):</td>
<td></td>
</tr>
<tr>
<td>Real equity payback period (including taxation):</td>
<td></td>
</tr>
<tr>
<td>Profitability index:</td>
<td></td>
</tr>
<tr>
<td>IRR:</td>
<td></td>
</tr>
<tr>
<td>MIRR:</td>
<td></td>
</tr>
</tbody>
</table>
Then the Table 7 shows the calculations in order to find the Cost of Capital, which is then used as the discount rate in order to find the NPV and as hurdle rate in order to compare it with IRR. The user has the possibility to install the discount rate or to import the variables as are shown in Table 7 and to estimate the discount rate.

Table 7: Variables for estimating the Discount rate.

<table>
<thead>
<tr>
<th>EQUITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk free rate:</td>
</tr>
<tr>
<td>Beta:</td>
</tr>
<tr>
<td>Base premium for mature equity market:</td>
</tr>
<tr>
<td>Country premium:</td>
</tr>
<tr>
<td>Equity risk premium (SUM of the previous 2):</td>
</tr>
<tr>
<td>Percentage of financing that is equity (w1):</td>
</tr>
<tr>
<td>Cost of equity:</td>
</tr>
<tr>
<td>DEBT</td>
</tr>
<tr>
<td>Annual Nominal Interest rate:</td>
</tr>
<tr>
<td>128/75 default spread</td>
</tr>
<tr>
<td>percentage of financing that is debt (w2):</td>
</tr>
<tr>
<td>Cost of debt:</td>
</tr>
<tr>
<td>COST OF CAPITAL (WACC):</td>
</tr>
</tbody>
</table>

5.6 Emissions

Due to the fact that only the basic composition of the biomass feedstock is taken under consideration, which includes the elements of carbon, oxygen and hydrogen, the estimation on the produced emissions is limited to the chemical compounds of carbon dioxide (CO₂) and carbon monoxide (CO). Therefore it is important to notice that there are a large number of chemical compounds that can be emitted into the atmosphere through the technologies of combustion, gasification and anaerobic digestion.

Regarding the emissions from the combustion process, the amount of carbon dioxide and monoxide in metric tons was estimated by assuming that the percentage of the moles of carbon monoxide (CO) in the products, including excess air, is known. The emissions from the gasification process include only (in the program) the chemical
compound of carbon dioxide which derives from the exhaust gases of the Brayton heat engine. Lastly, in the anaerobic digestion process only the amount of carbon dioxide was computed by making the assumption that the quantity in moles of the carbon dioxide, after the combustion in the Diesel engine, is equal to the quantity in moles of the carbon dioxide and methane existing in the produced biogas.
Chapter 6: Case studies in Skopelos and Kos (Most probable scenario)

In order to make predictions concerning the feasibility of each energy production technology, based on the available feedstock derived from the annual waste production in the islands of Kos and Skopelos, the mass flow of the biomass feedstock is needed to be calculated. Therefore and assuming that all energy facilities operate without interruption for the whole year, and that the mass flow of the biomass is equal at any given moment for each island, the corresponding amount of biomass feedstock is 0.044615677 kg/sec for the island of Skopelos and 0.447502133 kg/sec for the island of Kos. The amount of the biodegradable fraction of the waste produced annually in each island is 1,407,000. and 14,112,427. kg for the islands of Skopelos and Kos respectively. (1,407 tons and 14,112 tons)

The next necessary step in order to accomplish the desired calculations is to define the elemental composition of the biodegradable fraction of the waste which is also the feedstock of each technology. Since there are no available studies concerning the elemental composition of the municipal solid waste for any of the islands of Kos and Skopelos, or any other geographical region in Greece in particular, the required data were acquired from the ECN database for biomass and waste and are corresponding to the dry ash free biodegradable fraction of the municipal solid waste collected and measured in Netherlands. Data concerning the percentage of moisture and ash in the biodegradable fraction of municipal solid waste was obtained from a recent study which took place in the island of Cyprus, an island with relatively similar geographical, climatic, sociological and nutritional characteristics, especially with that of the island of Kos. The composition of the waste concerning the percentages of carbon, hydrogen, oxygen and moisture is influenced from the nutritional habits of the people of each region. However, this project assumes that the variance of the percentages is in small scale and is not able to influence significantly the project valuation.
Figure 18: Composition of Dry Biomass.

Figure 18 shows the composition of the biodegradable fraction of the municipal solid waste [33], and [34].

The combustion and gasification would be more efficient, with lower percentage of moisture. Specifically moisture content around 10% would be great for the thermochemical procedures. Though, the procedure of drying the biomass increases the cost. That’s why it is considered wiser to put the biomass without pre drying.

Also the volatile part of the biodegradable fraction of the municipal solid waste, an element required for the anaerobic digestion process, is estimated to be 80% according to the same data required from the ECN database [33].

For the simulation of the combustion procedure for both islands, the temperature of the exhaust gases is assumed to be 150 °C and the excess air feed is assumed to be 25%. The percentage of carbon monoxide contained in the exhaust gases is presumed to be 1%. All the above values are considered to be typical for combustion technologies and were obtained from the university notes of the course Introduction to energy Systems [5].

Similarly, for the gasification procedure, the percentage of the required air entering the gasifier is assumed to be 10%, the extent of the complete combustion by weight is
assumed to be 90%. Also, in order to acquire results, the amount of methane found in
the produced gas is presumed to be 5%.

The presumptions made for the anaerobic digestion are limited to the percentage of
conversion of total solid biomass that is expected to be 50% [5].

Economic variables

Regarding the economic inputs of the technology simulation, for all three available
technologies and for both the islands, the annual cost per employee was estimated at
12000 euros while the number of employees required for the operation of each waste
to energy facility is estimated to be analogous to the magnitude of the installation
capacity, with a ratio of 3 employees per 1 MW of installed capacity. The annual cost
of maintenance is presumed to be equal for all three technologies and both islands,
and it is estimated at a level of about 66% of the annual labor cost.

The percentage capital investment funding is set to zero due to the lack of capital
investment funding on similar projects by the state or relevant development projects.

Also, no price for the obtaining of the biomass was calculated, since it is considered
that the biomass feedstock will arrive at the waste to energy facility without any extra
cost for the acquisition, transportation and required treatment of the biomass
feedstock, prior to its usage by the corresponding waste to energy facility.

The level of depreciation, according to the Official Government Gazette (OGG),
A96/5.5.1998, is different for the three technologies, and it is: 4% for the combustion
facility, 5% for the gasification facility and 8% for the anaerobic digestion facility
[35].

The sale price of electricity was the same for all three technologies, although different
for the two islands. The sale price for the island of Kos was 99.45 €/MWh, while for
the island of Skopelos was 87.85 €/MWh. The difference can be explained by the fact
that the island of Skopelos is connected to the main electrical grid, through four
submarine power cables, whereas the island of Kos is not connected to the main grid
and therefore relies mainly on conventional liquid fuels that are regularly shipped to
the island [36]. However, law 4254/2014 has changed the previous feed in tariffs. The
new ones do not have distinction between continental regions and not interconnected
island in the case of biomass. The only distinction appears when the project has taken subsidy or not. For the base case scenario the subsidy has been considered to be zero as a subsidy scheme could not be found at the time being. Therefore, the feed in tariff is for both islands 131 €/MWh for anaerobic digestion and 90 €/MWh for combustion and gasification [37].

No sale price for the produced heat was estimated, due to the lack of relevant infrastructures for the distribution of the heat power to the populated areas of both islands, although the scenario of future usage of the projected produced heat power for water heating, from nearby to the waste to energy facilities large scale hotels, should be taken under examination, as should the usage of the produced heat power for residential and other purposes.

The level of taxation is set to 35 % for all technologies and islands, according to the applicable laws.

The growth rate of labor cost and the growth rate of maintenance are set to be 0.01% for all technologies and islands. The growth rate of labor is influenced mostly from the inflation rate. The growth rate of maintenance is influenced both from the inflation rate and from the cost associated with the hours of operation.

The capacity factor is set to be 0.85 for all technologies and islands according to an average value estimated for bibliographic research [38], and [39].

Figure 19 illustrates the above mentioned economic inputs that have been used for the extraction of the results. The depreciation and the sale price of electricity are changed according to the technology.
Table 8 shows the Calculation in order to find the Cost of Capital, which is then used as the discount rate in order to find the NPV and as hurdle rate in order to compare it with IRR.

Table 8: Calculation of the cost of capital.

<table>
<thead>
<tr>
<th>EQUITY</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk free rate:</td>
<td>5.26%</td>
</tr>
<tr>
<td>Beta:</td>
<td>0.95</td>
</tr>
<tr>
<td>Base premium for mature equity market:</td>
<td>3.88%</td>
</tr>
<tr>
<td>Country premium:</td>
<td>10.50%</td>
</tr>
<tr>
<td>Equity risk premium (SUM of the previous 2):</td>
<td>14.38%</td>
</tr>
<tr>
<td>Percentage of financing that is equity (w1):</td>
<td>50%</td>
</tr>
<tr>
<td>Cost of equity:</td>
<td>18.92%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DEBT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Nominal Interest rate:</td>
<td>6.30%</td>
</tr>
<tr>
<td>128/75</td>
<td>0.60%</td>
</tr>
<tr>
<td>default spread</td>
<td>2%</td>
</tr>
<tr>
<td>percentage of financing that is debt (w2):</td>
<td>50%</td>
</tr>
<tr>
<td>Cost of debt:</td>
<td>8.90%</td>
</tr>
</tbody>
</table>

**COST OF CAPITAL (WACC): 12.35%**
In order to find the cost of equity the risk free rate is set to be 5.26% according to the Greek ten-year euro bond [40]. The beta is calculated to be 0.95 according to Bloomberg. The estimation was made from 12/01/2003 until 12/01/2013 in a weekly linear correlation between PPC GA Equity and ASE Index. For the estimation of the base premium for mature equity market the USA Treasury bond for 80 years (1928-2008) has been used. (3.88% for the USA, for 80 years according to Damodaran) The country premium is based in Damodaran estimations and the values are changing over time. The specific value 10.5 was taken in January 2014. The equity risk premium is the summation of the base premium for mature equity market and the country premium. After that, an assumption was made about the financial decision which corresponds to equal percentages of debt and equity.

The estimation of the cost of debt predominantly was based on an interview with the head of lending department of National Bank of Greece (Metavitsiadis K. department of Kastoria). The law 128/75 has to do with a levy on corporate loans. The default spread was set to be 2% after the assumption made in which the company is rated BBB. Finally the cost of capital is estimated according to Weighted Average Cost of Capital (WACC) [41], [43], and [43].

6.1 Results Skopelos

The first three Figures are finance tables for combustion, gasification, and anaerobic digestion respectively. Specifically are referred to incremental cash flows. The tables are constructed for 25 years, but here are visible only the first six, because then all the lines behave with the same way, except depreciation, the values of which are related to the type technology used, as described in chapter “economic variables”. For combustion is 4%, meaning that depreciation period lasts 25 years, for gasification is 5%, meaning that depreciation period lasts 20 years and for anaerobic digestion is 8% meaning that depreciation period lasts 13 years. In the end a project valuation is taking place.
Figure 20: Incremental cash flows for 25 years, Combustion, Skopelos.

![Figure 20: Incremental cash flows for 25 years, Combustion, Skopelos.](image)

Figure 21: Incremental cash flows for 25 years, Gasification, Skopelos.

![Figure 21: Incremental cash flows for 25 years, Gasification, Skopelos.](image)

Figure 22: Incremental cash flows for 25 years, Anaerobic digestion, Skopelos.

![Figure 22: Incremental cash flows for 25 years, Anaerobic digestion, Skopelos.](image)
In Figures 20, 21, and 22 the first line illustrates the revenues which can be considered predictable and stable, as they come from the fixed feed in tariff scheme that is applicable in the RES. Biodegradable fraction of MSW is considered RES which has priority in the dispatch of the system and fixed price for all the years of the contract. Then the operational costs appear to have a logical increase throughout the years. After that the influence of depreciation and the tax scheme takes place. The cash flows appear, starting with the year 0 which has the expenditure of the initial investment and after that the cash flows have a slight decrease due to the increase in operational costs. NPV of each year takes into consideration the time value of money and the cash flows appear much higher decrease as they take into account the discount rate.

Net Present Value (NPV) is the most common used finance indicator for project valuation. It is calculated form the sum of the present values of each of the cash flows, positive as well as negative that occurs over the life of the project. The decision rule for NPV for independent projects is if the NPV>0 the project is accepted if the NPV<0 the project is rejected. Moreover, when the NPV is greater than 0 the project makes a return greater than the hurdle rate [40]. In the current thesis the project for the waste to energy technologies is valuated as independent project. However, this procedure is considered an integrated waste management and presents a lot of side effects for the municipality and for the society. This adds more skepticism in the rejection of the project.

Payback period is calculated with the summation of cash follows until the Installation cost be equal to the summation. When the summation is not exactly balanced with the installation cost the months are also calculated. The pay pack period including taxation is absolutely logical in the case of anaerobic digestion for such an investment in Skopelos.

Profitability index (PI) is a scaled version of NPV, and is computed by dividing the NPV with the initial investment. The PI provides a rough measure of the NPV for the return of every invested euro. It is a very useful index when the capital is limited and many alternatives arise with positive NPV. The optimum solution is the one with the highest PI[40]. Therefore for the case of Skopelos this index would be useful if we had two positive NPV to select the more efficient project.
Internal Rate of Return (IRR) is the discount rate that makes the NPV of a project equal to 0 and takes into account the project’s scale. Because the IRR is a scaled measure it tends to push decision makers to smaller project which usually yields higher percentage of returns. If IRR > cost of capital the project is accepted, otherwise if IRR < cost of capital the project is rejected. In the current analysis cost of capital is used as the discount rate in order to find the NPV and as hurdle rate in order to compare it with IRR. [40] In the case of anaerobic digestion in Skopelos the IRR is slightly smaller than the discount rate, which yields to the rejection of the project. To this point the computation of the discount rate should be taken into consideration. The discount rate is computed through WACC according to real data for Greece at the time being where the finance situation in the country is a problematic one. A small variation in the discount rate could have significant modifications in the results. Therefore, a slight decrease in the discount rate could make the project of anaerobic digestion in Skopelos sustainable in financing terms. Moreover a similar region in another country with better economy like Germany could have a discount rate around 10% which makes the project economical viable. These discussions will continue in the chapter of parametric analysis of the discount rate.

Modified Internal Rate of Return (MIRR) assumes that the intermediate cash flows get reinvested at the hurdle rate (discount rate) instead of the assumption of IRR where the intermediate cash flows get reinvested at the computed IRR [40]. This explains the higher value of MIRR compared to IRR in the three projects under consideration, as in all projects the discount rate is higher than the IRR in case of Skopelos.

As it is obvious from the project valuation none of the three projects is economical sustainable.

Figure 23 illustrates the comparison between the 3 project in technological, financial and environmental terms for the island of Skopelos. It reveals the economy of scale for waste to energy facilities. Skopelos an island with average annually production of biodegradable fraction of municipal solid waste around 1407 tons, which is not economical feasible to proceed in such an investment. However the NPV in the case of anaerobic digestion is slightly below zero and the Payback period is logical for such an investment.
Moreover, the financial indicators IRR and MIRR are slightly below the discount rate. Therefore if someone sets off the economic benefits of a waste to energy facility, which is the extension of the lifecycle of the existing landfill, environmental benefits, a most sophisticated waste management stream with a NPV slightly below zero, the project of the anaerobic digestion in Skopelos could be accepted.

In environmental terms combustion has the higher CO₂ emissions and in financing terms is in the middle ground. Although gasification presents the highest installed capacity and the lower environmental impact per MW of installed capacity, it doesn’t contribute to any positive value in financial terms.

Figure 24 illustrates that gasification is the most efficient process and has the highest electricity production in the case of Skopelos. Although, combustion has higher efficiency and electricity production than anaerobic digestion, it doesn’t differentiate significantly.
Figure 24: Electricity production and Electrical Efficiency, Skopelos.

Figure 25: Thermal production and Thermal Efficiency, Skopelos.

For thermal generation the situation is different as Figure 25 shows. Combustion has the highest thermal efficiency and thermal production, gasification follows and in the end is the anaerobic digestion which is a biological procedure.
Figure 26: Installation cost, Installation cost per MWh, Skopelos.

On one hand Figure 26 shows that gasification requires high initial investment, around four times higher than the other two technologies, on the other hand installation cost per MWh is only double from combustion and anaerobic digestion. This could be explained from the much higher efficiency of the gasification due to the combined cycles (brayton and rankine).

Figure 27: CO2 emissions, CO2 emissions per MWh, Skopelos.
According to Figure 27 anaerobic digestion is the cleanest alternative in absolute terms. However, gasification is the cleanest in CO2 per MWh.

Figure 28: Payback period for combustion, Skopelos.

Figure 29: Payback period for gasification, Skopelos.
Figures 28, 29, 30 illustrate the payback period for each technology.

Figure 31: Feedstock with NPV for anaerobic digestion, Skopelos.

Figure 31 illustrates which is the appropriate feedstock in order for the project of anaerobic digestion to be economic viable for Skopelos. Skopelos has an average annual production of the biodegradable fraction of MSW around 1407 ton. If the
average annual production be 1550 ton the project of anaerobic starts to have positive value and this makes it sustainable in financing terms.

6.2 Results Kos

The first three Figures (31, 32, and 33) are finance tables for combustion, gasification, and anaerobic digestion respectively. Specifically are referred to incremental cash flows. The tables are constructed for 25 years, but here are visible only the first six, because then all the lines behave with the same way.

Figure 31: Incremental cash flows for 25 years, Combustion, Kos.

Figure 32: Incremental cash flows for 25 years, Gasification, Kos
Figure 33: Incremental cash flows for 25 years, Anaerobic digestion, Kos

The most important element to predict in the development of such tables is the revenues. However in the current tables revenues are fixed through the feed in tariff scheme. The latest feed in tariff scheme doesn’t make any difference about the continental regions and the not interconnected islands. So the feed in tariff scheme is the same for the two islands. Nevertheless, the feed in tariff between the technologies differs and the highest ranking belongs to the anaerobic digestion.

Figure 34 illustrates the comparison between the 3 projects in technological, financial and environmental terms for the island of Kos. The gasification is the most efficient route and for the same feedstock has the highest electricity installed capacity. However, combustion has the highest thermal capacity. This effect comes from the utilization of combined cycle in the gasification. The heat rejected from the brayton cycle feeds back the boiler of the rankine and what remains from the second cycle is the thermal generation in the case of gasification. In the case of combustion where only a rankine cycle exist the heat rejected from the rankine is the thermal generation which is higher than gasification with the same feedstock. That’s why the thermal generation and the thermal efficiency in combustion is slightly higher than gasification. If gasification process becomes with only one cycle, it will have higher thermal generation and thermal efficiency, but the main interest is in the electricity generation.
The higher installation cost and installation cost per MWh comes from gasification and the lowest from anaerobic digestion, while the combustion remains in the middle.

The finance indicators illustrate clearly that the only alternative that adds positive value in financing terms is the anaerobic digestion. The total amount of gain that the project of anaerobic digestion will produce compared to the amount that could be earned simply by saving the money in a bank or investing it in some other opportunity that generates a return equal to the discount rate is around 2.5 million (the value of NPV).

The payback period of anaerobic digestion is relatively low and much lower than the other alternatives. It doesn’t take into account the time value of money but gives a clear view about the time of the recovery of the initial expenditures, including taxation.

The PI illustrates a high percentage and shows that for anaerobic digestion every euro that is being invested now it will return in 25 years (the assumed life cycle of the
project) the double money discounted in the present. (It will return 1,98 euros in the present value of money)

The IRR is much higher than the hurdle rate (12.35%) in the case of anaerobic digestion, so again shows that the project is accepted. The MIRR which more accurately reflects the profitability of a project as the intermediate cash flows reinvested at the cost of capital (12.35%) appears again higher value than the hurdle rate and shows that the project is accepted.

Over again exactly like the case of Skopelos, in environmental terms combustion has the higher CO₂ emissions and in financing terms is in the middle ground. Although gasification presents the highest installed capacity and the lower environmental impact per MW of installed capacity, it doesn’t contribute to any positive value in financial terms.

The following charts are formed in the same way like in the case of Skopelos, but differentiate in the scale.

Figure 35: Electricity production and Electrical Efficiency, Kos.

Figure 35 illustrates that gasification is the most efficient process and has the highest electricity production in the case of Kos for the same feedstock. Although, anaerobic
digestion has the lowest efficiency and the lowest electricity production is that that adds positive value in the case of Kos according to the previous tables.

Figure 36: Thermal production and Thermal Efficiency, Kos.

For the thermal generation the situation is different (Figure 36). Combustion has the highest thermal efficiency and thermal production, gasification follows and in the end is the anaerobic digestion which is a biological procedure.

Figure 37: Installation cost, Installation cost per MWh, Kos.
On the one hand gasification requires high initial investment (Figure 37), around four times higher than the other two technologies, on the other hand installation cost per MWh is only double from combustion and anaerobic digestion. This could be explained from the much higher efficiency of the gasification due to the combined cycle (brayton and rankine).

![Figure 38: CO₂ emissions, CO₂ emissions per MWh, Kos.](image)

According to Figure 38 anaerobic digestion is the cleanest alternative in absolute terms. However, gasification is the cleanest in CO₂ per MWh.

![Figure 39: Payback period for combustion, Kos.](image)
Figures 39, 40, and 41 illustrate how long it will take for the projects to "break even," or generate enough money to cover the startup costs.
6.2.1 Energy production and percentage covered from WtE technologies in Kos.

The aim of this section of the chapter is to illustrate the energy production in the island of Kos and the magnitude of the WtE technologies. Table 9 constructed according to data obtained from the Public Power Corporation of Kos.

Table 9: Energy production in Kos[44].

<table>
<thead>
<tr>
<th>Months</th>
<th>Production of electricity from oil (MWh)</th>
<th>Production of electricity from RES (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>3.396</td>
<td>2.034</td>
</tr>
<tr>
<td>February</td>
<td>3.029</td>
<td>1.909</td>
</tr>
<tr>
<td>March</td>
<td>2.801</td>
<td>1.687</td>
</tr>
<tr>
<td>April</td>
<td>2.896</td>
<td>1.763</td>
</tr>
<tr>
<td>May</td>
<td>4.171</td>
<td>1.682</td>
</tr>
<tr>
<td>June</td>
<td>5.677</td>
<td>2.428</td>
</tr>
<tr>
<td>July</td>
<td>6.910</td>
<td>3.942</td>
</tr>
<tr>
<td>August</td>
<td>7.028</td>
<td>4.266</td>
</tr>
<tr>
<td>September</td>
<td>5.268</td>
<td>2.854</td>
</tr>
<tr>
<td>October</td>
<td>4.005</td>
<td>2.102</td>
</tr>
<tr>
<td>November</td>
<td>2.439</td>
<td>1.871</td>
</tr>
<tr>
<td>December</td>
<td>3.115</td>
<td>1.744</td>
</tr>
<tr>
<td>Total annual energy production:</td>
<td>50.734</td>
<td>28.283</td>
</tr>
</tbody>
</table>

The data from the production of energy are in the same year with the data from the landfill. The Figure 42 constructed from the previous table.
The Figure 42 indicates that in the summer period the electricity production is much higher. Energy production is leaded from the energy demand which appears increased from the population growth due to the tourists. Moreover, the Figure shows the portion of the energy production covered by RES every month, which comes only from wind parks and photovoltaics. The percentage of the total energy production covered by RES for the year 2012 in Kos is 36%.

Table 10: Percentages covered by WtE technologies in Kos.

<table>
<thead>
<tr>
<th>WtE technologies</th>
<th>Annual energy production from the WtE technologies</th>
<th>Percentage of total energy production covered by the WtE technologies</th>
<th>Percentage of electricity coming from oil covered by WtE technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion:</td>
<td>8.300 MWh/year</td>
<td>10,50 %</td>
<td>16,36 %</td>
</tr>
<tr>
<td>Gasification:</td>
<td>15.905 MWh/year</td>
<td>20,13 %</td>
<td>31,35 %</td>
</tr>
<tr>
<td>Anaerobic digestion:</td>
<td>7.417 MWh/year</td>
<td>9,39 %</td>
<td>14,62 %</td>
</tr>
</tbody>
</table>

From table 10 useful conclusions may arise for the contribution of the WtE technologies in the electricity needs of Kos. Although gasification produces the highest amount of energy, anaerobic digestion is the financing sustainable alternative
with the lowest annually energy contribution. The summation of the production of electricity from oil and from RES from Table 9, gives the total energy production for Kos. It is a not interconnected island and is formed of an autonomous microgrid mainly based in the combustion of oil to cover the electricity demand plus the contribution of the wind farms and the installed photovoltaics. In year 2012 RES covered the 36% of the total energy production in the microgrid of Kos. The adaption of the gasification alternative for Kos could add to the existing percentage of renewable energy production a percentage around 20% and the adaption of combustion or anaerobic digestion could add a percentage of 10% (second column of Table 10). So, adopting the alternative of gasification could be covered around 56% of the energy needs of the island and adopting the other two alternatives around 46%.

As it has been mentioned earlier, Kos is strongly dependent on oil. The third column of Table 10 indicates the percentages of independence from oil with the adaption of each technology. Anaerobic digestion could cover 15% of the production of electricity coming from oil and gasification up to 31%.

![Figure 43: Distribution of the production of electricity for the year 2012 with the adaption of anaerobic digestion alternative, Kos.](image-url)
Figure 43 developed taking into account the adaptation of the alternative of anaerobic digestion in Kos, which is the only alternative that adds positive economic value. WtE technologies are operating in steady state conditions as it is clear from the Figure, which aims to illustrate the reduction of the electricity coming from oil with the operation of a WtE power plant.
Chapter 7: Parametric analysis

In this chapter an analysis will take place, for both case studies Skopelos and Kos, about the influence of some variables in the viability of the project, keeping all the other variables constant.

7.1 Feed in tariff parametric analysis

Initially an analysis about the influence of the feed in tariff in the financing viability of the projects will take place.

Case of Skopelos

![Figure 44: Influence of feed in tariff in the financing sustainability of the projects in Skopelos.](image)

Figure 44 illustrates that for Skopelos, the anaerobic digestion starts to be financially sustainable from a feed in tariff around 140 €/MWh, combustion around 160 €/MWh and gasification around 240 €/MWh.
Case of Kos

Figure 45: Influence of feed in tariff in the financing sustainability of the projects in Kos.

Figure 45 illustrates that for Kos, the anaerobic digestion starts to be financially sustainable even with a feed in tariff much lower than the authorized at the time being around 65 €/MWh. It is mentioned previously that combustion and gasification do not add value in the case of Kos with a feed in tariff of 90 €/MWh, but they do add value with a feed in tariff around 105 €/MWh for combustion and a feed in tariff around 170 €/MWh for gasification.

The previously mentioned feed in tariffs for which the technologies start to be financially sustainable are not extraordinary values, as these values of feed in tariff or even higher are authorized for other types of biomass or other types of RES. For example, according to law 4254/2014 the feed in tariff in different types of biomass could be from 90 €/MWh up to 230 €/MWh for projects without subsidy. For other types of RES the variation of feed in tariff fluctuates between 90 €/MWh and 280 €/MWh for projects without subsidy. Moreover, according to law 3734/2009 feed in tariff for photovoltaic varies between 260 €/MWh and 320 €/MWh.

Therefore, it can be easily understood that the financial sustainability on a project in RES sector strongly depends from the value of the feed in tariff scheme. The waste to energy facilities (WtE) which use as feedstock the biodegradable fraction of the
municipal solid waste, as it has been mentioned earlier are considered RES and have a feed in tariff scheme. Although, these projects have a lot of side effects from the environment and the society as it contribute to an integrated waste management that solves the problem of waste while it produces clean energy and reduce the ground pollution of landfills and the emissions in the atmosphere when the waste decomposes, they have reduced values of feed in tariff compared to other types of biomass or photovoltaic in Greece. On the other hand photovoltaic projects produce clean energy without emissions and without the possibility of odors, problems that may arise from WtE projects. However, waste to energy technologies produce much more renewable energy in the same installed capacity because they have much higher capacity factor and are not have the problem of intermittency that arises in photovoltaic projects. Therefore, the value of feed in tariff is a debate and strongly depends on what renewable alternatives the state wants to boost. Figures 44,45 and similar Figures of the current thesis could help the state to define the level of feed in tariff scheme according to each region, so that such projects could be developed. For example, different regions with different special characteristics and amount of available biomass could have different feed in tariff schemes, enabling the projects to be sustainable in financing terms.

### 7.2 Thermal power parametric analysis

The base case scenario doesn’t take into account the thermal power that waste to energy technologies produce. Initially due to the climate in Greece the heating period is restricted especially in the case of Kos. Though, the solar thermal power could be used for domestic hot water or for a district heating network. Moreover, the usage of the solar thermal power needs the construction of a grid that will transfer the hot water to the final usage. This will have an extra cost. Furthermore, there is a lack of a support scheme in the distribution of thermal energy like the feed in tariff scheme and it would be difficult to predict the revenues.
Case of Skopelos

Figure 46: Influence of the sale price of thermal power in the financial sustainability of the projects in Skopelos.

In the current parametric analysis the thermal power is taken into account. The Figure 46 illustrates the contribution in the economic viability of the projects in Skopelos through the NPV, of the combined purchasing of thermal energy with electricity. Specifically, it shows the differentiation of the NPV through a variation of sale prices of thermal energy.

In the case of Skopelos none of the three alternatives is economic feasible by selling only electricity. The trade of thermal energy corresponds to an added value for the projects which makes the alternative of anaerobic digestion financing sustainable with a selling price of thermal 9 €/MWh, and for combustion with 28 €/MWh. Gasification is not appropriate for this scale and this is obvious once again. It doesn’t add any positive value even with trading the thermal power with the electricity.
Case of Kos

![Figure 47: Influence of the sale price of thermal power in the financial sustainability of the projects in Kos.](image)

In the case of Kos the anaerobic digestion is sustainable in financing terms even without the contribution of the trading of thermal energy. Nevertheless, the trading of thermal energy increases linearly the NPV, as shows the Figure 47. Combustion starts to be financing sustainable with a sale price of thermal around 7 €/MWh and gasification around 70 €/MWh. The sale price of thermal where gasification starts to be financially sustainable seems high, since logical price for the thermal energy is around 20 €/MWh.

### 7.3 Price of biomass parametric analysis

The feedstock for the WtE power plants is the biodegradable fraction of the municipal solid waste. The assumption of the base case scenario is that the biodegradable fraction has no price and that the municipality collects it from the bins where the people have the commitment to accumulate it. Then the municipality instead of transferring it in the Landfill has the obligation to transfer it to the WtE power plant in order for the plant to use it as feedstock. There is a debate about incentives that could be given to the people in order for them to be willing to accumulate the biodegradable fraction of the municipal solid waste. The incentives could be direct with a given
price in the accumulated biodegradable waste or indirect with an exemption from the license fee of the people that follow the plan. This section of the chapter examines the direct incentive scenario with a given price of biomass in the case of Kos.

Figure 48: Influence of the price of biomass in the financial sustainability of anaerobic digestion in Kos.

Anaerobic digestion is an alternative that adds positive economic value in the base case scenario. A question that may arise is, in which point of which level can you give incentives to individuals for accumulating the biodegradable waste, while the project remains economic sustainable? Figure 48 gives the answer to the previous question for the alternative of anaerobic digestion in Kos. The biodegradable waste could be sold by the individuals in a price that fluctuates between 1 €/ton until 35 €/ton in order for the project to remain sustainable in financing terms.

Figure 49 has been constructed with the assumption that the thermal power in Kos is also utilized with a price of 20 €/MWh. Assuming this, the project of anaerobic digestion has improved financing indicators and the alternative of combustion also adds positive value. In this case, the biodegradable waste could be sold by the individuals in a price that fluctuates between 1 €/ton and 45 €/ton for anaerobic digestion and between 1 €/ton and 20 €/ton for combustion, in order for the project to remain sustainable in financing terms.
7.4 Discount rate parametric analysis

The discount rate that comes from the WACC formula is very important for the project valuation. WACC formula is used in order to find the Cost of Capital, which is then used as the discount rate in order to find the NPV and as hurdle rate in order to compare it with IRR. This clearly defines that a small change in the discount rate could make the decision maker to accept or reject the project. Moreover, the discount rate is not steady and fluctuates continuously, affected from the general economical and financial situation of each country. This situation is reflected from the country risk and the banking system policies.
Case of Skopelos

Figure 50 illustrates the values of the discount rate that makes the projects to be financially sustainable. Although, there is not something that someone can do to change the value of discount rate, the Figure shows that for a value of 11.5% the anaerobic digestion in Skopelos displays a positive NPV.

Figure 50: Influence of the discount rate in the financial sustainability of the projects in Skopelos.

A percentage that is not irrational, if you take into consideration that most of the firms use as a discount rate for the valuation of their projects, when is not computed analytically, a percentage of about 10% to 12%. On the other hand, combustion starts to have positive NPV with values of discount rate less than 5% and gasification less than 2.5%. These values are difficult to display in a real project valuation, unless you take into consideration only the inflation rate.

Case of Kos:

In the case of Kos the anaerobic digestion is financially sustainable anyway and as the Figure 51 shows, it continues to have positive NPV for extreme values of discount rate up until 25%.
Figure 51: Influence of the discount rate in the financial sustainability of the projects in Kos.

The combustion starts to have positive NPV for values less than 10.5%, which is a normal value for the discount rate. Gasification even in Kos which has more waste is financially sustainable only for extreme values of the discount rate, about less than 5.5%.

7.5 Subsidy parametric analysis

Subsidies are a support scheme and a major driver to undertake a project. They are often used for projects that have positive side effects to the specific industry, to the economy, and to the society in general solving major problems. Although, handling of the waste is such a major problem there is no subsidies at that moment in Greece. However, it is possible to have financial support for such a venture in the next years. That’s why this section examines the sustainability of the projects with different percentages of subsidies.

Case of Skopelos:

As it has been mentioned earlier in the base case scenario for Skopelos, anaerobic digestion is not far from displaying positive NPV. With a rational subsidy between 20 and 25 % it starts to be financially sustainable according to Figure 52. Contrariwise,
combustion and gasification need very high percentages of subsidy to be considered as sustainable in financing terms.

Figure 52: Influence of different percentages of subsidy in the financing sustainability of the projects in Skopelos.

Case of Kos

Figure 53: Influence of different percentages of subsidy in the financial sustainability of the projects in Kos.
Figure 53 illustrates that the combustion could be economically viable with a percentage of subsidy around 27. Gasification needs much higher subsidy up to 55%.

### 7.6 Annual cost per employee parametric analysis

The annual cost per employee varies proportionally to the minimum salary of each country and the demand for such work positions. A debate may arise about the highest possible level of salaries while the project remains financially sustainable. In this section of the chapter an investigation will take place about the influence of the high salaries in the project viability.

![Figure 54: Influence of annual cost per employee in the financial sustainability of the projects in Kos.](image)

Figure 54 show that the annual cost per employee doesn’t have significant contribution to the economic viability of the projects. The lines decrease but with a slight slope. Anaerobic digestion could easily have an annual cost of 20000 euros per employee instead of the basic scenario of 12000 euros annual cost per employee, without significantly differentiate the NPV. Similarly, for the other two alternatives, the increased annual cost per employee does not have significant negative influence to the economic viability of the projects.
7.7 Feedstock parametric analysis

The available feedstock for a WtE power plant is a vital characteristic and is one of the main factors that determine the scale of the plant and subsequently the installed capacity, the required initial investment, and the annual energy production. The biomass is a renewable source that doesn’t display the problem of intermittency that other RES have such as solar, wind, wave and tidal. Thus, the production of energy is not affected from the specific climatic conditions of every different region. Thereby, the conclusions of different amounts of feedstock could be considered as viable for other WtE power plants with different scales worldwide. However if someone wants to use the outcomes of the current section of this chapter concerning the feedstock, he has to take into consideration all the data that have been used for this study. These data have been described in the previous chapters. Therefore if someone takes into consideration the composition of the feedstock (waste), the percentage of moisture, and the feed in tariff scheme, he could easily take an idea on what is the most sustainable solution in financing terms according to the available feedstock. There is no separation between Kos and Skopelos in this section because after the new law, which modified the feed in tariff scheme, the main difference in the two islands is the available feedstock, so the cases of Skopelos and Kos are included in the following Figure.

![Figure 55: Influence of feedstock in the financial sustainability of the projects.](image-url)
The purpose of Figure 55 is to illustrate the key point where every technology begins to add value in financing terms according to the available feedstock. The feedstock varies from 1,000 tons up to 220,000 tons per year. The first zoom (left) indicates that anaerobic digestion begins to have positive NPV after 1600 tons, which are slightly higher than the available biodegradable fraction of the MSW that is used as feedstock in Skopelos (1407 tons). The second zoom (right) indicates that combustion begins to add positive value after 36,000 tons. This explains the negative value in the alternative of combustion in Kos where it has around the half of this value (14,112 tons). Gasification begins to indicate positive NPV after 220,000 tons feedstock per year which clearly specifies that gasification is addressed for a larger scale. Therefore, Figure 55, taking into consideration the default values that are used in this thesis, could easily illustrate in the case of Greece which alternative could be sustainable in financing terms according to the available feedstock. For example, a region somewhere in Greece that has available feedstock of 100,000 tons per year. This Figure shows that with the current situation in Greece at the time being, combustion and anaerobic digestion will be financially sustainable. Moreover, in this scale anaerobic accumulates more positive value than combustion. Thus, taking into consideration only the NPV, anaerobic digestion seems to be the optimum solution. However, the decision maker has to run the program and examines all the facts and the rest of the finance indicators to be accurate.
Figure 56: Influence of feedstock in the selection of optimum technology in financing terms.

Figure 56 has been developed to illustrate which is the optimum technology for every given available feedstock in the case of Greece with taking into consideration the present conditions. The Figure formed with annually feedstock from 1,000 up to 800,000 tons. Figure 56 shows that the anaerobic digestion is continuously above the combustion. The higher feed in tariff of anaerobic contributes significantly to this and the higher installation cost of combustion. Gasification seems to be a superior alternative to combustion after 400,000 tons per year of available feedstock and better than anaerobic digestion after 580,000 tons of annual feedstock. The mitigation of the difference in feed in tariff between gasification and anaerobic digestion could make gasification a superior alternative in financing terms in smaller scale. Gasification of the biodegradable fraction of the MSW could have higher feed in tariff because it is most efficient and has the lowest emissions per MWh. From this Figure useful conclusions can be obtained for the most economically efficient technology for different available feedstock in the case of Greece. If someone uses the program developed for this thesis and adjust the data to another country, he could have useful results for every region globally for the biodegradable fraction of the MSW. Moreover, if he modifies the composition of the feedstock, the program could be used for different types of biomass.
Chapter 8: Conclusions

The main driver associated with the usage of biomass is climate change. The use of biomass is not a matter of lack of resources, but a matter of necessity for clean renewable energy sources. Moreover, waste is a main type of biomass. Therefore, the treatment of waste to produce energy can solve the problem of waste accumulation and produce useful renewable energy.

The usage of biomass is associated with a number of challenges too. A problem may arise, when the feedstock comes from 1st generation biomass, which compete the food cultivation. For example in USA the production of ethanol from corn contributes to the increase of corn prices. Furthermore, environmental challenges have been arisen, such as deforestation, biodiversity loss, soil erosion due to intense cultivation, water and air pollution due to the extent use of fertilizers. Last but not least when the land is not cultivated, it is able to absorb CO$_2$. On the other hand when the soil is under the production of agricultural products, it emits CO$_2$.

The challenges described in the previous paraFigure do not exist when the source of biomass is waste. Waste is a 2nd generation biofuel and doesn’t contribute to the previous mentioned environmental concerns.

The biomass has the potential to cover a significant percentage of the energy demand. Today biomass is by far the largest RES contributor in the energy mix. However this also contains traditional biomass uses which are inefficient. In large scale power plants, as has been described in the current thesis, biomass (waste) plays a bigger role with more modern ways of using it which are much more efficient and environmentally-friendly (lower emissions).

Although the WtE facilities could be a sophisticated alternative to solve the problem of the accumulated waste and to produce renewable energy, at the same time it is not a widespread procedure. Nevertheless, these facilities tend to become the third generation of an integrated waste management with the minimum disposal for the landfills.

The necessity of this thesis on what is the optimal WtE facility for the two case studies (Skopelos-Kos) led to the creation of an integrated software program. It is a detailed program as it has been described which helps the decision maker or the
engineer to choose between different projects related to converting biomass to electricity. The independence of using biomass from the specific climatic conditions makes the program able to be used for any interested region worldwide.

By executing the program, the most probable scenario reveals the economy of scale for WtE facilities. Skopelos, an island with average annual production of the biodegradable fraction of municipal solid waste around 1407 tons is not economically feasible to proceed in such an investment at any available technology. However, a slight increase in the average annual production of the waste makes the project of anaerobic digestion sustainable in financing terms. Moreover, taking into consideration the positive side effects from a WtE venture in the environment, in the society and in the economy, the discussion of the acceptance of such a project with a NPV slightly below zero comes into the table.

In the same direction, executing the program for the case of Kos, the most probable scenario reveals that anaerobic digestion is the suitable alternative for this scale. It is the only alternative that adds positive value in financing terms. The gasification is the most efficient route and for the same feedstock has the highest electricity installed capacity while in the same time combustion has the highest thermal capacity. The higher installation cost and installation cost per MWh comes from gasification and the lowest from anaerobic digestion, while the combustion remains in the middle. Over again, exactly like in the case of Skopelos, in environmental terms, combustion has the highest CO\textsubscript{2} emissions and in financing terms is in the middle ground. Although gasification presents the lower environmental impact per MWh of installed capacity, it doesn’t contribute to any positive value in financial terms.

For the case of Kos useful data obtained from the PPC concerning the electricity According to the real case studies analyzed in the current thesis only the biodegradable fraction of the municipal solid waste under the anaerobic digestion route can cover the 9.39 % of the total energy needs in Kos. The anaerobic digestion route could also cover the 14.62 % of electricity coming from oil. The adaption of a more efficient route like the gasification could cover the 20.13 % of the total energy needs in Kos and the 31.35 % of electricity coming from oil.

The general conclusion from the parametric analysis for the case of Skopelos is that even through changing some variables, combustion and gasification are difficult to be
financially sustainable. Conversely, anaerobic digestion starts to display positive financing indicators when some variables change. Specifically, NPV starts to indicate positive value for anaerobic digestion in Skopelos with feed in tariff around 140 €/MWh which is a slight increase compared with the ongoing 131 €/MWh. Combustion and gasification could be financially sustainable with much higher feed in tariff around 160 €/MWh for combustion and 240 €/MWh for gasification when the ongoing is 90 €/MWh. Anaerobic digestion could be sustainable in financing terms along with selling the thermal power too in the price of 10 €/MWh, with a discount rate around 10% instead of 12,35% and with a subsidy around 25%. Combustion could also be financially sustainable with utilizing the thermal power in the price of 28 €/MWh.

The general conclusion from the parametric analysis in the case of Kos where the anaerobic digestion is already sustainable in the base case scenario is that changing some variables anaerobic digestion is enhanced and combustion and gasification starts to indicate positive finance indicators in some cases. Specifically, with a feed in tariff around 110 €/MWh for combustion and 170 €/MWh for gasification respectively NPV starts to illustrate positive value. The combined utilization of the thermal power makes the combustion financially sustainable even from 8 €/MWh and gasification from 70 €/MWh. Combustion is also sustainable in financing terms with discount rate around 10% or subsidy around 25%. Moreover, in the case of anaerobic digestion the citizens could compensate for the collection of the biodegradable fraction of the MSW with 35 €/ton, maintaining the economic viability of the project.

A very interesting conclusion coming from this thesis is the determination of which alternative of WtE facility could be sustainable in financing terms according to the available feedstock in the case of Greece with the default values that used in the current thesis. Anaerobic digestion begins to have positive NPV after 1600 tons, combustion begins to add positive value after 36,000 tons, and gasification begins to indicate positive NPV after 220,000 tons feedstock per year which clearly specifies that gasification is addressed for larger scale. Furthermore, useful conclusions may arise on which is the optimum technology for every given available feedstock in the case of Greece with taking into consideration the present conditions. Anaerobic digestion is superior alternative up to 580,000 tons annual feedstock where
gasification starts to be better alternative. Gasification seems superior alternative than combustion after the 400.000 tons per year of available feedstock.
Chapter 9: Future steps

Moving forward in a sustainable manner the use of biomass could be based in 2nd generation feedstock and mainly in waste and residues. It could be a major contributor in a high percentage and versatile renewable energy mix. Because it is a base load power plant that can mitigate the problem of intermittency that other renewable energy sources have as the wind and solar energy.

Last but not least, a general direction exists towards the development of sustainable solutions in the three bio based sectors; electricity and heat, transportation fuels, and bio based products. In my point of view it could also be sustainable to move mainly towards the electricity and heat. Since, all the conventional fuels can be only used in the transportation sector because they are more efficient, they have more economical production and it is easier to handle them.

To this point juxtaposition will be arisen. Fossil resources will eventually be depleted. This generates the need for finding alternatives for all sectors that will be compatible with the current infrastructure. However, latest investigation have shown that the conventional resources are have over 50 years to be depleted and leaving the fossil fuels only for the transportation sector will make this period longer and eventually will decrease the price of fossil fuels. Then gradually the electricity could cover a percentage of the transportation needs. For example, initially electricity could cover the public transportation and public vehicles.

Biofuels could be produced only from feedstock, which in not suitable for electricity production like algae. The production of Bio based products could be based according to the demand.

Towards this direction another conflict might arise about the sustainability of a bio refinery. Heat and electricity as final products are much cheaper than transportation fuels and chemicals. Producing transport fuels or chemicals from biomass would increase the profitability of the bio refinery and make it economically viable. However, as it has been mentioned before, leaving the fossil fuels for the transportation sector will have positive impact on the price of fossil fuels for the consumers. Moreover, it is most important the sustainability in general and not the sustainability of a bio refinery, which can always alert the percentage of production
between the electricity and heat, transportation fuels, and bio based products due to versatile behavior of biomass.

This movement will eventually contribute in a higher penetration of different renewable sources in the energy mix that could be based in electricity. Smart cities able to produce the required energy through renewable sources from large scale base load power plants and distributed energy resources, covering the needs for heating, cooling, use of appliances, and transportation, working all together in a smart grid like a virtual power plant.
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