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GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

TECHNO-ECONOMIC FEASIBILITY ANALYSIS OF RAW WASTE INCINERATION AND INTEGRATED WASTE PROCESSING SCENARIOS FOR MUNICIPAL SOLID WASTES IN ISTANBUL

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MASTER OF SCIENCE THESIS

Department of Environmental Engineering

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A thesis submitted by Zeynep Dilsad DEMIREL in partial fulfillment of the requirements for the Master Degree is approved by the committee on 02.03.2022 in Department of Environmental Engineering, Environmental Engineering Program.

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Zeynep Dilsad DEMIREL

Signature

Dedicated to my family

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LIST OF SYMBOLS

C_f	Capacity factor
C	Carbon
C/N	Carbon and nitrogen ratio
Z_n	Cash Flow
C/B	Cost / Benefit
δ	Discount rate
η	Electrical efficiency of incineration plant
Eef	Electrical efficiency of biogas plant
P	Electrical power in kW
E	Electricity generation in MWh/year
H	Hydrogen
I	Investment Cost
kW	Kilowatt
MW	Megawatt
CH_4	Methane
N	Nitrogen
O	Oxygen
O&M	Operation and maintenance cost
y	Project life
OM_{frac}	Utilized fraction of organic matter for cell tissue
W	Waste mass

LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
BFB	Bubbling Fluidized Bed
CAPEX	Capital Expenditure
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
FIT	Electricity feed-in-tariff
FIT	Electricity feed-in-tariff
GHG	Greenhouse gases
HEX	Heat exchanger
HRT	Hydraulic Retention Time
HEX	Heat exchanger
HRT	Hydraulic Retention Time
INV	Investment
ISKI	Istanbul Water and Sewerage Administration
ISTAC	Istanbul Environmental Management Industry and Trading Company
LCOE	Levelized Cost of Electricity
LFG	Landfill Gas
LHV	Lower Heating Value
MBR	Membrane Bioreactor
MBT	Mechanical Biological Pretreatment
MC	Moisture Content
MGC	Moving Grate Combustion
MSW	Municipal Solid Waste
NF	Nano Filtration
NPV	Net Present Value
O&M	Operation and Manual
OPEX	Operational Expense
OLR	Organic Loading Rate
OMSW	Organic Municipal Waste

RDF	Refuse Derived Fuel
RFB	Rotating Fluidized Bed
TUIK	Turkish Statistical Institution
TLCC	Total life cycle cost
USD	United States Dollar
VS	Volatile Solids
WHR	Waste Heat Recovery
WtE	Waste to Energy
YEKDEM	Renewable Energy Resources Support Mechanism of Turkey

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ABSTRACT

Techno-Economic Feasibility Analysis of Raw Waste Incineration and Integrated Waste Management Scenarios for Municipal Solid Wastes in Istanbul

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Department of Environmental Engineering

Master of Science Thesis

Supervisor: Prof. Dr. Mehmet Sinan BILGILI

Waste to Energy (WtE) applications utilize waste and produce sustainable energy in the form of heat, electricity, or alternative fuels such as biogas. In this study, two different WtE scenarios were evaluated in terms of technical and economical in order to efficient energy recovery from municipal solid waste (MSW) in Istanbul. First scenario is raw waste incineration process which provides to obtain thermal energy by directly combustion of waste then thermal energy is converted to electrical power by steam turbine. Second scenario was focused on the separation of organic fraction, recyclable materials such as metals, glass and non-combustibles from waste stream by mechanical pretreatment. After defining of the pre-treatment processes, fractions properties after pretreatment were determined according to literature research. Anaerobic digestion process for the stabilization of separated organic wastes to produce biogas, and incineration for the remained combustible fractions were proposed. Electricity generation of integrated waste processing scenario was calculated as total electrical power of two processes which are refuse derived fuel (RDF) incineration and biogas plant using by Istanbul MSW characterization values and mass&energy equations of processes. Results was compared raw waste incineration. After the detailed definition of

the processes and outputs of both scenarios, costs of processes were estimated roughly to conduct comparison of viability of the scenarios. Cash flows of scenarios were constituted according to project incomes and outcomes. Additionally, economic parameters such as net present value (NPV) and levelized cost of energy (LCOE) were determined.

The aim of the study is to determine the most viable and economical waste management strategy that provides maximum energy and material recovery efficiency during domestic solid waste management in Istanbul. This thesis points out requirements of reducing landfilling, also draw attention to importance of separate collection of the organic waste and recyclables materials at source.

Keywords: Municipal solid waste (MSW), waste to energy (WtE), mechanical biological treatment (MBT), electricity generation, economical assessment

ÖZET

İstanbul Belediye Katı Atıkları İçin Ham Atık Yakma ve Entegre Atık İşleme Senaryolarının Tekno-Ekonomik Fizibilite Analizi

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Atıktan Enerjiye (WtE) uygulamaları atıkları kullanır ve ısı, elektrik veya biyogaz gibi alternatif yakıtlar şeklinde sürdürülebilir enerji üretir. Bu çalışmada, İstanbul'daki evsel katı atıklardan verimli enerji geri kazanımı için iki farklı atık yönetimi senaryosu teknik ve ekonomik açıdan değerlendirilmiştir. Birinci senaryo, atıkların doğrudan yakılmasıyla termal enerji elde edilmesini ve ardından termal enerjinin buhar türbini ile elektrik enerjisine dönüştürülmesini sağlayan ham atık yakma prosesidir. İkinci senaryo ise, organik fraksiyonun, metaller, cam gibi geri dönüştürülebilir malzemelerin ve yanıcı olmayan maddelerin mekanik ön arıtma ile atık akımından ayrılmasına odaklandı. Ön arıtma prosesleri tanımlandıktan sonra, literatür araştırmalarına göre ön işlem sonrası fraksiyon özellikleri belirlenmiştir. Ayrılan organik atıkların stabilizasyonu için anaerobik çürütme işlemi, kalan yanıcı fraksiyonlar için yakma önerildi. Entegre atık işleme senaryosunun elektrik üretimi, İstanbul evsel katı atık (MSW) karakterizasyon değerleri ve proseslerin kütle ve enerji denklemleri kullanılarak, atık türevli yakıt (RDF) yakma ve anaerobik çürütme ile üretilen biyogaz olmak üzere iki işlemin toplam elektrik gücü olarak hesaplanmıştır. Sonuçlar ham atık yakma ile karşılaştırıldı. Her iki senaryonun ayrıntılı süreçleri ve çıktıları tanımlandıktan

sonra, senaryoların uygulanabilirliğinin karşılaştırılması için süreçlerin maliyetleri kabaca tahmin edildi. Proje gelir ve giderlerine göre senaryoların nakit akışları oluşturulmuş, net bugünkü değer (NPV) ve seviyelendirilmiş enerji maliyeti (LCOE) gibi ekonomik parametreler belirlenmiştir.

Çalışmanın amacı, İstanbul evsel katı atık bertarafı sırasında maksimum enerji ve malzeme geri kazanım verimliliği sağlayan en uygulanabilir ve ekonomik atık yönetimi stratejisini belirlemektir. Bu tez İstanbul'da düzenli depolamanın azaltılması gerekliliğine işaret etmekte, ayrıca organik atıkların ve geri dönüştürülebilir malzemelerin kaynağında ayrı toplanmasının önemine dikkat çekmektedir.

Anahtar Kelimeler: Evsel katı atık, atıktan enerji, mekanik biyolojik arıtma, elektrik üretimi, ekonomik değerlendirme

1 INTRODUCTION

1.1 Literature Review

Solid wastes that classified considering their source such as domestic, industrial, and commercial solid wastes become one of the significant environmental concerns, in the case of without implementation of correct waste management strategies. Steps of solid waste management sector consists of collection, transportation and final disposal. Rules during implementation of these steps are defined according to solid wastes content. Domestic wastes amount increasingly with high population growth are one of the solid wastes which is also difficult to treat due to involving different types of materials. According to World Bank global review world cities generate about 1.3 billion tons of MSW annually, the amount is expected to reach 2.2 billion tons by the end of 2025 [1]. Municipal solid waste (MSW) generation increases day by day depending on population growth, economic and industrial development [2]. This indicates that higher MSW generation is occurred in industrialized nations with the better economic standards [3,4]. As a result of urbanization expand, industrial and technological developments are contributed to MSW generation, beside population growth especially in developing countries [5]. MSW becomes significant environmental issue in many cities which have due dense population and industrialization with implementation of insufficient management technologies beside the inadequate separate collection and transportation. The huge expenditure required to provide the waste management service, the lack of financial support and failure of proper use of economic sources prevents the implementation of appropriate waste management methods [6]. Municipalities that obliged to establish, operate domestic solid waste disposal facilities prefer regular landfills because of cheap and easy operation however due to the inadequate recycling implementations, landfilled waste amounts are very large. Organic fractions that disposed in landfill significantly generate methane, nevertheless efficiency of gas capture from landfill is estimated %65-75 [7]. EPA reported collection efficiencies typically range from

60% to 85%, with an average of 75% most assumed. In 2012, U.S. EPA estimated global methane emissions from landfills, past and projected from 2015 to 2050. Global landfill CH_4 emissions were estimated to have increased about 19 percent between 1990 and 2015. In 2015, landfilling of solid waste was the fourth largest individual source of global CH_4 emissions, after enteric fermentation (the largest), coal mining and natural gas & oil systems. Also, the waste sector accounted for 13,6 percent of total non-CO_2 greenhouse gas (GHG) emissions in 2015 which 56 percent were contributed by landfilling of solid waste [8].

Population growth, increasing of personal incomes, and expanding industrial activities causes rising of waste generation. From 2015 to 2030, emissions from landfills were projected by Haokai Zhao, it was stated that the increase will be about 10 percent from 875 to 959 Mt CO_2-e because of growing populations, increasing of personal incomes, and expanding industrial activities [9]. On the other hand, primary energy resources are the fossil fuels which are depleting and causing environmental challenges [10]. Obligation of the reduction of greenhouse gas emissions and the requirement to find alternative fuels increase with the reduction of fossil fuels. As a solution for these problems should be focused on the Waste to Energy technologies which utilize waste and produce useful energy in the form of heat, electricity or alternative fuels such as biogas. WtE technologies have the potential to reduce the amount of MSW disposed in landfills while also provides electricity generation. Thus, GHG emission from fossil fuels and landfill areas can be reduced. If CO_2 emissions from WTE plants are captured and stored underground, these plants could be reached carbon negative credits as 66% of the carbon in MSW, that process is defined typically biogenic [11,12]. WTE with carbon capture and storage (WTE–CCS) has a potential to achieve carbon negative footprints [13].

The design of a viable process for the management of MSW is required the economic assessment and development of a feasible business plan after identifying the detailed characterization of MSW. There are many types of treatment methods for municipal solid waste management which changes depending on waste quantity and characteristics. Determination of waste characterization is essential to comprise sustainable and feasible treatment and disposal process model. MSW

involves different types of materials and effected from different parameters such as urban economic situation or education level, therefore for high efficiency energy and material recovery, detail characterization parameters should be considered when selecting appropriate treatment technologies. In this way, economic value from wastes can be obtained besides reduction of environmental pressure.

Istanbul is a metropolitan city of Turkey with a current population of around 15.5 million people. Due to the dense population and industrial activities, MSW generation is reached to 18.000 tons in a day. MSW collection transport and disposal processes in Istanbul is in the responsibility of Istanbul Environmental Protection and Waste-Processing Corporation (ISTAC) which is established by İstanbul Metropolitan Municipality. Current MSW management strategy in Istanbul is landfilling including landfill gas (LFG) collection. Also, one incineration plant was commissioned in 2021 with 3.000 ton/day capacity. However municipal wastes are generally occurred from high amount of biodegradable fractions which increases the moisture content to causes low combustion efficiency in the incineration processes. World Bank report stated that for an effective incineration operation with energy recovery the average calorific value of MSW should be at least 1700 kcal/kg [14], whereas International Energy Agency reported that the calorific value must be greater than 1900 kcal/kg for the sustainable feasible operation [15].

1.1.1 Overview of Solid Waste Management Technologies

Determination of waste characteristic is essential to define the implemented treatment methods especially where have insufficient recycling activities. An inadequate MSW management strategy threatens the environment and public health and prevents utilizing of wastes effectively. According to waste management hierarchy principles that are reduce, reuse, recycle and dispose; recycling materials and compositions with involving energy content should be evaluated when implementing waste treatment methods. According to Intergovernmental Panel on Climate Change [16], MSW consist of biodegradable waste which are mostly kitchen waste has highest percentage MSW (25–70%), also includes plastic, metal, glass, textiles, wood, rubber, leather, paper, food waste and

others except for industrial waste. Municipal waste components were classified according to materials in Table 1.1.

Table 1.1 MSW components

MSW Components	Contents
Organic	Food wastes, wood and garden wastes
Paper/cardboard	Magazines, newspaper
Packing wastes	Tetra-pak, paper or plastic
Glass	Jars, colorful and colorless glasses
PET bottles	Water and other drinking bottles
Plastic bags	All of type plastic bags
Plastics	Other plastics
Metals	Iron materials
Aluminum	Cans and other aluminum materials
Electrical equipment	Phones, radios, pc equipment's
Hazardous wastes	Batteries and accumulators
Textile	All textile products
Other combustibles	Combustible materials
Non-Combustible	Ash, stone rock

In recently years, waste to energy technologies become promising solution that give opportunity to generate sustainable energy. There are two basic energy recovery methods of WtE technologies: thermal energy conversion methods such as waste incineration, pyrolysis and gasification processes, and biochemical energy conversion by anaerobic digestion or landfill gas (LFG) utilizing processes. According to a study related investigation of the effect of LFG collection from landfills in Brazil on the energy recovery and the GHG emissions reduction mentioned that solid waste disposed in landfills without LFG utilizing impacted on

public health [17]. They also stated that collection of occurred LFG by anaerobic degradation of the organic matter therefore utilizing of LFG is essential for protecting ambient air from the CO_2 and CH_4 emissions, beside energy generation. Even if landfilling is a cheap and easy method of waste management, reducing landfilling especially in metropolitan cities because of high amount of MSW to go disposal is important considered energy savings and protecting available surface spaces. In addition, a leachate-collection system in sanitary landfills should be designed and operated well, and contamination of soil prevented well with impermeable zones from leakage. However, beside usage of huge areas large amount of leachate that is hard to treat occurs in landfills because of the inadequate separately collection in source. According to waste management study for Istanbul by Kanat, main fractions of landfilled MSW in İstanbul are organic and recyclable materials, these recoverable materials are collected with other waste such as metals or hazardous waste which leading to increasing leachate treatment costs and efficiency (or discharge problems) [18]. Because of these reasons, this study pointed to reduction of landfilling and different WtE processes were evaluated based on technical and economic analysis for more effective waste disposal.

Incineration process is most commonly used waste management process to reduce waste volume in many countries that have high amount of mixed municipal wastes. Effective incineration process gives the opportunity of high energy recovery efficiency beside decreasing the landfill demand. Incineration is thermochemical degradation of waste devastation in a furnace by combustion at high temperatures which carried out between 750 and 1100 °C [19]. The recovered energy could be used for, heating, steam production and electricity generation. The aim of this technique is the degradation and destruction of combustible materials in MSW with the presence of oxygen thus the volume of MSW to convert into heat and energy [20]. However, a lower heating value (LHV) of the waste is important to enable to continue a thermal chain reaction it is called self-supporting combustion. In practice, the HHV involves the latent heat of water vapor depending on moisture content of MSW that cannot be used for energy recovery efficiency, while the LHV excludes from the heat of evaporation of the water formed from the hydrogen contained in the waste feedstock and its moisture. Therefore, LHV is appropriate

calorific value to assess the available energy content of waste. Incineration provides almost 70% mass reduction and 90% volume reduction [21], depending on composition and degree of recovery of certain materials like metals from the ash for recycling. Optimum "3T" requirement (Time, Temperature and Turbulence) should be ensured for effective operation by the boiler design both regarding the solid mass and gaseous products during combustion of MSW [22,23]. Steam temperature and pressure were defined approx. 400ºC and a pressure of approx. 4 MPa according to waste incineration standards [24,25,26,27]. These parameters constitute a balance between energy recovery efficiency and tolerable high temperature corrosion of the heat exchange surfaces within a combustion furnace [25].

Typical incineration plants constitute of waste weighing, reception and handling site, feeding system, combustion chamber, boiler, system for the removal of residues and air pollution control units. There are various combustion technologies that used in waste incineration which are grate technologies, fluidized bed and rotary kiln. There are two different grate combustion technologies which are moving grate and fixed grate. Moving grate system is the most used combustion system for unprepared and high amount of MSW. Waste enters the combustion chamber continuously and slowly by a mechanically actuated grate and ash is discharged from the bottom of the furnace. There are several different types design of moving grate including the roller grate, the rotating grate and counter-rotating grates. The roller grate consists of adjacent drum or rollers located in a stepped formation with the drums rotating in the direction of the waste movement. Generally, roller grate technology used for high amount of MSW incineration. The rotating grate system uses bars, rockers or vibration to move the waste down each of the grates (typically three) which is appropriate for small capacity systems. In the counter-rotating grates system, grate bars rotate backwards to agitate the waste and prevent it tumbling down the forward inclined grate until burn out [28]. The other grate combustion technology is fixed grate which involves three steps. Moisture removal then initial combustion occur in first stage, after that remained materials combustion carry out. Following the second phase final carbon burn-out takes place in third phase. The furnace geometry and air injection configuration should be optimized depending on the

grate type design. The direction of the flue gas flow is one of the most important factors in design of the furnace in comparison to the waste transport.

Selection of waste treatment methods and design of combustion technologies are significant issue for energy recovery efficiency and should be defined appropriate for waste characterization for efficient waste disposal. Average energy efficiency of WtE plants in Europe which are used moving grate technologies is 26.1% for electricity generation efficiency, 77.2% in case of heat recovery and 52.1% in case of combined heat and power [29]. An efficient combustion process depends on the particle distribution on the grate, the materials mix to allow for a good contact between the combustible and air, a sufficient temperature in the pre and post combustion chambers [30]. Number of nozzles, nozzle diameter and configuration for the secondary air injection should be optimized according to furnace geometry. Schematic grate combustion furnace is shown in Figure 1.1

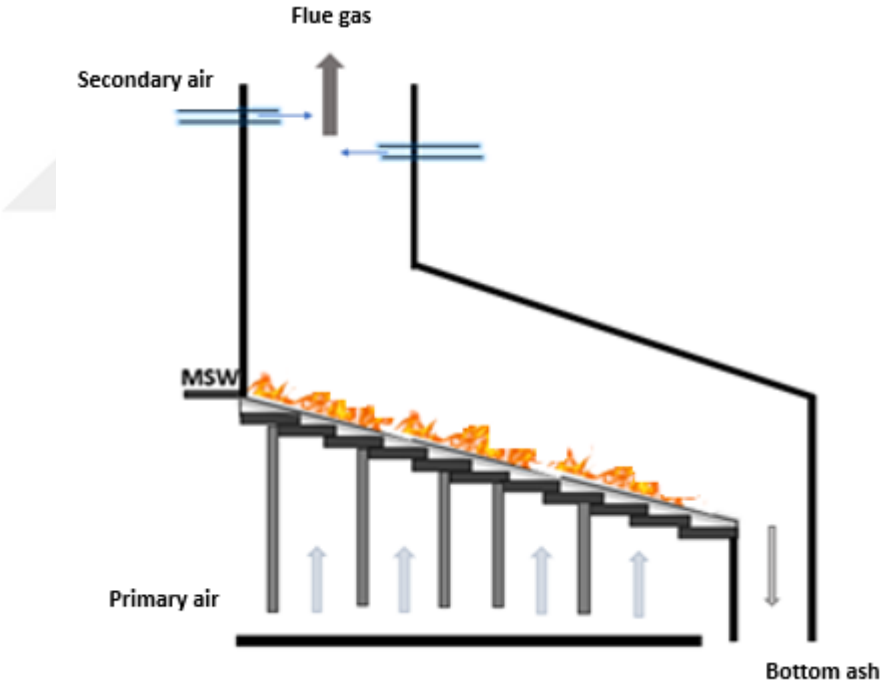

Figure 1.1 Grate type furnace schematic view

Fluidized bed incineration is used for the treatment of several types of industrial wastes and sewage sludge, recently is also implemented for MSW management. Fluidized bed combustion (FBC) occurs in a bed of sand which involves in direct in an upward flowing airstream suspended combustion ash, or other materials sand-

like, schematic fluidized bed furnace is shown in Figure 1.2. Heat transfer is supported with enhanced thermal devastation which created by high turbulence and well mixing of particles. The fluidization is mostly relevant with particle properties such as particle size, particle density, particle shape etc. and fluid potential [31]. However, additional parameters can affect the fluidization such as bed diameter, geometry, aspect ratio and sufficient design for distribution as well [32]. Gas velocity difference between fixed bed to fluidized bed arise from minimum fluidization velocity, which is one of the most important parameters in the design of FBC [33]. Three types of fluidized bed reactors are used for waste incineration: the traditional bubbling fluidized bed (BFB), the rotating fluidized bed (RFB) and the (external) circulating fluidized bed (CFB) [34]. The type of fluidized bed technology changes according to design parameters such as particle size and distribution, fluidization velocities and distributed air inlets. In bubbling fluidized bed combustors (BFB), an initially stable bed of solid particles, located in the bottom part of the combustor, is brought into a fluidized state by primary air, supplied through a distributor: the bed particles are kept in suspension at fluidization velocities between 0.5 and 3.0 m/s [34]. For BFB applications, the particle size distribution of input materials should be evaluated in detail to avoid excessive degradation of fine particles that completely combusted or dominate of large particles that will not allow sufficient fluidization. BFB are used for combustion of e.g., coal, bio-solids, plastic solid waste and wastewater treatment sludge. High degree thermal devastation is occurred by collection of the particles in the primary cyclone of a BFB and returning to sand. In contrast to BFBs, rotating fluidized bed (RFB) combustors are more reliable to uneven distribution of the primary air over the distributor, causing an internally imposed circulation through the sand bed with zones of strong aeration (up flow sand stream) and zones with less aeration (downflow sand stream), and creates mixing pattern [35]. The bubbling fluidized beds (BFB) used for wide range of solid waste types and sizes such as sewage sludge, MSW and comparable industrial waste after pretreatment. Fluidized bed technologies have high heat generation capacity which provide more energy recovery efficiency. In addition, the technique has capable to burn high moisture wastes with low calorific value, such as sludge. Controlled combustion is achieved by provided turbulence together with thermal inertia of reactor bed and

friction effect. Low stack emissions and char content are assured depending on uniform burning [34]. Relatively lower combustion temperatures than other technologies provide low NOx emission also high combustion efficiency reduces CO levels. BFB and CFB principles are also used for other thermal conversion processes which include the gasification and pyrolysis of biomass, plastic solid waste and RDF.

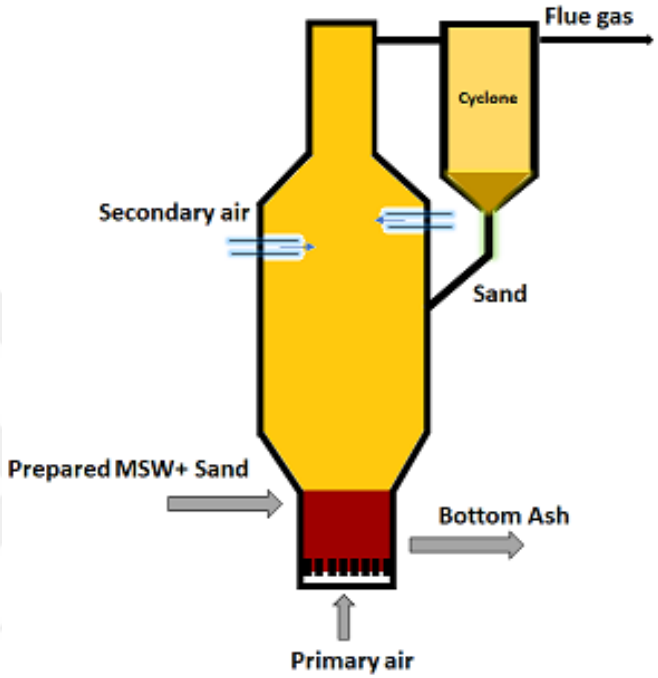

Figure 1.2 Fluidized bed reactor schematic view

Another type of incinerator is rotary kilns which are large diameter, inclined steel tubes lined internally with refractories. The tube rotates at about 3-6 rpm, the waste is introduced from the top of the inclined tube and as it moves down the kiln, the waste is dried by the up flowing stream of combustion gas before it begins to burn [36]. Incineration in a rotary kiln has been widely used for hazardous waste incineration for volume reduction and energy recovery from hazardous wastes. Rotary kiln is not preferred for raw MSW because of requirement of size reduction. This technique is generally preferred for industrial wastes due to the wide disposal range, strong adaptability of process, large capacity, incineration capable of harmful pollutants, safety and reliability and long-term operation.

The other waste management processes are Advanced Thermal Treatment (ATT) technologies which includes pyrolysis and/or gasification processes. These

technologies provide more value from MSW than waste incineration, but it requires pretreatment of raw MSW. Recently, pyrolysis and gasification implementations are developed to increase energy and material recovery during the treatment of MSW. There are installed pyrolysis and gasification plants for pretreated MSW whereas the design of technologies and some configurations are in still under development. Large scale ATT plants have been built and are in operation in UK, Nort America, Europe and Japan [37]. Advanced thermal treatment processes become alternatives to traditional combustion processes and to give opportunity for the reduction waste volume, to obtain more suitable and reusable final products than incineration. ATT require the solid waste to be sorted and pretreated (shredded and sometimes pelletized) by using mechanical biological separation (MBT), thus the waste is turned to alternative fuel that called RDF prior to gasification.

Pyrolysis is the thermal degradation of materials in the absence of oxygen. This process requires an external heat source to preserve required temperature in contrast to combustion with air. Typically, relatively low temperatures of between 300ºC to 850ºC are used during pyrolysis of MSW. Pyrolysis is initiated at around 230 ºC when thermally unstable feed constituents (for example, lignin in biomass and volatiles in coal) break down and evaporate with other volatile constituents. Thermal degradation that called pyrolysis or devolatilization start above 350 ºC, in the absence of oxygen and particles converted to volatile and condensable end-product (steam and tars) or non-condensable (H_2, CO, CO_2, CH_4 and C_2H_x) or a solid carbonaceous residue which described as char [38]. The end-products are a solid residue and a synthetic gas (syngas). The solid residue (sometimes described as a char) is a combination of non-combustible materials and carbon. Char production is carried out as a result of low temperature of pyrolysis process and composition of char changes according to waste characteristics. The final pyrolysis temperature and process residence time plays a significant role on the chemistry pyrolysis products as well as on the structure and the reactivity of char [39]. An increase in the pyrolysis temperature increases the yield of gas and decreases the yield of char. Stability of char structure is more settled with high temperature and retention time in the reactor and inclined to graphite-like structure [40]. The syngas is a mixture of gases such as combustible constituents include carbon

monoxide, hydrogen, methane and a wide range of other VOCs which can be converted to oils, waxes and tars by condensing. Condensable fractions can be separated after the syngas cooling then used as liquid fuel if required. However, tarring problems are the most important key issue that can lead to operational challenges such as blockages problems because of deposition of tars during energy recovery from syngas in ATT facilities.

Another ATT technology is gasification which is thermochemical conversion process of carbonaceous substances, means that oxygen is added but the amounts are not sufficient to allow the fuel to be completely oxidized and full combustion with presence of oxygen to occur. The solid waste gasification constitutes from many complex steps that include several physical and chemical interactions. Gasification takes place at temperatures generally higher than 600 ºC, the exact temperature depending on the reactor type and the waste characteristics, in particular the ash softening and melting temperatures [41,42,43]. The gasification agent (another gaseous compound) provides to speed up the combustion phase by various reactions. The main product of gasification is a syngas which contains carbon monoxide, hydrogen and methane, carbon dioxide, H_2O, ashes, hydrocarbons and inorganic gas impurities such as HCN, H_2S, COS and NH_3. The heating value of gas is typically between 4 -10 MJ/Nm^3, depending on the technology and gasifying agent (air, oxygen, CO_2, H_2O or combinations of these) that applied. Partial oxidation with air generates a gas which diluted by the atmospheric nitrogen (up to about 60%) that has a heating value ranging between 4 and 7 MJ/m^3 [44]. Some processes are operated with oxygen-enriched air which obtained by using air separators membrane technologies i.e., a mixture of nitrogen and oxygen having an oxygen content up to 40% [44]. The partial oxidation with pure oxygen generates a syngas free (or almost free) of atmospheric nitrogen and then with a higher calorific value, ranging between 10 and 15 MJ/Nm^3 [44]. The goal is to obtain a higher heating value gas because of the reducing nitrogen content, that makes it possible to carry out auto-thermal processes at higher temperature, without consumption of expensive oxygen [45]. The additional investment and operating costs for oxygen production in an air separation unit (ASU) are significant and appear feasible only for large scale units (larger than 100kt/y), appropriate design allows to obtain higher syngas heating value,

reduced volumetric flow rate, also important for low tar content and, in particular vitreous ash production for easier disposal options [44]. “Tar” is condensable output stream of gasification operation in the gasifier or other processing units which includes post conversion steps. Tar content is relevant to operational problems. Therefore, determination of tar parameters (a complex mixture of condensable hydrocarbons, which includes single ring to 5-ring aromatic compounds along with other oxygen-containing hydrocarbons and polyaromatic hydrocarbons) is essential to control the process as well as to prevent damage of process equipment [46]. Generally, downdraft gasifier has relatively low tarring and acceptable as cleanest in contrast to updraft gasifiers which incline higher tar content and can be defined "dirtiest" [45]. Secondary processing at higher temperature is implemented to crack the tars and clean up the syngas. Operational challenges, equipment damages during the energy recovery depending on tarring in gasification process is prevented by post processing of syngas which is called ‘gas clean up’ or ‘polishing’. It is enabled to increase energy recovery efficiency providing more thermal degradation thus more available energy than other thermal treatment methods [37]. The other main product from the gasification process is a solid residue of non-combustible materials (ash) which involves relatively low level of carbon [37]. Successful waste gasification is achieved with appropriate waste composition that obtained by good recycling practice, separate collection of non-combustible and combustible wastes or suitable mechanical pretreatment [47]. Advanced treatment methods are not convenient for unprepared MSW. Mechanical pretreatment that consists of sorting, material recovery or RDF production processes should be designed before the gasifier for the places where have insufficient separately collection practice. Properties of feed are crucial for most of gasification process therefore pretreated waste or RDF are utilized in generally gasification plants [48]. The performances of a gasification-based waste-to-energy process are necessarily affected by the specific properties of the municipal solid waste. The most important properties for gasification are elemental composition, lower heating value (LHV), ash content (and composition), moisture content, volatile matter content, other contaminants (like N, S, Cl, alkalies, heavy metals, etc.), bulk density and size [49]. Outputs of gasification and pyrolysis of MSW are shown in Figure 1.3. Gasification chemistry

occurs from complex processes which influenced by fuel composition, design and operating conditions, it can be simply defined as gasification following by pyrolysis stage [50]. The syngas can be combusted to generate electricity or further processed to manufacture chemicals, fertilizers, liquid fuels, substitute natural gas (SNG), or hydrogen production [37]. The steam gasification generates a high hydrogen concentration, medium heating value (15–20 MJ/m^3N), nitrogen-free syngas as a different from air-agent [44]. The typical process is carried out with steam gasification followed by methanation and shift equilibrium to improve the efficiency of H_2 production. In this case, external energy source is required when steam is the only gasifying agent for the endothermic reactions that is necessary for process permanency. In the last years, low oxygen technologies such as pyrolysis and gasification become promising solutions to improve the energy efficiency and decreasing the greenhouse gas emissions [44]. Gross powers based on reactor types that generally used is presented in Table 1.2 [51].

Table 1.2 Thermal capacity of different gasifier design

GASIFIER	**CAPACITY**
Downdraft	1 KW-1 MW
Updraft	1.1 MW-12 MW
Bubbling fluidized bed	1 MW-50 MW
Circulating fluidized bed	10 MW-200 MW

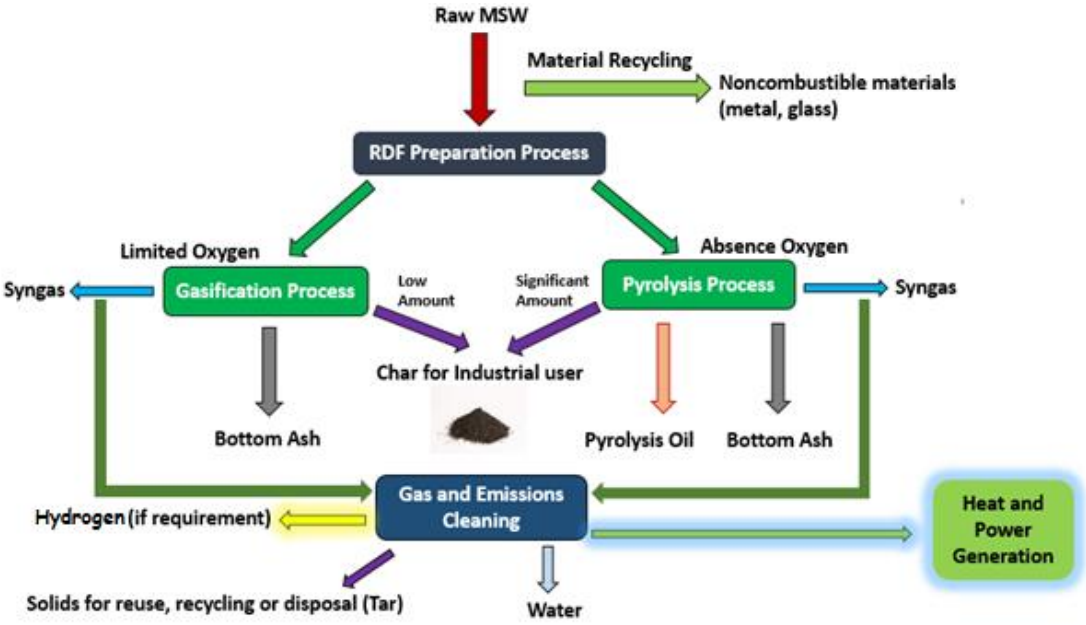

Figure 1.3 Advanced thermal treatment for MSW general process flow

The other gasification technology is plasma gasification which interests research with increasing in recent years. Plasma forms is occurred by passage of sustain electrical arc on electric current (continuous, alternate or high frequency) through a gas. Plasma means to ionize atoms or molecules of any gas partially or totally, required energy to ionize at least a percentage of atoms or molecules can be thermal, electrical or electromagnetic [52]. Thermal energy that created by electrical resistance allows to strip the electrons from the gas molecules then the stream converts to ionized gas or plasma [53]. Reduction to basic molecular structure of waste stream is occurred by plasma gasification in absence of oxygen. Plasma gasification is carried out in several processing which include feeding a gas to between particles with sufficient differences in electrical load or, to keep gases under high temperatures in the case of arc welding or graphite electrode torches. Plasma arc torches is applied by combination of these techniques that is under development, usage for waste management is accepted as relatively new technology [54]. Plasma gasification applications consist of different steps such as plasma pyrolysis, gasification, compaction and vitrification, or combinations of these. Plasma-based waste treatment systems provides high heat stream therefore inclined to join with transferred arc reactors [55]. Processing with gas forms in

plasma arc offers to prevent melting or failing in contrast to solidly heat transfer, robust heating process is the main advantage of plasma gasification. Reactions between the arc and process gas that released into the torches can increase the temperatures of the gas up to 10,000°C when leaving from the plasma torch. High temperatures provide totally decomposition of any type of waste [56]. A serios of reactions applied by energy that ensured from the plasma and increasing temperature give opportunity for completely destroying, also resistance to variable feed properties such as feeding rate, moisture content and elemental composition of the waste material [57]. Robust heat transfers allow to control of the syngas content and temperature and contamination reduction by increasing heating capacity [58]. Therefore, plasma gasifiers can also be applied for different particle size from coarse piles to fine dust, after minimal feedstock preparation [53]. Criteria of gasification process are presented in Table 1.3. The application performances of the syngas usage could increase in the Integrated Gasification Combined Cycle (IGCC) systems up to 24–30% which offers more effective energy recovery than incineration considering medium small scales [59]. Thanks to lower operating temperatures than directly combustion provides to reduce the potential of alkali volatilization, fouling, slagging, heavy metal volatilization. Risk of bed agglomeration for fluidized bed reactors are set down, also dioxins and furans emissions are significantly limited. However, inadequacy of commercial gasification plants, and the operational difficulties experienced at several pilot and demonstration plants can cause some technical and economic problems for highly heterogeneous feedstock like MSW. As a result of there are relatively limited number of plants for large scale in worldwide based on this technology. This situation indicates necessity of correctly design criteria according to details characterization of wastes and improvements in operating conditions and gas cleaning technologies before gasification, to accept be reliable solution to the waste disposal problem of large municipalities.

Table 1.3 Criteria of gasification process

Gasification Criteria	**Types**
Heat Supply	Directly heated (auto-thermal) gasifiers Indirectly heated (allo-thermal) gasifiers
Pressure	Atmospheric gasifiers Pressurized gasifiers
Gasification Agent	Air gasifiers Oxygen enriched-air gasifiers Oxygen gasifiers Steam gasifiers Plasma gasifiers
Reactor Type	Fixed bed gasifiers – Up-draft – Down-draft Fluidized bed gasifiers – Bubbling fluidized bed – Circulating fluidized bed – Internally circulating fluidized bed Entrained flow gasifiers Rotary kiln gasifiers Moving grate gasifiers Plasma gasifiers
Temperature	Low-temperature gasifiers (typically below 900 C) High-temperature gasifiers (typically above 1200 C)

Organic waste management policies, which are economical, sustainable and environmentally friendly, provide renewable energy resource beside beneficial end-product that increase the yield of the soil, gain importance every day in the world. MSW generally consist of organic (food, and garden waste) fractions. Developing countries have higher OMSW fraction for example about 74% of municipal solid waste generated in Indonesia, 75% in Bangladesh, 76.4% in Sri-Lanka, 42% in India, 52.6% in China and 52% in Turkey is organic [60]. Inadequate management of waste that rapidly decompose lead to several environmental concerns such as GHG emissions, and devastation of ecosystem [61]. In addition, because of high moisture content, OMSW led to decrease energy recovery efficiency of thermal treatment, also increases wastewater treatment cost in landfills. Organic waste management methods described as bio-chemical conversion of organic fractions of the waste under microbial proceedings in the presence of oxygen (aerobic composting) or absence of oxygen (anaerobic digestion). End-product of aerobic decomposition is compost while main outputs of anaerobic digestion process are biogas and digestate.

Anaerobic digestion is widely used for biodegradation of organic matter into biogas and nutrient-rich digestate residue. Anaerobic digestion offers treatment opportunity for different types of organic waste, produces biogas, which is one of the sources of renewable energy, whereas the other output digestate can be used as compost for agriculture. Anaerobic digestion is accepted as a popular organic waste management option due to the cost effectiveness, limited environmental footprints, high potential for energy recovery and digestate utilizing that can be used as bio-fertilizer by composting [62]. The methane is generated by anaerobic digestion process which includes several sequences of biochemical conversion, from organic wastes such as the organic fractions of municipal solid waste (OMSW) [63]. Anaerobic digestion process is a microbial decomposition of organic matter in absence of oxygen, which begins with hydrolysis of higher molecular substrate such as lipids, protein and carbohydrates into soluble and less complex molecules such as glucose, amino acids, and fatty acids as shown in Figure 1.4. Subsequently, the smaller molecular and soluble organic matter are degraded into volatile fatty acids (VFAs) then methanogenesis step for production of biogas via methanogenic bacteria is occurred [64]. When the biodegradable substrate has a

dry matter content of ≤12% (in some research, 15%), then the wet fermentation process is conducted otherwise, the dry fermentation process is used [65]. Around 90% of the biogas plants in Germany operate under wet fermentation conditions [66]. Biogas efficiency, concentration of other gases such as H_2S, N_2, NH_3 included in biogas and digestate quality parameters basically depend on composition of the waste. The biodegradability of the waste that is directly relevant to biogas production is affected from impurities in waste. On the other hand, there are many factors affecting bacterial decomposition such as temperature, hydraulic retention time (HRT), organic loading rate (OLR), and pH. Other factors affecting the gas production also include tank volume, feedstock type, feeding pattern, and carbon to nitrogen (C/N) ratio [67].

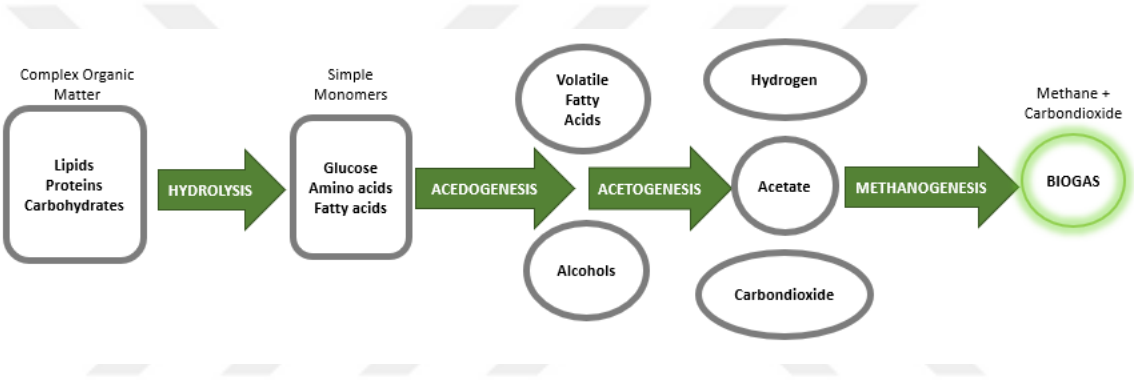

Figure 1.4 Anaerobic digestion steps

Temperature is a crucial parameter for the AD process to keep microbial activity and to consistently produce biogas, influence of temperature corresponded decreasing the biogas production falls by 50% for each 6 °C (20 °F) [68]. Thermophilic bacteria work at high temperature circumstance (48.9–60.0 °C or 120–140 °F), thus, retention time requirement for biodegradation decreases more substrate decomposition is ensured, and more biogas is produced. However, to decrease energy demand and maintain costs during operation, anaerobic digesters are generally operated in mesophilic condition (30–40 °C), thus operation expenses is reduced with low energy requirement and easy to operate at low temperature [69]. Mesophilic bacteria operate at lower temperatures and produces less biogas in contrast to thermophilic but these offer to easily controlling, and low investment costs requirement. Hydraulic Retention Time (HRT) is a critical operational parameter for the anaerobic reactors which influence the conversion of volatile solids (VS) into biogas [72]. Retention time for

optimal biogas production is usually changes from a few days to 40 days, depending on the content of organic waste and type of digester, it is reported that HRT of 20 days is proper for anaerobic digestion of maize [71]. HRT affects the methane production in the early stage where the microorganisms consume the substrate to yield more biogas. However, the extended HRT can be led to decreasing of microorganism concentration and consequently causes lower methane production. Various HRTs were assessed by literature, the optimum HRT was limited in the range of 16 to 60 days [72,73]. Similarly Organic Loading Rate (OLR) is another parameter which have significant impact on biogas yield that can be defined as the number of volatile solids fed per unit volume of digester per unit of time. Biogas conversion is affected positively from increasing OLR; however, higher OLR disrupts the bacterial cultivation, leading to methanogenic bacteria reduction with increasing of hydrolytic bacteria population and acetogens, or process inhibition [74,75]. Determination of OLR based on different feedstocks is required to ensure optimal conditions for efficient biogas production [76]. The literature stated OLRs range for various organic feedstocks to prevent from acidification and to increase biogas conversion rate (9.2 kg VS/m^3/day for sludge, 10.5 kg VS/m^3/day for food waste), with an optimal range between 1.5 and 6 kg VS/m^3/day for all waste [77,78].

The design of an AD system that can be a single stage or of multiple stages consist of processing steps of hydrolysis, acidogenesis, acetogenesis, and methanogenesis which can be applied separately or combined. Generally anaerobic digestion process that installed and operated in worldwide are single stage. Biochemical interactions are occurred in a single anaerobic reactor. This method is compromised 95% of the full-scale biogas plant in Europe [79]. However, it is stated that with increasing of pilot scale research, the multistage reactors have many benefits over single reactor design. Multiple reactors generally consist of two stage reactors firstly hydrolysis and acidification are occurred in first tank then organic material fed into second reactor thus methanogenesis reaction occurs. According to previous lab scale research about enhancing biogas production, actual methane production in two-stage anaerobic digestion have been found to be minimum 10% higher than single-stage reactors. Similarly, Massanet-Nicolau et al. presented 13% of increase in the biogas yield for two-stage reactors [80].

Supporting this, Suresh et al. stated that biogas yield increased by 10%, also put forward a higher methane production from 48 to 71%, in contrast to 37 to 62% for a single-stage reactor [81]. Another advantage of the two-stage design is the high stability compared to single-stage systems. First stage helps to stability of organic materials and provides easily buffering them by homogenizing of organic material before it is transferred to the methanogenesis stage thus the effects on methanogens which are sensitive to environmental changes is prevented [69].

Another organic waste management process is composting which is a traditional way which occurs as a result of natural decomposition of organic matter with biochemical processes that are operated by microorganism activity. This technology offers a sustainable solution for organic waste management by converting to compost that would be evaluated as bio-fertilizer for agriculture which is useful for soil condition also productivity and qualification of agricultural products is supported with the natural resource conversion [82], beside the protection of soil and decreasing environmental impacts [83]. Compost increases the nutrient concentration of the soil which prevents nitrogen transport to groundwater, the water permeability of clay soils and the water holding capacity of sandy soils. Nutrient-rich soils allow the grown plants to be healthier and more resistant to diseases and pests thus chemical using in agricultural activity is decreased. Additionally, organic fertilizer usage reduces runoff and soil erosion in sloping region by increasing the organic matter and water content of soil [84,85]. Organic matters are biologically decomposed by microbial activities in presence of oxygen then converted to final stable product which is called compost. Under sufficient conditions composting process is carried out by different microbial communities with several biochemical reaction steps which includes mesophilic and thermophilic stages. As the microbial population starts to degrade the most readily degradable material and the microorganism population and temperature increases as a result of the microbial activity accumulates within the piles. Generated thermal energy provides the increasing of temperature continues steadily, then is passed from the mesophilic range (25–45 °C) to the thermophilic one (more than 45 °C) therefore destroying of pathogens, weed seeds and fly larvae in the composting materials is ensured with high temperatures of 55 °C and above [86]. During the process, there are important parameters which recognized

as process control for production of a good-quality compost, these are temperature, oxygen, moisture, porosity and C/N ratio. Crucial parameter that affects composting efficiency is temperature which is an important environmental variable. Not only microbial metabolism rate depending on highly temperature but also the microbial dynamics (e.g., composition and density) are significantly affected from temperature. Thermal energy from metabolic activities combines with the thermal potential of compost materials which come from their self-insulating properties [87]; in consequence, high thermophilic temperatures are usually maintained during the maturation period [88]. Pathogen killing depends on temperature rising during composting process (75 °C) therefore temperature is the most essential parameter that influenced compost quality [89]. On the other hand, moisture content of 60% is required during the composting period for efficient operation of the microorganisms. The previous research stated that required moisture content range of the raw material must be between 45 and 65% [90]. Decreasing of moisture content to below 45% prohibit to enough water for life of microorganisms whereas if the moisture content is higher than 65%, connection of microorganisms with oxygen is prevented as a consequence of filling the cell pores with water [90]. Composting can occur at oxygen levels as low as 10%, half that in air [91]. At oxygen levels below this value the system tends to be anaerobic and can produce methane so it may be required to supply air to the system. Nutrient availability and stability of the end-product form tends to type of organic materials and main process conditions. N and C are the most important elements that should be controlled in maturation period of piles and the C/N ratio should be between 25 to 30 and the average bio-compost must contain about 33,3% organic matter, but not less than 20% [92].

Mechanical biological treatment (MBT) technology has been widely operated in several countries around the world, especially in Europe. Over 180 MBT plants were installed in Europe in order to reduce disposal of organic and recyclables wastes in landfills between 1990 and 2010 [93]. The main purpose of Mechanical Biological Treatment (MBT) plant is stabilizing the waste and separating recyclable materials and to produce RDF for thermal applications. Mechanical biological pre-treatment (MBT) is well-established, cost-efficient, processes for RDF production from MSW which is implemented since long years. Refuse derived

fuel (RDF) may be obtained from the advanced processing of MSW which included recovery of combustible fractions or non-hazardous materials such as paper, cardboard, wood, textiles and plastics [94]. The process combines mechanical sorting, biological processes (aerobic, anaerobic) and many technical units. Mechanical process is applied for ejecting oversize fractions and non-combustible materials such as metals, glass, rock which provides more suitable waste flow for thermal treatment methods. The mechanical units of MBT, generally consist of shredding and sieving units, followed material recovery including a density separation which is called advanced MBT (e.g., air classification, ballistic separation, magnetic separation, eddy current separation, optic separation). Aerobic or anaerobic bio-conversion methods are used for management of the organic waste which is separated by mechanical units or can be implemented directly to obtain more stabilize waste that called bio-drying. Comparing the aerobic bio-conversion method, bio-drying is applied to the same fractions, but the final product aimed to the use as RDF for co-processing or to thermal treatment plants fuel according to Dir.2000/76/CE [95]. Bio-stabilization process is aimed that waste conversion to material by biochemical reactions with aeration of the feed whereas bio-drying process is shorter and exothermic and provides less-humidity by evaporation of the moisture content without processing of organic carbon [96]. Bio-drying removes water by microbial activities is a good potential for pretreatment of organic wastes with high water concentration. The process generally realized under aeration condition then heat is generated by the natural force and aeration then the waste is dried by using the natural aerobic bioconversion of organic matter [97]. Moreover, metabolic heat from bio-drying process can be supported by outdoor thermal force such as solar-energy in greenhouse for the increasing of the air temperature. Colomer-Mendoza et al. stated that, during their research studies, the greenhouse dryer provided more than 50% within 12-30 days by the initial volume reduction of wastes depending on the months [98].

MBT consist of variety treatment processes which can be integrated and then different types of outputs. The main outputs of typical MBT plant are i); refuse derived fuel (RDF) that presenting a low moisture content (25 %) also involving typically enriched in materials (paper and plastics) which characterized by

significant LHV (15 MJ/kg), ii); stabilized organic waste which is produced from the biological treatment of organic fraction iii); ferrous and non-ferrous metals according to recycling potential, iv); inert wastes (scrap/residues) that will disposed in landfills [99]. The configuration of mechanical pretreatment changes based on the characteristics of MSW. The process should be designed according to input waste composition and desired material outputs with aim to increase effectiveness of utilized methods (material/energy recovery). MBT that optimized and well-designed give opportunity to produce marketable outputs [100], such as metals (that are recycled in the metallurgical industry), high-calorific materials (RDF, that can be used in waste to energy systems or for co-incineration in high energy-demanding industries like cement plants), as well as biologically stabilized organic waste is used for land/soil applications [100,101].

1.1.1.1 Municipal Solid Waste Management (MSW) Practice in Istanbul

Due to the increase in population also residential areas in Istanbul, the amount of MSW is increasing day by day. To make a solid waste management plan; carrying out services for the re-evaluation, storage and disposal of solid wastes coming to transfer stations, regular storage areas and other facilities, except for collecting solid wastes at source and transporting them to the transfer station, establishing and operating the necessary facilities for these services waste management department of the metropolitan municipality is carried out by the directorate. District municipalities are responsible for waste transferring to the collection and transfer station from the source according to the rules of the Solid-Waste Control Regulations. Waste collection and disposal steps are shown in Figure 1.5. In the last decades, significant progress in solid waste management strategy in Istanbul was achieved as a result of working on several fields such as stronger organization, new legislation, improved financial resources, detailed feasibility assessments also waste analysis, research and development of waste treatment, privatization of some services that provided flexibility and efficiency is carried out to create efficient and sustainable waste management strategy [18]. The regulation clearly stated that MSW must be disposed of in a sanitary landfill which must have leachate collection and gas-control and utilizing practices are also well defined in the regulation. Most of MSW is disposed in Class II Landfill facilities. Operation,

additional field construction, field monitoring and control, leachate collection-treatment and landfill gas management, etc. continues according to international standards and national regulations. In the design and operation of sanitary landfills, possible hazards arising from the disposal processes are prevented by forming an impermeability layer, laying and compacting wastes, intermediate cover formation, leachate protection of underground and surface waters, collecting, controlling and storage of generated gas.

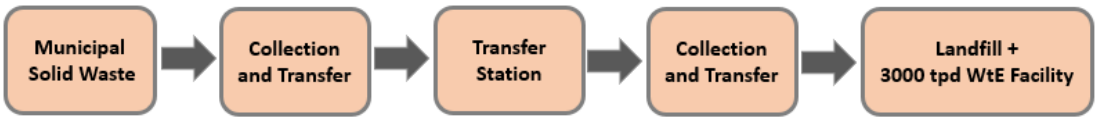

Figure 1.5 Waste management steps in Istanbul

Since 1995, the municipal waste of Istanbul has been started to be disposed of in landfills established on the European and Asian sides. These facilities were established in Eyüp Göktürk Odayeri and Silivri Seymen on the European side and Şile Karakiraz Kömürcüoda on the Asian side as shown in Figure 1.6 [102]. Daily MSW production in Istanbul is over 18,000 tons in Istanbul. This means more than 10 million kilograms of organic materials (waste) are going to the landfill every day due to the inadequate separately collection at source. Therefore, for the utilizing the organic fractions of MSW that disposed in landfills, landfill gas (LFG) is collected by gas collection systems in Odayeri and Kömürcüoda landfills and converted to electricity. According to ISTAC report in 2020, 244.494 MWh from Odayeri landfill, 173.349 MWh from Kömürcüoda, 38.927 MWh from Seymen landfills electricity was produced [102]. Also, high amount of leachate that hard to treat are collected and treated using by MBR and NF methods. On the other hand, 1000 ton/day recycle and compost facility for separately collected organic waste has been started to operate in 2001 and 18.000 ton/year fertilizer is obtained from organic waste. PE, PP type wastes that collected from material separation unit of the facility is converted to granules thus pet burrs are produced in the granule facility and economic value is provided.

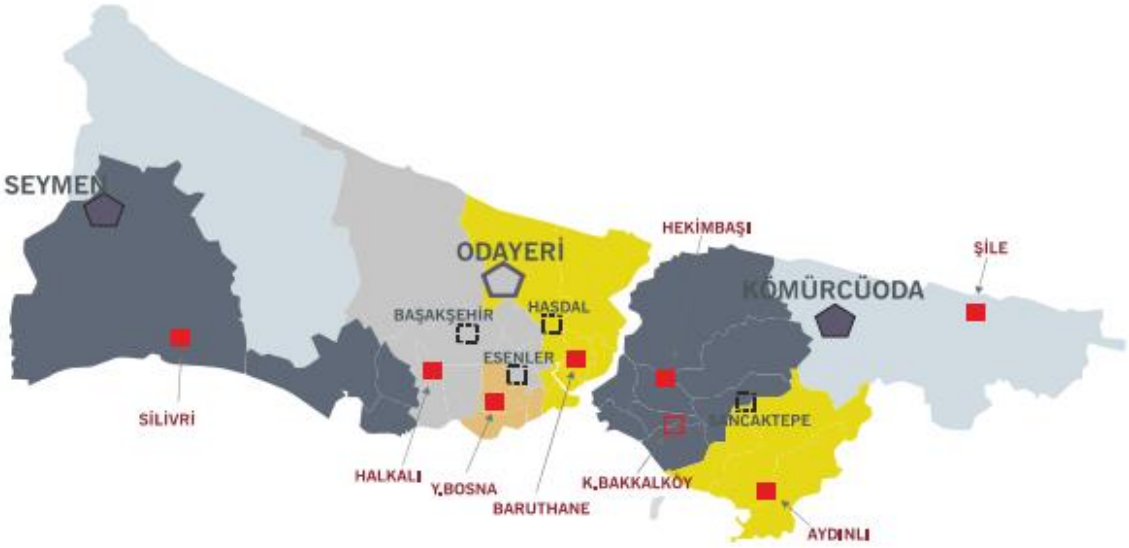

Figure 1.6 Transfer station and landfills in Istanbul

Another progress of the municipality to reduce landfilling is incineration plant which was commissioned in 2021. The WtE plant generates energy from municipal waste collected in Istanbul through grate type incineration process. The capacity of the plant is 3000 ton/day with three combustion lines and guaranteed gross power of the plant is 77 MW of electrical energy [103]. The combustion technology is provided from Hithachi Zosen Inova (HZI) and technical scope covered the waste processing, heat recovery, power generation and flue gas treatment requirements for energy from waste projects. The plant was constructed in the scope of the following systems; waste acceptance system, waste storage/bunker and unloading bay, crane and waste feeding system, waste incineration furnace, additional incineration system for providing of required combustion temperature against the irregular calorific value and start up period, steam boiler, turbine generator, cooling system, air pollution control units, wastewater treatment plant, ash slag and other waste removal and utilization system, odor emissions control system, noise emission control system [103]. The Project Site is located at Eyüp district, Kısırmandıra Location in European site, the waste will be transferred to the plant from Halkalı, Yenibosna, Baruthane transfer stations, the waste management map and project locations are shown in Figure 1.7 [104]. At the same time, in the close place from project location one biogas plant was commissioned in 2021. Biogas is produced from separate collected organic wastes (food wastes, vegetable-fruit wastes, etc.) by anaerobic digestion process in

the facility with a daily capacity of 90 tons of organic waste and 1,3 MWh of electrical power is generated.



Figure 1.7 Transfer stations locations according to WtE project field

MSW characteristics change depending on economic and technological improvements geographical situation, and habits of community. Waste detailed characteristics should be determined for the efficient utilization of the MSW energy content and recycling of the materials. According to Istanbul MSW characterization studies in literature over 50% percentage organic content is involved. According to a study related Istanbul municipal solid wastes characteristic by Yildiz et al in 2014, was the rather high organic matter content of 54.09%. The paper / board group was next in ranking with a proportion of 15.57% [105]. The paper / board and the organic substance groups comprised 69.66% of the total waste composition. In the same study, the average calorific value of the samples was found as 1435 kcal/kg. In addition, moisture content of Istanbul's municipal solid waste was calculated as 59.49%. By contrast, calorific value of Istanbul MSW is determined 1968 kcal/kg in a study in 2010 [106], also this study involves all districts of Istanbul. Material composition analysis from 2005 to 2010 as shown in Table 1.4 is taken from EIA report that prepared in 2012 for the

incineration plant which commissioned in 2021 [104]. The MSW is mostly consist of kitchen waste as average percentage of 54,42%, consequent high moisture content that involved in organic fractions the average moisture content of MSW between 2005 and 2010 years stated as 60%. On the other hand, according to Istanbul Metropolitan Municipality Waste to Energy Plant Environmental and Social Due Diligence Report prepared by The Black Sea Trade and Development Bank, in the summer the average LHV is 1734,3 kcal/kg, in the winter the average LHV is 1642 kcal/kg which involved districts in European side (Beşiktaş, Beyoglu, Eyup, Fatih, Kagıthane, Sariyer, Sisli , Arnavutkoy), while the average HHV for all year is 4488,7 kcal/kg. In the same report average humidity of the waste for all years is 54% and average ash percentage is %16,2 [103].

Table 1.4 Istanbul MSW material composition from 2005 to 2010

YEARS / **Material Group %**	**2005**	**2006**	**2007**	**2009**	**2010**	**Average**
Paper/Cardboard	13,30	12,06	12,37	15,57	11,05	12,87
Glass	5,82	5,93	3,97	3,03	3,72	4,49
PET Bottles	1,52	1,21	1,02	1,13	1,36	1,25
Plastic Bag	9,48	7,83	8,42	9,96	9,47	9,03
Plastic	3,39	2,56	2,60	2,62	2,28	2,69
Textile	5,28	1,93	4,08	3,42	5,74	4,09
Tetrapak	0,64	0,77	0,49	0,86	0,66	0,68
Diapers	3,90	4,19	4,49	5,45	5,03	4,61
Metals	1,63	1,49	0,66	1,12	1,10	1,20
Electrical Equipment	0,15	0,01	0,00	0,03	0,17	0,07
Hazardous Wastes (Batteries and Accumulators)	0,01	0,02	0,00	0,01	0,31	0,07
Kitchen Waste	50,22	56,34	59,75	54,09	51,71	54,42
Other Combustibles	2,97	2,00	2,14	2,09	6,16	3,07
Other Non-combustibles	1,70	3,66	0,00	0,63	1,23	1,44

The results of the last detailed solid waste characterization study realized by ISTAC Inc. are summarized in Table 1.5. The moisture content is reported to be 51,03% and 61,22% for summer and winter seasons, respectively. Additionally, the LHV of Istanbul solid waste is reported as 1558,20 kcal/kg and 1587 kcal/kg, respectively, for summer and winter. The higher heating value (HHV) is calculated as 3884,60 kcal / kg for summer, and 4973,31 kcal / kg for winter. Energy calculations were carried out according to this characterization study.

Table 1.5 Istanbul MSW material composition in 2017

Material Group %	Winter	Summer
Paper/Cardboard	10,38	4,80
Glass	4,93	5,72
PET Bottles	1,48	1,24
Plastic Bag	9,57	5,50
Plastic	2,38	2,56
Metals	1,00	1,13
Kitchen Waste	48,17	48,36
Electrical Equipments	0,18	0,19
Hazardous Wastes (Batteries and Accumulators)	0,86	0,90
Composite	0,89	0,54
Textile	4,69	5,11
Diapers	4,86	4,90
Other Combustibles	8,90	17,09
Other Noncombustibles	1,71	1,96

1.2 Objective of the Thesis

Waste generation increases faster than population as a result of urbanization and economic growth. Waste management becomes crucial issue especially in metropolitan cities which have due dense population and high industrial activities like Istanbul. On the other hand, energy requirement increases with the high population and industrial activities, also decreasing of the fossil fuels reserves as well as high emissions from fossil fuels are increased requirement of to find alternative fuels. Appropriate municipal waste management strategies give opportunity to obtain economic value during disposal of municipal solid waste. Developed countries focus on integrated waste management strategies which include recycling and WtE technologies due to the purpose of reduction of the

landfilling and evaluating wastes effectively. However, as a result of the socio-economic situation in many low to middle developed countries, informal recycling activities in the waste handling system tend to reduce the amount of paper, cardboard, and certain types of plastics in the waste. Additionally, the municipal solid waste generally consists biodegradable fraction which can led to low calorific value because of high moisture content. These reasons cause to decrease the efficiency of waste incineration plants.

In this study, an integrated waste processing including mechanically separation, thermal treatment and anaerobic digestion process are evaluated for determination of efficient thermal and biochemical energy recovery from Istanbul MSW. This study is focused on the separation of organic municipal waste (OMSW) which have high moisture content by mechanical pretreatment and accepted that OMSW is managed by anaerobic digestion (AD). Treatment system does not require an oxygen supply [107] and have two end products which are biogas and digestate. It was accepted that digestate is sent to composting after dewatering then ready as fertilizer for market sale after compost sieving. Electricity generation from anaerobic digestion of MSW was estimated by constitution of mass and energy balance of process. Under steady conditions, the AD process provides useful products from the OMSW such as biogas and organic sludge that is compostable. In many developed countries, biomethanization of OMSW has become promising solution to sustainable and renewable energy generation. Popularity of biogas production from OMSW increased in recently, technology of anaerobic digestion process and designs on different pilot scales have been developed [108]. On the other hand, for the remaining waste stream, the noncombustible materials such as metals and glass separation was considered to obtain refuse derived fuel (RDF) with higher calorific value. After particle size reduction unit, it was accepted that RDF was dried by thermal energy from exhaust gas of biogas plant, and moisture content of RDF is decreased to half. Electricity generation was calculated based on calorific value and mass of dried RDF. Electricity generation of the entire facility was calculated as total of biogas plant and RDF incineration plant. The results were compared with raw waste incineration scenario. Viability of the scenarios were evaluated by calculating the two financial parameters which are net present value (NPV) and levelized cost of

energy (LCOE) based on electricity generation and outputs. Revenues of scenario were defined as electricity and scrap metal sales for raw waste incineration whereas electricity, metal & glass and fertilizer sales for integrated waste processing scenario. Costs of scenarios were estimated according to process capacities then cash flows of scenarios were constituted according to project incomes and outcomes. Economic parameters such as Payback period, NPV, LCOE were determined according to future cash flows of scenarios.

1.3 Hypothesis

In this study, two waste management scenarios were evaluated in order to assess energy potential of Istanbul municipal waste (MSW). The first scenario is raw waste incineration plant with capacity of 3000 ton/day with %2 of reject material. Second scenario is integrated waste processing scenario which includes MBT and RDF incineration. Anaerobic digestion process is suggested for organic fractions that separated by mechanical pre-treatment from raw MSW, on the other hand metal&glass recovery and particle size reduction and drying units before incineration for RDF fractions were defined.

Integrated waste processing scenario involves three essential steps including mechanical pre-treatment, RDF incineration and anaerobic digestion. RDF is obtained after mechanical pre-treatment processes such as crushing, metal separation and screening. After the mechanical pretreatment, organic fraction and RDF fraction masses were calculated according to separation efficiency of processes and plant capacity of anaerobic digestion process and RDF incineration process were defined. Material size distribution, process capacities and calorific values were estimated according to mechanical separation design by using literature values of Istanbul waste characterization, and separation efficiency of mechanical units from literature. Methane production efficiency of anaerobic reactors were determined by using biogas yield based on total solids of OMSW in literature. Considering electrical and thermal efficiency of biogas engine, generated electricity, recovered thermal energy from exhaust and engine cooling system were calculated then it was evaluated that thermal energy from exhaust gas is used to decrease RDF moisture. For other energy source of scenario 2 as RDF incineration, two different RDF qualifications which are RDF and undried RDF

were considered for energy calculations. It was accepted that moisture content of RDF was decreased to half by thermal energy from exhaust gas of biogas plant, when calculating calorific value and mass changes of RDF. Energy from thermal treatment of RDF and actual methane production from anaerobic digestion process were calculated according to fraction properties that identified, was compared the outputs with mass burn incineration scenario. After defining the outputs, investment costs of processes were estimated based on input waste mass. Operation and maintenance costs were estimated regarding investment cost then cash flows of both scenarios were constituted. Economic feasibility of both scenarios was assessed based on facility incomes and outcomes. As a regard electricity selling incomes were calculated considering inflation rates, however for the anaerobic digestion process not only electricity production but also fertilizer for agriculture sell income that obtained by composting of digestate were evaluated. During constitution of cash flow, recycled metals was considered for both scenarios also recycled crushed glass materials was also included in economic benefit for integrated waste processing scenario. Costs of each process were estimated based on study and equations in the literature after defining the processes and fraction properties that determined according to raw MSW material composition. Total plant investment cost was calculated with literature equations depending on the process capacities while O&M costs were estimated depending on investment. Net present value (NPV), levelized cost of energy (LCOE) and return rates were determined with comprised cost benefit analysis, according to plant costs, and several incomes such as waste tipping fee, electricity sale, recyclables for sale. In this study, an integrated waste processing process including mechanical separation, thermal treatment and AD process is examined based on Techno-Economic analysis for the evaluation of efficient energy recovery from Istanbul MSW and compared with raw waste incineration process.

2
MATERIALS AND METHODS

2.1 Electricity from Raw Waste Incineration (Scenario 1)

The basis for the generation of energy through incineration is the use of the calorific value of the waste by taking advantage of the amount of energy per unit of mass or unit of volume of matter that can be released when a chemical oxidation reaction occurs. Using the calorific values taken from ISTAC, the produced energy by mass burn incineration was estimated based on 3000 ton/day input waste mass with 2% reject material for not suitable for combustion, using Eqs. (2.1) and (2.2). Energy generation was estimated according to average values of summer and winter waste properties from ISTAC study, which are LHV 1572,6 kcal/kg, HHV 4429 kcal/kg, 56,125% MC as shown in Table 2.1. The estimation of power calculated using by a unit adjustment constant of 0.04843 for obtained the resulting power is in kW. Considering grate type waste incineration plant design as shown in Figure 2.1, the electric recovery considered a thermal replacement achievable of 30% based on reported by Silva et al and a capacity factor of 85% [109, 110].

Table 2.1 Istanbul MSW properties by ISTAC

ISTAC VALUES	Summer	Winter	Average
Moisture Content (%)	61,22	51,03	56,125
Lower Heating Value (kcal/ kg)	1558,2	1587	1572,6
Higher Heating Value (kcal/ kg)	4973,31	3884,6	4428,955

$$P_{inc} = LCV * \eta * W * k \quad (2.1)$$

$$E_{inc} = P * C_f * 8760 \quad (2.2)$$

LHV=Lower heating value of MSW (kj/kg)

k= Unit adjustment constant

η= Electric recovery considering a thermal replacement achievable

P = Electrical power (MW-e)

C_f= Capacity factor

W=Waste amount (kg/day)

8760= Working hours per year

E = Electricity generation (MWh/year)

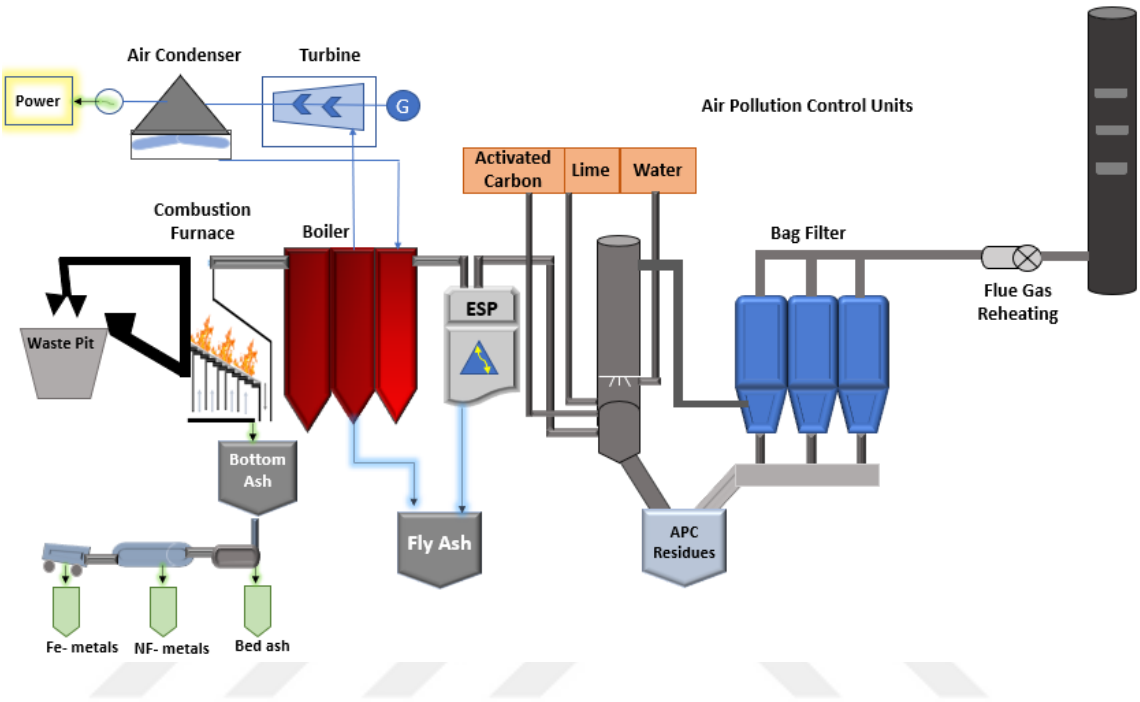

Figure 2.1 Grate type incineration plant (Scenario 1)

2.2 Electricity from Integrated Waste Processing (Scenario 2)

Integrated waste processing scenario focused on the separation OMSW for biogas production thus aimed decreasing the moisture content of remaining waste. Plant configuration is shown in Figure 2.2. Input waste mass was accepted as the same with first scenario which is 3000 ton/day. Integrated waste processing scenario includes mechanical pretreatment for separation of recyclable and organic fractions, biogas production from OMSW by AD and RDF incineration. Material types that separated by mechanical pretreatment are shown in Table 2.2 and mass percentages were taken as average values in winter and summer from ISTAC study. After pre-crushing and material separation unit, organic fraction is separated by 60 mm screening which is undersize fraction that goes to AD process. It was accepted that the undersize fraction of the trommel screen is 30% of waste stream, it is transferred to AD process preparation unit for mixing well and arrangement of moisture content before digestion. Mechanical pretreatment is

composed of a low velocity shredder, magnetic separators, air classifiers thus before the OMSW separation in trommel screen (<60 mm), risk of recyclable materials in digester that can decrease efficiency of AD process is eliminated. RDF production steps are following: The MSW, after the first shredding, is sent to the waste conveyor for material separation, trommel screen for separation of OMSW: organic fraction (<60 mm); combustible fraction (>60 mm). Oversize fraction is mostly combustible fraction and conveyed to the hammer mills after air classifier. Glass materials are separated by optical sorting from mid-heavy fraction of the air classifier. It was accepted that remaining waste stream returns to process after glass removal. RDF was obtained from middle and heavy fractions of MSW and RDF mass that sent to incineration plant was calculated as 64% of the input waste mass that excluded materials in Table 2.2. Particle size is decreased to 9 cm or less by materials shredding in the hammer mills. After the particle size reduction, two different RDF properties were evaluated for electricity production. It was aimed that the moisture content of RDF was decreased to the half by thermal energy from exhaust gas of biogas plant. Thermal energy from exhaust gas of biogas plant was estimated based on combine heat and power (CHP) plant energy balance assumptions. According to energy efficiency of biogas engines, recoverable thermal energy from exhaust gas and jacket water was accepted 50% of total thermal energy and it occurs 30% from exhaust heat and 20% from jacket cooling water. According to thermal energy from exhaust gas of biogas plant, the mass of water that can be evaporated in the RDF has been determined. Depending on the decreasing moisture content, RDF mass was determined, and lower heating value change was calculated with Eq (2.3).

Table 2.2 Separated material percentages for recycling

Symbol	Percentage	Material Type (2017)
$M_{waste\text{-}Glass}$	5,33%	Glass Content
$M_{waste\text{-}Metal}$	1,07%	Metals Content
$M_{waste\text{-}El.Eq.}$	0,19%	Average Electrical Equipment Waste Content
$M_{waste\text{-}Battery}$	0,88%	Hazardous Waste Content (Batteries and Accumulators)
$M_{noncombustible}$	1,8%	Noncombustible Waste Content (heavy fractions)

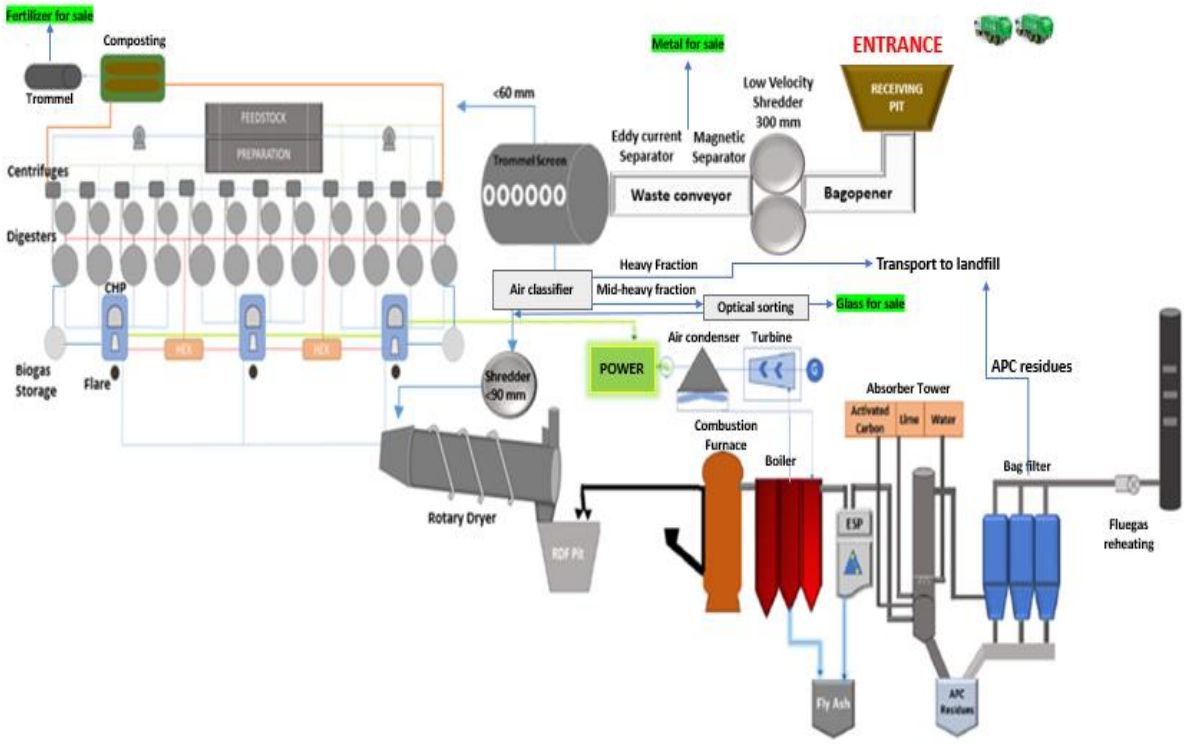

Figure 2.2 Integrated waste processing configuration (Scenario 2)

Material percentages after mechanical pretreatment were taken from the study revealed by Arina [111]. It was stated that the coarse fraction percentage (>120 mm) is 23%, the medium fraction percentage is 41% and the fine fraction percentage is 30% of the total waste stream. In addition, in the same study the calorific values of these fractions are specified according to Limonella WtE plant in Italy. Taking reference from distribution of calorific values after screening in Limonella WtE plant, the calorific values of fractions were determined according to mass percentages of fractions and raw MSW calorific values. After determination of HHVs and LHVs, the moisture contents of the fractions were calculated by using Eq. (2.3) from Biomass Energy Databook [112]; and confirmed with MSW moisture content in ISTAC study. The average moisture content is 56,13% that was determined by ISTAC, the calculated moisture content according to average ISTAC calorific values (MJ/kg) was found to be 56,99 % by using Eq. (2.3). It was found that properties of separated fractions were acceptable depending on negligible difference between the calculated and measured moisture content therefore, properties of all fractions were defined and shown in Table 2.3. Biochemical energy from anaerobic digestion of the organic fraction and thermal energy from

RDF incineration were calculated as a result of mass, calorific values and moisture distribution determination after screening. Process flow diagram is presented in Figure 2.3, coarse and medium fractions is represented as oversize fraction of screening (>60 mm) which is mostly combustible, whereas fine fraction (<60 mm) is OMSW which is sent to biogas plant.

$$LHV = HHV_d * (1 - MC) - 2{,}44 * MC \quad (2.3)$$

Table 2.3 Fractions properties after mechanical separation

	Mass (Ton)	HHV (kcal/kg)	LHV (kcal/kg)	Moisture Content (%)
Coarse fraction	630,522	5203,34	2086,70	53,86%
Medium fraction	1123,974	4792,34	1666,84	58,14%
Fine fraction	822,42	3338,64	1049,66	58,37%

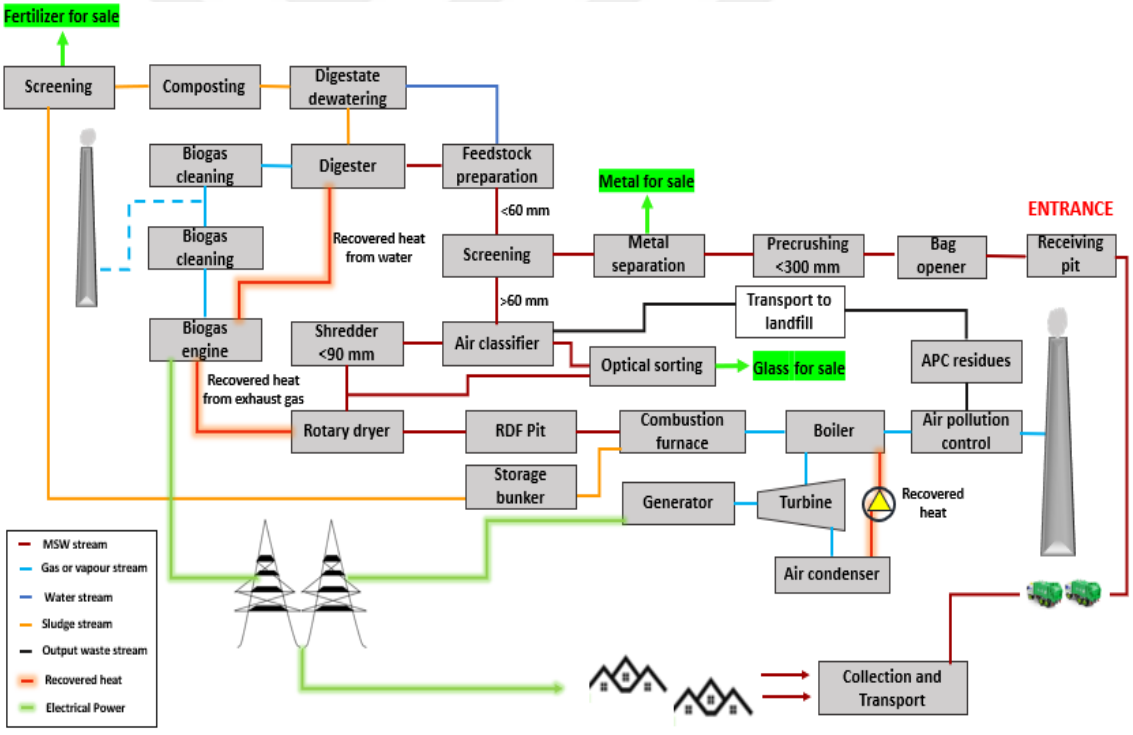

Figure 2.3 Integrated waste processing process flow (Scenario 2)

2.2.1 Biochemical Energy from Anaerobic Digestion

Biogas consists of methane and carbon dioxide, and it can be generated by anaerobic digestion technology from organic fraction of municipal solid waste. Electricity generation potential of anaerobic digestion technology that means

methane production from the kitchen waste (feedstock) depends on the feedstock amount fed to the digester which is the highest fraction of MSW. While calculating the biochemical energy from anaerobic digestion process, firstly solid mass percentage of feedstock was accepted as 12,5% then water requirement was calculated regarding 822,4 ton/day input waste with 58,37% moisture content and total feedstock volume was found. Methane production from organic fractions were calculated in two ways which are based on theoretical and biogas yield. Due to the deviations from the theoretical methane yield are likely; the dynamic nature of anaerobic digestion can easily cause digester upsets and process failures. Moreover, the rate and quantity of biogas generation depend on the volume of organics left, the availability of the organics for digestion, and the over-accumulation of inhibitory compounds, and sudden changes in the digester pH [113]. Therefore, energy and mass balances of AD process were constituted by considering biogas yield based on total solid according to biogas yield of MSW in the literature then biogas conversion efficiency of reactors were determined according to that calculated methane volume based on total solids. Methane content of biogas was accepted as 63% which is the average value in the literature. Digestate mass was determined by excluding biogas conversion rate of total solids from input total solid mass.

2.2.1.1 Methane Estimation Based on Theoretical Methane Generation

The Istanbul Theoretical methane generated from the digester can be determined based on ultimate elemental content using the Bushwell's Equation Eq. (2.4) [114]. Theoretical methane production was calculated according to MSW elemental analysis that defined by ASTM Standards by using mass balance of chemical reaction.

$$C_aH_bO_cN_d + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4}\right)H_2O \rightarrow \left(\frac{a}{2} - \frac{b}{8} - \frac{c}{4} - \frac{3d}{8}\right)CO_2 + \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8}\right)CH_4 + tNH_3 \quad (2.4)$$

a, b, c, and d values could be obtained as;

$$mole\ ratio = \frac{K[C,H,O,N]}{M[C,H,O,N]}$$

where M is the molar mass of the elements (carbon, hydrogen, oxygen, and nitrogen) as presented in Table 2.4 [114]. K is the element composition of (carbon, hydrogen, oxygen, and nitrogen) which is obtained from the ultimate analysis of OMSW, in this study elemental analysis results are taken from average values of MSW elemental analysis range (ASTM Standards) ash shown in Table 2.5 [115].

Table 2.4 Molar mass of the elements

Elements	*Oxygen*	*Carbon*	*Nitrogen*	*Hydrogen*
	O	*C*	*N*	*H*
Molar mass	16	12.01	14.01	1.01

Table 2.5 MSW elemental analysis range

MSW Elemental Analysis Range (ASTM Standards)		
Elemental Analysis	Range	Average
C %	44.95-45.10	45,03
H %	6.17-6.23	6,2
N %	1.95-2.01	1,98
O %	40.78-41.54	41,16

Volume of theoretical methane (m3/ton) can be determined as,

$$CH_4(v) = \frac{CH_4(kg)}{0{,}717(\frac{kg}{m^3})} \quad (2.5)$$

$$CH_4\ (act) = CH_4(v) * OM_{\text{frac}} \quad (2.6)$$

where 0.717(kg/Nm^3) is the density of methane [114]. Actual methane production is less than theoretical methane production due to the insufficient biodegradation of organic materials in digester this loss is corresponding nearly 10% of actual methane production. Also, 5–10% of the organic materials utilize for internal organism activities such as to cell renovation [116]. Hence biological activities organic fraction of waste allocated to anaerobic digestion technology, OM_{frac} is the fraction of organic matter utilized for cell tissue synthesis and is given as 85% [117]. Using actual methane generation potential obtained from Eq. (2.6),

electricity generation potential of anaerobic digestion technology was calculated as,

$$P_{AD} = \frac{CH_4\ (act) * 37{,}2 * E_{ef}}{86400} \quad (2.7)$$

$$E_{AD} = P_{AD} * C_f * 8760 \quad (2.8)$$

Where P_{AD} is the gross power of plant (MW-e), $CH_4\ (act)$ is the actual methane generation from the digester, E_{ef} electrical efficiency of conversion device is given as 35% [118], 37.2 (MJ/m^3) is the methane lower heating value [119], and C_f is capacity factor given as 85% [110].

2.2.1.2 Methane Estimation Based on Biogas Yield and Reactors Efficiency

Biogas consists of mainly methane and carbon dioxide. It can be produced from organic fraction of municipal solid waste by AD technology. Electricity generation potential of AD process depends largely on the amount of methane produced from the food waste (feedstock) fed to the digester which consist of the main fraction of MSW. While calculating the biochemical energy from AD process, firstly solid mass percentage of feedstock was accepted as 12,5% then water requirement was calculated regarding 822,42 ton/day input waste with 58,37% moisture content and total feedstock volume was found. Considering two stage anaerobic reactors design for the twelve-processing line as shown in Figure 2.2. Two-stage process suggested due to improved substrate hydrolysis with increased amounts of volatile fatty acids. Methane generation was estimated by using solid mass biogas yield of kitchen waste in the literature. Biogas yield of food waste based on solid mass was taken as 646 m^3/ton TS which is reported by Arpit H. Bhatt and Ling Tao [120]. Methane content value of the biogas was taken as 63% [121]; which is the average value in the literature. Electricity from methane generation was calculated with Eqs. (2.9) and (2.10), biogas conversion efficiency based on solid mass for both reactors was 45%, the methane density at normal conditions is 0,717 kg/m^3 [114] and LHV is 37,2 MJ/m^3 [119], heat to electrical power efficiency (E_{ef}) was taken as 35% [118], capacity factor is taken as 85% [110]. Two-stage anaerobic digestion offers high methane production by improving hydrolysis of substrate then increased the VFA which is ready to use in second digester. Literature studies support that production of biogas that consist higher hydrogen content can be

achieved by two-stage process. It is stated that actual methane production can be increased to 70% in two stage food waste digestion [113]. Moreover, it should be noted that heat recovery from exhaust and gas engines should be considered for a self-sufficient facility beside energy saving. Therefore, the required energy to keep the temperature of the digesters constant can be provided by heat recovery from combine heat and power (CHP) unit with the heat exchanger.

$$P_{AD} = \frac{CH_4(v)*37,2*E_{ef}}{86400} \quad (2.9)$$

$$E_{AD} = P_{AD} * C_f * 8760 \quad (2.10)$$

2.2.3 Thermal Energy from RDF Incineration

Electricity from RDF incineration were calculated according to RDF properties which is shown in Table 2.6, by using Eq. (2.1) and Eq. (2.2). Moisture content and HHV of RDF was determined according to mass, moisture content and HHV of medium and coarse fractions (>60 mm) that separated by mechanical pretreatment then LHV of RDF was calculated by Eq. (2.3). Moisture loss due to the leachate from mechanical separation units has been neglected. Also, two different configurations that change RDF properties were evaluated for this section. In this case, before incineration of RDF, thermal drying unit using waste heat from biogas plant exhaust gas included to increase the calorific value. LHV were calculated by aiming to decrease to half of moisture content that in RDF using by the waste heat. Thus, more energy can be generated with less input waste volume at the same time investment cost of incineration plant will decreased and one combustion line is sufficient according to RDF mass. Electricity producing were estimated using by different qualified RDF properties that shown in Table 2.6. Electrical power efficiency was taken as 30% from Silva et al. and a capacity factor as 85% [109,110].

Table 2.6 RDF properties

	Mass (Ton)	HHV (kcal/kg)	LHV (kcal/kg)	Moisture Content (%)
RDF	1754,50	4940,04	1812,73	56,60%
Dried RDF	1061,90	4940,04	3377,15	28,30%

2.3 Fertilizer by Composting from Digestate

There are many investigations about composting of anaerobic digestate from different organic waste such as pig slurry, sewage sludge, OMSW. Meissl et al. reported that the composting of digestate from anaerobic digestion of kitchen waste can produce high-quality compost [122]. Smidt et al. reported that the transformation of final product by anaerobic digestion following composting achieved better quality humification indices when digestate is properly mixed before composting [123]. However, Bustamante et al. reported that, due to the nature of the digestate, such as low C/N ratio, high pH, and scarcity of available carbon (C), optimization of composting conditions of the solid phase of anaerobic digestate and additive strategies can be required [124].

Digestate mass was estimated by accepting to have 90% moisture content and digestate generation percentage as 55% based on solid mass of feedstock. Therefore, for the evaluation of fertilizer by composting from digestate, digestate are collected from each line and dewatered for decreasing the moisture content to 60% before the composting. The separated water fed into the feedstock preparation unit; thus % 74 of water demand provided by digestate dewatering. Mass balance of OMSW treatment processes based on yield was stated in process flow diagram in Figure 2.4. It was evaluated that dewatered sludge utilized in the thermophilic composting; the homogenized feedstock of volume is heaped into conical piles with moisture of 50–60% [125]. Outputs were determined based on windrow composting technology. Windrow composting that is used very common is an open-air system requiring mechanical turning to ensure aerobic conditions [126]. Generally, windrows dimensions are designed about 2 to 3 meters high, 3 to 5 meters wide and up to 100 meters long as long and narrow piles [126]. Thus, keeping the high temperatures and circulation of oxygen in the windrow are allowed. Sufficient aeration is provided by turning machine which used to mix of windrows piles to prevent the anaerobic parts. Also watering equipments are included in these turners to keep optimum of the moisture contents. Compost efficiency of dry basis defined based on literature studies with assumptions like C/N ratio between 26-35 [127]; sufficient air that introduced to provide the oxygen needed for biological conversion, and the convenient temperature

conditions within the pile. About the large-scale windrow composting from MSW in literature, experimental analysis by A.K. Karunarathna et al. reported 28% of feedstock mass based on dry basis [128]. Feedstock recovery regarding compost efficiency is achieved by using bulking agents in windrow piles which generally consisted of small pieces of film plastics, slowly decomposable organic materials and residues such as small pieces of textiles. Referencing from this study, compost mass was determined by using the dry basis conversion. Fertilizer mass for marketing was accepted to be undersized fraction of screen as 20% of compost mass whereas it was accepted that oversize fractions are sent to incineration plant of the facility.

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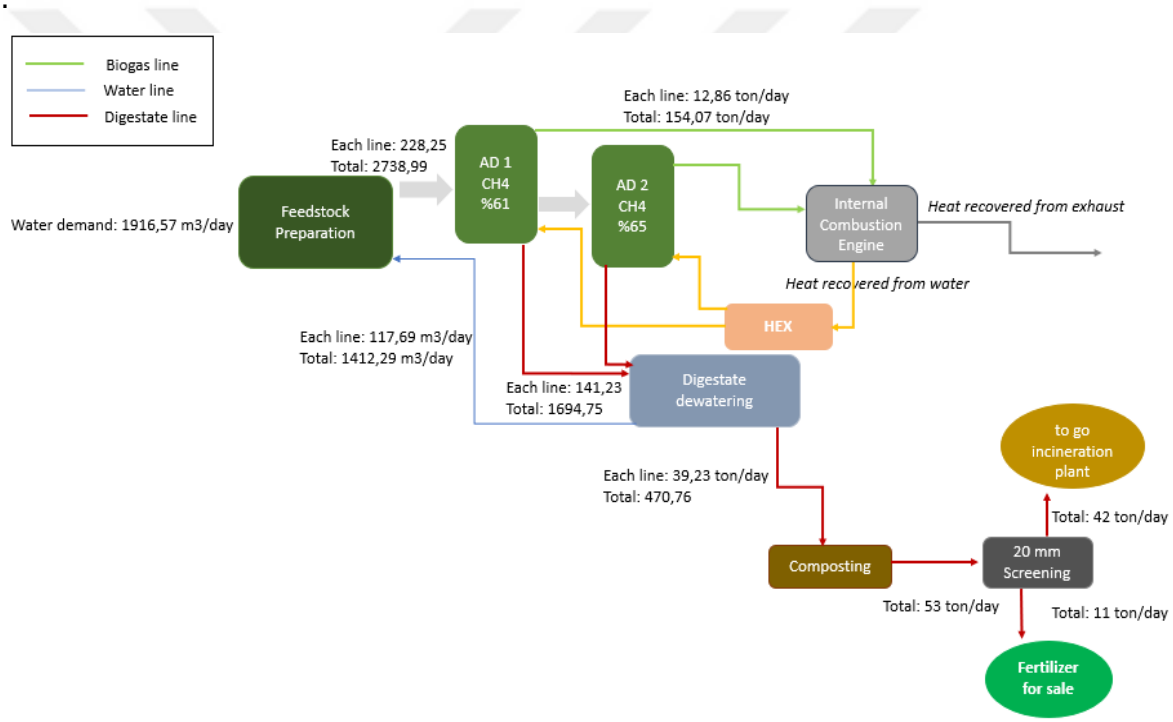


Figure 2.4 Biogas plant process flow diagram

2.4 Economic Analysis

Before investing in any project, it is very important to know its economic feasibility that will help decision making during the investment of project. The present study assessed the economic feasibility of two scenarios which are raw waste incineration and integrated waste processing (MBT+RDF incineration) using economic metrics such as Net Present Value (NPV), and Levelized Cost of Energy (LCOE). In order to economic assessment of waste to energy projects, revenue and

costs should be defined before the constitution of the plant cash flow. Constitution of cost/benefit (C/B) analysis of scenarios require determination of investment cost. The investment cost includes estimations of equipment and devices cost, engineering and construction costs, land use and other costs, preparation funds, loan interest and risk management whereas the O&M cost includes estimations of requirements raw materials preparation, plant power consumption, staff salaries, depreciation loss, maintenance charge, and environmental expenses. Fly ash handling, bottom ash processing, leachate treatment and environmental monitoring, financial expenses and additional expenditure are also included [129]. Incineration plant investment cost was estimated based on input waste mass by using Eq. (2.11) which developed by Waste to Energy International OU (WTEI) company that develops waste to energy projects [130].

$$I_{inc} = 2{,}3507 * W_{inc}\text{^}0{,}7753 \quad (2.11)$$

where I_{inc} is the investment cost of incineration plant in million dollars and W_{inc} is the plant capacity (1000 metric tons of waste/year). The average O&M cost of waste incineration plant including installation, operation and maintenance considered 4% of initial investment [129,142,143]. Incineration plant costs were calculated based on determined capacities for raw waste, RDF and undried RDF. Biogas plant investment cost was estimated by using specific cost of AD plant which is 4339 $/kW referenced from IRENA [110]. It is taken as 5207 $/kW with the ten years inflation; inflation rate taken as 2 % which is the average dollar inflation for the last twenty years from World Bank Report [131].

$$I_{AD} = 5207 * (E_{AD}) \quad (2.12)$$

where I_{AD} is the investment cost of biogas plant in million dollars and E_{AD} is the plant capacity (kWh) whereas O&M cost of biogas plant can be calculated as:

$$O\&M_{AD} = I_{AD} * 0{,}03 + E_{AD} * 0{,}0058 \quad (2.13)$$

where fixed operation cost percentage taken as 3% of the investment cost according to Ayodele et al [116]. Variable operation and maintenance cost relates to the output of the plant and expressed as a per unit value of the plant output. Therefore, 0.5% of electricity generation is assumed in accordance with Ogunjuyigbe et al [114]. Revenues of WtE plant involves tipping fees paid by waste

producer, sales from electricity, heat, or steam, sales from other co-products (recovered metals, compost). Water consumption cost of biogas plant is negligible because of wastewater return from dewatering unit with high reuse efficiency. Remain water requirement can be also supplied with raw water or treated water. The selling price of raw water in 2021 that identified by İstanbul Water and Sewerage Administration (İSKİ) is 1,25 TL/m^3, this value decreases to 0,44 TL/m^3 for treated water [132]. Investment cost of biogas plant occurs installation of biogas utilization and engine systems, building the digester with insulation, mixers, cover and accessories, process control and safety equipment, management, engineering costs, piping, safety system, connection to grid, tanks and backup storage and other related electrical, electronic and civil work. It was accepted that required heat to keep temperature constant in digester is provided jacket cooling system of cogeneration unit thus energy consumption during operation is only electrical power for the operation of the pumps, mixers and injectors. The management of liquid digestate from wet AD process is included in digestate utilizing units. Costs of digestate utilizing processes including dewatering and composting were estimated by large scale case studies in literature. There are several common mechanical dewatering methods for solid-liquid separation such as screw presses, belt presses, or centrifuges. In this study, centrifuge dewatering was selected depending on low O&M cost. Solid fraction from digester subjected to decanter centrifuge up to 30% of solids content can be achieved with the addition of polymer. Dewatering unit cost was estimated according to WRAP report which assessed annually throughput capacity as 50.000 ton/day centrifuge decanter prepared by Baddeley et al. investment cost of centrifuge unit was determined according to centrifuge output capacity of scenario 2 by using Eq. (2.14). Considering inflation adjusted, investment cost of centrifuge dewatering including main equipment item, control system, ancillaries, poly make up system, building was taken as 7,2 $/ton feedstock whereas O&M cost including polymer, ferric, electricity, labor, ancillary and maintenance stated as 4,33 $/t feedstock was considered [133]. Polymer and electricity consumption are main costs during operation in centrifuge dewatering. Another process is composting, costs are highly variable and greatly depend on the feedstock as well as the selected technology. Based on windrow composting technology, plant requirements and

costs of units were defined according to Renkow et al. [134] as shown in Table 2.7. O&M cost which includes labor costs for daily operation, maintenance and operating costs for the relevant equipment was determined based on compost mass. O&M cost for composting was taken as 6,5 $/ton that defined by Hareen et al. adjusted with inflation [126].

Table 2.7 Investment cost of composting process (200.000 tons/year)

Requirement		Cost	Unit
Land *	$	37,30	20
Front-end loaders	$	168.448,00	1
Thermometers	$	6.016,00	20
Compost turner	$	194.016,00	1
Screener	$	100.993,60	1
Scale	$	22.560,00	1
Sediment basin *	$	812,16	1
Centrifuge	$	1.239.783,19	12
Water pump	$	1.353,60	2
Total	$	1.734.019,85	

* The unit cost has been estimated in dollars per acre.

Investment cost of mechanical pretreatment as called RDF production process was estimated according to Aleluia et al. [135]. In the study investment cost of RDF production units include construction, equipment and installation, land use and preparation, load interest, circulating capital costs. RDF production can be in variable configurations which effected the investment cost depend on material recovery facilities, particle size reduction and palletization. In this study scope, proposed mechanical pretreatment configuration as shown in Figure 2.5 include separation of metallic, non-metallic and glass materials from waste stream and particle size was accepted to decrease to 9 cm before the combustion of RDF. Recovered glass fractions (cullets) can be separated by using optical sorting techniques via color-based classification, as glass cullets typically have pieces with various colors like red, blue, green or any combinations [136,137]. Separation is carried out by allowing various colors which pass through controlling by the sensor which measures attenuation of light by scanning [138]. Regarding RDF production process of scenario 2, investment cost was determined according to upper limit of cost range that stated by Aleluia et al. with 3000 ton/day input

waste mass and correlation rate depend on capacity was taken as 0,6 which is the earliest mention of this concept stated by Williams Jr. (1947) and installation cost was calculated by Eq. (2.14) and adjusted to dollar inflation [139].

$$C_B = C_A * \left(\frac{S_B}{S_A}\right)^{0,6} \quad (2.14)$$

where C_B is the approximate cost ($) of equipment having size S_B (cfm, Hp, ft2, or whatever) C_A is the known cost ($) of equipment having corresponding size S_A (same units as S_B), and S_B/S_A is the ratio known as the size factor, dimensionless. On the other hand, RDF dryer installation cost was determined based on according to evaporated water content capacity for thermal drying by waste heat. Several types of dryers are used for industrial applications such as rotary dryers, belt dryers. Rotary dryer is the most common type used for industrial drying depending on relatively limited operational costs. Rotary dryers can accept hot flue gas whereas belt dryers are operated at low temperature than rotary dryers which give an advantage because more reliable and safety applications [140]. It was accepted that the direct use of the flue gas as the heat source, without the need for a heat exchanger. For the cost estimation, rotary dryer was chosen however type of dryer can change based on plant optimization. Water removal capacity was determined regarding moisture content decreasing that is aimed. Investment cost was estimated based on per kg/h of water evaporated. Cost estimation was realized according to Technology Application Laboratory study which investment cost of rotary dryer stated as 176 $ / kg/h for wet fuel [141]. Rotary dryer unit cost determined with accepted evaporated water content is 8 kg/sec, OPEX was estimated as 4% of initial cost [142,143].

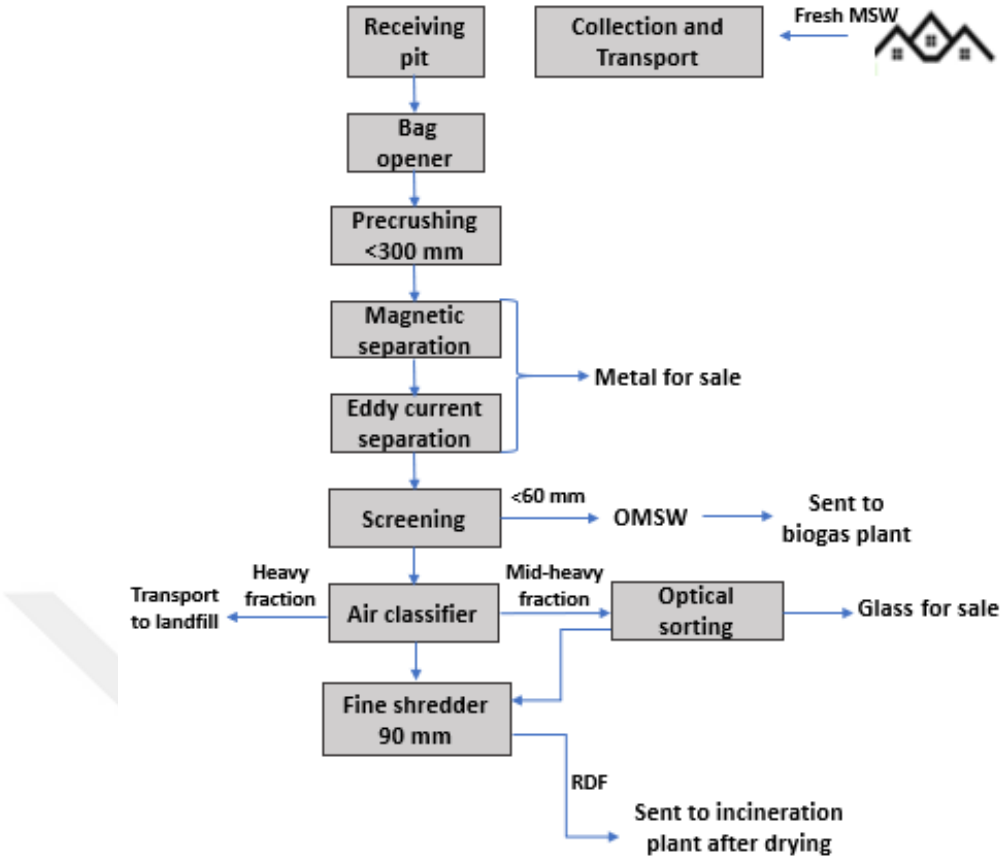


Figure 2.5 Proposed RDF production process

MBT comprises mechanical pretreatment biogas plant and digestate utilizing processes. Mechanical pretreatment units include screening, shredding, metal & glass removal and dryer. OMSW management occurs from biogas plant and digestate utilizing process which involves centrifuge, composting and sieving. Main units of biogas plant occur from feedstock preparation to obtain well mixture, hydrolysis and digester tanks, gas storage, cogeneration units. Investment cost of biogas plant occurs installation of biogas utilization and engine systems, building the digester with insulation, mixers, cover and accessories, process control and safety equipment, management, engineering costs, piping, safety system, connection to grid, tanks and backup storage and other related electrical, electronic and civil work. O&M cost is relatively low because there is no requirement of any chemical and material consumption in anaerobic digestion process. It was accepted that required heat to keep temperature constant in digester is provided by jacket cooling system of cogeneration unit thus energy consumption during operation is only consist of electrical power for the operation

of the pumps, mixers and injectors. The management of liquid digestate from wet AD process is included in digestate utilizing units. Digestate utilizing units involve centrifuge dewatering, composting and sieving. 74% of water consumption in feedstock preparation of biogas plant is provided from dewatering units and it reused in the system. O&M cost of biogas was calculated as total of fixed operating and variable operating costs. Fixed costs include labor, scheduled maintenance, routine equipment replacement, insurance, etc. variable O&M costs include incremental serving costs, and unplanned maintenance.

As a conclusion of cost estimations, for three different process configuration, investment and O&M cost is presented in Table 2.8. Incineration plant has highest investment and operating cost in the evaluated waste processes. Therefore, depend on volume reduction in the RDF drying unit for the scenario 2, remarkable decreasing was stated on the initial investment cost of plant. On the other hand, the process that have lowest investment cost is digestate utilizing processes which include centrifuge dewatering and compost plant. Also, while estimating the investment cost of scenario 2, oversize fraction volume from the last screening of the composting plant was included in the capacity of incineration plant. O&M cost of first scenario is corresponded 4% of initial investment whereas O&M of second scenario is equal to 4,2% of initial investment after processes cost of scenario 2 determination of separately. If RDF is not dried by waste heat, investment and O&M cost of scenario 2 increase with the increasing incineration plant capacity however dryer costs was excluded, in this case O&M cost is corresponded to 4,1% of initial investment.

Table 2.8 Costs of scenarios

million $	Scenario-1	Scenario-2	Scenario-2 without RDF drying
CAPEX	534,14	429,54	540,17
OPEX	21,37	17,83	22,25

Investment costs of all process were presented in Figure 2.6. MBT consists of mechanical pretreatment units which called RDF production process, and biogas plant. Cost of dryer was included in cost of MBT plant. If RDF not dried, this cost excluded from MBT cost, but this led to increasing the cost of incineration plant. In any case, incineration costs decreased considerably as a result of decreasing waste

mass after pretreatment when compared with raw waste incineration. Waste incineration has a low energy recovery rate due to the irregular calorific values and to protect the system from irregular fuel conditions incinerators are expensive and hard to design, waste incineration displays relatively insufficient evaluation of waste value and environmental benefits [144]. On the other hand, the second scenario is hard to operate because of biological conditions. Anaerobic digestion and composting are affected from temperature, feedstock quality such as impurities, C/N ratio, these parameters are also relevant with mechanical pretreatment process operations. Digestate utilizing includes centrifuges and composting processes. Same approach is the point for O&M costs of processes. On the other hand, with RDF drying, power output of the system is more stable depending on robust to changes of calorific values. This provides less unpredictable operational challenges.

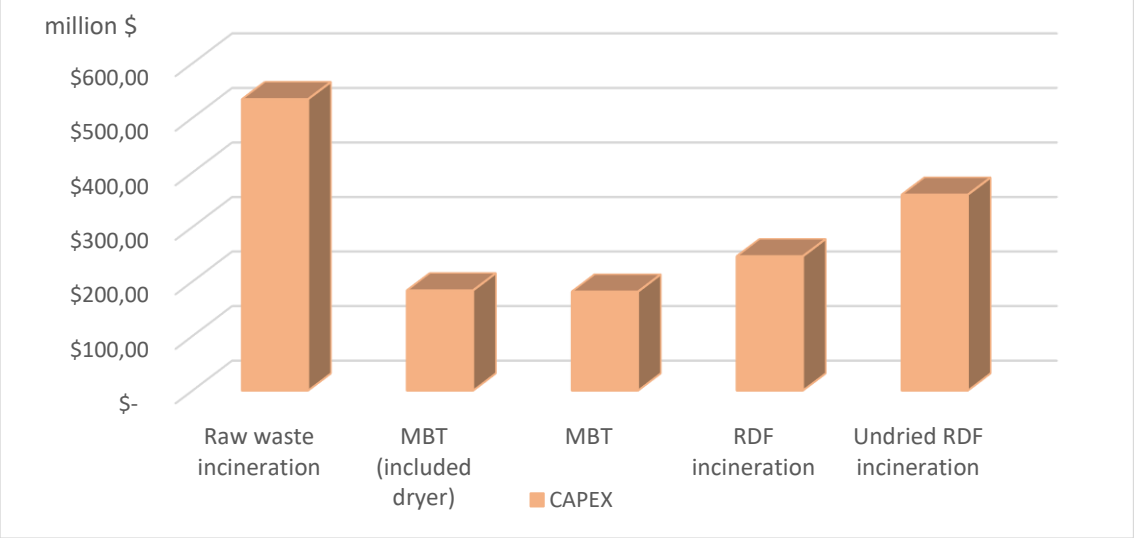


Figure 2.6 Investment cost of all processes

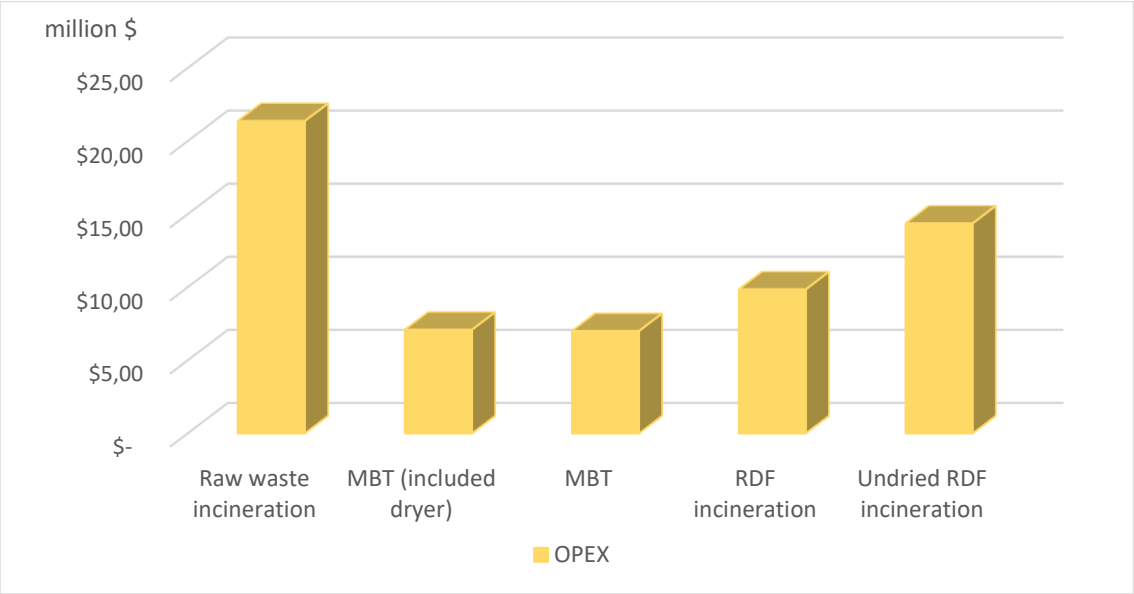


Figure 2.7 Operation and maintenance cost of all processes

2.4.1 Net Present Value

Net present value is all future the costs that the system incurs over its lifetime, minus the present value of all the revenue that it earns over its lifetime. Determination of NPV is important to analyze revenues and costs of the project by constitution of the cash flows. Positive NPV represents to make decision as project economically feasible [145]. NPV can be calculated as;

$$NPV = \sum_{0}^{y} \frac{Z_n}{(1+\delta)^n} \text{ (Oak Ridge 2011)} \quad (2.13)$$

where Zn is the net cash flow, y is the period of calculation, and δ is the discount rate [144]. Net cash flow can be obtained as;

$$Z_n = Proj_{rev} - Proj_{O\&M} - Tax_{paid} - I \quad (2.14)$$

where Projrev is the revenue accrued from the incomes of the plant, Taxpaid is the tax paid on the profit of the project, δ is the discount rate and is given as 10% [110], PROJCo&M is the cost of operations and maintenance, I is the initial cost of investment. Project revenue (Projrev) and tax paid on the project (Taxpaid) can be obtained as [146]:

$$Proj_{rev} = E * FIT + M * Tapping_{price} + F * Sale_{price} + R * Sale_{price} \quad (2.15)$$

$$Tax_{paid} = INV_{profit} * Tax_{rate} \quad (2.16)$$

$$INV_{profit} = Proj_{rev} - Proj_{O\&M} \quad (2.17)$$

where, E is the electricity generation potential of the projects, sale FIT is the feed-in-tariff and according to decision 2021 of Renewable Energy Resources Support Mechanism (YEKDEM) constituted by Turkish Energy Market Regulatory Authority, plants that commissioned after July 2021, will be able to purchase 8 $ cent/kW for incineration plants, and 8,6 $ cent/kW for biogas plants [147]. These tariffs are the identified upper limit price values-based dollar in the first ten years according to decision 2021. YEKDEM Limit prices based on dollars were taken as feed in tariff (FIT) for the first ten years of the project, for remaining years it was taken 5,5 $ cent/kW as average market exchange price in 2021 which was detected by Turkish Energy Markets Operating Corporation [148]. It was accepted that electricity selling price will increase as dollar inflation rate, electricity selling price was calculated as 6,6 $ cent/kW after ten years at the end of the YEKDEM tariff. Annual electricity inflation rate as 2% was also considered for the remaining project life. M is the waste mass disposed and waste tapping fee was determined by taking the dollar exchange rate as 15, domestic waste disposal price was taken as 113 TL/ton which identified by ISTAC in 2021 [149]. Inflation rate for electricity selling and disposal fee prices is taken as 14,60 % which is the average value of 2020 that is explained by Turkish Statistical Institution (TUIK) [150].

F is the fertilizer mass to sale from composting. For the determination of fertilizer selling income, sale price identified as 150 $/ton after market researching. Project revenue from fertilizer sale was calculated with 2% inflation for every year. *R* is the recyclable materials which is only consisted of separated metals for first scenario, although *R* is both of separated metals and glass material for second scenario. Separation efficiency of equipment was taken as 85% and inflation rate taken as 2%. Selling price of scraps was identified as an average value after detail market research. It was accepted that selling price is 220 $/ton for metals and 320 $/ton for crushed glass. INV_{profit} is the profit gain from the investment, and Tax is identified based on investment profit, Tax_{rate} is the marginal tax rate of Turkey. The corporate income tax rate levied on business profits was taken as 20% [151].

2.4.2 Levelized Cost of Electricity (LCOE)

Levelized cost of electricity is an economic measure which is evaluating comparison of the lifetime costs of electricity generation. LCOE is the average electricity price that must be earned by system to break even. LCOE is an important economic metric to make decision about the feasibility of a project also for investors to understand long-term economic trends. It determines by the minimum cost in ($/kWh) of electricity generated.

The lifetime costs of the electrical power generation include capital costs, operation and maintenance cost. O&M costs consist of various outcomes that involve plant requirements during commissioning and operating such as fuel costs, service costs, utility usage, disposal of the plant outputs such as ash from incineration, noncombustible wastes. Variable O&M costs are directly relevant to power generation and operating condition of the plant. Fixed operating costs include personnel salaries, security costs and insurance etc. LCOE's of scenarios were calculated based on OPEX costs as shown in Figure 2.7.

The levelized cost of energy was determined as;

$$LCOE = \left(\frac{TLCC}{E}\right) * \left(\frac{\delta(1+\delta)^{y}}{(1+\delta)^{y}-1}\right) \tag{2.17}$$

$$TLCC = I + \frac{Proj_{O\&M}}{(1+\delta)^{1}} + \frac{Proj_{O\&M}}{(1+\delta)^{2}} + \cdots \ldots \ldots \ldots \ldots \frac{Proj_{O\&M}}{(1+\delta)^{y}} \tag{2.18}$$

where; TLCC is the total life cycle cost of the project, and y is the economic life of the project (30 years), δ is discount rate [152]. LCOEs were calculated considering different discount rates to present effect of discount rate on LCOE, however 10% discount rate was considered during comparison of scenarios.

2.5 Sensitivity Analysis

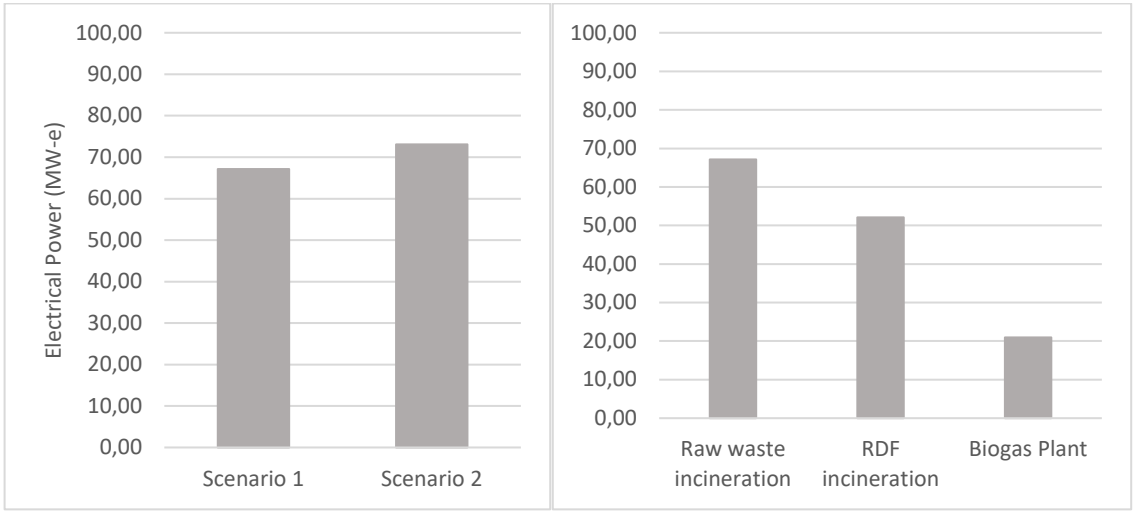
Sensitivity analysis was carried out to state the influence of thermal drying of RDF fraction by exhaust gas of biogas plant on the electricity generation and economic assessment. Thermal energy can be recovered in two ways from cogeneration of biogas plant; these are engine cooling system and exhaust. In the second scenario, it was accepted that recovered heat from jacket water will be used for heating the digesters if required and recovered thermal energy from exhaust is used to decrease the moisture content of RDF to half. This section shows differences on

Techno-Economic analysis of integrated waste processing scenario in the case of undried RDF combustion. Electricity incomes decrease as a result of the less calorific value, also investment cost of incineration plant increase with the more input waste mass if RDF not dried. This section presents second scenario that in the case of undried RDF for evaluation of effect of RDF drying on NPV, LCOE and payback period. Electrical power output was calculated according to undried RDF properties by using Eq. (2.1) and Eq. (2.2), after that electricity selling income was calculated according to gross power of plant. Investment cost of incineration plant was estimated depending on undried RDF mass. Total investment cost of scenario 2 was determined by including MBT cost which excluded dryer cost. Future cash flow was constituted, economic parameters were calculated and net present value and levelized cost of energy were determined for the case of undried RDF incineration. Results compared with other scenarios. Discount rate was considered as 10% during comparison of economic analysis.

3
TECHNO-ECONOMIC FEASIBILITY ANALYSIS

3.1 Electrical Power

Electrical power from the raw waste incineration and integrated waste processing scenarios were presented in Figure 3.1 (a). Electrical power of raw waste incineration was calculated as 67 MW-e whereas MBT+RDF incineration was estimated as 73 MW-e. It can be seen from Figure 3.1 (b), for the second scenario, 21 MW-e of electrical power comes from the biogas plant. According to these results, it is stated that 9% of gross power increasing can be achieved with second scenario. The natural biodegradation is influenced ambient situation easily and can cause failing of process or digesters. Therefore, reactor and feedstock conditions are very important for biological processes. This is also relevant with operational conditions of mechanical separation processes. However, the two-stage system achieves a hydrogen rich biogas in the first fermentation reactor and provides improvement of methane content in the second methanogenic digester. It is stated that, methane content can be reached to 70% in two stage food waste digestion [113]. In this study, biogas conversion rate was calculated as 45% and methane content of biogas was taken as 63%. Methane generation can be increased with sufficient design and operating conditions. On the other hand, according to thermal energy calculations, if RDF is dried by waste heat before combustion, 78% of the electrical power of raw waste incineration can be generated with the waste volume which is almost one third of the raw waste.



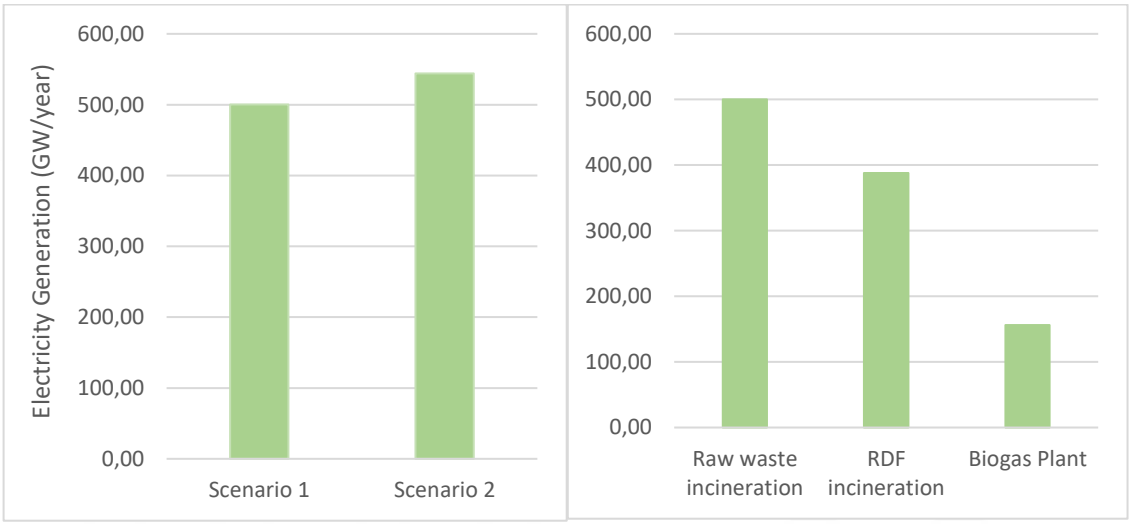
a b

Figure 3.1 Electrical power of both scenarios (a) and all processes (b)

3.2 Electricity Generation

While looking at annual electricity generation of scenarios shown in Figure 3.2, considering the 85% capacity factor for both scenarios, it was stated that 44,1 GW/year more electricity generation can be achieved with second scenario. Electricity generation of second scenario was calculated as total of 544,2 GW/year representing as 156,3 GW/year from anaerobic digestion of OMSW with 388 GW/year from RDF incineration while it was calculated as 500 GW/year from raw waste incineration. Biogas plant is constituted 29% of total electricity of scenario 2, remained electricity is generated from RDF incineration. Results show that with increasing calorific value of RDF after drying process, electricity generation can be increased by 9% compared to raw waste incineration. As the calorific value increases after RDF processing and the particle size of the waste is small, combustion equipment can be smaller, less robust and therefore less expensive, comparison to raw waste incineration technologies such as grate type furnace. Also, the system is more resistant to waste composition changes than raw waste incineration. Therefore, advanced thermal treatment such as gasification methods which are low emission and high efficiency applications can be evaluated. On the other hand, obtained RDF after dryer can be evaluated by using in cement industry. Elemental analysis such as chlorine, sulfur and determination of calorific value and

moisture content are essential to able to usage of RDF in clinker production. According to an experimental study related RDF production from Istanbul MSW, organic fraction, and recyclable materials such as metals, glass, plastic were separated from MSW by RDF processing plant in Istanbul and used in pilot cement rotary kiln to production of clinker. They stated that RDF usage in levels of 20% is appropriate for production of clinker after many quality tests and experimental analysis. Also, the values found by the chemical analysis were within the limit values of Portland cement [153].



a b

Figure 3.2 Electricity Generation of both Scenarios (a) and all Processes (b)

3.3 Economic Analysis

Economic and financial results were determined after constitution of cash flows of scenarios. This section presents the calculated financial metrics NPV and LCOE based on future cash flows of each scenario. The projects revenues considered as electricity, fertilizer, scraps selling incomes in addition to waste disposal fee. The electricity revenues considered a sale tariff of 8 $ cent/kW for thermal treatment, 8,6 $ cent/kW for biogas plant as constant price for first ten years according to YEKDEM decision, whereas 6,6 $ cent/kW for remaining years. Scraps incomes include only metals for raw waste incineration plant whereas metal and glass materials for integrated waste processing scenario, with 85% equipment efficiency. Sale prices of scraps was accepted as 220 $/ton for metals and 320 $/ton for glass. Also, 11 ton/day fertilizer that send to markets for sale with the

150 $/ton price is included in revenues of second scenario. Lifetime of all projects was considered as 30 years and NPV of scenarios was calculated based on different discount rates. Only waste disposal fee was integrated by the inflation rate in Turkey (14.60%), selling price of other revenues such as electricity, fertilizer or metallic material adjusted dollar inflation rate with 2%.

3.3.1 Net Present Value (NPV)

Net present value (NPV) shows the current value of all future cash flows generated by a project including the investment cost. Before the determination of net present value, cost and benefit projections were made throughout the life of the facility and the plant incomes at the end of 30 years was calculated. Cash flows of the scenarios were presented in Figure 3.3 and 3.4. Annual cash flow projection shows that scenario 2 crossed to positively cash earlier than scenario 1. Payback period of raw waste incineration was determined as 10 years whereas it is 7 years for integrated waste processing scenario. Effect of YEKDEM support mechanism on project incomes is seen with decreasing of scenarios annual cash flow at the end of the ten years depending on less electricity sale price. Annual project revenue at the end of the project life of the scenarios were calculated, as 416,3 million $ for raw waste incineration, 447,8 million $ for integrated waste processing scenario. NPVs were determined by discounting the cash flows of the scenarios by different discount rates during the 30 years of project life and presented in Figure 3.5. Both projects are economically viable with a positive NPV. However, scenario 2 is highly feasible than raw waste incineration. Considering 10% discount rate and 30 years plant life, net present value of raw waste incineration was determined as 380,4 million $ while integrated waste processing scenario is 553,7 million $ during the project period. This means an increasing of 45,6 %. It can be concluded that, thanks to different revenues of second scenario, cash flow increases more rapidly than raw waste incineration. Also, thanks to decreasing waste capacity as a result of the RDF drying by waste heat recovery, incineration plant investment cost is less than raw waste incineration and other processes such as anaerobic digestion and composting are relatively cheaper than combustion process. Therefore, the causes like this effected on payback period of the waste management scenarios.

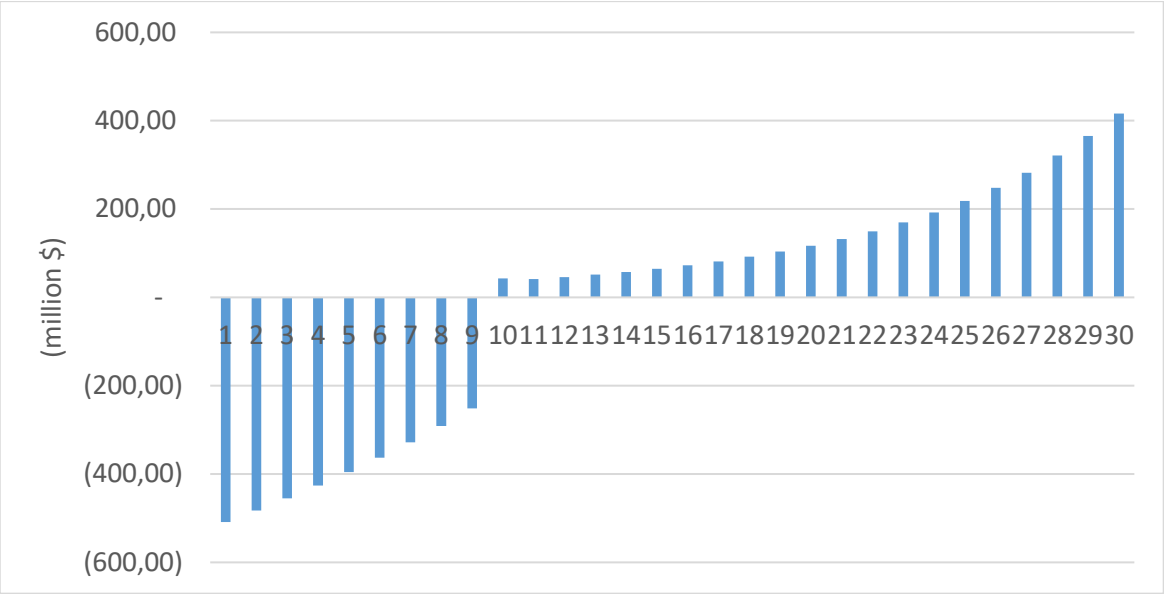


Figure 3.3 Annual cash flow of raw waste incineration (Scenario 1)

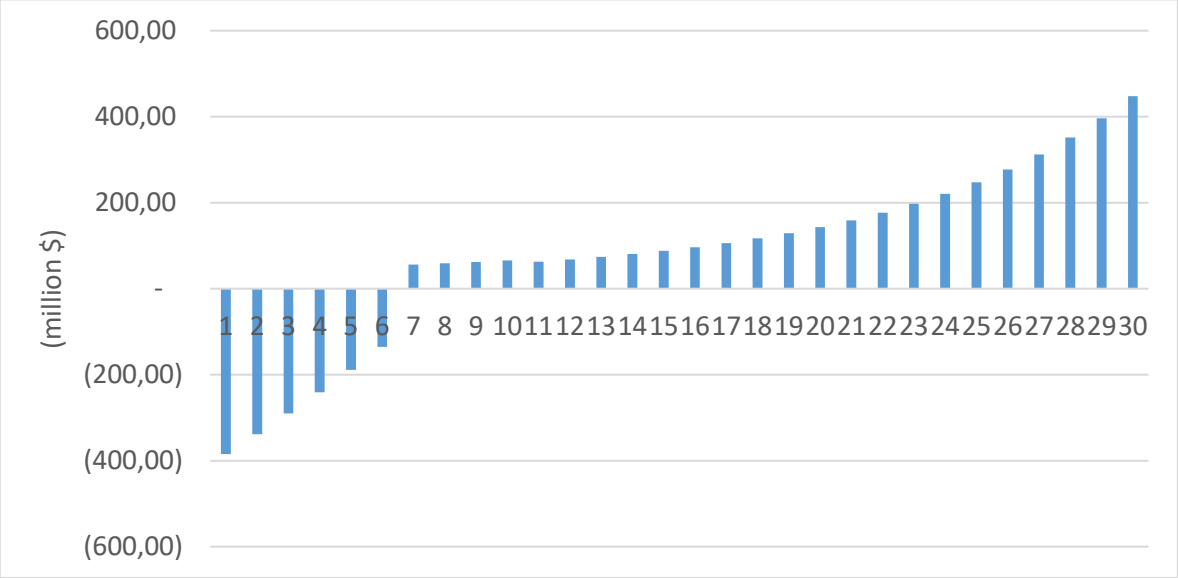


Figure 3.4 Annual cash flow of integrated waste processing (Scenario 2)

NPV of the scenarios were determined by discounted of the cash flows. In Figure 3.5, for evaluation effect of increasing discount rate on NPV of scenarios, NPV's were determined with different discount rate. Discount rate is the rate of return used to discount future cash flows back to their present value. The rate is used to discount future cash flows of a financial instrument in corporate finance. The annual discount rate decreases the amounts of future cash flow to yield their present value. NPV decrease if discount rate increase, this expectable result occurred from inverse relationship between discount rate and net present value.

3% increasing of the discount rate decreased 42% NPV of first scenario, 38% NPV of second scenario.

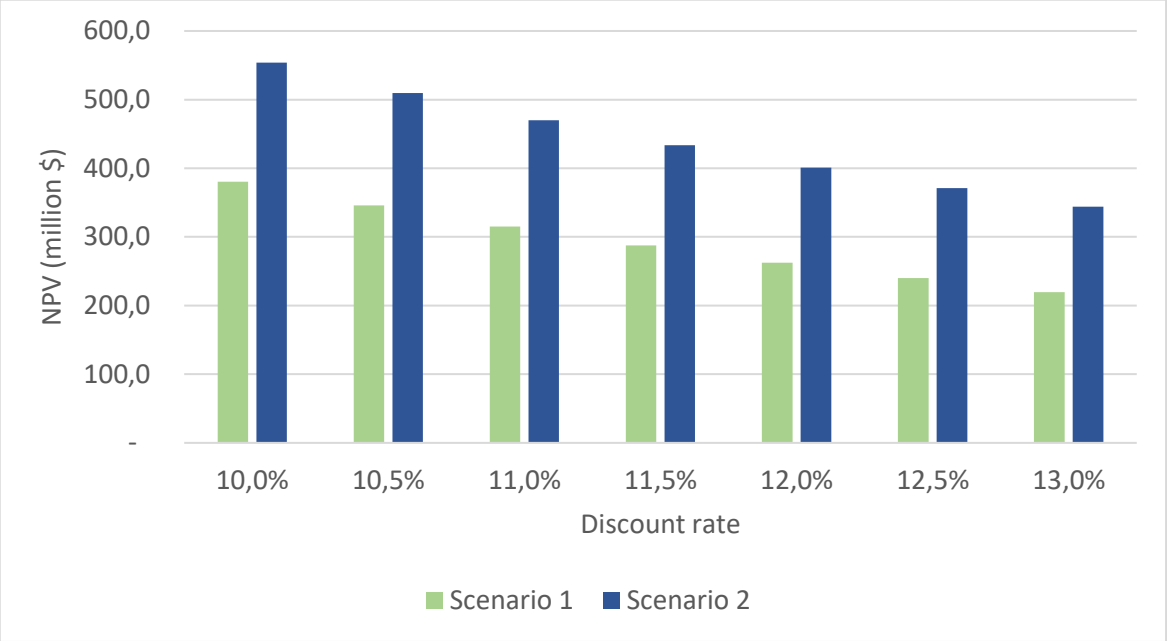


Figure 3.5 Net present value (NPV) of scenarios based on different discount rate

3.3.2 Levelized Cost of Electricity

The LCOE means per-MWh cost of constructing and operating a generating plant over the assumed project life. It is determined with total lifetime cost divided by total lifetime energy production. LCOEs that calculated based on different discount rate is presented in Figure 3.6. Considering 10% discount rate, LCOE was found as 15,4 $ cent/kW for raw waste incineration scenario and 11,5 $ cent/kW for integrated waste processing scenario. This means integrated waste processing scenario is more feasible. Waste incineration required higher cost during installation and operation due to the robust equipment need, contamination control mechanisms, controlling and monitoring gas emissions. It is expected result that the LCOE of first scenario is higher than second scenario due to the more life cycle costs. Even if O&M costs of integrated waste processing scenario is higher than raw waste incineration due to the more complex processes, several project incomes, LCOE can be lower than raw waste incineration as a result of the more electricity generation. However, investment and O&M costs can decrease significantly up to 50% by applying decision such as the integration of government

legislation that help in the financing of projects [154], the limitation of infrastructure only to the necessary equipment depending on the installed capacity and the characteristics of the waste [155]. Also, choosing the appropriate waste management technology according to waste characteristics, and design based on energy efficiency approach can decrease the unit cost with improving facility incomes such as selling of electricity or useful end products. Gomez et al. stated that if the electricity sale price is higher than the LCOE, then the project is economically viable [143]. The research, development and implementation of sustainable energy approaches such as energy from waste applications should be further supported thus costs of waste management processes can be decreased. Figure 3.6 presents effect of increasing the discount rate on LCOE, LCOE increases with increasing of discount rate unlike NPV.

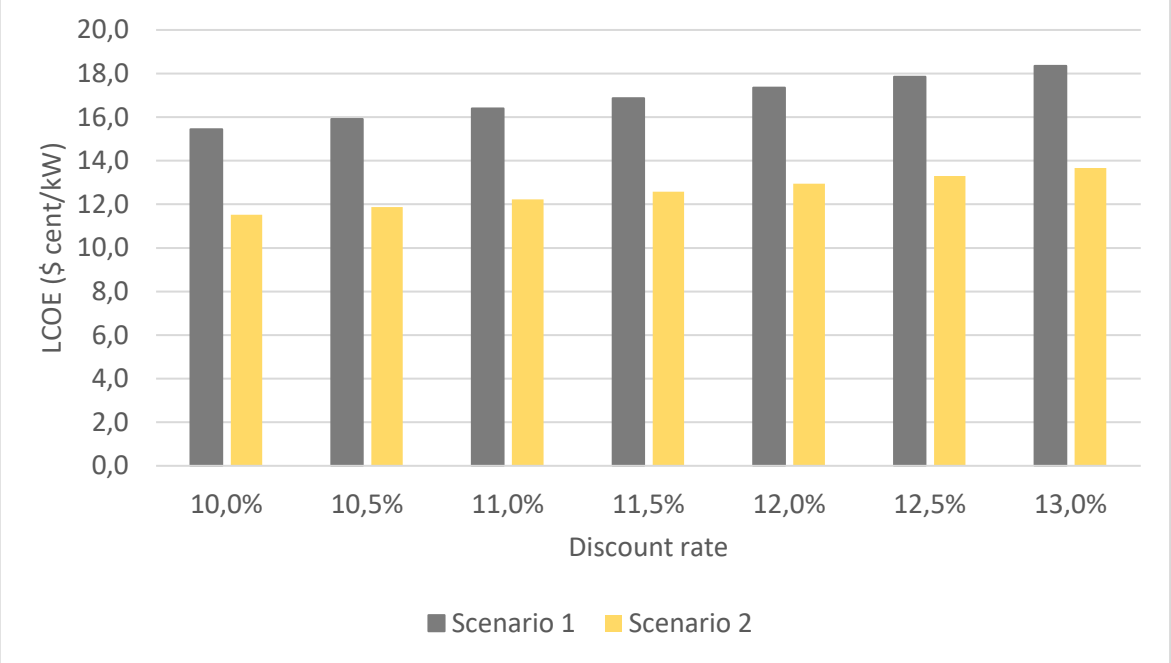


Figure 3.6 Levelized cost of electricity (LCOE) of scenarios based on different discount rate

3.4 Sensitivity Analysis

Waste heat recovery systems (WHR) give opportunity to use thermal efficiency of gas engines thus improve the energy efficiency and efficient usage of energy resources. Thermal energy is recovered from exhaust and coolant system of gas engine and convert to steam, hot air, hot water to use for plant requirements. It

was accepted that in the integrated waste processing scenario, exhaust gas of biogas engines is fed into the dryer and thermal energy from exhaust is used to decrease moisture content of RDF. In this section, effect on energy recovery of this process was evaluated.

3.4.1 Effect of RDF Drying by Waste Heat on Scenario 2

Purpose of a cogeneration plant driven by biogas internal combustion engines (ICE) is to utilize the methane produced and produce electrical and heat power. According to feedstock volume, with deciding the biogas engine type, and its electrical output, number of genset driven by biogas engine can be defined. Recently, electrical efficiency of biogas engines is improved, for a high efficiency Jenbacher biogas engine this can reach 43% depending upon the model and electrical output. In this study, the electrical efficiency of biogas engine is hold smaller and accepted as 35%. Thermal energy from exhaust and coolant system was accepted as 50% thus it was predicted 10-15 % energy losses. Energy balance of CHP plant is shown in Figure 3.7. It was accepted that thermal energy from engine cooling system is used to keep temperature constant in digesters, energy from exhaust used for RDF drying before combustion. Waste heat from exhaust gas of biogas plant will be used for decreasing the moisture content of RDF to half before combustion by using the flue gas directly used as the heat source without any equipment. Thus, the LHV of RDF increases, the size of incinerator equipment will decrease and therefore the cost of the plant will decrease beside more energy production. Also, external heat source is not required for this. There are several different types of dryers that are available for industrial applications. Rotary dryers, for instance, are the most common type for industrial drying applications and have low maintenance costs also they can accept hot flue gases.

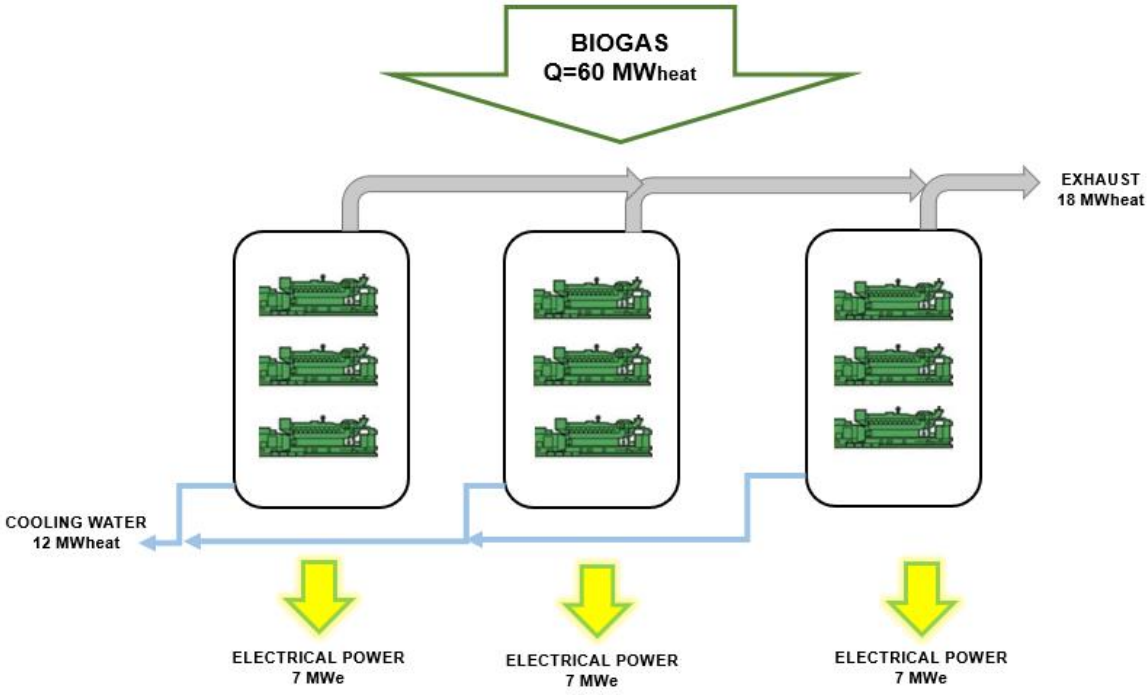


Figure 3.7 Energy balance of CHP plant

To show the effect of RDF drying by using waste heat, electrical power estimation of scenario 2 was calculated based on two different RDF qualifications (as can be seen in Table 2.6). Electrical power generation of scenario 2 without RDF drying was estimated as 67 MW-e which is the same with electrical power generation of raw waste incineration as shown in Figure 3.8. This means that the difference of 6 MW-e electrical gross power between scenarios is due to drying of the RDF. In addition, total electricity generation of scenario 2 even if RDF not dried can be increased by using biogas engines which have high electrical efficiency. Thermal energy from exhaust of biogas plant can be used for another aim such as district heating for energy efficiency in the case of not used for RDF drying.

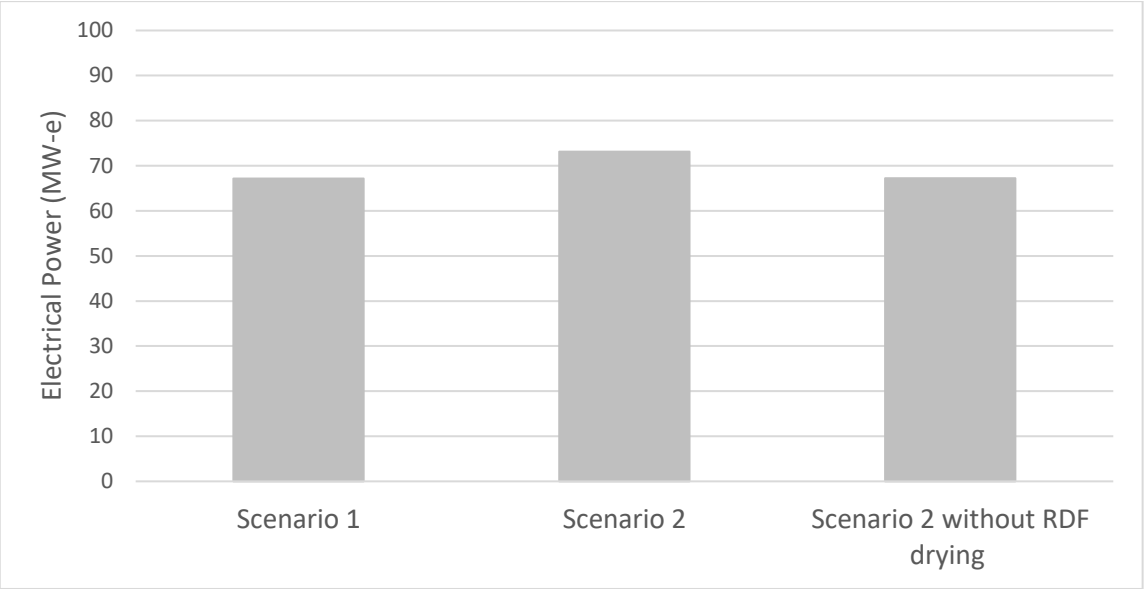


Figure 3.8 Electrical power of all scenarios

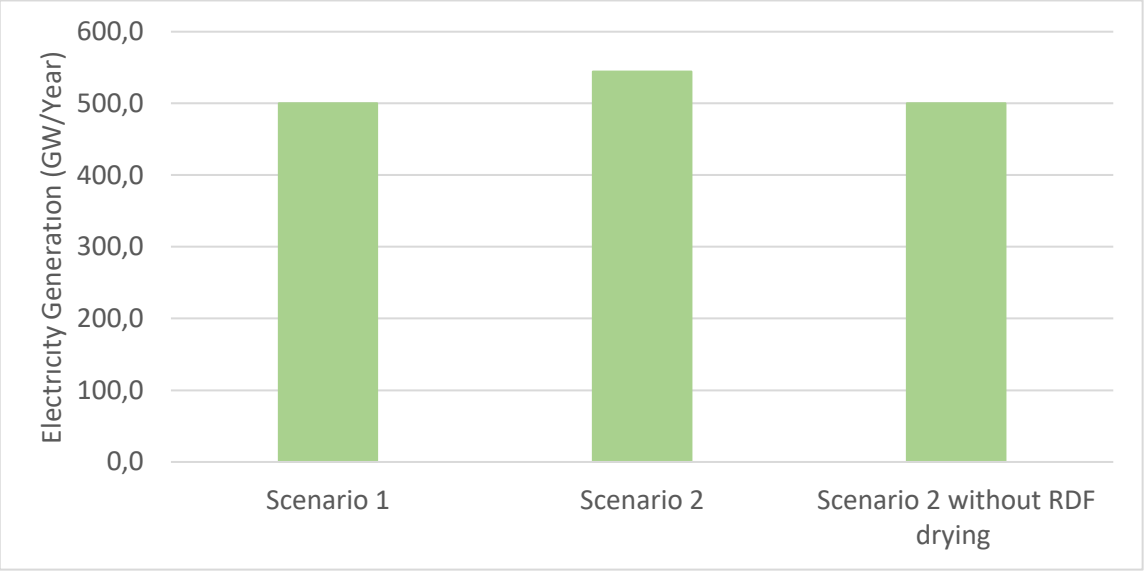


Figure 3.9 Electrical power of all scenarios

In this case, if RDF not dried, NPV of integrated waste processing scenario decreased by 15% due to the less electricity generation. NPV of scenario 2 decreased from 553,7 million $ to 472,1 million $ in the case undried RDF combustion as shown in Fig 3.10. It can be said that decreasing of 6 MWe of gross power by combustion of undried RDF is corresponded to 15% decreasing of NPV in scenario 2. On the other hand, LCOE increased from 11,6 $cent/kWh to 15,7 $cent/kWh. This can be explained by the higher investment and operating costs of the incineration plant for undried RDF and decreasing of electricity generation depending on lower LHV. RDF drying decreased investment cost of incineration

plant because of the mass reduction, also provided higher LHV depending on decreasing of moisture content. Positive effect of RDF drying on economical assessment presents is supported with sensitivity analysis results. The scenario that has highest costs is integrated waste processing scenario which in the case of without RDF drying. Therefore, it is expected result that highest LCOE is in the integrated waste processing scenario in the case of undried RDF combustion due to the more investment cost and O&M cost than raw waste incineration depending on the more complex processes. Although, even if RDF not dried, LCOE is close to LCOE of raw waste incineration. However, NPV is much higher than raw waste incineration depending on several project incomes. This means integrated waste processing has several project profits than raw waste incineration thanks to useful end products. In addition, if it is provided that RDF drying by thermal energy from exhaust of biogas plant, more economically viable waste management scenario will be ensured by decreasing costs of project. Figure 3.10 and Figure 3.11 show NPV and LCOE of all scenarios, in the case of without RDF drying. NPV of scenario 2 decreased to 472 million $ with 15% decreasing, whereas LCOE raised to 15,7 $ cent/kW with increasing 4,2 $ cent/kW. In addition, the payback period of scenario 2 increased to 9 years in the case of without RDF drying. Even if RDF not dried, NPV of scenario 2 was estimated as 24% more than raw waste incineration depending on several project incomes.

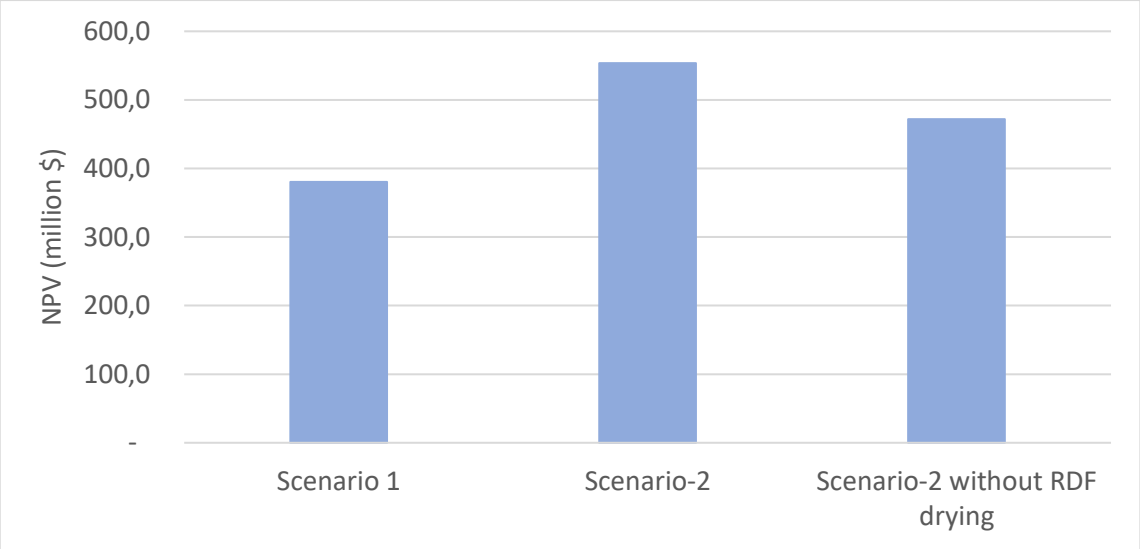


Figure 3.10 Net present value (NPV) of all scenarios

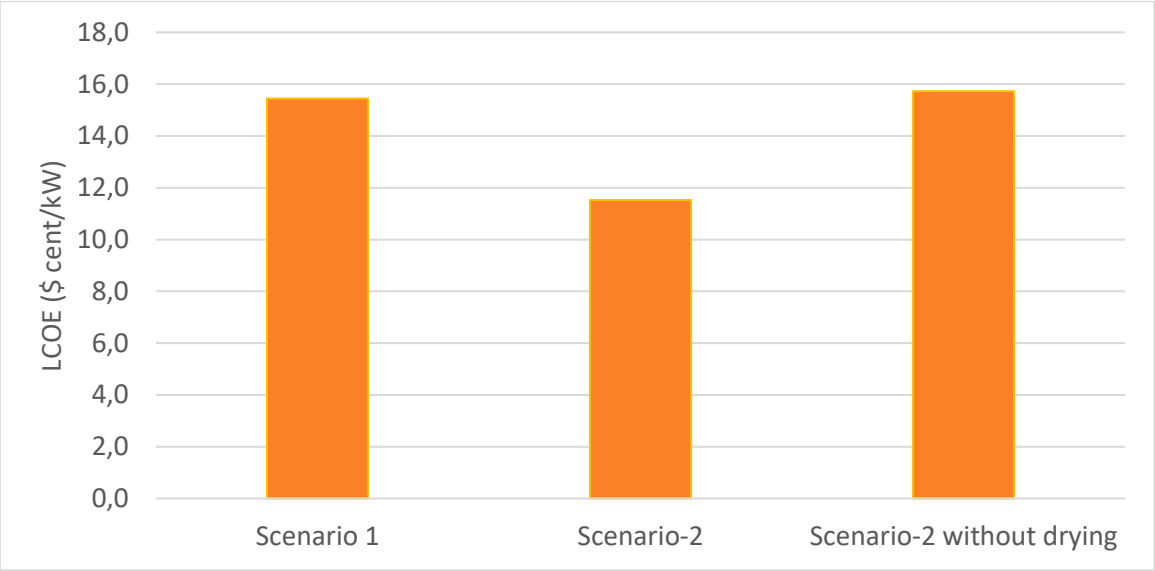


Figure 3.11 Levelized cost of electricity (LCOE) of all scenarios

3.5 Limitation of The Study

In this study, any moisture losses due to the mechanical separation of mixed MSW is not included in the calculations. Drainage system and wastewater treatment plant should be designed for leachate from mechanical pretreatment. Therefore, it should be noticed that after shredder (<9 cm) more qualified RDF which have more LHV can be reached due to moisture losses. Thus, if supported with drying by thermal energy from exhaust gas of biogas plant, calorific value of RDF can be increased more. Recoverable thermal energy of exhaust depends on mechanical data of biogas engine which will be choose. This study evaluated that moisture of RDF will be decreased to half using by waste heat from exhaust gas of cogeneration unit of biogas plant, calorific value increasing determined depend on 28% moisture loss acceptance. Another assumption that influences the energy potential is the methane content in biogas which was taken as 63%. Methane percentage can be increased with two stage digester design, but irregular feedstock and operating conditions can cause process failures in digesters. Therefore, pretreatment and feedstock preparation should be operated well for efficient biogas production. On the other hand, this study is a prefeasibility assessment, the comparison of economic viability of scenarios was carried out by roughly cost determination. Although operation costs of second scenario increased depending on more complex processes or labor requirement, it is clear that integrated waste

processing give opportunity to obtain several revenues during waste management by energy and material recovery. These plant revenues can be increased by improving energy and material recovery efficiency under well operation conditions.

4
RESULTS AND DISCUSSION

4.1 Techno-Economic Feasibility Assessment

Currently, a large part of the domestic waste that produced in Istanbul is still disposed of in landfills. Due to the insufficient recycling activities very large amount of mixed MSW goes to landfills. Although energy recovery from landfill gas is operated-well, it is obvious that the need to use other technologies with high energy efficiency, excluding landfill gas, for MSW management in Istanbul. On the other hand, although the current waste characterization in Istanbul is variable according to the regions, high organic fraction that it contains, and informal recycling activities is caused to decrease the energy efficiency of the raw waste incineration process. Therefore, this study focused on to obtain refused derived fuel (RDF) from MSW by separation of metallic, non-metallic, glass and organic fractions before combustion in incineration plant. Also, it was accepted that organic fractions will be evaluated for biogas production by anaerobic digestion process. Energy potential was calculated depending on both thermal and biochemical processes. Material distribution and their calorific values were determined according to raw waste characterization and mechanical pretreatment which is RDF production process. Mechanical units were defined, and fractions properties were determined using their separation efficiency according to literature studies. This study, also focused on increasing quality of RDF with increasing the lower heating value (LHV) by RDF drying using thermal energy from exhaust gas of biogas plant. Electricity generations were calculated according to both RDF properties, also considering the electricity from biogas plant, and the results were compared with raw waste incineration. Biogas plant type was accepted wet type anaerobic digestion, biogas production was calculated based on biogas yield of kitchen waste which indicated in literature studies according to solid mass of feedstock. Other main product of anaerobic digestion process as digestate is sent to composting plant after dewatering. Fertilizer for agriculture is obtained from composting with appropriate retention time and optimum

temperature then screened for market sale. Recycled materials and fertilizer are other useful outputs of integrated waste processing scenario beside electricity generation. After determination of the outputs, costs and revenues of the scenarios were estimated for assessment of economic analysis of the scenarios. Before the determination of economic parameters, investment costs of all process were estimated by using costs equations that defined in the literature. Mechanical biological treatment investment cost was calculated as total investment cost of mechanical pretreatment process, biogas plant, digestate utilizing units including dewatering and composting. On the other hand, incineration plant costs were calculated depending on input waste capacity which defined according to raw waste, RDF and undried RDF masses. O&M costs of processes were determined based on their investment costs. After that, cost benefit analysis of the scenarios was constituted. Future cash flows were projected and economic parameters such as net present value, levelized cost of energy and payback period were determined. Results show that integrated waste processing scenario is more economically viable and applicable than raw waste incineration depending on higher material and energy recovery efficiency. Also, efficient energy recovery occurred with higher calorific value of RDF by mechanical units including separation and drying. Separation of organic and noncombustible materials from waste stream can be evaluated for RDF production. In addition, after drying, it can be evaluated that obtained RDF fraction can be used in cement factories according to results of quality analysis or evaluated by advanced thermal treatment methods such as gasification, pyrolysis which have less environmental impacts. Another process is anaerobic digestion process which should be considered for OMSW management in consequences of its useful outputs. Thus, it is ensured that separation of fractions with high moisture content effect positively on calorific value of remaining waste stream before combustion. Also, usage of waste heat from cogeneration unit of biogas plant in RDF drying was decreased the moisture content of RDF. Sensitivity analysis shows impact of more electricity generation with less capacity on economical assessment. LCOE was significantly affected from RDF drying because of decreasing costs of incineration plant beside increasing electricity generation. Electricity generation of integrated waste processing scenario and LCOE were determined as almost same with raw waste incineration

in the case of undried RDF incineration. However also in two different RDF incineration cases, NPV of integrated waste processing scenario was found higher than raw waste incineration as a result of more several revenues such as glass and fertilizer sales. Municipal solid wastes are hard to treat due to the different kind of materials which involves. Energy and material recovery decrease the amount of waste sent to landfill areas. Efficient energy recovery depends on calorific value and moisture content of MSW. This study focused on different waste management scenarios which involves thermal and biochemical treatment methods for efficient energy recovery from Istanbul MSW. Integrated waste processing that involves anaerobic digestion, RDF production and incineration was compared with raw waste incineration based on technical and economical evaluations. Techno-Economic feasibility assessment shows that 9% more electricity than raw waste incineration can be generated with integrated waste processing scenario. Besides, unit cost per kWh of waste management process can be decreased as 25% considering 10% discount rate and 30 years of project life. During constitution of cash flows, project revenues were accepted as electricity and scrap metals sales for raw waste incineration while revenues of integrated waste processing scenario also include crushed glass and fertilizer for market sale beside electricity and recovered metals. NPV can be increased by 45% with integrated waste processing scenario depending on more electricity generation and material recovery compared with raw waste incineration, and payback period can be decreased from 10 to 7 years.

MSW is unending source which can be converted to alternative fuels with efficient waste management strategy. This study draws attention to the need to reduce landfill sites in Istanbul and to disposed of MSW effectively. Thus, while greenhouse gases emissions from landfilling are decreased with reduction of landfill areas, also fossil fuels usage and emissions from them can be decreased by waste to energy applications. In this study, aiming to increase energy recovery from Istanbul MSW, different WtE scenarios were evaluated in terms of technical and economical characteristics. Also, this thesis also points out to the increase in the applicability of data with the development of separation applications at source. In order to increase the energy and material recovery efficiency from MSW and reduce waste management costs, the awareness of separation of organic waste and

recyclables at source should be aimed in accordance with sustainable waste management applications.

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PUBLICATIONS FROM THE THESIS

Conference Papers

1. Evaluation of Energy Recovery from Istanbul Municipal Solid Wastes by Different Scenarios, The 3rd International Symposium of Engineering Applications on Civil Engineering and Earth Sciences 2021 (IEACES2021) 22-24 September