POTENTIAL OF WASTE-TO-ENERGY TECHNOLOGIES IN SAUDI ARABIA – IMPACT OF INCREASED POPULATION, HAJJ AND UMRAH, AND GLOBAL WASTE REDUCTION TRENDS IN 2030

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Municipal Solid Waste (MSW) Management is an ever-present environmental issue in many developing nations, including the Kingdom of Saudi Arabia (KSA), where each year millions of Muslims across the world visit the Holy City of Makkah to perform the Hajj pilgrimage and Umrah. The aim of this study was to determine the most suitable Waste-to-Energy (WTE) technologies for the MSW generated by KSA, Makkah, Hajj and Umrah. The WTE outcomes of energy, power and economic savings produced from the selected technologies were predicted for 2030, taking into account the increased targets for Hajj pilgrims and Umrah visitors as part of KSA's Vision 2030 plan. Furthermore, the impact of potential reduction policies to meet the UN sustainability development goals (SDGs) for waste reduction were investigated and four scenarios were developed: Current practice scenario (no reduction), and reduction scenarios: 50% food and plastic, 50% food only and 50% plastic only.

Anaerobic Digestion (AD) and pyrolysis technology were found most suitable for treating the food and plastic waste components from MSW separately. Increases in the population growth of KSA and Makkah by 2030 and the increased numbers of Hajj pilgrims and Umrah visitors due to KSA's Vision 2030 plan resulted in increased waste generation and increased WTE outcomes. Although the targeted visitor/pilgrim numbers for 2030 were greater than the local population of Makkah residents in 2030, the waste generated by the tourists was less than the waste from Makkah residents, due to the short duration of Umrah and Hajj. Policies that would result in the reduction of waste in 2030 would result in reduced WTE outcomes, where the highest WTE outcomes could be obtained from the current practice scenario and the lowest WTE outcomes obtained from the scenario with 50% reduction of both food and plastic.

KSA gave the highest WTE outcomes followed by Makkah city, Umrah and Hajj. For KSA, the highest WTE outcomes were savings of 13,922 million SAR (3,711 million USD) and total energy of 202,472 TJ resulting in 2.15 GW that could subsidize the future KSA electricity demand gap. AD of food waste typically had higher economic savings from landfill diversion of food waste, for cases where food waste was the major type of waste, however the savings from electricity production from biogas were relatively small; pyrolysis of plastic waste resulted in equal savings from landfill diversion of plastic waste and electricity savings.

WTE outcomes for Umrah and Hajj using the Vision 2030 targets for visitors were approximately double those achieved with normal growth to 2030, thus more energy and economic benefits from WTE technologies could be obtained with the Vision 2030 plan. In relation to Makkah city, the food and plastic waste from Umrah and Hajj events in 2030 could contribute approximately half of the corresponding WTE outcomes for Makkah alone. Therefore, if added to the WTE outcomes for Makkah, the city would have a total energy of 18,018 TJ available from WTE technologies, which could be transformed to 192 MW (0.2 GW) of power capacity to subsidize the Makkah electricity grid and reduce the power gap of Makkah city by 12%. It is suggested that recycling, along with WTE technology, could help the kingdom to reach its sustainability goal of reducing the amount of waste by 2030 in tandem with the UN's SDGs.

LIST OF ABBREVIATIONS USED

AD	Anaerobic Digestion
BTU	British Thermal Unit
°C	Degrees Celsius
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CHP	Combined heat and power
Gg	Gigagram
GW	Gigawatts
GWP	Global warming potential
GHGs	Greenhouse gases
GWh	Gigawatt hours
HV	Heating value
kWe	Kilowatt-electric
kWh	Kilowatt hour
kW_{th}	Kilowatt thermal
LCA	Life cycle assessment
LCC	Life cycle cost
LCV	Lower calorific value
MW	Megawatts
Mt	Million ton
MPW	Municipal Plastic Waste
MSW	Municipal Solid Waste
MWh	Megawatt hour
PPPD	Per person per day
RDF	Refuse-Derived fuel
SAR	Saudi Arabian Riyal
SDGs	Sustainable development goals
TJ	Terajoules
USD	United States Dollar
WTE	Waste-to-Energy

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CHAPTER 1. INTRODUCTION

Municipal Solid Waste (MSW) management has been developing markedly in the past years, and it has no longer consists of the traditional practice of collecting waste and disposing of it in a landfill. According to (EPA, 2017), the pattern of handling waste has changed from a "waste management" method to "sustainable materials management" over the past three decades, concentrating on renewable resources, better environment, and public health impacts over the whole life cycle of materials. However, the amount of waste that is generated has increased greatly due to the development of industrial and financial activities, population growth, as well as improved living standards.

The issue of waste management is an existing problem in many developing countries, including the Kingdom of Saudi Arabia (KSA). The accelerated urbanization and the population growth in the kingdom have caused significant environmental and health problems due to the inadequate waste management that has accompanied the steady increase in population. This rapid development has created a boom in the population from 7 million to 27 million over the past 30 years, with a yearly growth rate of 3.4% (Nizami et al., 2015a). The massive growth of population coupled with urbanization and raised living standards have resulted in a high generation rate of MSW, with a generation rate of 1.4 kg per person per day (PPPD), where over 15.3 million ton (Mt) of waste was generated in 2015 (Nizami et al., 2015a).

Every year, KSA hosts millions of Muslims from all around the world who visit the Holy City of Makkah to perform Hajj pilgrimage and Umrah. The accumulation of waste and its disposal are challenges for the local authorities during those events due to the massive increase in waste generation during a short time and limited space (Rehan et al., 2016). According to Memish et al. (2012), Hajj brings together more than 2 million pilgrims annually in the city of Makkah, where they spend approximately 5 to 6 days visiting sacred places in order to perform Hajj. Similarly, around 8 million visitors perform Umrah in 2016 (Mourad & Paul, 2017). It was estimated that 1.23 Mt of MSW was generated in Makkah city during 2014, which includes 1 million ton of waste generated by 1.96 million local residents, 0.14 Mt from Hajj pilgrims, and 0.09 Mt generated by umrah visitors. This amount of MSW is predicted to be more than double to 2.6 Mt by 2020 based on the forecasted population of Makkah city, Hajj pilgrims and Umrah visitors (Nizami et al., 2015b).

In KSA, food and plastic wastes are the most significant waste streams at 50.6% and 17.4%, respectively, while for Hajj the composition of these streams is 38% and 37%, respectively, comprising approximately 70% of the total MSW (Shahzad et al., 2017; Nizami et al., 2015a; Alsebaei, 2014). In terms of the food waste, Rehan et al. (2016) report that more food is wasted than any other item during the Umrah season, and during Hajj, discarded blood and other animal processing byproducts from ~2.5 million animals slaughtered as part of ritual practices were disposed of in the landfill without any treatment (Nizami et al., 2015b). In addition, the excessive use of plastic water bottle and cups due to the hot weather in Makkah during Hajj and Umrah seasons make it a significant source of waste (Aziz et al., 2007; Nizami et al., 2015b). While for KSA overall, the generation of the massive quantity of food waste in KSA has been credited to various socio-economic circumstances and the vast amounts of plastic waste are attributed to the excessive use of disposable plastics for serving food and drinks (Nizami et al., 2015a). The waste management practice used for the municipalities in KSA usually involves waste disposal into a landfill without segregation or any treatment methods (Alsebaie, 2014; Ouda et al., 2013; Nizami et al., 2015a). Most of the landfills in KSA are reaching their limits with several problems reported such as leachate, sludge, odor, and methane discharges (Ouda et al., 2013). According to AlHumoud et al. (2004), a landfill volume of approximately 28 million m^3 is needed each year to accommodate the rapid increase of waste.

New approaches for MSW management that include resource recovery are opportunities to improve the environment and also add value to the economy in terms of energy and value-added products. For example, Waste-to-Energy (WTE) technologies for MSW could be used in KSA to provide renewable energy and as a solution to landfill issues. There are primarily five to six WTE technologies widely used for MSW management worldwide: incineration, gasification, pyrolysis, plasma arc gasification, refuse-derived fuel (RDF), transesterification and biomethanation i.e., anaerobic digestion (AD) (Nizami et al., 2015a; Ouda et al., 2017). According to Ouda et al. (2017), there is significant potential for WTE plants in KSA, due to the large amount of MSW generated and its high energy content. Currently, KSA is amongst the 12th highest energy consumer countries of the world, with total energy consumption of 9 quadrillion Btu (EIA, 2019b) and nearly all of the electricity needs provided by fossil fuels with 55% from oil and 45% from gas (Shahzad et al., 2017). Furthermore, KSA's current peak demand for electricity is around 55 Gigawatts (GW), which is expected to double 120 GW by 2032 (Ouda et al., 2017). Thus, the potential contribution of WTE facilities in meeting the electricity demand for KSA would help to reduce its reliance on fossil fuels and may provide economic savings to aid the local and national economy.

KSA's long-term goals for the country are outlined in it is national plan "Vision 2030" to "create a vibrant society in which all citizens can fulfill their dreams, hopes and ambitions to succeed in a thriving economy" (Vision 2030, 2016). One of the goals is to increase the number of Hajj pilgrims and Umrah visitors to 6 and 30 million respectively by 2030 (Vision 2030, 2016). Therefore, there is a need for an effective waste management system to accommodate the accompanying increase in waste generated. As part of Vision 2030, KSA has also set sustainable development goals (SDGs). These goals are consistent with the United Nations SDGs 2030. According to UN (2018), the United Nation SDGs targets are integrated into the government's detailed plans and programs that are being developed under the Vision 2030 structure. The environmental issue of waste management is addressed in the UN SDGs, where countries have agreed to reduce waste by 50% in 2030. Additionally, Vision 2030 aims to diversify KSA's economy to reduce the reliance on oil revenue.

This study is motivated by the challenge of supplying energy and waste in a circular economy. In this work, the overall goal is to assess the impact of Vision 2030 on the feasibility of WTE technologies for KSA by assessing the economic savings and energy produced from MSW streams. Achieving the Vision 2030 goals would result in increased quantities of MSW due to the greater numbers of Hajj pilgrims and Umrah visitors in 2030, however there would also be a decrease in MSW if the UN goal for sustainable development and 50% waste reduction is met. Therefore this investigation will report on the economic savings and energy produced from WTE technologies by analyzing the MSW generated from the local population in KSA and Makkah city as well as through Hajj and Umrah events, and study the impact of: (1) increased MSW from more pilgrims and visitors and (2) reduced MSW resulting from sustainable development goals.

CHAPTER 2. OBJECTIVES

The overall aim of the study was to report on the economic savings and energy produced from treating the main components of the waste streams (food and plastic), using suitable waste-to-energy (WTE) technologies. The specific objectives were:

1. To evaluate prominent WTE technologies based on:
   (a) Waste composition, sustainability and technical requirements of the technologies.
   (b) Compatibility with the local waste and conditions of the studied area.
2. To investigate the impact of potential waste increase due to population growth of KSA and Makkah by 2030 and Hajj pilgrims and Umrah visitors following the Vision 2030 plan.
3. To investigate the impact of waste reduction by 2030, considering global sustainability policies that aim to reduce food waste and use of plastics.

In this thesis, Chapter 3 presents a literature review for the project. Then in order to meet Objective 1, a comparative analysis is included in Chapter 4 to evaluate WTE technologies. Then Objectives 2 and 3 are addressed in the following chapters, where Chapter 5 describes the methodology used to determine WTE outcomes and several waste reduction scenarios (i.e. no reduction in waste, reduction of food and plastic waste by 50%, reduction of food waste only by 50% and reduction of plastic waste only by 50%). Chapter 6 then discusses the following:

- General impact of waste reduction scenarios;
- WTE outcomes from all waste reduction scenarios for KSA, Makkah, Umrah and Hajj in 2030, using Vision 2030 visitor targets;
- Comparison of WTE outcomes from Umrah and Hajj in 2030 using the normal growth rate for visitors vs targeted visitor numbers from Vision 2030;
- Impact of WTE outcomes from Umrah and Hajj in 2030 (using targeted visitor numbers from Vision 2030) on Makkah's energy sector and local economy.

This is followed by Chapter 7, which summarizes the conclusions and recommendations for future work.

CHAPTER 3. LITERATURE REVIEW

3.1 Kingdom of Saudi Arabia (KSA)

KSA is located in the south-western region of Asia, occupying nearly 70% of the Arab Peninsula with an area of 2 million km^2 (SGS, 2012), making it the third largest country in the Middle East and the thirteenth largest state in the world. In general, KSA has a desert climate designated as extremely hot during summer and mild in winter and deficient in annual rainfall (World Atlas, 2019). KSA's economy is one of the top twenty economies in the world (G20) and is one of the biggest petrol producers. Most of the economy is dependent on oil revenue, as the country is the largest exporter of petroleum in the world (EIA, 2017a). The kingdom has the second-largest proven petroleum reserves, as well as has the fifth-largest natural gas reserve (Dillinger, 2019) and is considered to have the second most valuable natural resources in the world (Migiro, 2018). The kingdom has experienced substantial socioeconomic growth over the last four decades from profits generated from producing crude oil and a population increase of 20 million (7 million in 1975 to 27 million by 2010), which according to Ouda et al (2013), is approximately a 3.4% annual rate of increase. The rapid growth of the country's economy has led to urbanization, where there is domestic immigration from rural to urban areas (Nizami et al., 2015a). The kingdom is recognized as an important destination for Muslims around the world to visit City of Makkah in order to perform Hajj pilgrimage and Umrah (Alsebaei, 2014)

3.2 City of Makkah

Makkah city is considered the capital city of Islam. One of the world's biggest mosques (Masjid-Al-Haram) is located there and it is considered the holiest place for billions of Muslims all across the world, making it is extremely busy during the year. It is situated in the western region of KSA, as displayed in Figure 3-1. Makkah covers an area of almost 600 km^2, and about 90 km^2 is populated by it is 1.5 million residents in 2015 (General Authority for statistics, 2016). The city of Makkah is positioned in a valley which is surrounded by mountains, making the city a wind-free zone, it has an average humidity of almost 50% and average temperature between 35-45°C (Alsebaei, 2014). Each year, millions of people attend Makkah for the Hajj pilgrimage and Umrah (Rehan et al., 2016). The central area of Makkah City, which covers an area of almost 6 km^2, is deemed to be the busiest section in Makkah during the year. The number of visitors is growing with a yearly rate of 1.2% from the mid-1990s to 2014 because of the enormous enlargement of the Holy Mosque and surrounding holy sites, as well as expanded facilities for accommodations, health services, transport, and security services (Rehan et al., 2016).

Figure 3-1 Map of KSA, showing the Makkah region (Saudi Tourism, 2018)

3.3 Hajj and Umrah

Hajj and Umrah are performed by Muslim people who come every year from around the world to practice their faith in Makkah. Hajj is the fifth pillar of Islam and is considered the most significant annual religious event in the world (BBC, 2009), where Muslims come from all over the world to visit holy sites and perform religious rituals over a period of 5-6 days. It is obligatory for every Muslim who can afford to do so to perform Hajj at least once in their lifetime (BBC, 2009). While Hajj means "pilgrimage" in Arabic, Umrah means "visit" and is not obligatory for Muslims. Umrah can be performed at any time throughout the year and is held inside the Grand Holy Mosque of Makkah. After practicing Umrah, most visitors will also include a short trip 200 km north to Medina, where the Mosque of the Prophet Mohammad is located.

3.3.1 Hajj season

Hajj is the pilgrimage where Muslims visit Makkah and perform several rites in several locations around Makkah. Every adult Muslim who is physically and financially able to do so, is required to complete Hajj once in his or her lifetime (Williams, 2016). This section will discuss the Hajj season and provide details about the Hajj duration, the number of pilgrims and locations for performing the Hajj rituals, as these factors are important in managing the waste generated during Hajj.

3.3.1.1 Time period and pilgrims

Hajj is an annual pilgrimage that is performed by adult Muslims during specified time periods, commonly occurring during the 12th month of the Muslim lunar calendar. Hajj has frequently occurred from the 8th to the 12th days of Dhu al-Hijja, the last month of the Islamic calendar (Raj, 2015). The timing of Hajj occurs at different times throughout the Gregorian calendar - for example, in 2013 Hajj occurred during October 13th to October 18th, while in 2017, Hajj was performed during August 30th to September 4th (Albardi et al., 2016).

The number of Hajj pilgrims has grown rapidly from 1950 to 1975 by 400,000, though it did not exceed a million pilgrims till the mid-1990s (Hatrash, 2012). In the last 15 years, there are almost 2.5 million pilgrims from nearly a hundred nations that have been a part of Hajj every year (Figure 3-2). The Saudi Arabian authorities regulate the number of Hajj visitors permitted into KSA, as they issue permits for the pilgrims who must join an official Hajj operator that provides transportation and accommodation in certified camps at the holy locations. According to Nizami et al. (2017), the escalation in the number of pilgrims visiting KSA over the past decades has been facilitated by the expansion of the Holy Mosques, with a yearly rate of 1.15% from 1993–2014.

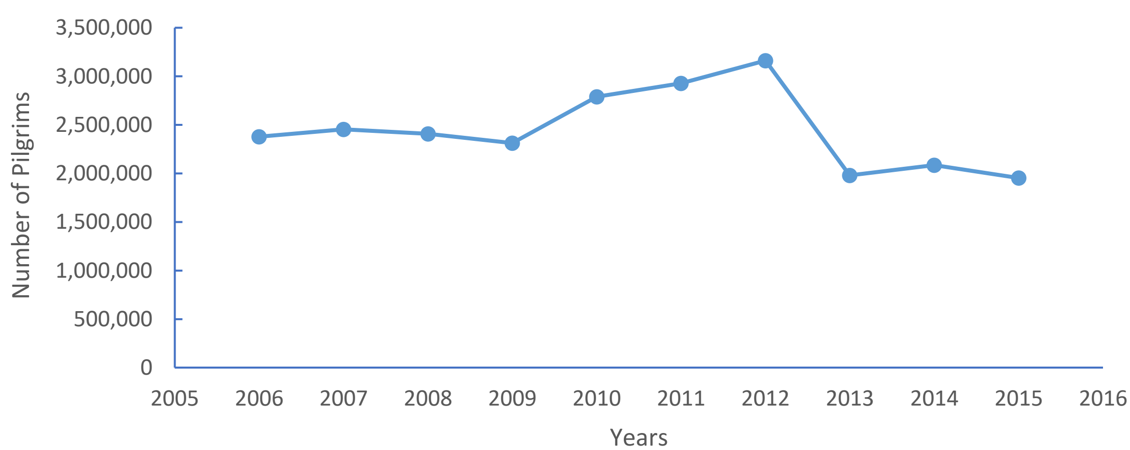

Figure 3-2 Number of pilgrims in the past 10 years (General Authority for Statistics, 2016)

3.3.1.2 Locations

During Hajj, the pilgrims travel around several sacred areas around Makkah, including Mina, the plain of Arafat and Muzdalifah as shown in Figure 3-3. According to the Ministry of Hajj (2011), on the 8th day of the month of Dhu al-Hijja, most of the pilgrims come from Makkah and enter Mina on foot or by bus and would stay in tents within the organized campsites. At sundown, on the 9th day of Dhu al-Hijja, pilgrims walk almost 14 km from Mina to Mount Arafat. After sunset, they march nearly 9 km from Mount Arafat to Muzdalifah and sleep outdoors in the open air. The next morning, pilgrims collect small stones and return back to the camp in Mina, where they will remain for three days, and a stoning ritual is performed. After this, the pilgrims leave Mina for the final time, traveling to the Grand Mosque at Makkah for final rites – this completes the practice of Hajj. Even though the city of Medina (200 km north of Makkah), is not part of the Hajj, most of the pilgrims often travel there in order to visit the second holiest region of Islam, which is the Mosque of Prophet, where the Prophet Mohammad's tomb is located. These days, air travel is the most common way for pilgrims to enter KSA for Hajj with the city of Jeddah's airport as the main point of entry and departure. According to Khan et al. (2011), in the past 10 years, about 90% of pilgrims come by air, 1% by ship, and 7% over land.

3.3.2 Umrah Season

Umrah visitors usually come to KSA during Ramadan, however there is no restriction as to when Umrah can be performed (Nizami et al., 2015b). In addition, the visitors do not follow the same regulated transportation and accommodation arrangements as during Hajj. This section will provide a summary of Umrah and highlight some important factors that will impact waste generation.

3.3.2.1 Time periods and visitors

Muslim pilgrims may conduct Umrah throughout the year (Nizami et al, 2015b), except for the last month of the Arabic year when Hajj takes place. However, a popular time for Umrah occurs in the three months prior to the time for Hajj, which coincides with Ramadan, held during the 9th month of the Hijri calendar (Ahmed et al., 2006). Unlike Hajj, which is held over several locations and requires a total of 6 days to complete, the several rituals associated with Umrah can be performed within few hours, within the Grand Mosque in Makkah (Nizami et al., 2015b).

Figure 3-3 Map showing important locations for Hajj pilgrims

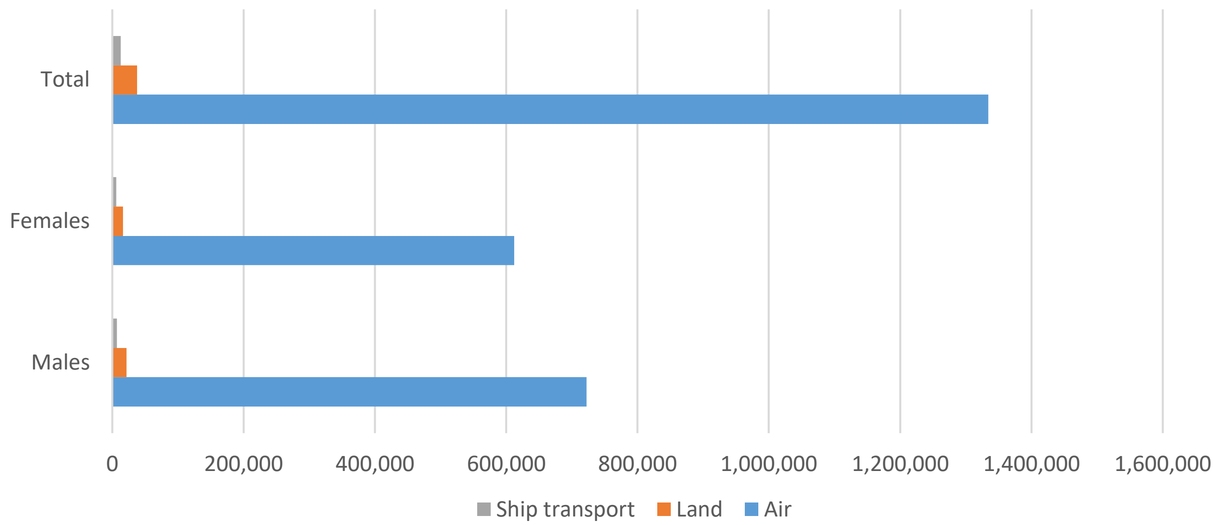

Figure 3-4 Foreign pilgrims in 2015 by gender and way of arrival (General Authority for Statistics, 2016)

The number of Umrah visitors arriving at holy sites from out of the country has shown a substantial increase in the past years. For example, there were under a million visitors in the early 1990s and almost 5 million in 2011 (Figure 3-5), and more recently near 8 million visitors in 2016, as a result of the expansion of the Two Holy Mosques (General Authority for Statistics, 2016). By increasing the capacity, the Saudi government promised by 2020 to make it possible for over 15 million Muslims per year to perform Umrah (Vision 2030, 2016).

3.3.2.2 Location

The rituals associated with Umrah are performed at the holy Grand Mosque of Makkah, which is different from Hajj, where several locations are visited as part of the pilgrimage. Another critical difference between Umrah and Hajj is that the rites associated with Umrah can be completed within a few hours, whereas Hajj requires a total of 6 days for completion. After performing Umrah, many visitors travel to Medina, to visit the Mosque of the Prophet, although this is not part of Umrah (Ahmed et al., 2006). Some Umrah visitors and pilgrims also go on to other Islamic sites in Hijaz Area and the historical old city of Jeddah (Memish et al., 2012). While a small number of religious tourists will land at Medina's international airport, the city of Jeddah remains the main port of entrance for all pilgrims and visitors as it used to be for centuries.

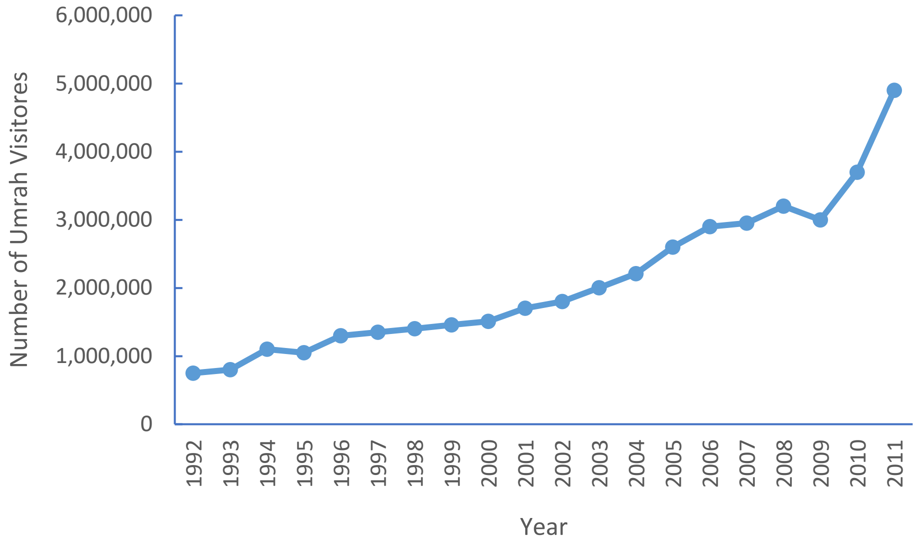

Figure 3-5 Number of Umrah visitors 1992-2011 (General Authority for Statistics, 2016)

3.4 Vision 2030

The Saudi Vision 2030 plan for KSA aims to make the country an investment powerhouse, to develop the geographical location of the nation into a global hub for the Islamic and Arab world, and to make connections with the neighboring nations as well as the three continents (Salameh, 2016). The Vision is built around three main themes: a vibrant society, a thriving economy and an ambitious nation.

According to the GRC (2018), KSA is focusing on elevating tourism and religious pilgrimage in order to boost the economy by diversified sources, based on its unique position of being host to the two holiest places in the Islamic faith (Al-Masjid Al-Haram in Makkah and the Al-Masjid Al-Nabawi in Medina). The country's tourism industry consequently performs a vital role in providing a quality experience to the religion tourists from over the world. This would contribute to the national economy and provide a revenue stream that is not dependent on oil exports, which is essential, given the state budget deficit of nearly $100 billion in 2015, due to low global oil prices. As part of the Saudi Vision 2030, the kingdom plans to increase the number of annual Umrah visitors from 8 million to 30 million by 2030 (Vision 2030, 2016). It is projected the Umrah visitors may reach 15 million people annually by 2020 and will double by 2030 (Yezli et al., 2017).

By then, the kingdom could be hosting as many foreign visitors for Umrah as it does for it is own population. The Vision 2030 plan also aims to make it possible for over 6 million Muslims per year to perform Hajj and be completely satisfied with their pilgrimage experience (Vision 2030, 2016). This growth in capacity will be accompanied by improving the quality of services available to visitors. Thus, the Saudi authority has begun expansion of the Two Holy Mosques and improvements to the transportation facilities to accommodate the more significant numbers of Hajj pilgrims and Umrah visitors.

Recently KSA has released it is first Voluntary National Review "Towards Saudi Arabia's Sustainable Tomorrow", presented to the UN High-Level Political Forum in 2018 to report on strategies and programs that have been initiated as part of Vision 2030 and that align with the UN's 17 Sustainable Development Goals (SDGs). The report indicates that the Vision 2030 provides a framework that can support the SDGs, however it highlights the need to take into account national realities and priorities, such as the need for economic diversification, which is required for achieving the other goals. In terms of solid waste management, SDG 7 "Ensure access to affordable, reliable, sustainable and modern energy for all" and SDG 12 "Ensure sustainable consumption and production patterns" are the most applicable (UN, 2018). The report indicates that KSA is committed to strengthening energy security and has recently launched several large-scale projects to develop an environmentally friendly renewable energy sector. The report also states that the process of waste management, recycling, re-use, energy recovery and circular economy are important elements to KSA's approach to conservation of natural resources, creation of job opportunities, reduction of greenhouse gas emissions from landfills and conversion of waste to energy, and gives several examples of projects and initiatives that have been launched to reduce waste and address waste management issues through recycling and waste integration. At present, there is no existing regulation or policy for managing the enormous quantity of MSW in KSA. However, the kingdom is moving forward with plans to develop environmental sustainability laws and mechanisms to conserve the natural resources of the country.

3.5 Municipal Solid Waste (MSW) Management

3.5.1 KSA

In KSA, MSW management is currently governed by the municipalities (Gharaibeh et al., 2011). MSW has traditionally been collected and dumped into landfills, and since this has been relatively low cost, it has made recycling programs for MSW unattainable thus far (Ouda et al., 2016). In fact, the only widespread recycling system that exists in KSA at present, is the labour collection for refuse from trash containers that sorts out cardboard and metals (Alhumoud et al., 2004). However, some cities, such as Medina, sort and recycle the MSW on a small scale. The landfill requirement in KSA is about 3 million m^2/year and as most of the dumping sites in the country are aged landfills, the capacity of the landfills will be exceeded in the coming years (Alhumoud et al., 2004).

KSA creates approximately 14 million ton of MSW annually and averages 1.4 kg PPPD (Ouda et al., 2013). According to Nizami et al. (2015a), the waste composition of KSA consists of 50.6% food waste, 17.4 % plastics, 11.9% paper, and 6.7% cardboard and others (Figure 3-6). It is evident that food waste is the most significant waste stream within MSW in KSA. The food waste has a chemical composition of 38.4% moisture content, 25.6% carbohydrates, 17.3% crude proteins, and 15.3% fats, with the main types of food waste being: 38.7% rice, 25.4% meat, and 18.7% bakery products (Ouda et al., 2016). However, the dumping of other waste types into landfills, such as wastewater sludge, is also resulting in problems with leachate, methane generation, odor, and other health hazards (Ouda et al., 2013). For example, the waste sector in KSA produced 66% of the total CH_4 emissions, which is around 1,300 Gigagram (Gg), with most of the methane gas produced originating from sanitary landfills (Selimuzzaman, 2012). Nonetheless, the vast amount of MSW generated plus the energy potential within it is contents and composition, make WTE facilities an attractive waste management option for KSA (Ouda et al., 2013).

3.5.2 Makkah

Makkah city's MSW management system is similar to what is used for the other cities in KSA, and consists of waste collection, transfer and transport, and disposal in the Makkah landfill (Alsebaei, 2014). Here, most of the cost is in waste collection, as it requires a significant number of labourers as well as time and effort, particularly during the Hajj period and the peak season of Umrah (Ramadan). MSW in Makkah is gathered from waste containers, which are dispersed in the roads and this occurs three times a day in the central area of Makkah where the Grand Mosque located, and twice a day in the main districts and once a day in the rest of Makkah city (RACI, 2008). The collected waste is transported to the transfer stations or to the Makkah landfill by compactor trucks. There are six transfer stations in Makkah, each one has capacity of 140 m^3. The primary purpose of the transfer stations is to collect waste from the compactor trucks and transfer them to the landfill in bigger containers (Alsebaei, 2014). Like most of the landfills in KSA municipalities, the Makkah landfill has no lining or any system for the collection of leachate or gas. However, the landfill is segregated into cells, with each of the individual cells having dimensions 15 m deep, 25 m wide and 75 m in length, and where the cells are filled within a week (Aziz et al., 2007). The increased quantities of waste that are disposed of in landfills results in increased landfill area (Salameh, 2016), and this reliance on landfills are problematic for environmental regulation. In the absence of other waste management options, proper landfill management is required. According to Nizami et al. (2015b), the waste stream in Makkah consists of around 50.6% food waste, followed by plastic waste, which comprises around 17.4% (Figure 3-6). The present recycling method for MSW is conducted by the "informal recycling sector" (IRS), which is comprised of individuals or enterprises not authorized by the official waste authority, such as collectors and pickers, resulting in selected materials with recyclable properties such as metals, cardboard, paper and plastics being recycled at only 10% of the overall waste generation rate (Alsebaei, 2014).

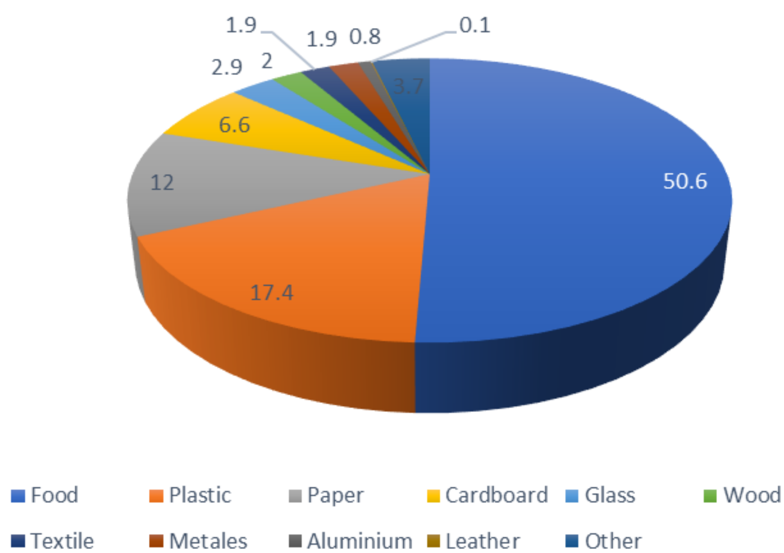

Figure 3-6 Waste composition in KSA and Makkah city (Nizami et al., 2015b)

3.5.3 Hajj and Umrah

The obligation for Muslims to participate in Hajj has led to approximately 3 million pilgrims visiting Makkah, during the same time period, on an annual basis. Pilgrims generate multiple types of solid waste, and there is at present, no source separation of these different types of wastes. Shahzad et al. (2017) estimate that the waste generated during the Hajj pilgrimage ranges between 3.1 to 4.6 thousand tons on a daily basis. In Mina, where most of the waste is generated during Hajj, the individuals stay approximately 4 to 5 days and produced an estimated 17 thousand tons of MSW, which is then disposed of in the Makkah landfill without any resource recovery or treatment (Alsebaei, 2014). When the pilgrims visit the Grand Mosque in Makkah, more than 200 tons of MSW is generated on a daily basis (Aziz et al., 2007). In addition, there is a significant challenge related to the animal processing waste generated during the religious rituals performed during Hajj (Aziz et al., 2007).

The total waste produced in the holy Grand Mosque in Makkah and its surrounding area during Umrah can reach almost 190 tons during Ramadan (Aziz et al., 2007), where food waste is the most significant type of waste generated during Umrah (Rehan et al., 2016). The waste from Umrah visitors is combined with the local waste collected for Makkah, and as much as 5 thousand tons of waste can be generated in Makkah city (Nizami et al., 2017). Makkah city generates about 2.4 thousand tons of MSW daily, although this reaches more than 3,000 tons each day and more than 4,500 tons each day throughout the months of Ramadan and Hajj, respectively (Nizami et al., 2017). The maximum quantities of waste produced are during the last ten days of Ramadan and from 8^{th} to 13^{th} of the month of Dhu al-Hijja; which is during Hajj (Aziz et al., 2007). The total quantity of MSW generated in Makkah city during 2014 was about 950,000 tons where around 900,000 tons was produced by the residents, and 90,000 tons was produced by pilgrims (Shahzad et al., 2017).

It has been identified that a wide range of wastes is generated during the Hajj. These range from the household and household hazardous waste to street litter and biological waste (Nizami et al., 2015b). The primary type of waste generated during Hajj is food waste (39%), followed by plastic (36%), paper and cardboard (14%), and textile (2%) (RACI, 2008) (Figure 3-7). For Umrah, the waste composition is similar to the waste composition of Makkah city, according to Nizami et al., (2015b), since the visitors are engaging with the local population, unlike Hajj, where the camping aspect affects the total waste stream. During Umrah, food waste is a prevalent issue across the regions where the visitors are situated, which ranges from Makkah to Medina city (Alsebaie, 2014). During Umrah, the donation of food and use of disposable utensils are significant sources of waste.

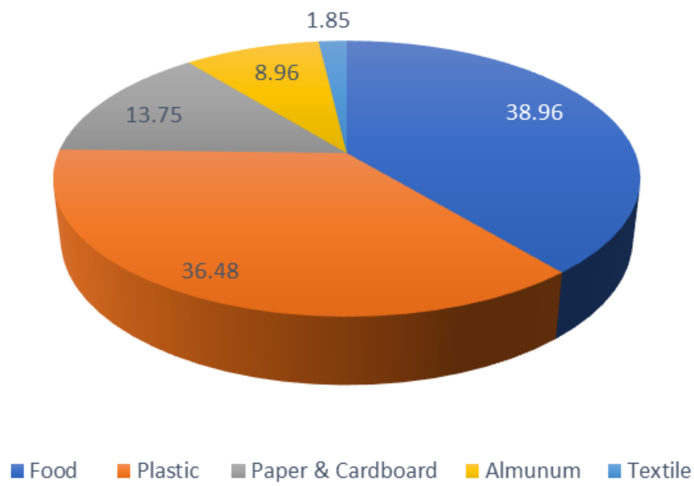

Figure 3-7 Waste composition of Hajj (RACI, 2008)

The extremely hot weather conditions that can occur during the Hajj and Umrah seasons are an important challenge for waste management, as the massive quantities of plastic disposable cups and plastic disposable water bottles available for drinking holy Zamzam water inside the Grand Mosque, are a significant source of waste. For example, 100 million plastic disposable cups were supplied for the 2019 Hajj season (Saudi Gazette, 2019). The additional problem associated with Hajj rituals is managing the waste from slaughtered animals. Although much of the meat from the animal sacrifice is given away to other countries, the disposal of the animal by-products is a huge problem (Aziz et al., 2007). For example, around 700 thousand goats are typically slaughtered each Hajj season, where each goat produces approximately 7 kg of waste and 1.5 liters of blood (Aziz et al., 2007). In 2014, the Islamic Development Bank (IDB), mentioned that 874,667 sheep were slaughtered for Hajj. In addition, there are larger animals such as cows, camels, etc. that can also contribute considerably to the quantity of waste produced during Hajj. This challenge has caused massive pollution to the environment as current methods use the landfill in Mina and Arafat to dispose of this waste (Aziz et al., 2007).

3.6 Policy Trends for Food and Plastic Wastes

3.6.1 Food waste

In general, food waste can account for more than half of all solid waste that is generated. According to Lin et al (2013), as much as 50% of food is wasted before and after it reaches the consumer and equals over 1.3 billion ton yearly of food produced for global human consumption. In China, for instance, the volume of food waste in 2014 reached 245,000 tons a day, which is around 50% of China's MSW (Gao et al., 2017). Similarly, food waste is the second-largest fraction of MSW sent to landfills in the United States, where food waste reached about 35 million tons (EPA, 2013). In the European Union, around 90 million tons of food is wasted yearly, and experts predict it could grow to 126 million tons by 2020 if no steps for reduction are implemented (Baig et al., 2018).

Globally, food waste is one of the top problems threatening food security, and KSA is no exception. According to Baig et al. (2018), up to 70% of the food in the kingdom is wasted during special celebrations, where the provision of food is a form of greeting and hospitality to the guests. As part of the culture, Saudis host generous meals during Eid festivals, weddings, parties, and informal get-togethers. However, KSA is ranked poorly for food waste and obesity is an issue for the Saudi population (Entz, 2015). Indeed, in a recently published report by the (The Economist, 2016) , KSA is ranked the lowest out of 25 countries in terms of an index used for food loss and waste, and is reported as producing 427 kg of food wasted per person each year, which is higher than the USA and Indonesia with 277 and 300 kg of food waste per person each year, respectively.

In view of Vision 2030 and the UN SDG 12 with target 12.3 to reduce food waste by 50% in 2030, KSA has launched a national program to reduce food loss and waste and to prevent inadequate use of natural resources. The government is teaming up with social organizations and private sector to improve issues related to food loss, and establishing partnerships with food donation organizations, specialized recycling business and composting facilities. For example, the Eastern Province "AMANAH" organization has launched a facility for the production of organic fertilizers from table scraps and food leftovers, with an estimated yearly generation capacity of 6000 tons (UN, 2018). As well, the kingdom's consultative Shoura Council has discussed the exorbitant food waste and has recommended that individuals and businesses be fined for excessive waste, for example fining people eating at restaurants who waste food (Gulf Business, 2018). The Council has further recommended establishing a national center to create public awareness about food waste. However, the decisions of this Council are advisory and not mandatory. Nevertheless, there are countries and local governments that have also set their own food waste reduction targets. For instance, in 2012 the European Union set a target to reduce food waste within it is members by 50% by the year of 2020 (Lipinski et al., 2013) and German authorities have established a target of decreasing food waste by 2030 following the UN SDG target (The Local, 2019). Italy has passed a law that intends to reduce the food wasted in the country each year by one million ton from the five million tons of food currently wasted. (BBC, 2016). As well, France recently became the first country in the world to ban supermarkets from throwing away unused food (Beardsley, 2018).

3.6.2 Plastic waste

For more than 50 years, the global production of plastic has risen, for example, in 2013 around 300 million tons of plastics were generated, representing a 4% rise from 2012 (Sharuddin et al., 2018). According to Czajczyńska et al (2017), the consequence of the growth in global plastic production is plastic waste that enters the land and oceanic environment, with China producing the most significant amount of plastic waste, followed by Europe and then NAFTA. Within MSW, plastics are not nearly as biodegradable as organic materials, which makes management of plastic waste one of the biggest challenges (Czajczyńska et al, 2017). For instance, less than 10 % of the plastic waste was recycled in the USA in 2015, compared to around 40% in the European Union and 22% in China. As shown in Figure 3-8, 15 % of US plastic waste is typically incinerated and the remaining 75% goes to landfills (EPA, 2016).

Until recently, China imported plastic wastes from other countries. However, China has since imposed plastic waste trade restrictions, forcing municipalities and waste companies around the world to look for alternatives for plastic waste recycling. The effects of China's plastic import restrictions on global trade are evolving where the plastic trade volumes have dropped dramatically; for instance, China's imports of plastics waste from the European Union collapsed from around 100 thousand tons to less than 10 thousand tons. Also, China's imports of plastics waste from the USA decreased by a similar amount, from 75 thousand tons to 6 thousand tons (OCED, 2018).

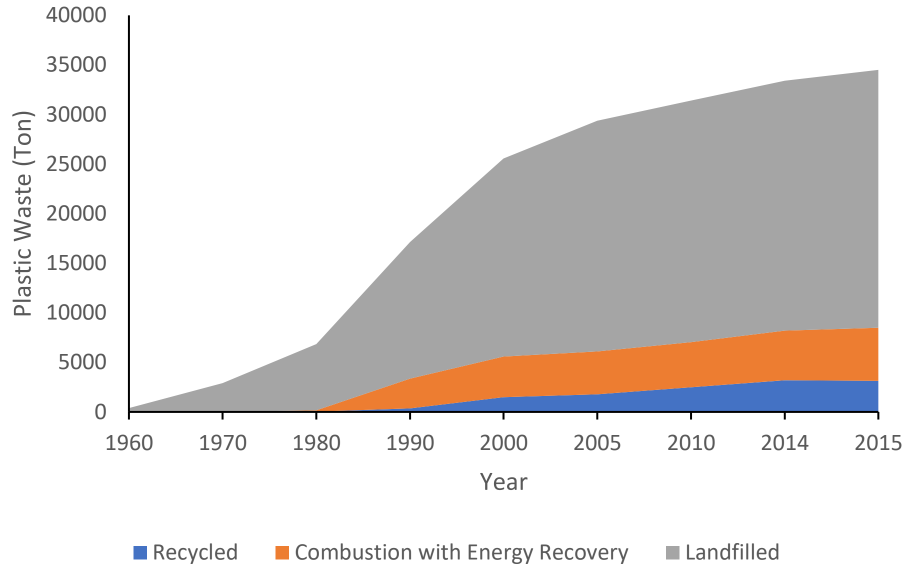

Figure 3-8 Plastic waste management in the U.S from 1960- 2015 (adapted from EPA, 2016)

There has been a growing awareness globally of the problem of plastic waste that has led to strategies that target the use of plastics. Because of the damage to the environment caused by the excessive use and disposal of plastic products, the United Nations Environmental Assembly (UNEA) agreed in 2019 to significantly decrease single-use plastic products such as bags, bottles, and straws by 2030 (Bhalla & Ndiso, 2019). As well, several countries have introduced policies to reduce or ban plastics as summarized in Table 3-1 (Leone, 2018). For example, India declared a policy to pass all single-use plastics in the country by 2022; Chile, Peru and Botswana will ban plastic bags; Nigeria has pledged to implement recycling facilities; and Brazil has announced a national program to target plastics (Leone, 2018).

KSA is a significant producer of plastics in the world with a yearly plastic production of about 6 million ton (Khan & Kaneesamkandi, 2013). According to Miandad et al. (2016), the average lifetime of approximately 40% of the consumed plastic in KSA is less than a month. Moreover, substantial amounts of plastic waste are created due to the serving of meals in disposable plastics to millions of Umrah visitors and Hajj pilgrims, coming every year to KSA (Nizami et al., 2015b). As a consequence, the plastic waste in the KSA is the second-largest portion of the waste stream (17.4%).

Table 3-1 Examples of countries with strategies to reduce or ban plastic (adapted from Leone, 2018)

Country	Strategy
Aruba	Ban single-use plastics by 2020, following its 2016 ban on single-use plastic bags
Brazil	Declared a national plan on plastics
Colombia	Plan for banning packaging waste and making use of 30% of its waste by 2030
Costa Rica	Declared national strategy to replace single-use plastics with renewable plastics
India	Ban single-use plastic by 2022
Iceland	Introduce a recycling fee on plastic goods
Kenya	Collaborated with the East African Fellowship to extend its plastic bag ban to other countries
Norway	Ban single-use plastics in combination with the European commission
Spain	Ban plastic bags in 2021

Unlike food waste reduction, KSA does not have a strong commitment toward banning or reducing the use of plastic. For instance, the kingdom, along with the USA, has weakened the UNEA 's decision on minimizing plastic waste by 2030, guided by the massive interests of the petrochemical industry in both countries (Bhalla & Ndiso, 2019). Despite this, there are several indicators that show the kingdom is working towards a sustainable solution for plastic waste. For example, KSA has established a new regulation that affects a wide range of imported and local plastic products, such as plastic bags, plastic cases, and plastic plates. According to the Saudi Standards, Metrology and Quality Organization (SASO), plastic products must be made of an approved oxo-biodegradable material. The second phase of regulations will come into effect in 2020, covering new categories of plastics (Giger, 2019), and if passed, these regulations will count as an important step towards a more sustainable environment since oxo-biodegradable plastic degrades quicker in the open environment or if disposed of in a landfill. Nonetheless, such a regulation, might affect the feasibility of implementing a future Waste to Energy (WTE) plant in the country as the energy viability of the plastic might be downgraded. It should be noted however, that the European Commission considers the oxo-plastic products non-biodegradable and is seeking for a total ban, as they claim there is no proof plastic bags will completely biodegrade in a short time and it is not convenient for long term usage, recycling or even composting (Crawford 2018).

3.7 Energy Sector in KSA

The consumption of energy is essential to the prosperity of any nation's economy. Generally, it is expected that a country with high energy consumption also has a high living standard (Alkhathlan & Javid, 2013). KSA is one of the countries with plentiful fossil fuel supplies. As of 2012, KSA was the world's leading oil producer and the second-largest holder of crude oil, only second to Venezuela (EIA, 2017b; Mosly & Makki, 2018). Furthermore, the gross domestic product (GDP) of KSA is mainly reliant on energy exports with petroleum exports accounting for nearly 75% of the country's total export value in 2016 (EIA, 2017b).

According to EIA (2017b), KSA was the world's 10th most extensive consumer of total primary energy at 266.5 million tons of oil equivalent (10 Quadrillion BTU) in 2016, of which around 63% was crude oil and liquid-based petroleum, with natural gas making up the rest of the energy consumption in the kingdom at around 37% (Figure 3-9). Energy is excessively subsidized in KSA, which has led to the overuse of oil and natural gas resources (Alshehry & Belloumi, 2015). The massive fuel subsidies have cost the government an estimated 61 billion USD in 2015, which has driven growth of about 7% per year between 2006 and 2016 (EIA, 2017a). For example, KSA now consumes more oil than Germany, a nation with a population that is three times bigger than KSA, and an economy almost five times higher (Fulbright, 2017). The kingdom's abundance in these resources has driven the overuse of energy and the generation of high amounts of Carbon dioxide (CO_2), leading to a harmful impact on the environment (Alkhathlan & Javid, 2013; Alshehry & Belloumi, 2015).

3.7.1 Electricity Sources

KSA relies on crude oil and other fossil fuels, such as heavy fuel oil products and natural gas, for power generation purposes and is beginning to invest in solar energy, though the capacity is relatively small in comparison to fossil fuels as shown in Figure 3-10 (EIA, 2019a). From the three million barrels of oil consumed in the kingdom per day, around 700,000 barrels are utilized to produce electricity (Fulbright, 2017), making KSA one of the world's largest consumers of oil for electricity production. Similar to most developing nations in the Middle East and North Africa, KSA faces an increasing demand for power. Demand for electricity from 2006-2010 in KSA rose at a 5.8% rate on average, according to Ouda et al. (2013), with current peak demand equaling around 55 Gigawatt (GW) and the peak demand for electricity projected at 120 GW by 2032. The US Energy Information Administration reported that the kingdom generated twice the amount of electricity in 2013 compared to 2000 in order to meet the demands, while Electricity & Cogeneration Regulatory Authority of KSA (ECRA) calculated that KSA would need to invest 140 billion USA by 2020 in order to meet the electricity demands (OBG, 2015). As for Makkah, according to Alkhamalie (2014), the city power demand was around 3,145 MW in 2014 and it recorded the highest growth in the kingdom to 4,150 MW in 2015 (Althubaiti, 2015).

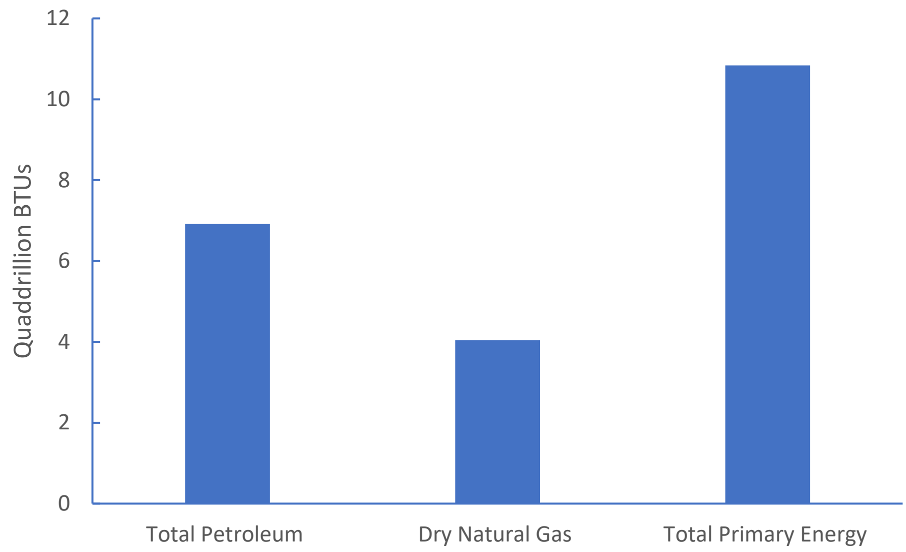

Figure 3-9 KSA energy consumption as of 2016 (EIA, 2017a)

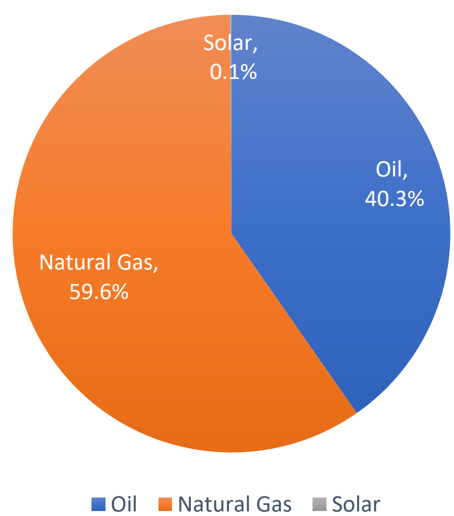

Figure 3-10 Installed power capacity in KSA by fuel type (EIA, 2017a)

3.7.2 Renewable Energy Sources

Since all of the existing electricity generating capacity is powered by oil or natural gas, KSA plans to diversify its sources of power generation, and the Saudi Electricity Company (SEC) intends to continue decreasing direct crude burn for electricity production by turning to renewable sources for electric power generation (EIA, 2017a). As renewable energy is considered an important part of expanding and diversifying the country's economy and reducing dependence on oil, the Vision 2030 targets for KSA include the production of 9.5 GW of renewable energy by 2030 (Vision 2030, 2016). The Saudi authorities have also launched a short-term program called the National Transformation Program 2020, and this program aims to have 3.45 GW of renewable energy by 2020, which would provide 4% of the total power consumption of the country (Mosly & Makki, 2018). In addition, the King Abdullah City for Atomic and Renewable Energy (KACARE) aims to have an additional 40 GW of solar power, 18 GW of nuclear power, and 9 GW of wind power by the year of 2032 (EIA, 2017b). The government also intends to build 600 MW of solar panels in the Makkah region (Hill, 2019) and develop 3 GW of WTE facilities by 2030 to manage the country's MSW, as well as to contribute to its electricity load and to diversify energy sources (Elattari, 2018). Currently, KSA does not have a policy framework for the development of a renewable energy market and electricity regulation has not been included for renewable energy sources (Fulbright, 2017; Mosly & Makki, 2018). Nevertheless, as part of KSA's overall energy strategy, the country has declared numerous objectives for establishing a legal framework that could lead to the development of the local renewable energy market (Vision 2030, 2016).

3.8 Waste-to-Energy (WTE)

WTE (Waste to Energy) refers to the recovery of energy from waste. WTE technologies utilize wastes to generate heat, electricity, and transport fuels from multiple conversion (Hinchliffe, 2017; Jacobi, 2011), and are typically able to process medical waste, sewage, industrial gases, and most commonly, MSW (Hinchliffe, 2017). WTE plants can reduce MSW deposits within landfills by as much as an 80% and 90% reduction in mass and volume, respectively (Ouda et al., 2013). WTE is a viable opportunity in many areas of the world as an efficient way to implement waste management as it also provides energy, lowers the requirements for land acquisition and use for landfills and it helps reduce emissions from greenhouse gases (GHGs) (Cho, 2016).

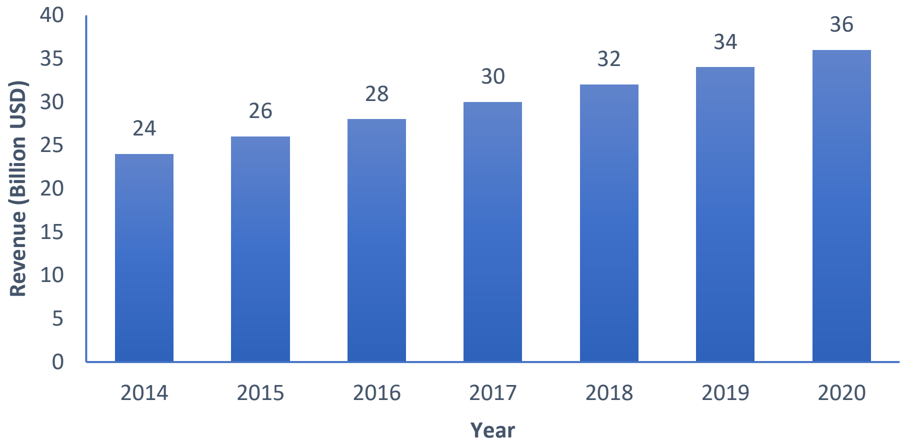

Figure 3-11 Global WTE market, 2014-2020 (Billion USD) (World Energy Council, 2016)

According to the World Energy Council (2016), the size of the global WTE market is worth billions of USD and expected to further increase (Figure 3-11). Governments have promoted WTE due to the increase in domestic and industrial waste streams, and tax benefits and other financial incentives have positively influenced the growth of WTE as environmental concerns over non-renewable energy sources have simultaneously developed (Grand View Research, 2013). The resulting growth of WTE facilities, even with economic crises in different parts of the globe, has led to the establishment of more than 1,200 operating plants between 40 different countries (Yap & Nixon, 2015). The most commonly proven and utilized WTE technologies, according to Gilbert et al. (2008), use combustion methods in order to produce energy as either electricity or heat from sources of waste. According to Antony (2017), biological WTE is becoming more feasible commercially and should expand at an approximately 10% growth rate in the near future. Some examples of WTE technologies in the world are shown in Table 3-.

Table 3-2 Example of WTE technologies in the world

Location	Description	Source
Abu Dhabi/ Sharjah	A plant costing 8.2 m USD was commissioned in Abu Dhabi in 2012. Sharjah and Abu Dhabi treat waste using both pyrolysis and gasification	(Todorova, 2014)
Australia	Plasma gasification plant being built in Kwinana, Australia	(Antony, 2017)
Canada	Older plants in Canada that use incineration have been upgraded, so that they use plasma gasification plants (from Nevitus Plasma Inc. and Plasma Energy Group). Facilities constructed more recently use gasification conversion	(Shareefdeen et al., 2015)
China	China has 28 CFB (circulating fluidized bed) incineration plants operating, the most recent of which was built in 2012 and deals with over 800 tons/day. A plant being built in Shenzhen, considered the world's largest WTE facility will have a capacity of about 5,000 metric tons/day	(Antony, 2017)
Europe	RDF plants are operating in France, Denmark, and Italy. Denmark and Sweden, due to their colder region, use CHP WTE plants, such as Herning, Vartan, Aros, etc., which are producing over 100 kWe of energy. Sweden and Germany, the two leading countries for WTE technology, import waste from other countries to produce energy. An incineration plant was constructed in Naples, Italy in 2013, which can take on 650,00 tons annually	(Antony, 2017)
India	Only four plants out of 14 that are commissioned are operating (in differing states) that use either dry AD or RDF technology. Dry AD technology appears to be more efficient, so four additional plants were recently commissioned using this technology	(Dhar et al., 2017)
Japan	Japan is more modernized than many countries and employs the most up to date thermal treatment plants, which process about 39 million tons annually	(Antony, 2017)
Turkey	Turkey uses a micro-scale KI plant for energy via the treatment of biomass. The energy generated equals about 300 kW_{th} and 50 kWe using pyrolysis (fixed bed gasification)	(Antony, 2017)
UK	Manchester, UK hosts an Energos gasification plant. MSW can be treated as well as commercial and industrial waste. The capacity of this gasification plant is 78,000 tons annually	(Ellyin & Themelis, 2011)
USA	Four states in the U.S. run Novo Energy, a small-scale WTE utility plant that uses combustion technology and processes ~ 66,000 tons annually. Massachusetts has a mobile gasification system that can convert about 200 lbs/hour of dry waste	(Ellyin & Themelis, 2011)

3.8.1 Classification of WTE

Different WTE technologies generate different energy products, such as heat, power and fuel. The suitability of a WTE technology will depend on the characteristics of its waste feedstock and each technology has its benefits and limitations. WTE technologies can be classified into two categories: thermochemical and biochemical conversion technologies. Thermochemical techniques include incineration, gasification and pyrolysis, while biochemical techniques include anaerobic digestion and landfill gas recovery (Figure 3-12).

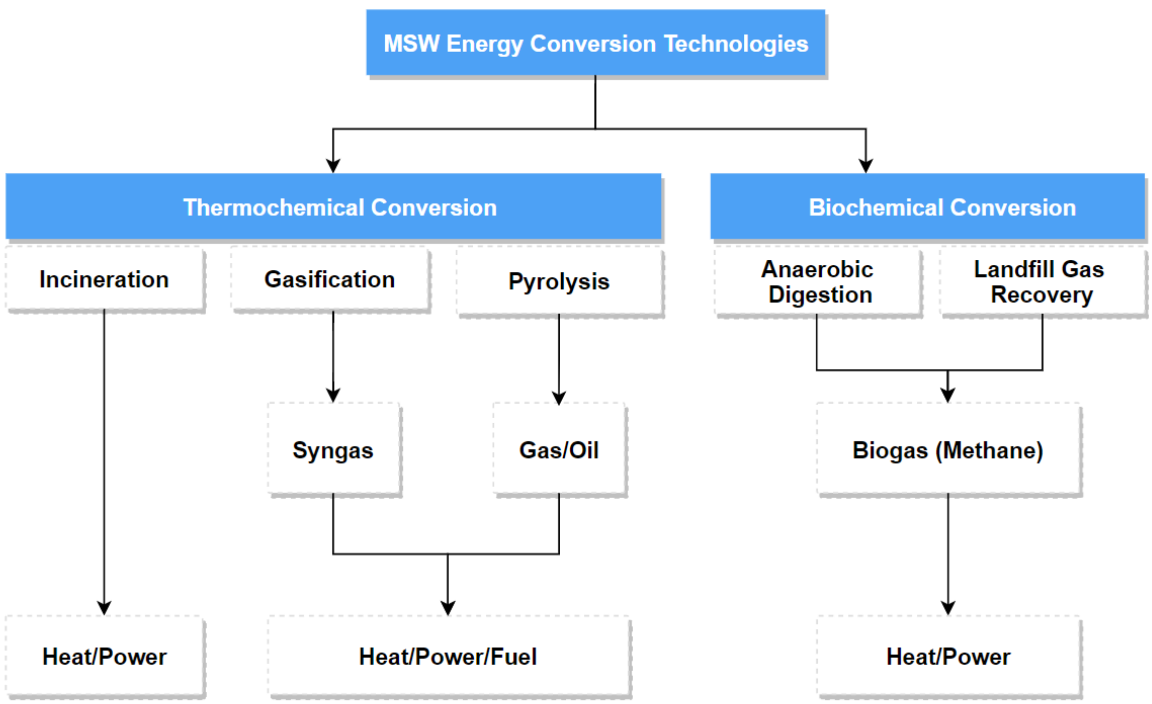

Figure 3-12 MSW energy conversion technologies and their outputs (adapted from Yap & Nixon, 2015)

3.8.2 Prominent WTE Technologies

The following section is a description of prominent thermochemical and biochemical technologies that are currently implemented worldwide.

3.8.2.1 Anaerobic Digestion

Anaerobic digestion (AD) works by converting organic matter into biogas, which can be utilized in heating processes and generating electricity (Nizami et al., 2015a). Figure 3-13 shows a diagram of the inputs and outputs from AD. The process, involves the breakdown of biodegradable material without oxygen, the remaining slurry (digestate) can be used as an organic fertilizer and the biogas, which is mostly CO_2 and methane, can be utilized to produce energy (Holm-Nielsen & Al Seadi, 2004; Nizami et al, 2015a). The digestate can be used in gardening, horticulture, as well as agriculture to help improve ecosystems in the areas of land reclamation, stream reclamation, controlling erosion, wetland construction, and landfill covering (Nizami et al, 2015a). Different styles of anaerobic digesters can be used, based on factors such as whether the process is wet or dry, continuous or batch, the operating temperature, the number of stages or phases of digestion involved, and the organic loading rate or retention time (Nizami & Murphy, 2010).

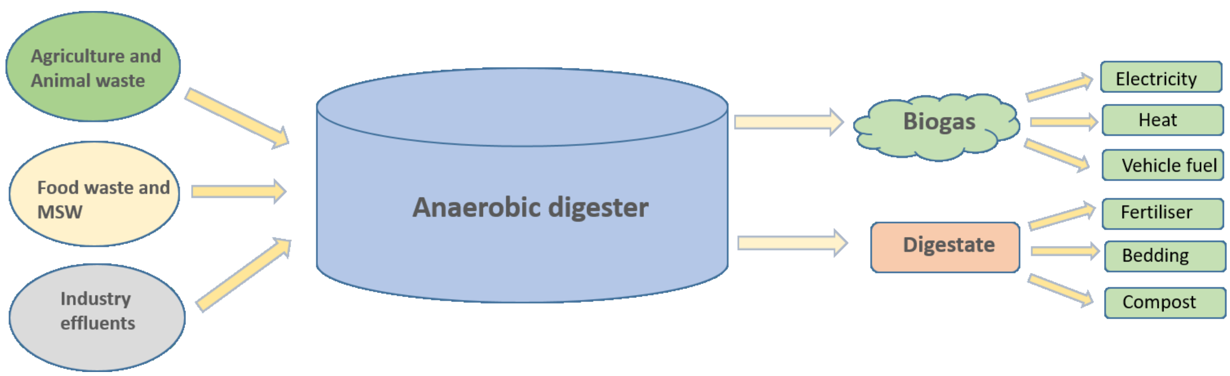

Figure 3-13 AD technology process (adapted from Celignis Analytical, 2019)

3.8.2.2 Pyrolysis

While incineration requires oxygen to work, pyrolysis does not, except in rare situations when partial combustion is permitted for needed thermal energy (Czajczyńska et al., 2017). Pyrolysis decomposes waste using thermal heat at temperatures up to 500°C before it is converted into gaseous fractions (syngas), solids (charcoal), and liquids (fuel-oil) (Nizami et al, 2015a), where the fuel-oil is comparable to diesel but with higher cetane and lower amounts of sulphur and the syngas can be converted to biodiesel or other liquid hydrocarbons (Jahirul et al., 2012). Pyrolysis is an efficient way to convert the waste into a liquid fuel, however, the process is not exothermic like combustion (Basu, 2018). Pyrolysis is associated with advantages including a high power generation capacity when compared to other WTE technologies like plasma arc gasification or RDF (Tatemoto et al., 1998) and does not require as much space (Mekonnen et al., 2014). There are fast and slow types of pyrolysis, where liquid fuel, or biooil is produced using fast pyrolysis, whereas gas and charcoal are produced by slow pyrolysis (Sadaka & Boateng, 2009). According to Stringfellow & Witherell (2014), different types of pyrolysis technologies range from simple carbonization to flash or rapid type systems, but most systems that are operating around the globe are small modules, not large industrial-sized systems. A diagram of the pyrolysis process and typical products is shown in Figure 3-14.

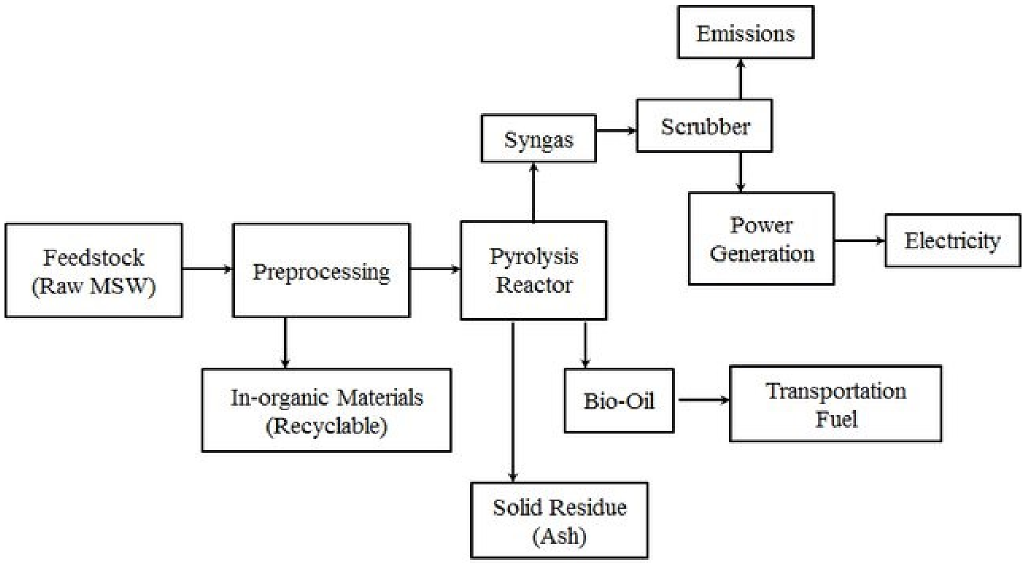

Figure 3-14 Pyrolysis technology process (adapted from Campos et al., 2015)

3.8.2.3 Incineration

Incineration involves the combustion of organic material like MSW with energy recovery. This technology is the most common WTE application at present. According to Perrot & Subiantoro (2018), the method comprises of waste combusting in furnaces and utilizing the heat delivered to produce valuable energy that can be employed to generate electricity or for heat purposes. By-products of the incineration technology are mostly ash and exhaust gas, where the ash slag can be further treated to extract metals for recycling, with the remainder used for construction materials (Perrot & Subiantoro, 2018).

Figure 3-15 shows a diagram of a WTE incineration process. Here, the MSW feedstock is mixed for even distribution to gain an even heating value before being loaded into the hopper/bunker, or other system to deliver it to the furnace or incineration reactor where it is combusted and burned with additional oxygen at temperatures over 800°C (Ouda et al., 2017). Heat is released during the burning process, which heats water in a boiler that then generates steam to drive the steam turbine, and therefore produces energy from there. By-products from incinerating waste include bottom ash, which can consist of iron, silicon, aluminum, calcium, potassium, and sodium while in their oxide state

(Psomopoulos et al., 2009), as well as heavy metals and hazardous waste components that remain after incineration and require disposal.

Some of the benefits to using incinerators, according to Cybulska et al. (2000) include: energy generation from waste and waste reduction. The incineration process reduces around 80% of the waste, and 70% of the mass, all while costing less than other WTE technologies (Cheng & Hu, 2010; Rogoff & Screve, 2011). According to Ouda et al (2017) there are numerous well-developed incineration techniques that exist around the world. MSW management in several countries includes incineration as a commonly used method for WTE and developed nations often utilize incineration of waste with energy recovery as a viable method for eliminating household waste.

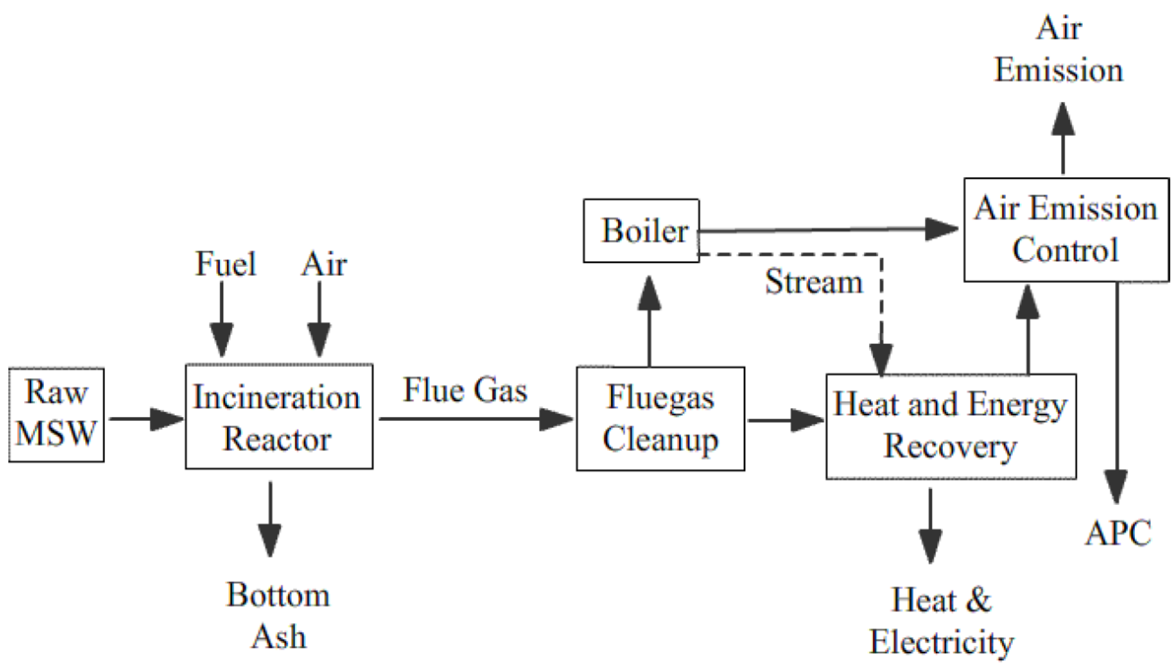

Figure 3-15 Incineration technology process (adapted from Uz Zaman, 2009)

3.8.2.4 Gasification

Gasification involves the thermal conversion of waste materials at a temperature of 800-1000°C, with a limited presence of oxygen (Stringfellow & Witherell, 2014). The method is a process in which partial combustion of material occurs to produce gas and char (Barik, 2018). According to Barik (2018), gasification technology involves three key components: (1) the gasifier, critical in providing the combustible gas; (2) the gas clean up system, needed to eliminate toxic compounds from the flammable gas; (3) the energy recovery system. Figure 3-16 shows a diagram of a gasification process where MSW is converted into valuable syngas. The syngas is easily ignitable in a gas turbine engine to produce electricity, which is around 30% more efficient than the incineration technology (Antony, 2017). The production of the syngas differentiates gasification technology from incineration, as in the gasification method, the MSW is not a fuel, but a feedstock for a high-temperature chemical conversion process. The produced syngas can be applied in many applications after the cleaning process, which is, according to Higman & Burgt (2008), the most significant challenge in commercializing gasification plants on a large scale. Some applications for the syngas are as valuable commercial products such as transportation fuels, chemicals, fertilizers, and even a substitute for natural gas (GSTC, 2019). There are different sorts of gasifiers that can be utilized for waste gasification that vary in size and the nature of MSW that they can gasify. For example, there are gasifiers intended to gasify construction and demolition materials, and others for MSW (GSTC, 2019). Many gasifiers, however, need pre-processing of the MSW to exclude metals and glass that cannot be gasified.

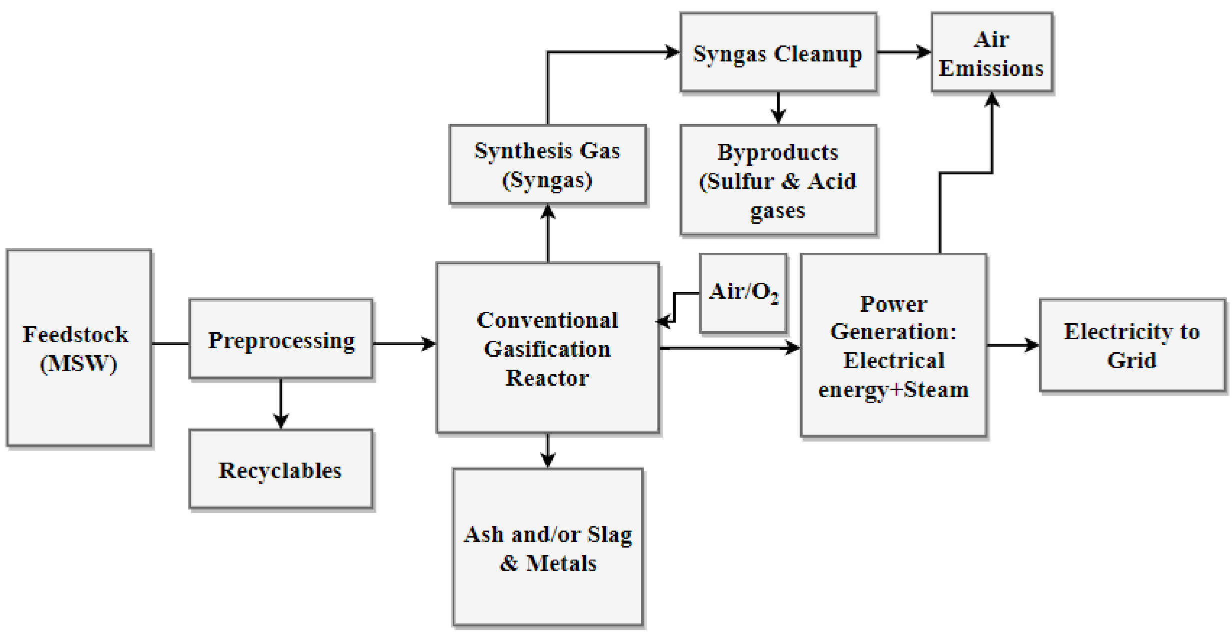

Figure 3-16 Gasification technology process (adapted from Young, 2010)

CHAPTER 4. WASTE-TO-ENERGY (WTE) COMPARATIVE ANALYSIS AND EVALUATION

4.1 Methodology

In this section, four prominent WTE technologies (Incineration, Anaerobic digestion (AD), Gasification and Pyrolysis) were evaluated to determine the most suitable WTE technology for MSW treatment in the case studies examined later in the thesis. The four WTE technologies chosen have been previously described in the literature review, where two technologies are considered proven, and two are emerging, and the evaluation of each WTE technology uses both general and specific criteria. General criteria for selecting WTE technologies depends on variety of factors such as the category of waste type, operation and capital cost, technology complexity and efficiency, as well as labour skill and the form of energy desired for any associated plants (Nizami, 2015a; Tan, 2013). Specific criteria include consideration of the local MSW composition, as well as operational aspects of the WTE technologies in the local environment.

4.1.1 General criteria used for evaluation

For the general evaluation of the WTE technologies, three criteria were used: (a) waste composition and the suitability for general/mixed waste treatment, (b) sustainability of the WTE technologies in terms of economic, environmental and social acceptability, and (c) technology requirements in term of capital cost, labour requirements, complexity and energy efficiency (Table 4-1). The following subsections discuss the rationale for including these criteria in the evaluation.

Table 4-1 General criteria and sub-criteria for WTE technologies evaluation

Criteria		Sub-Criteria
Waste Composition	i.	Mixed waste
Sustainability	i.	Economic viability
	ii.	Environment friendly
	iii.	Social acceptability
Technology requirement	i.	Capital cost
	ii.	Skilled labour requirements
	iii.	Complexity
	iv.	Energy efficiency

4.1.1.1 Waste composition

The selection of WTE technology will depend on the quantity and type of the incoming waste stream. The quantities of solid waste influence the plant capacity required, need for landfills to manage residues, and other ancillary facilities (Hinchliffe, 2017). Moreover, the quantities of MSW generated by the community are an essential factor in determining the financial feasibility of a proposed WTE site and the revenues generated through the sale of energy. The MSW composition, on the other hand, is a critical factor for evaluating WTE technology since it can affect the energy content of the waste received by site (Table 4-2), as well as the quantities of recyclable materials and residues that might be produced (Rogoff and Screve et al., 2011).

Energy conversion from waste can be achieved by employing various technologies. Each WTE method has specific features and could be more or less practicable depending on various parameters, one of which is the waste composition (World Energy Council, 2016). For instance, some technologies are suitable for mixed waste, and other technologies are inadequate in handling mixed waste due to its sensitivity to a particular type of waste and only considered suitable for a specific waste fraction (Hinchliffe, 2017). Nevertheless, the physical characteristics of the waste, such as size, density, and moisture are critical in determining a suitable WTE technology (Beyene et al., 2018). In terms of energy production, the calorific value of the waste, determines how much energy can be obtained from incoming MSW, as illustrated in

Table 4-3 (Nizami et al, 2015a; Rogoff and Screve, 2011) and suitable WTE technologies based on waste type have been proposed, as shown in Table 4-4 (Ouda et al., 2016). However, the choice of WTE technology will be mostly dependent on the nature and volume of the incoming waste stream.

Table 4-2 Type and composition of MSW (World Energy Council, 2016)

Source	Type	Composition
Municipal Solid Waste (MSW)	Residential	Food, Plastics, Cardboard, Textiles, Wood, Leather & Metals, Hazardous & E-wastes
	Industrial	Packaging, Wood, Food wastes, Concrete, Housekeeping Waste, Concrete Ashes & bricks
	Commercial	Plastic, Wood, Paper, Cardboard, Food, Glass, Metals, Hazardous & E-Wastes
	Construction	Steel, Wood, Bricks, Soils, Tiles, Glass, Concrete, Plastic & hazardous waste
	Municipal services	Sludge, Tree trimming & street sweepings

Table 4-3 Energy content of different types of wastes (Nizami et al, 2015a; Rogoff and Screve, 2011)

Type of waste	Energy content (Btu/lb)
Mixed paper	6800
Mixed food waste	2400
Mixed green yard waste	2700
Mixed plastic	14,000
Rubber	11,200
Leather	8000
Textiles	8100
Demolition softwood	7300
Waste hardwood	6500
coal	12,300
Fuel, oil	18,300
Natural gas	23,700

Table 4-4 Suitable WTE technologies based on waste type (Ouda et al., 2016)

	Food	Paper	Wood	Garden	Plastic	Cardboard	Textile	Leather
AD	✓	✓	✗	✓	✗	✗	✗	✗
Pyrolysis	✗	✓	✓	✗	✓	✓	✗	✗
Gasification	✗	✓	✓	✗	✓	✓	✓	✓
Incarnation	✗	✓	✓	✓	✓	✓	✓	✓

4.1.1.2 Sustainability

According to Campos et al. (2015) WTE technologies provide a sustainable alternative solution to conventional MSW management options, such disposal in a landfill and incineration. Certain WTE technologies have the advantage of producing a relatively small amount of pollutants, providing syngas and oil as alternative energy sources, and requiring a small footprint (Jacobi, 2011). WTE technologies can reduce the need for electrical generation from other sources, which is advantageous, especially in view of rising electricity prices, and the ever-increasing demand for oil. WTE technologies vary in terms of their economic, environmental and social sustainability (Varma, 2009), and researchers have assessed several WTE technologies on the basis of these factors as summarized in Table 4-5 (ESI, 2017; Qazi et al., 2018).

According to Giovanni & Stefano (2015), the commercial feasibility of WTE technologies depends greatly on the regions and countries involved. Moreover, the commercial viability and maturity of the technology, gross revenue from the technology, such as the tipping fee and energy sale (electricity or heat), product application, the scale of the site and the operations and maintenance (O&M) costs of WTE technologies are important economic considerations.

WTE technologies that are considered environmentally sustainable may result in outcomes such as a decrease in landfill usage, reduction in air emissions and minimization of waste residues that require landfill disposal or secondary treatment. Every WTE technology will produce contamination in a solid, liquid, and/or gaseous form that might have some influence on the environment, as well as affecting water quality and living organisms.

Public acceptance of WTE technologies is another an important consideration and the environmental implications of particular WTE technologies can lead to social concern (World

Energy Council, 2016). The general attitude regarding waste management matters is wide-ranging and can often be extreme. Usually, the most accepted waste management alternatives for MSW are recycling and composting. However, it should be acknowledged that there is always to be some opposition to any waste management plant within a local community. This criterion discusses the acceptability of the suggested WTE plants with the project site in terms of factors such as odors, noise, dust, and number and hours of waste delivery trucks. Moreover, plants would require additional utilities such as water, power, natural gas, sewage, and transportation (McLaughlin, 2017).

Table 4-5 Sustainability criteria for several WTE technologies (ESI, 2017;Qazi et al., 2018)

Criteria	Incineration	Anaerobic Digestion	Gasification	Pyrolysis
Economic				
Technology status (maturity)	Proven	Proven	Emerging	Emerging
Commercial viability	Less viable	Readily viable	Varies considerably	Varies considerably
O & M Cost	High	Low	Limited	Limited
Products Application	Low	High	Medium	High
Environmental				
Environmental impacts (Air Pollution)	Can be minimized, but requires expensive technology investments	Minimum	Can be controlled to a significant extent	Can be controlled to a significant extent
Waste disposal process	Complete, except for ash to landfill.	Complete except for sludge	Complete	Complete
Social				
Public acceptability	Not fully satisfactory	Satisfactory	Satisfactory	Satisfactory

4.1.1.3 Technology requirements

The technology requirements for the treatment of MSW are reliant on different aspects that generally consist of capital cost, labour requirements, complexity, and energy efficiency. These have been reported on by several researchers, as summarized in Table 4-6. Generally, the main capital costs are land and equipment purchase, installation, and building cost. For instance, emerging WTE plants use advanced components for plant operations, processing waste, recovering energy efficiently and controlling emissions compared to conventional waste management options, which directly impacts the initial capital (Wu, 2018). According to Funk, Milford, & Simpkins (2013) the capital cost for the development and implementation of WTE technologies, and the expenses required to operate them for the whole lifetime of a chosen technology can influence decisions when determining the suitability of a WTE technology.

According to Hengevoss et al. (2017), some emerging WTE technologies require highly skilled labour. The disadvantage of highly skilled labour is that they are compensated at a relatively high average wage. For instance, employees in the WTE industry in the USA earn about $450 million in annual salary and bonuses (Berenyi, 2013). Thus, in this study, the technology that requires less skilled labour will have a higher score for evaluation.

WTE technologies are complex processes in which MSW is obtained, treated and turned to energy via thermal, chemical, or biological treatment. WTE sites require professional planning, manufacturing, and operation. They are more complicated to operate than a sanitary landfill and require more qualified staff and skilled labour. The operation of such site and the type of energy produced can increase the level of difficulty, for example, the combination of electricity and heat raises the complexity and the required capital investment of the site (ISWA, 2013). WTE technologies vary in the level of complexity, and in this study, the less complicated technologies will score more highly and be evaluated as more suitable.

The evaluation of the energy efficiency of the WTE technology is generally determined by analyzing the gross energy generated, and whether it is in the form of electricity or heat. The energy efficiency of the technology represents the amount of energy that is actually transferred into the grid as electricity. However, Perrot & Subiantoro (2018) noted that the efficiency of a particular WTE technology is dependent on several factors such as the thermodynamic cycle used, the scale of the site and all the techniques used for optimizing each technology.

Table 4-6 Technology requirements for several WTE technologies (Ducharme, 2010; EAI, 2017;Ouda et al., 2013;Nizami et al., 2015b;Tan, 2013)

Criteria		Incineration	Anaerobic Digestion	Gasification	Pyrolysis
Technology requirements					
i.	**Capital cost**	Intermediate	Low	High	High
ii.	**Skilled labour requirements**	Low	Low	Intermediate	Intermediate
iii.	**Complexity**	Low	Low	High	High
iv.	**Energy efficiency**	20%-25%	25%-35%	10%–27%	16%-33%

4.1.2 Specific (local) criteria used for evaluation

Since the waste stream and local conditions in most developing countries are radically different from those in industrialized countries, additional evaluation criteria were used to accommodate the local MSW characteristics and operating conditions. These specific criteria were: (a) waste composition of the local MSW which comprises mostly of food and plastic waste, and (b) the operational aspect of installing new technologies such as the energy requirement and the plant scale (Table 4-7). Table 4-9 summarizes some of the relevant parameters for the specific criteria (Beyene et al., 2018; Hinchliffe, 2017; Kalyani & Pandey, 2014; Ouda et al., 2013) and the following subsections discuss the rationale for including these criteria in the evaluation.

Table 4-7 Specific (local) criteria and sub-criteria for WTE technologies evaluation

Criteria	Sub-Criteria	
Waste composition	i.	Food waste
	ii.	Plastic waste
Operational aspects	i.	Energy requirement (e.g. temperature)
	ii.	Scale & peak load

Table 4-8 Specific criteria for KSA for several WTE technologies (Beyene et al., 2018; Hinchliffe, 2017;Kalyani & Pandey, 2014;Ouda et al., 2013)

Criteria	Incineration	Anaerobic Digestion	Gasification	Pyrolysis
<u>Waste Composition</u>				
Food Waste	Low suitable	High	Low suitable	Low suitable
Plastic Waste	Moderate	Not suitable	Moderate	High
<u>Operational Aspect</u>				
Energy requirement (Temperature)	(750-1450°C)	i. (< 25°C), (Psychrophilic) ii. (35-45°C) (Mesophilic) iii. (> 50°C) (Thermophilic)	(800-1000°C)	(300-850°C)
Capacity (Scale)	Large	Small	Medium	Medium

4.1.2.1 Local waste composition – KSA, Makkah, Umrah and Hajj

Identifying the waste composition and quantity for the studied area is important for the research to determine the best fit technology that can process that particular portion of waste. The MSW generated by KSA, Makkah and during Umrah can be considered as having the same composition of food waste (50.6%), plastics (17.4%), paper (11.9 %) and cardboard (6.7 %) (Nizami et al. 2015b). While the MSW generated during Hajj differs with food waste (38.96 %), plastics (36.48 %), paper and cardboard (13.75%) and Aluminum (8.96%) (RACI, 2008), as shown in Figure 4-1. It is evident that for KSA, Makkah, Umrah and Hajj, food and plastic are the most prevalent wastes present.

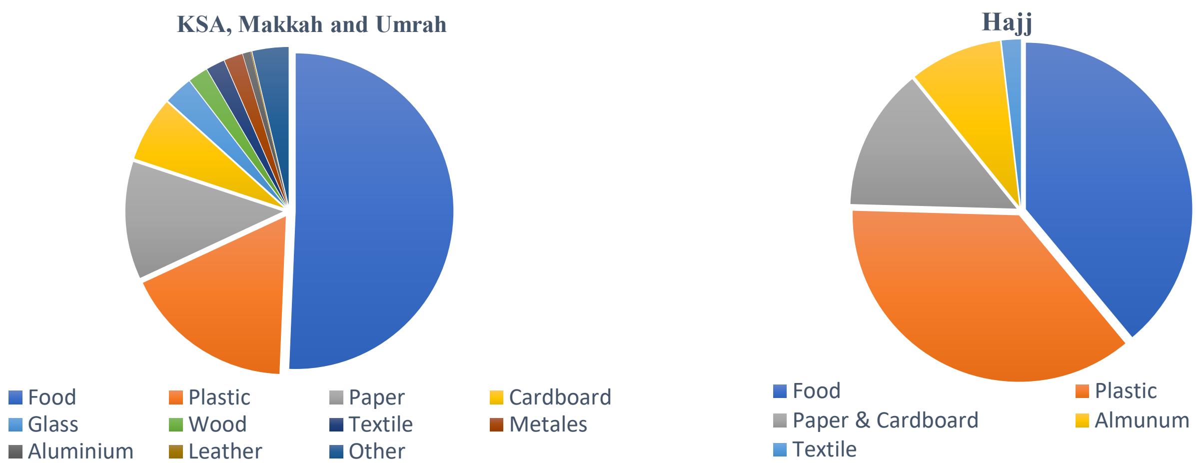

Figure 4-1 MSW composition: KSA, Makkah, and Umrah (Nizami et al. 2015b) (left) and Hajj (RACI, 2008) (right)

The physical and chemical compositions of food waste produced in Makkah city are shown in Table 4-9 (Khan and Kaneesamkandi, 2013; Nizami et al. 2015b). These values will help determine the best suitable WTE technology for the food waste. In this study, the composition of food waste from KSA is assumed to be similar to that from Makkah and during Umrah.

Plastic waste is the next most prevalent waste generated in KSA and in Umrah (about 17%), however during the Hajj season, plastic waste reaches 38% of the total waste stream (Figure 4-1) Just about 20% of all generated plastic waste is recycled (Anjum et al. 2016), and the rest is disposed of directly into landfills, which results in an environmental problem due to the slow degradation process of the plastic.

4.1.2.2 Operational aspect

There are important operational aspects that should be considered when evaluating the suitability of establishing a WTE technology plant in KSA. The energy requirement is one of the main factors that should be considered for investing in a new WTE plant as most of the WTE processes require a heat source to maintain the temperature required for the technology and the temperature of the environment can affect the additional energy needed. In this study, the WTE technology that has the lowest energy demand is preferred. In addition, the loading of waste into the WTE plant affects the scale of the WTE and capacity for the peak load. These considerations are important, especially for Makkah city, where the waste that is generated during Umrah and Hajj seasons, results in a high peak load.

4.1.3 Scoring system for both general and specific level evaluation

Each criterion was assigned a scale from 1 to 3 which was determined by the importance and suitability of the technologies based on relevant factors, as shown in Table 4-10 and Table 4-11, where definitions of what would result in a high score for each of the criteria are also described.

The local factors are very important for the evaluation of WTE outcomes for the case studies in this thesis, therefore they were given more weight in comparison to the general criteria in the final evaluation. The main specific parameter that is relevant to the local waste composition is the suitability of the WTE technology for utilizing the food and plastic waste generated, thus those two factors were given a double weighting in the final evaluation, while the operational aspects regarding energy requirement and coping with load peak had a 1.5 weighting. The final evaluation combined the results from the general and specific criteria with appropriate weightages.

Table 4-9 Physical and chemical composition of the food waste in Makkah city (Khan & Kaneesamkandi, 2013; Nizami et al., 2015b)

Physical composition (%)	
Rice	38.72
Bakery products	18.74
Meat	25.15
Fat	13.03
Bones	2.19
Fruit & Vegetables	2.16

Chemical composition (%)	
Moisture	38.4
Carbohydrates	25.56
Crude protein	17.26
Crude fat	15.27
Fiber	0.3
Ash	3.21

Table 4-10 Scoring of general criteria for WTE technologies

Criteria		Scale 1	2	3	Description
Waste Composition					
i.	**Mixed Waste**	Unsuitable	Moderately suitable	Suitable	A high score indicates the WTE technology is very suitable for mixed waste
Sustainability					
i.	**Economic viability**	Unviable	Moderately viable	Viable	A high score indicates a mature technology with proven commercial viability. a variety of product application and low O&M cost.
ii.	**Environment friendly**	Unfriendly	Moderately friendly	Friendly	A high score indicates the least possible risk to the environment such that there is minimal air and water pollution, and low residue waste.
iii.	**Social acceptability**	Unacceptable	Moderately acceptable	Acceptable	A high score indicates low odor, manageable waste transportation and low impact on neighboring businesses and homes.
Technology requirement					
i.	**Capital cost**	High	Moderate	Low	A high score indicates a low plant establishment cost
ii.	**Skilled labour requirements**	Maximum	Moderate	Minimum	A high score indicates minimum skilled labour requirements
iii.	**Complexity**	High	Moderate	Low	A high score indicates low technology complexity
iv.	**Energy efficiency**	Low	Moderate	High	A high score indicates high energy efficiency

Table 4-11 Scoring of specific (local) criteria for WTE technologies

Criteria	Scale 1	Scale 2	Scale 3	Description
Waste Composition				
i. Food Waste	Unsuitable	Moderately suitable	Suitable	A high score indicates the WTE technology is suitable for Food waste
ii. Plastic Waste	Unsuitable	Moderately suitable	Suitable	A high score indicates the WTE technology is suitable for Plastic waste
Operational Aspects				
i. Energy Requirements	High	Moderate	Low	A high score indicates the WTE technology has comparatively low energy requirements
ii. Capacity (Scale)	Small	Moderate	Large	A high score indicates the WTE technology is suitable for accommodating large peak loads

Table 4-12 Weightages for all criteria

Criteria		Weightage*	WTE Technologies Score
Waste composition			
i.	**Food Waste**	2	0-3
ii.	**Plastic Waste**	2	0-3
Operational Aspects			
i.	**Energy Requirement (Temp)**	1.5	0-3
ii.	**Capacity (Load Peak)**	1.5	0-3

*All the general criteria were given a weighting of 1

4.2 Results of the WTE Evaluation

In this section, a comparison is made between four WTE technologies (incineration, anaerobic digestion (AD), gasification and pyrolysis) based on various criteria, to find the most suitable technology to predict WTE outcomes for selected case studies. Firstly, scores for evaluation of the general criteria are presented followed by the results from evaluation of local criteria. Finally, the results from the overall evaluation considering all criteria are presented.

4.2.1 Evaluation of the WTE technology based on general criteria

In this section, results will be presented based on the general criteria: waste composition, sustainability, and technical requirements. The rationale for scoring all criteria is summarized in Table 4-10.

4.2.1.1 *Waste Composition*

The results from the comparative analysis of waste composition are shown in Table 4-13. Here incineration scores the highest followed by gasification and pyrolysis with anaerobic digestion scoring lowest. Incineration scores highly as it can handle nearly any type of waste, with the exception of wet waste. Incineration technology is designed to handle usually mixed waste and mostly untreated residential and commercial wastes (Hinchliffe, 2017). A fundamental aspect of this technology is the energy content, which is the lower calorific value (LCV) in MJ/kg of the feedstock. The LCV for combustion of the waste should not be under 7 MJ/kg on yearly average (World Bank, 1999). In some developing countries, the LCV of unsegregated MSW is regularly below the minimum LVC for the combustion process because of the higher moisture in the organic content (Hinchliffe, 2017).

Table 4-13 Comparison of WTE technologies in terms of waste composition

Waste Composition (mixed waste)	Incineration	AD	Gasification	Pyrolysis
Mixed waste	3	1	2	2
Total	**3**	**1**	**2**	**2**

Gasification and pyrolysis technology might be able to treat several types of waste separately, with limited influence on the environment and at a lower cost as compared to incineration technology, yet those emerging technologies are less mature, and there are no successful practices of gasification and pyrolysis with the process of larger quantities of mixed MSW because of its diverse composition (Hinchliffe, 2017). However, while there are possibilities for the production of liquid fuels from different waste composition through pyrolysis technology, the mixed composition of MSW creates severe technical hurdles. On the other hand, anaerobic digestion (AD) is the most unsatisfactory option in this aspect, since it is limited as it cannot process non-biodegradable materials, such as plastic waste, and it is only suitable for treating organic material such as household, market and garden waste. There are no successful experiences with the treatment of more significant volumes of mixed MSW for AD technology due to its heterogeneous composition (Hinchliffe, 2017).

4.2.1.2 Sustainability

The results from the evaluation of WTE technologies in terms of overall sustainability are presented in Table 4-14, where anaerobic digestion scored highest followed by pyrolysis, gasification and then incineration. In this section, discussion of the WTE technologies will follow based on the economic, environmental and social aspects of sustainability.

Table 4-14 Comparison of WTE technologies in terms of sustainability

Sustainability	**Incineration**	**AD**	**Gasification**	**Pyrolysis**
Economically viable	3	3	2	2
Environment friendly	1	3	2	3
Social acceptability	1	2	2	2
Total	**5**	**8**	**6**	**7**

4.2.1.2.1 Economic

Incineration and AD scored the highest in terms of economic sustainability. In terms of the level of maturity of the technologies, incineration technology is the most mature and a proven technology (Tan, 2013). This is followed by AD, while pyrolysis and gasification are still emerging technologies and not yet mature (Lombardi et al., 2015).

Incineration provides the biggest capacity of all the WTE technology considered here, which is approximately up to 1500 t/day, as well it is a proven process that provides a cost-effective solution for medium and large-scale investment (World Energy Council, 2016). Still, incineration may not be profitable for small scale application (Yurtsever et al., 2009). The installation of the AD site can be relatively fast, also, in contrast to different WTE technologies can be comparatively inexpensive (DEFRA, 2011). Furthermore, AD has flexibility in terms of feedstock and the final product that is produced, which makes it easy to fit the local community needs while still being connected to the national electricity grid (DEFRA, 2011). Yet, AD technology usually operates at small scale in comparison to other technologies.

Pyrolysis technology is an emerging method for WTE conversion of MSW and is considered cost-effective and environmentally viable, especially in terms of waste reduction and carbon recovery (Beyene et al., 2018). Gasification is promoted as a cleaner practice than incineration as the MSW is not directly combusted, however, it is costs are significantly higher and the availability considerably lower than mass-burn incineration technology. Also, the syngas that is produced can be employed in a variety of applications, such as in gas engines for conversion to heat and electricity (Normandeau, 2017).

4.2.1.2.2 Environmental

AD and pyrolysis scored the highest in environmental sustainability, followed by gasification, with incineration scoring the lowest. The main impacts considered are the effect on air quality and need for landfill.

AD is considered the lowest air polluting technology here, with methane and carbon dioxide being the major gases produced (Li et al., 2011). The significant environmental benefit of this technology is that it is considered a carbon-neutral process for waste conversion, and it has the lowest discharge of methane gas as compared to landfill (Gruner 2007). Pyrolysis emits less air pollution than incineration technology since there is no oxygen in the waste treatment process and it uses a comparatively low temperature (Samolada & Zabaniotou, 2014). Furthermore, pyrolysis technology is less air polluting than gasification technology well for similar reasons (Tan, 2013). Thus, AD and pyrolysis technologies can be considered the most environmentally friendly in term of gas emissions.

It should be noted that the gas emissions can be treated to decrease air pollution, however these added technologies will add to the overall cost. For example, gasification discharges less carbon dioxide than incineration (Kumar & Samadder, 2017), but it is costly to treat the emissions from incineration compared to gasification (Matsakas et al., 2017). Gas emissions control is the primary obstacle for installing incineration plants, as most cases require the installation of costly additional equipment to comply with the air pollution standards in the host country (Hinchliffe, 2017).

In terms of reducing the need for landfill capacity, incineration is one of the best choices since it reduces a significant amount of various types of MSW that might have otherwise been disposed of in a landfill. Nevertheless, according to Hinchliffe (2017), incineration results in the production of approximately 25% of the waste as residues (ash), which require secondary treatment and final disposal in a new landfill. In comparison with incineration, gasification technology also produces a bottom ash which needs to be removed for suitable disposal (Beyene et al., 2018). For pyrolysis, the residue produced is slag, ash (low carbon), or char. These residues can be considered by-products from pyrolysis and can be recovered for beneficial applications. Pyrolysis has the advantage of reducing the residuals that need to be landfilled and the ability to recovery condensate from the process as a useful by-product (Grycová et al., 2016). In comparison, AD produces sludge as a residue, which is rich in nutrients and can be applied as compost (Varma, 2009).

4.2.1.2.3 Social

AD, pyrolysis and gasification scored the highest in environmental sustainability, followed by incineration scoring the lowest.

In general, AD only attracts a small amount of public attention in comparison to incineration (Khan, 2011). With AD, public acceptability will be affected depending on where the AD facility is located and there will be greater acceptance if the community has been consulted beforehand. Typically, AD plants are located in rural areas, though still within a reasonable range from the population, to avoid odor and noise pollution (Gruner, 2007).

Pyrolysis and gasification are thermal conversion processes and, in most cases, the public associates them with incineration and combustion processes. However, public acceptance of these technologies has improved during the past decades, as more information has become available regarding the advantages and disadvantages of pyrolysis and gasification. Indeed, these two methods are considered environmentally friendly, as they discharge fewer contaminants compared to incineration, and their process requirements are limited to natural resources such water (Crowe et al., 2002). With incineration, public acceptance has been linked to concerns associated with older plants where the facility management requirements and emissions control standards were not as demanding as they are now (Tan, 2013). This perception of incineration technology being environmentally unfriendly may result in future incineration projects being not entirely supported by the public.

4.2.1.3 Technology requirements

The results from the evaluation of WTE technologies in terms of their technical requirements are presented in Table 4-15, where AD scored highest followed by incineration, pyrolysis, and then gasification. In this section, discussion of the WTE technologies will follow based on the capital cost, labour requirements and complexity and energy efficiency.

Table 4-15 Comparison of WTE technologies in terms of technical requirements

Technology requirement	Incineration	AD	Gasification	Pyrolysis
Capital cost	2	3	2	2
Skilled labour requirements	3	3	1	1
Complexity	2	3	1	1
Energy efficiency	2	3	2	3
Total	**9**	**12**	**6**	**7**

4.2.1.3.1 Capital cost

AD scored slightly higher in terms of the capital cost criteria than the other technologies. AD technology has the lowest capital cost comparing to all technologies examined in this paper due to the process simplicity and maturity of the technology (Perrot & Subiantoro, 2018). According to Khan (2011) AD technology demands less capital and O&M costs compared to thermal technologies. Its capital cost is even lower than other renewable energy sources technology such solar and wind power (Thi, Lin, & Kumar, 2016).

The capital cost of incineration is lower in comparison to other thermal WTE technologies, yet, it does not directly correspond to its profitability or viability (Perrot & Subiantoro, 2018). Also, the installation of additional components for air pollution control and other supporting features for incinerators can cost up to 70% of total project value (Ouda, 2016). Gasification and pyrolysis both have significant capital costs in comparison with traditional WTE technology such as AD and incineration.

4.2.1.3.2 Skilled labour requirements and complexity

For the labour requirement and complexity, AD and incineration technologies scored similarly higher than pyrolysis and gasification technologies. Indeed, AD has a low capital cost demand, related to its ease of operation (Ouda et al., 2013), while incineration also has relatively low capital requirements and labour skill levels in comparison to gasification and pyrolysis. Gasification is a more complicated process than waste incineration technology, although the reactors involved are similar (AES, 2004). It is generally accepted that gasification is a sophisticated technology that needs more skilled labour and maintenance work (Klein, 2002). Pyrolysis is also considered a complex process, where the mechanism and the primary chemical reactions comprise various steps and involve a range of reactions that are affected by different factors (Bridgwater et al., 1999; Zaman et al., 2017).

4.2.1.3.3 Energy efficiency

AD and pyrolysis scored high in term of the energy efficiency, followed by incineration and gasification. In general, there are different viewpoints regarding the energy generation efficiency for each technology. The energy efficiency of a technology is dependent on various aspects such as the scale of the plant and the thermodynamic cycle, as well as the techniques used for optimization (Perrot & Subiantoro, 2018).

For AD technology, the highest efficiency achieved in the generation of biogas based on the heating values is 35% (Ouda et al., 2013). In terms of incineration, steam turbines are generally employed, and the electrical generation efficiency is usually typically around 25% (Ouda et al., 2013). With only heating, the efficiency of incineration can reach 90%, and with combined heat and power (CHP) is up to 40% (Perrot & Subiantoro, 2018). According to Tan (2013), gasification has an efficiency of between 10–27% while pyrolysis has an efficiency of between 16–33%. The electrical efficiency is quite high in pyrolysis technology compared to all other thermal alternatives, including gas turbines of the gasification technology and the direct burning of biomass like incineration method to produce power. Unlike incineration, gasification and pyrolysis technologies produce syngas and high yield liquid fuel respectively ,and those forms of energy can be fed directly into a gas turbine or an engine to produce power.

4.2.1.4 Summary – general criteria evaluation

Four technologies (incineration, AD, gasification and pyrolysis) were evaluated based on three general criteria: waste composition for mixed waste, sustainability, and the technical requirement. As shown in Table 4-16, AD was the most suitable WTE technology, with the highest score, followed by incineration, pyrolysis and gasification technologies.

Table 4-16 Overall results for the evaluation of WTE based on general criteria

General Criteria	Incineration	AD	Gasification	Pyrolysis
Waste composition (mixed waste)	3	1	2	2
Sustainability	5	8	6	7
Technology requirement	9	12	6	7
Total	**17**	**21**	**14**	**16**

4.2.2 Evaluation of the WTE technology based on specific (local) criteria

In this section, results will be presented based on specific (local) criteria: local waste composition and operational aspects. The rational for scoring all specific criteria is summarized in Table 4-11.

4.2.2.1 Local waste composition

As discussed previously, food and plastics are the main types of waste present in the MSW streams for all cases (KSA, Makkah, Umrah, Hajj). Therefore, evaluation of the WTE technology most suitable for these feedstocks was performed and the results are presented in Table 4-17. This analysis shows that AD was found most suitable for the food waste and pyrolysis was most suitable for the plastic waste. Further detailed discussion of these results is included in the following sections.

Table 4-17 Comparison of WTE technologies in terms of local waste composition

Criteria	Incineration	AD	Gasification	Pyrolysis
Waste Composition				
Food	1	3	1	1
Plastic	2	1	2	3
Total	**3**	**4**	**3**	**4**

4.2.2.1.1 Food

It is generally accepted that AD is the best choice for food waste treatment both environmentally and economically (DEFRA, 2011; World Energy Council, 2016). AD is generally preferred because it produces both renewable energy and a biofertilizer, which together do more to limit greenhouse gas (GHG) emissions and creating compost (Thi et al., 2015). Furthermore, the treatment of food waste through AD may raise the capability of methane as well as hydrogen production for possible energy usage, which could provide a reliable electricity source for many countries (Dung et al., 2014). Additionally, AD is considered a desirable technology to reduce GHG emissions. For example, expansion of AD technology is one of the main goals for the United Kingdom to reach a reduction of GHG by 80% in 2020 (DEFRA, 2011). In the case of KSA, Anjum et al. (2016) state that AD is the most suitable technology to for the MSW due to the significant organic content present due to the massive consumption of food that is generated. AD is an attractive option for KSA and Makkah, as food waste is typically combined with animal waste to enhance biogas generation (Wang 2010), where millions of animals are slaughtered as part of the rituals conducted by pilgrims in the Hajj season. In this study, a major reason for selecting AD over incineration, gasification and pyrolysis is due to the high moisture content in the food waste, which makes it not suitable for a thermal process (Nizami et al., 2015a). However, the main obstacle for AD technology is the long duration of the microbial reaction, which can range between 20-40 days (Pham et al., 2015).

Generally, there are few studies on energy recovery from food waste using thermal methods. Commonly, food waste is discarded into the overall stream of MSW and transformed into heat and energy by incineration technology (Mardikar and Niranjan, 1995). Energy recovery by incineration of separated food wastes is not always feasible, usually because of the energy lost due to the water content in the organic wastes. The fundamental issues behind the energy losses are the high moisture content, lower heating values and the diverse nature of food waste, which results in technical and economic problems not only for incineration but other thermal processes such as pyrolysis and gasification (Pham et al., 2015). As a result, there seem to be almost no gasification or pyrolysis processes that have been completely developed for food waste. However, in one study by Ahmed & Gupta (2010), pyrolysis and gasification were compared for processing food waste by varying parameters such as flow rate, total yield of syngas and hydrogen, output power and the efficiency. They noted that gasification was more convenient for food waste processing than pyrolysis based on the examined parameters.

4.2.2.1.2 Plastic

The conversion of plastic to energy can be done using different thermal processing technologies like gasification, pyrolysis, incineration or even via biochemical treatment such as AD technology. Yet there is a clear disparity between these techniques in plastic waste treatment in terms of performance, efficiency, the form of the output product from the plastic waste as well as the environmental aspect from the conversion process. Pyrolysis is considered the most beneficial method for plastic waste, as the initial amount of the waste is notably decreased, and more energy can be obtained with various valuable products (liquid fuel oil, synthesis gas, and char) which require a lower breakdown temperature and therefore less energy than other thermal technologies (Sharuddin et al., 2018). Additionally, pyrolysis could provide effective management of plastic waste, as it requires only a limited capacity of landfill, and produces less contamination and is more cost-effective compared to recycling. Furthermore, pyrolysis can convert plastic waste into a marketable liquid fuel, with high energy content, that is easy to store and transport, reduces the dependence on fossil fuels by providing a renewable alternative and can be used for different uses; this is an advantage over incineration and gasification.

Pyrolysis is an attractive WTE technology for KSA, as the volume of plastic wastes available in KSA is reaching millions of tons and is likely to further increase with population unless drastic measures are taken. After food waste, plastic waste is the next largest component of MSW in KSA, and can be attributed to the massive consumption of disposable items during Hajj and Umrah seasons, when millions of pilgrims and visitors come every year from other countries (Anjum et al., 2016). Examples of activities that contribute to the large generation of plastic waste include the use of disposable polystyrene plates for the regular provision of food in KSA (Miandad et al., 2016) and the use of plastic zam-zam water cups where about 2 million plastic cups were disposed of each day through Ramadan season, and about the same number in Hajj time (Nizami et al., 2015b). There is no regular sorting of plastic waste and collection for recycling is not economical for low-density polystyrene (Sharuddin et al., 2016). However, polystyrene plastic has the highest oil yield (90-97wt%) and high calorific value (43 MJ/kg) in comparison to other plastics, which makes it a valuable source of energy (Sharuddin et al., 2016) and suitable for pyrolysis. Pyrolysis does not require much water in comparison to incineration, which typically requires steam to run a turbine to produce energy (Walker, 2012); this is an advantage since KSA has limited to water resources.

Gasification has some of the same advantages as pyrolysis as it can also produce a fuel product (synthetic gas) and does not produce dioxins (Chidambarampadmavathy et al., 2017). Gasification benefits include energy production and also recovery of valuable recyclables such as metals and glass (RTI, 2012). However, pyrolysis has several benefits over gasification for plastic waste conversion. For instance, the pyrolysis operation temperature range is between (300–850 °C) which is lower than gasification (900–1100 °C), thus reducing the energy demand, also pyrolysis occurs in the absence of oxygen whereas gasification produces CO or CO_2 gas.

Although it would be possible to produce energy from plastic waste using incineration to generate steam to run a steam turbine generator, there are a number of disadvantages with this technology. For example, incineration requires a huge amount of daily feedstock as well as a huge capital investment cost (Areeprasert et al., 2017). In addition, high temperatures are needed, as well as complex gas flue washing systems that add to the overall cost of the facility (Czajczynska et al., 2017). Also, there is a lot of controversy about the incineration of plastic waste and it is environmental impact due to the release of greenhouse gases, creation of dioxins from polyvinyl chloride and production of nitrogen oxides from polyamides (Bockhorn et al., 1998). Finally, for AD technology, there are few plants that do take plastics, however, it is usually not profitable.

4.2.2.2 Operational Aspect

The results of evaluating the WTE technologies in terms of the operational aspects most suitable for local conditions are presented in Table 4-18. This analysis shows that pyrolysis was found most suitable of the four technologies examined. Further discussion of these results is included in the following sections.

Table 4-18 Evaluation of WTE technologies in terms of operational aspects

Operational Aspect	Incineration	AD	Gasification	Pyrolysis
Energy requirement (temperature)	1	3	1	3
Capacity (scale and peak load)	3	1	2	2
Total	**4**	**4**	**3**	**5**

4.2.2.2.1 Energy requirement

From the results, AD was found to be most suitable in terms of energy requirement, as it can operate at much lower temperatures than the other WTE technologies. AD technology is sensitive to the operational temperature and in most situations, the mesophilic temperature (moderate temperature) range between 35-48°C is recognized as the most stable. Operation at higher temperatures greater than 50°C can require smaller reactor volumes, and heating and insulation. In colder climates, cryophilic AD (low temperatures) has been favorably employed for small-scale digesters (Vögeli, 2014). Accordingly, the standard temperature range of 35°C to 48°C is well-suited to the environment in KSA, since this corresponds to the local temperature throughout the year, making AD technology an ideal option for treating food waste without needing to supply additional heating.

Thermal technologies such as incineration, gasification and pyrolysis are controlled processes where the temperature and other parameters are specified. They may require additional energy inputs to reach the required temperatures for the reactions to occur. For incineration, it is essential for the reaction temperature to reach between 750°C and 1450°C for waste decomposition (Beyene et al., 2018; Hinchliffe, 2017). For gasification, temperatures of 900°C to 1100°C are required, with a controlled amount of oxygen and steam (Whiting, Wood, & Fanning, 2013). During pyrolysis, thermal decomposition takes place at temperatures between 300°C and 850°C in the absence of oxygen (Chhabra et al, 2016; Hinchliffe, 2017), with optimum temperatures between 450°C to 550°C (Miskolczi et al., 2009). Thus, pyrolysis operates at lower temperatures than the other thermal technologies making this technology more favorable in terms of energy required.

4.2.2.2.2 Plant Scale (capacity and peak load)

From the results, incineration was found to be most suitable in terms of plant scale (i.e. capacity and peak load) for KSA. Comparison of standard capacities for the WTE technologies based on existing facilities in the world indicate that incineration can process about 1500 tons of waste per day, pyrolysis and gasification can handle 10-100 tons of waste per day, and finally around 500 tons of waste per day can be processed by AD technology (Hinchliffe, 2017;Perrot & Subiantoro, 2018;World Energy Council, 2016). As incineration has the greatest capacity for processing waste per day, it is the most suitable option for handling future peak loads of waste during the busy seasons. For the other WTE technologies with smaller capacity, the installation of a feedstock storage unit should be considered when planning for a future WTE plant, as this would help operation when the incoming targeted waste availability is either higher or lower than plant capacity. For example, in Makkah city, MSW generation peaks during Hajj and Umrah and could exceed plant capacity. Another way to handle the MSW peak load is to merge MSW management between Makkah city and Jeddah, which is the second biggest city in KSA and 40 km away, with it is own waste management facilities.

4.2.2.3 Summary – specific criteria evaluation

Four WTE technologies (incineration, AD, gasification and pyrolysis) were evaluated based on two specific local criteria: local waste composition (in particular the major components of food and plastic waste) and operational aspects. As shown in Table 4-19, AD and pyrolysis were the most suitable WTE technologies considering these local criteria.

4.2.3 Overall evaluation of WTE technologies based on all criteria

Four WTE technologies (incineration, AD, gasification, and pyrolysis) have been evaluated and the overall results based on scores from the general and specific local criteria are shown in Table 4-20 (not weighted) and in Table 4-21 (following the weightages outlined in Table 4-12). The evaluation shows that incineration is the most attractive choice after AD and pyrolysis technologies. It is a mature WTE technology and can process almost any MSW effectively. However, the high moisture content in the MSW from KSA due to the large amount of food waste does not make incineration a preferable choice to treat food waste in KSA. In addition, incineration scored poorly on environmental sustainability in comparison to the other thermal WTE technologies. The weightings in Table 4-21 indicate that in this study, priority was given to WTE technologies that were suitable for the specific local criteria: MSW rich in food and plastic wastes rather than mixed wastes, low energy requirement and capacity suitable for the seasonality of MSW generation in KSA .

Table 4-19 Final evaluation of WTE technologies for the specific (local) criteria

Special Criteria		Incineration	AD	Gasification	Pyrolysis
Waste Compositions					
i.	**Food Waste**	1	3	1	1
ii.	**Plastic Waste**	2	1	2	3
Operational aspects					
i.	**Energy requirement**	1	3	1	3
ii.	**Capacity (scale)**	3	1	2	2
Total		7	8	6	9

The results from the overall evaluation of WTE given in Table 4-21 show that AD and pyrolysis are the most attractive WTE solutions for KSA. AD is environmentally friendly and economically viable and is also compatible with the large food waste component of MSW in KSA. However, a significant deficiency of AD technology is its low capacity and slow waste processing. Pyrolysis suitable for processing the large plastic waste component of MSW in KSA. It is more environmentally sustainable in terms of gas emissions in comparison to the other thermal technologies and it is economically feasible since it has a high efficiency for energy production and produces useful by-products. Furthermore, in comparison to incineration, pyrolysis does not require water for energy generation, and is more suitable for KSA, where water resources are scarce, however disadvantages are it is high capital cost, complexity, and low level of maturity. Although AD and pyrolysis appear the most compatible WTE solutions for KSA, more detailed analysis is required to determine the impact of policies driven by Vision 2030 where increases in MSW are expected with the targeted increase in Hajj and Umrah visitors and also where decreases in MSW may be encouraged in keeping with global sustainability goals to reduce food waste and plastics. The remaining chapters of this thesis will explore these case studies and report on the effect on WTE outcomes.

Table 4-20 Overall evaluation of WTE technology without weightage

Criteria		Incineration	AD	Gasification	Pyrolysis
Waste composition					
i.	**Mixed Waste**	3	1	2	2
ii.	**Food Waste**	1	3	1	1
iii.	**Plastic Waste**	2	1	2	3
Sustainability					
i.	**Economy**	3	3	2	2
ii.	**Environment**	1	3	2	3
iii.	**Social**	1	2	2	2
Technology requirement					
i.	**Capital Cost**	2	3	2	2
ii.	**Labour**	3	3	1	1
iii.	**Complexity**	2	3	1	1
iv.	**Efficiency**	2	3	2	3
Operational Aspects					
i.	**Energy requirement**	1	3	1	3
ii.	**Capacity**	3	1	2	2
Total		**24**	**29**	**20**	**25**

Table 4-21 Overall evaluation of WTE technology with weightage

Criteria		Weightage	Incineration	AD	Gasification	Pyrolysis
Waste composition						
i.	**Mixed Waste**	**1**	3	1	2	2
ii.	**Food Waste**					
iii.	**Plastic Waste**	**2**	2	6	2	2
		2	4	2	4	6
Sustainability						
i.	**Economic**	**1**	3	3	2	2
ii.	**Environment**	**1**	1	3	2	3
iii.	**Social**	**1**	1	2	2	2
Technical Requirement						
i.	**Capital Cost**	**1**	2	3	2	2
ii.	**Labour**	**1**	3	3	1	1
iii.	**Complexity**	**1**	2	3	1	1
iv.	**Efficiency**	**1**	2	3	2	3
Operational Aspects						
i.	**Energy requirement**	**1.5**	1.5	4.5	1.5	4.5
ii.	**Capacity**	**1.5**	4.5	1.5	3	3
Total			**29**	**35**	**24.5**	**31.5**

CHAPTER 5. METHODOLOGY FOR PREDICTION OF WASTE-TO-ENERGY OUTCOMES

The purpose of this chapter is to present the scope of the calculations and the assumptions used to predict WTE outcomes (energy produced and the electricity generated, as well as the economic benefit from landfill diversion and electricity savings) for KSA and the city of Makkah, where Hajj and Umrah occur. In Chapter 4, AD and pyrolysis were evaluated as the most suitable WTE technologies for KSA, and will be used to calculate WTE outcomes for food and plastic wastes in the MSW.

The methodology will be described in the subsequent sections where Section 5.1 outlines the estimation of the population and the waste generation of KSA and Makkah residents, Hajj pilgrims, and Umrah visitors in 2030; Section 5.2 describes the calculation for energy production and power from AD and pyrolysis technologies; Section 5.3 describes the economic savings calculations in for landfill diversion and electricity production and Section 5.4 describes the assumptions used for different case studies based on the future growth as well as potential reduction of the MSW by 2030.

5.1 Population and waste generation estimates

Estimations of the population and waste generated by the local population in KSA and Makkah, as well as during Hajj and Umrah are important in order to predict WTE outcomes. Here, 2016 was considered a baseline year for predicting the local population and waste generated in 2030 for KSA and Makkah City, as well as during Hajj and Umrah using the Vision 2030 targets for visitors. All the estimates of population and waste generation growth rate and relevant time period are summarized in Table 5-1 and further discussed in the following sections.

5.1.1 KSA

KSA has experienced considerable growth in the last four decades due to the profits generated from the production of crude oil resulting in substantial improvements in the socio-economic conditions in KSA. The total population of KSA has been increasing from 7 million in 1975 to 27 million in 2010 corresponding to an annual population growth rate of 3.4% (Ouda et al., 2013), therefore this growth rate was used to forecast the increase in future population by the year of

2030. The current rate of waste generation is reported as 1.4 kg per person per day (PPPD) (Nizami et al., 2015a), and was used over 365 days to calculate the waste generation in KSA in 2030.

5.1.2 Makkah residents

The local population of Makkah has grown at an annual rate of 3.15% as a result of the economic opportunities and migration from countryside areas (Nizami et al., 2015b) and this rate was used to predict the population of Makkah residents in 2030. The rate of waste generation was assumed to be similar to that used for KSA (1.4 kg PPPD for 365 days) (Rehan et al., 2016).

5.1.3 Umrah visitors

Umrah visitors to Makkah have increased from one million in the 1990s to 5 million in 2011 (General Authority for statistics, 2016) and in 2016, surpassed 8 million visitors. This continued increase has led to a substantial expansion of the Two Holy Mosques. As part of KSA's national Vision 2030 plan, the government seeking to further increase the growth of Umrah visitors, to reach 30 million by 2030. Thus, in this study, the annual growth rate was assumed to be 20% for Umrah according to the Vision 2030 target. Estimates of the MSW generated by Umrah visitors in 2030 were based on the assumption that each Umrah visitor will stay for an average period of 10 days in the peak month of Ramadan and will produce on average 2.05 kg PPPD (Rehan et al., 2017).

5.1.4 Hajj pilgrims

The Hajj pilgrims have been increasing by 1.15% on an annual basis due to normal growth. However, as part of the Saudi Vision 2030 plan, the government are looking to have 6 million pilgrims to perform Hajj annually by 2030. Therefore, the increase rate for Hajj pilgrims used in this study was 10.3%. It was also assumed that the pilgrims would generate MSW over 7 days, corresponding to the duration of the Hajj rituals and that the rate of waste generation would be 2.2 kg PPPD (Nizami et al., 2015b).

Table 5-1 Population growth, MSW generation rates and time period for KSA, Makkah, Umrah, and Hajj estimates

	Population Growth and Waste Generation Rates		Time Period
	Population	MSW	
KSA	3.4% per year	1.4 kg PPPD	365 days
Makkah	3.15% per year	1.4 kg PPPD	365 days
Umrah	20% per year	2.05 kg PPPD	10 days
Hajj	10.3% per year	2.2 kg PPPD	7 days

5.1.5 Waste stream characterization

As mentioned previously, the major waste categories in KSA are food waste representing 50.6% of total waste, followed by 17.4% plastics, 12.0% paper and 6.6% cardboard (Figure 4-1) (Nizami et al., 2015a). In this study, the composition of MSW generated by Makkah residents and by Umrah visitors was assumed to be similar to the MSW for KSA, as Makkah is a city in KSA and Umrah is practiced by visitors whose activities are conducted amongst the local population, according to the approach taken by Nizami et al. (2015b). As the waste management differs for Hajj with the event occurring in a more limited time and space and under heavy regulation, a different waste composition was assumed for MSW generated by the Hajj pilgrims: 38.96 % food, 36.48%, plastic 13.75% paper & cardboard, 8.96% aluminum and 1.85% Textile (Figure 4-1) (RACI, 2018). The food waste in all cases was considered to have around of 38.4% moisture (Nizami et al., 2015b). The caloric energy content of the various types of waste are listed in Table 4-3 and were used to calculate the total energy content per kg of the MSW**.**

5.2 Energy calculation

The calculations used to convert food and plastic wastes to energy and power for AD and Pyrolysis technologies will be illustrated in following sections. These calculations were based on the approach used in other studies (Nizami et al., 2017; Nizami et al., 2015b; Rehan et al., 2016; Shahzad et al., 2017) and are represented in the flow diagram shown in Figure 5-1. Standard values obtained from literature that were used for energy calculations are summarized in Table 5-2.

5.2.1 AD biogas calculation

The total volume of biogas produced per year from AD of food waste (Mm^3/year) was calculated using Eq. 1, where the amount of biogas produced from AD per ton of food waste estimated as 180 m^3. The total energy obtained from AD of the food waste was calculated with Eq. 2 using an energy content of 22 MJ/m^3 of biogas (Banks, 2009).

Biogas produced (Mm^3/year) = Quantity of food waste (Mt/year) * 180.6 m^3/t   Eq. 1

Energy from food waste (M.MJ/year) = Biogas produced (Mm^3/year) * 22 MJ/m^3 Eq. 2

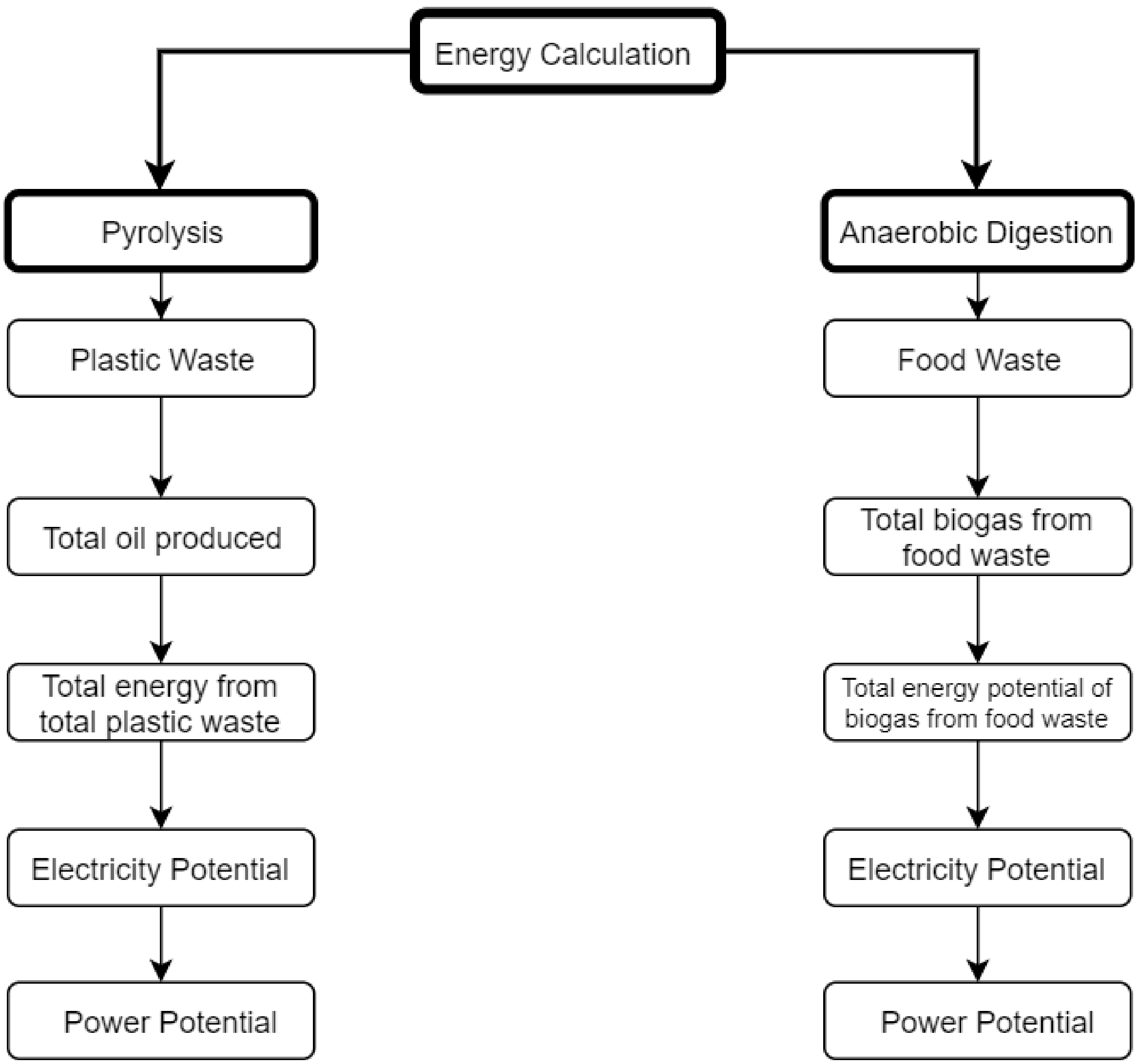

Figure 5-1 Diagram summarizing energy calculations for pyrolysis and AD

5.2.2 Pyrolysis biodiesel (liquid fuel oil) calculation

The total quantity of oil produced per year from the pyrolysis of plastic waste (Mkg/year) was calculated using Eq. 3, where the yield of liquid fuel oil per ton of the plastic waste using pyrolysis was assumed to be 0.8 ton (Nizami et al., 2015b). The total energy obtained from the pyrolysis of plastic waste was calculated with Eq. 3 using a heating value (HV) for biodiesel (liquid fuel oil) of 40 MJ/kg (EPA, 2012).

Oil produced (Mt/year) = Total Plastic Waste (Mt/year) * Oil yield from pyrolysis (80%) Eq. 3

Energy from plastic waste (MMJ) = Oil produced (Mt) * 40,000 (MJ/t) Eq. 4

5.2.3 Power calculation

The electricity potential (MWh) was calculated with Eq. 5 using the estimated energy from food or plastic waste (Eq. 3 and 4). Then, Eq. 6 was used to calculate the potential electrical power (MW) in a year. The actual electrical power generated in a year was calculated using Eq. 7, where the process efficiency for biogas was 35% and 33% for liquid fuel oil (Nizami et al., 2015b).

To calculate the electricity potential, see Equation.

Electricity potential (MWh)= Total energy from waste (food or plastic) (MJ) /3600 (MJ/MWh) Eq. 5

Potential Power (MW/year)= Electricity potential (MWh) / 8760 (hour/year) Eq. 6

Actual power (MW)= Potential Power (MW)* Process efficiency for AD or pyrolysis Eq. 7

Table 5-2 Standard literature values for energy estimations from AD and pyrolysis (Banks, 2009; EPA, 2012; Nizami et al., 2010; Nizami et al., 2015a; Nizami et al., 2015b)

AD Biogas yield	Pyrolysis fuel oil yield
Typical biogas value from food waste = **180.6 m^3/ton** Biogas energy potential = **22 MJ/m^3 of biogas or 6.1 kWh/m^3 of biogas** Time basis =**8760 Hour Per Year** Process efficiency =**35%**	Typical fuel oil production from pyrolysis **(1 kg of mixed plastic (PE, PP and PS type) = 0.8 kg oil** Pyrolysis oil energy potential= **40 MJ/ Kg** Time basis= **8760 Hour Per Year** Process efficiency =**33%**

5.3 Economic savings

The economic savings from WTE conversion of food and plastic wastes using AD and pyrolysis were calculated based on the potential savings from landfill diversion and electricity generation. The following sections describe the calculations in detail and a diagram summarizing the approach is shown in Figure 5-2. The calculations for economic savings were based on previous studies by other researchers (Nizami et al., 2017; Nizami et al., 2015b; Rehan et al., 2016; Shahzad et al., 2017).

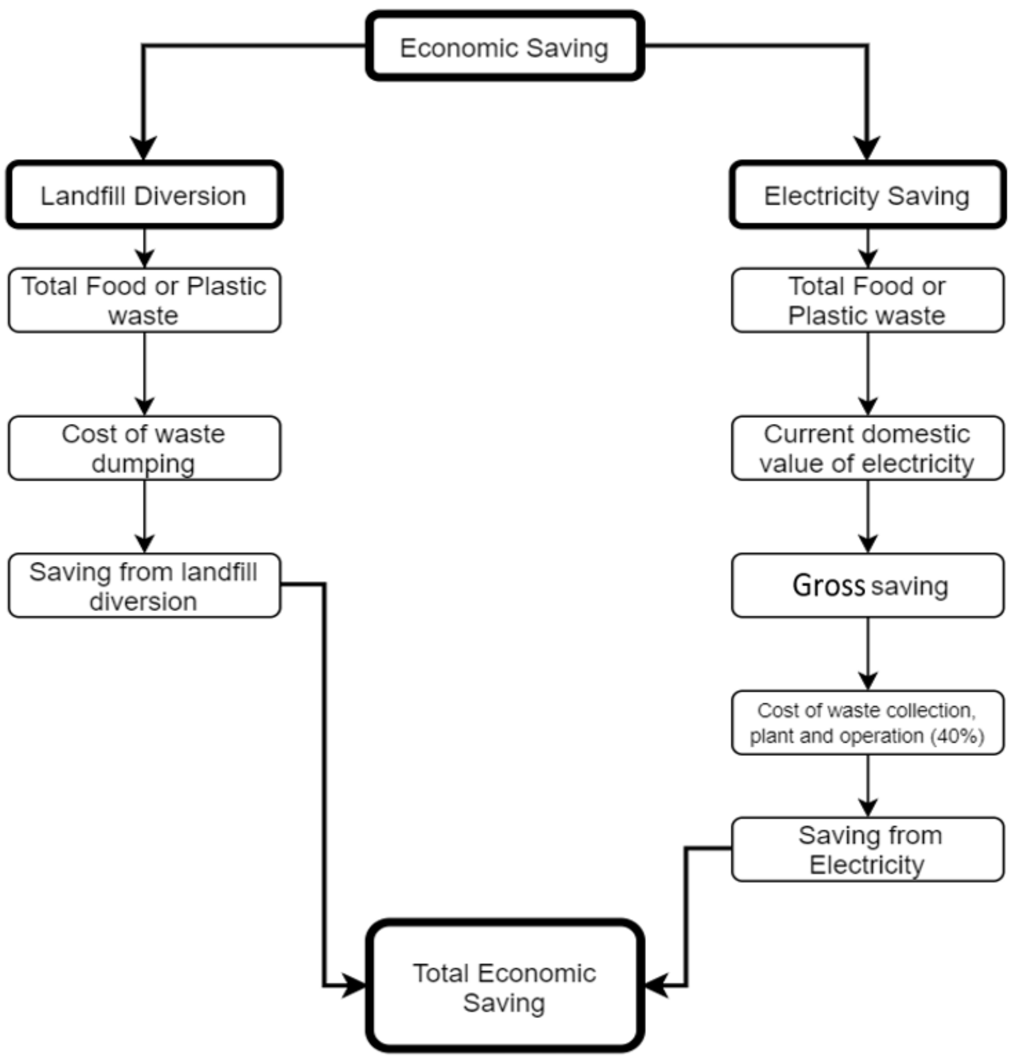

Figure 5-2 Diagram summarizing economic savings calculations from landfill diversion and electricity for pyrolysis and AD

5.3.1 Landfill savings

The waste diverted from the landfill and converted to energy through WTE processing would result in economic savings. In this work, the cost of MSW disposal in a landfill was assumed to be 567 SAR (151.2 USD) per ton of waste. Thus, the savings from landfill diversion was calculated using Eq. 8.

Landfill Saving (SAR/year) = Total waste (food or plastic) Mt/year * 567 SAR/t Eq. 8

5.3.2 Electricity savings

The revenue obtained from electricity generation using AD and pyrolysis for WTE conversion would result in economic savings. In order to calculate this, the total energy value of the food or plastic waste stream obtained from AD or pyrolysis was determined using Eq. 2 and Eq. 4. Then the gross electricity savings were calculated (Eq. 9) where an electricity tariff of 0.32 SAR/kWh was used (Shahzad et al., 2017). The net revenue from electricity generation was then calculated from the gross savings by deducting the cost of waste collection and plant operation (estimated at 40% of the gross electricity savings) (Eq. 10).

Gross Electricity Saving (SAR) = Total energy value of Food or Plastic (kWh) * 0.32 (SAR/kWh) Eq. 9

Net revenue from electricity generation (SAR) = Gross Electricity Saving (SAR) * 0.4 Eq. 10

5.3.3 Total net revenue

The total net revenue was calculated by adding the savings due to diversion of MSW from landfill sites, and net revenue collected from electricity generation (Eq. 11).

Total net revenue (SAR) = Landfill diversion saving (SAR) + Net revenue from electricity generation (SAR) Eq. 11

5.4 Waste reduction scenarios

In this research, different waste reduction scenarios were simulated for KSA, Makkah, Umrah and Hajj, and their predicted WTE outcomes in 2030 were compared. The purpose was to assess the impact of possible policy changes that may target one or both of the main components in the waste stream (food and plastic). The assumption is based on the global trends and, local and international plan that aiming to reduce MSW, particularly food and plastic waste, by almost half by 2030. For all scenarios, 2016 was used as the base-line year for population estimations with 2030 as the target, using the appropriate population growth rate (either historic or considering Vision 2030). Waste composition data from 2016 was used for waste generation estimates and modified according to the reduction policy. The following waste reduction scenarios for this research are described below.

- *Scenario 1 (S1): Current practice.* This assumes that there would be no reduction of food or plastic waste by the year of 2030.
- *Scenario 2 (S2): Reduction of food and plastic wastes by 50%.* This assumes there would be reduction of both food and plastic waste by 50% in the year of 2030.
- *Scenario 3 (S3): Reduction of food waste by 50%.* This assumes there would be a reduction of food waste by 50% in the year of 2030.
- *Scenario 4 (S4): Reduction of plastic waste by 50%.* This assumes there would be a reduction of plastic waste by 50% in the year of 2030.

CHAPTER 6. RESULTS AND DISCUSSION

In Chapter 4, a comparative analysis was conducted, and AD and pyrolysis were evaluated as the best WTE technologies for further investigation. Chapter 5 then described the methodology used to estimate the WTE outcomes from using AD and pyrolysis to process the food and plastic waste components of MSW. In this section, results are first reported for predicted population numbers and quantity of MSW as well as food and plastic wastes generated in 2030. Then the WTE outcomes for various waste reduction scenarios are presented for KSA, Makkah, Umrah and Hajj, followed by the general impact of the waste reduction scenarios. Then, the impact of Vision 2030 on increasing visitors during Hajj and Umrah above the historical or "normal growth" rate is discussed as well as the impact on Makkah's energy sector and local economy. More detailed results are found in Tables A1-A48 of the Appendix.

6.1 Population and MSW generation of the studied areas

This section will present predictions of KSA and Makkah city population and visitors during Umrah and Hajj, as well as the estimated quantity of MSW generated for 2030.

6.1.1 Projected population

The results for projected population and visitors in 2030 considering Vision 2030 targets are shown in Figure 6-1. It can be seen that the KSA population will be projected to reach 52.3 million in 2030, which is an increase of 60% from 31.7 million in 2016. For Makkah, the local population will reach 3.1 million in 2030 from 2.03 million in 2016. If historical growth rates are used for Umrah visitors, it would be expected that the total number of visitors would grow from 8 million in 2016 to about almost 14 million in 2030. However, the Vision 2030 target for Umrah visitors is 30 million in 2030, which is a drastic increase and close to the entire population of KSA in 2016. Using the historical growth rates for Hajj pilgrims, it would be predicted that in 2030 there would be just over 4 million Hajj pilgrims compared with 2.5 million in 2016 (Ascoura, 2013). The Vision 2030 target for Hajj pilgrims is 6 million pilgrims in of 2030, which is almost double the population of Makkah residents predicted in 2030.

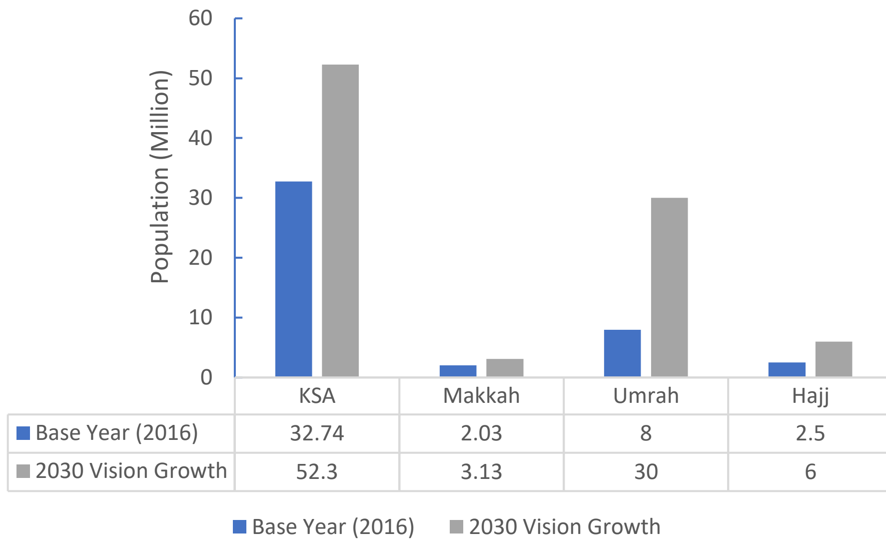

Figure 6-1 Population of KSA and Makkah residents and visitors during Umrah and Hajj in 2016 and 2030 considering Vision 2030 targets

6.1.2 Projected generation rates for MSW, food and plastic waste

The increased population in KSA and Makkah city in 2030 and Vision 2030 targets for increased numbers of Hajj pilgrims and Umrah visitors, indicates that there would also be an associated increase in the overall amount of MSW generated, assuming that there is no change in the waste composition or policies for waste reduction (Figure 6-2). The corresponding breakdown of food and plastic wastes generated are shown in Figure 6-3.

The results show that KSA is forecasted to generate 26.71 Mt of MSW by 2030, with 13.51 and 4.64 Mt of food and plastic waste generated, respectively. On the other hand, the local population in Makkah will generate around 1.6 Mt of MSW in 2030, with 0.81 Mt and 0.28 Mt of food and plastic waste generated, respectively. The MSW generation from Umrah visitors is estimated to increase significantly from 0.16 Mt in 2016 to 0.62 Mt in 2030. It is evident that although the Umrah visitors far outnumber the Makkah residents, the waste that is generated is lower, due to the relatively short duration for Umrah. The MSW generated from Hajj pilgrims will be around 0.092 Mt generated in 2030, which is much lower than for Umrah visitors and Makkah residents.

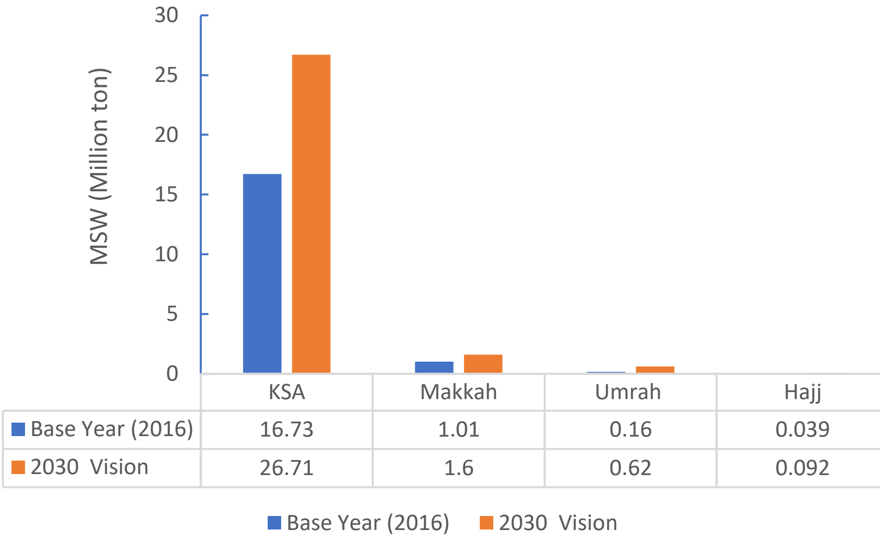

Figure 6-2 MSW generation in KSA, Makkah, Umrah and Hajj in 2016 and 2030 considering Vision 2030 targets for visitors

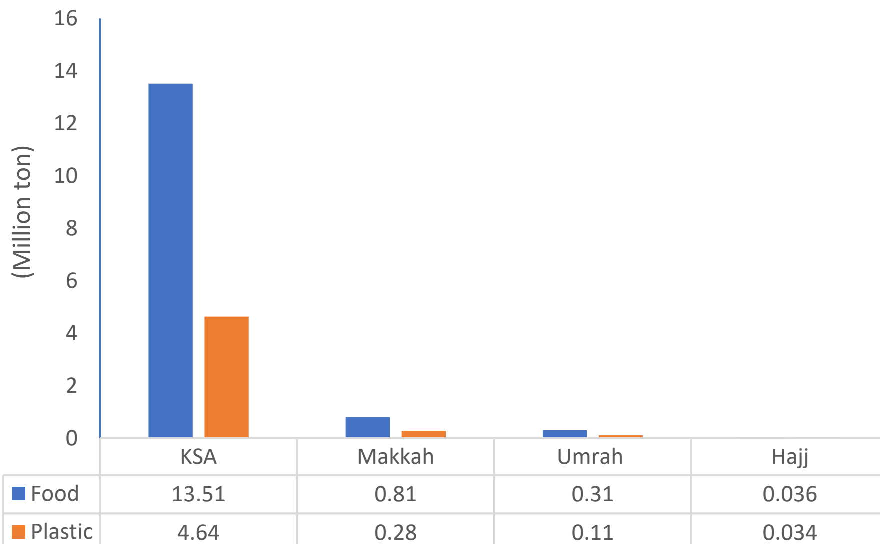

Figure 6-3 Food and plastic waste generation in KSA, Makkah, Umrah and Hajj in 2030 considering Vision 2030 targets for visitors

6.2 WTE Outputs for KSA, Makkah, Umrah and Hajj

The following section presents the WTE outcomes, energy and power potential and economic savings, from AD and pyrolysis. Results are presented for various waste reduction scenarios (current practice, reduction of food and plastic waste by 50%, reduction of food waste by 50% and plastic waste reduction by 50%) for each of the studied areas (KSA, Makkah, Umrah and Hajj) in 2030.

6.2.1 KSA

The following section will illustrate the energy production, power production, and economic saving of electricity and landfill diversion from AD and Pyrolysis technologies in KSA.

6.2.1.1 Energy produced

The results for the total energy potential for different waste reduction scenarios in KSA are shown in Table 6-1 and Figure 6-4. Out of all the scenarios, the total potential energy from AD and pyrolysis for the current practice (with no change in waste composition) had the highest energy production of 202,472 TJ, with most of the predicted energy obtained from pyrolysis of plastics (148,760 TJ) and the remainder is from AD of food waste (53,712 TJ). The scenario with both food and plastic waste reduction of 50% would produce a total energy of 101,236 TJ, which is approximately half of what would be produced with the current practice scenario, and has the lowest energy production of all the scenarios, which is not surprising as it has the least amount of waste. However, the scenario with 50% plastic waste had less total energy produced (128,092 TJ) than the scenario with 50% food waste (175,616 TJ). For the scenario with 50% plastic reduction, it should be noted that unlike the other scenarios where the energy from pyrolysis of plastic is much greater than from AD of food waste, the energy from pyrolysis is only slightly greater than from AD.

KSA’s primary energy consumption is comprises of oil (55%) and natural gas (45%) (Shahzad et al., 2017). In KSA, the lack of renewable energy contribution and massive dependence on fossil fuels might lead to the loss of natural resources in the future. In 2016, KSA was the world's 10th highest consumer of energy with a total of 270 million tons of oil equivalent (10.5 million TJ) (EIA, 2017a). It has been reported that the region’s domestic fuel demands will be doubled by 2024, which means most of KSA’s energy production will be consumed locally; though, KSA could become a net energy importer by 2020-2038 if current consumption rates continue

(ArabNews, 2017). However, introducing energy recovery in the form of WTE in KSA could partly reduce the dependency on fossil fuels, which is one of the goals of Vision 2030, to diversify the country's economy and reduce the reliance on oil. The total energy of 202,472 TJ from the food and plastic waste in the current practice scenario is comparable to the total energy consumption in Hong Kong during 2012 (around 280,000 TJ) and could contribute 1.14% of the total energy consumption for KSA in 2030, which is approximately 17,630,000 TJ based on growth rate of 1.02%.

Table 6-1 Total energy potential for various waste reduction scenarios for KSA in 2030

	AD			Pyrolysis			AD+Pyrolysis
Scenario	Total Food Waste (Million ton)	Total biogas production (Million m^3)	Total energy potential (TJ)	Total Plastic Waste (million ton)	Total fuel oil production (Million Kg)	Total energy potential (TJ)	Total energy potential (TJ)
Current Practice	13.51	2,441	53,712	4.64	3,373	148,760	202,472
Food+Plastic Reduction	6.75	1,220	26,856	2.32	1,686	74,380	101,236
Food Reduction	6.75	1,220	26,856	4.65	3,373	148,760	175,616
Plastic Reduction	13.51	2,441	53,712	2.32	1,686	74,380	128,092

6.2.1.2 Power potential and electricity demand

The electricity peak demand in KSA for the base year of 2016 is assumed to be 55 Gigawatt (GW) and is projected to reach 112 GW by the year of 2030 based on (Ouda et al., 2013) data. Moreover, the current and existing electricity demand by population is 54 GW and will reach up to 85 GW by the year of 2030 (Ouda et al., 2013). Therefore, there will be a gap between the two electricity demands by 2030 which is around 28 GW as shown in Figure 6-5. This gap in electricity demand will be used as framework to compare the potential power obtained from the WTE in KSA for the different waste reduction scenarios, where the food and plastic that will be processed by AD and pyrolysis can provide electricity to the national grid to reduce the future gap.

Table 6-2, Table 6-3 and Figure 6-6 show that the current practice scenario has the highest production of power in KSA by the year of 2030 with total power of 2.15 GW (0.6 GW from AD and 1.5 GW from pyrolysis), and this value will form about 7.7% of the 28 GW gap in KSA by 2030. In the food reduction scenario, the total actual power shrank to 1.85 GW due to the reduction of food waste by half, with most of the energy from pyrolysis since the plastic waste was not reduced in this scenario, and this could contribute as much as 6.6% of the 28 GW gap in KSA. For the scenario with 50% plastic reduction, the total power would be 1.4 GW, or around 5% of the KSA power gap. The lowest amount of power produced for KSA was 1.07 GW from the scenario where both food and plastic waste were reduced by 50%, contributing to around 3.8% of the total KSA power gap.

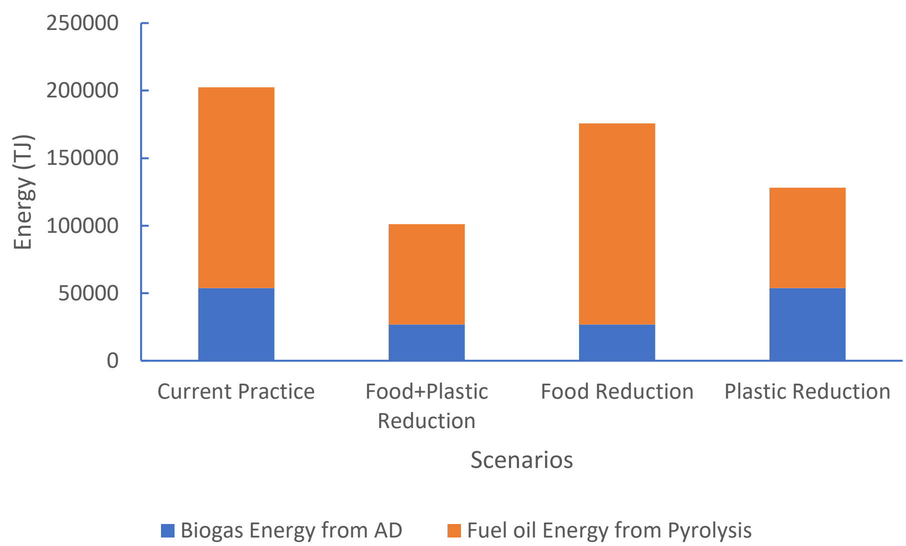

Figure 6-4 Energy from different waste reduction scenarios in KSA in 2030

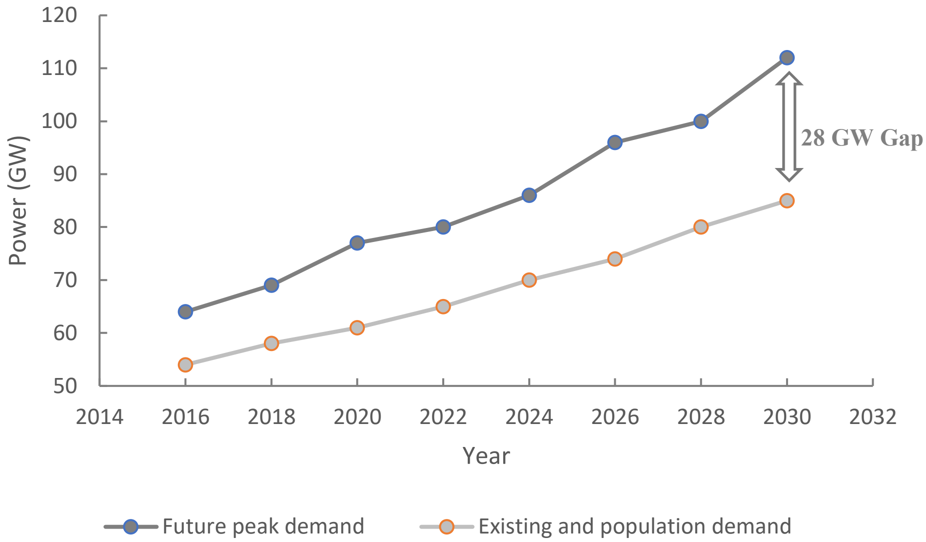

Figure 6-5 Power demand for KSA and the potential gap between future peak and population demand in 2030

Table 6-2 Electricity and power from different waste reduction scenarios for KSA in 2030

	AD				Pyrolysis				AD+Pyrolysis
Scenario	Total Food Waste (million ton)	Electricity potential (Gwh)	Power Potential (GW)	[1]Actual Power (GW)	Total Plastic Waste (million ton)	Electricity potential (Gwh)	Power Potential (GW)	[2]Actual Power (GW)	Total Actual Power (GW)
Current Practice	13.51	14,920	1.70	0.6	4.64	41,322	4.7	1.5	2.15
Food+Plastic Reduction	6.75	7,460	0.85	0.3	2.32	20,661	2.3	0.77	1.07
Food Reduction	6.75	7,460	0.85	0.3	4.65	41,322	4.7	1.5	1.85
Plastic Reduction	13.51	14,920	1.70	0.6	2.32	20,661	2.3	0.77	1.37

[1]After 35% process efficiency for AD technology

[2]After 33% process efficiency for Pyrolysis technology

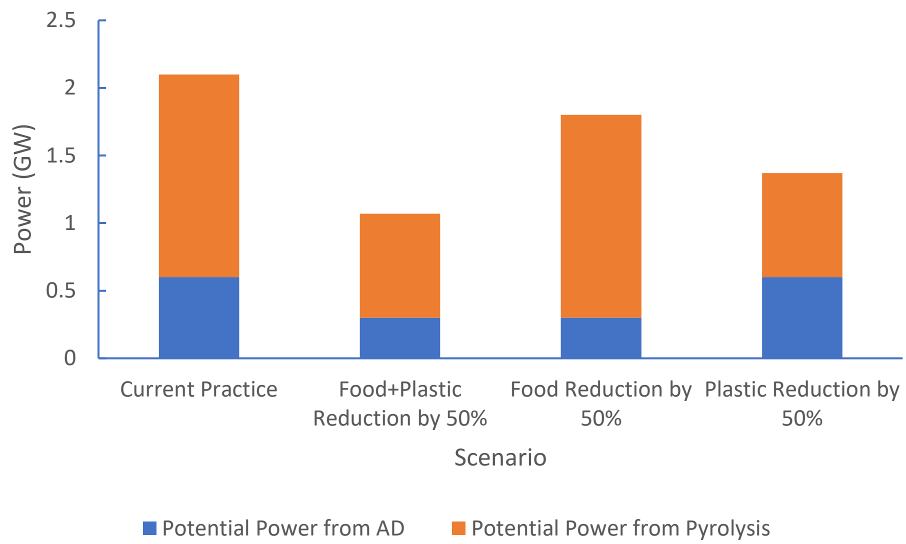

Figure 6-6 Power from different waste reduction scenarios for KSA in 2030

Figure 6-6 also indicates that the power production in each scenario is dependent mainly on the power produced by pyrolysis technology despite the quantity of the plastic waste for each scenario, and the reason is that plastic waste holds more energy than food waste (Table 6-2). Also, it should be noted that for each technology, the amount of actual power generated differs for two main reasons: (1) the different efficiencies for each technology, and (2) the various energy content from food and plastic.

Various researchers have examined the power and electricity demand of KSA and have concluded that there will be a high consumption of electricity especially for air-conditioning and this will require more capacity to cope with future demand. According to Ouda et al. (2013) and Nizami et al. (2015a), the demand of electricity for cooling purposes in KSA is significantly high due to hot weather. Khan and Kaneesamkandi (2013) illustrate that around 30% of domestic electricity is only consumed for refrigeration usage. Other researchers have predicted that the electricity demand in KSA will be 120 GW in 2032 (Aga et al., 2014; Al Garni et al., 2016; Ouda et al., 2016). According to Ouda et al (2013), there will be a gap of 60 GW between the peak demand of 120 GW and existing and planned capacity of around 60 GW by 2032 and incineration (mass burn of MSW in KSA) could provide about 2,073 MW (2.073 GW) of power in 2032, contributing around 1.7% of the 120 GW peak electricity demand and about 3.3% of the 60 GW gap. The same authors estimated power generation in 2035 (Ouda et al., 2016) predicting 1,447 MW from incineration technology and 699 MW from RDF with biomethanation.

Table 6-3 Potential power contributions from different waste reduction scenarios for KSA in 2030

Scenarios	Power (MW)	Contribution % of KSA Power Gap (28 GW)
Current Practice	2.15 GW (2150 MW)	7.7%
Food+Plastic Reduction	1.07 GW (1070 MW)	3.8%
Food Reduction	1.85 GW (1850 MW)	6.6%
Plastic Reduction	1.4 GW (1400 MW)	5%

KSA maintains 16% of world's electricity production, and it is the 12th biggest consumer of generated electricity (Export, 2018). Since oil is the main source of energy for generating power in the country, the Saudi Electricity Company (SEC) intends to reduce direct crude oil burn usage for electricity generation by utilizing more natural gas, in tandem with plans to expand renewable sources for electricity generation. At present, KSA does not have an official policy framework for the development and regulation of a renewable energy market, and the Electricity Law in the kingdom still does not cover renewable energy sources. However, as part of it is Vision 2030 plan to improve the overall energy strategy KSA has announced several goals to set up a legal framework that will help develop and oversee a renewable energy market (Aman, 2018).

As a fundamental component of Vision 2030, the National Renewable Energy Program (NREP) has been established, as part of a long-standing plan intended to balance the national power mix to increase the economic stability for KSA. According to Aman (2018), the program aims to mainly increase the portion of renewable energy in the total energy mix, targeting the generation of 3.45 GW of renewable energy by 2020 and 9.5 GW by 2023. In addition, the program has presented several renewable energy projects such as a 300 MW solar plant and around 2.5 thousand MW wind energy plants (Kabbara, 2018).

6.2.1.3 Economic savings

Besides energy generation and power production, the development of WTE technologies such as AD and pyrolysis will further benefit the KSA economically and environmentally. Landfill diversion could save millions of SAR in waste disposal, reduce land requirements and conserve natural resources. Further, the electricity saving from applying WTE site could benefit the KSA economy by limiting the use of fossil fuels where it is price fluctuating, utilizing the waste as a cheap source of energy as well as boosting the national grid with the extra power that might be needed to cope with peak demand.

The economic savings from the different waste reduction scenarios for KSA are summarized in Table 6-4 and Figure 6-7 shows a comparison of the landfill savings and electricity savings from AD and pyrolysis. It is estimated that in 2030 a net revenue of 13,922 million SAR will be added to the national economy with the current practice scenario, which is the highest savings in comparison to the other scenarios, with the total savings from AD of 8,668 million SAR (7,665 million SAR from landfill diversion and 1,002 million SAR from electricity), while pyrolysis provides a landfill saving of 2,635 million SAR and 2,618 million from electricity sales. The lowest savings for KSA are obtained from the scenario where both food and plastic waste are reduced by 50%, where the total savings from AD and pyrolysis are estimated at 6,960 million SAR. Whereas the scenario with 50% food waste has a total savings from AD and pyrolysis of 9,587 million SAR, the savings from the scenario with 50% plastic waste has a higher savings of 11,295 million SAR (8,668 million SAR from AD and 2,627 million SAR from pyrolysis).

Table 6-4 Economic savings from different waste reduction scenarios for KSA in 2030

Technology	AD			Pyrolysis			AD+Pyrolysis
Saving (Million SAR)	Landfill Saving	Electricity Saving	NET Saving	Landfill Saving	Electricity Saving	NET Saving	Total Net saving
Current practice	7,665	1,002	8,668	2,635	2,618	5,254	13,922
Policy Change By 50% (Food+Plastic)	3,832	501	4,333	1,317	1,309	2,627	6,960
Policy Change 50% (Food Reduction)	3,832	501	4,333	2,635	2,618	5,254	9,587
Policy Change By 50% (Plastic Reduction)	7,665	1,002	8,668	1,317	1,309	2,627	11,295

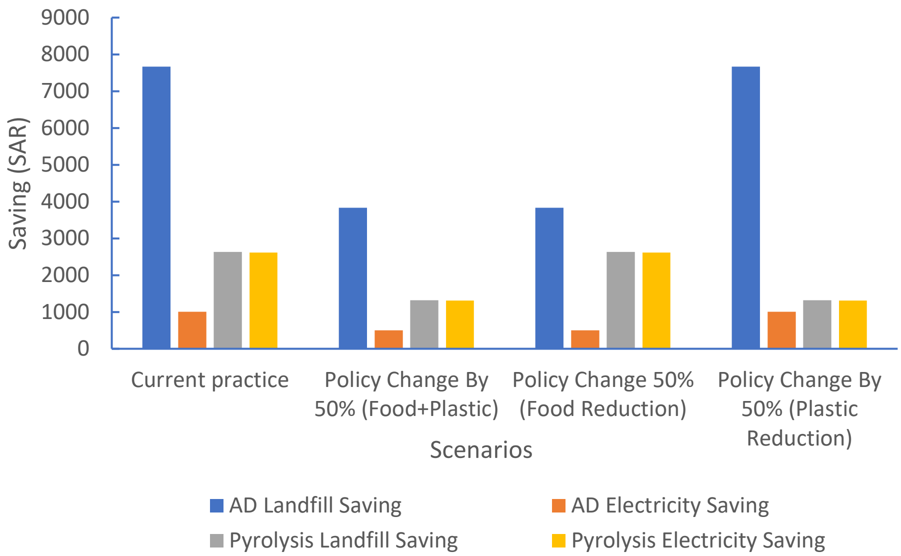

Figure 6-7 Comparison of landfill and electricity savings from different waste reduction scenarios for KSA in 2030

From Table 6-5, the current practice scenario delivers the highest landfill diversion savings of 10,251 million SAR and the scenario with 50% reduction of both food and plastic has the lowest landfill savings of 5,150 million SAR. It is evident that the landfill diversion of food waste provides more savings in comparison to the plastic waste, and the reason for this is that the amount of food waste in all scenarios is higher than the plastic waste. According to the UN Food and Agriculture Organization (FAO), around 7% of all global greenhouse gases (GHGs) come from food waste, in the form of methane (Murdock, 2017). While CO_2 is generally outlined as one of the most toxic greenhouse gases, methane is about 21-30 times more hazardous than its combustion product (Chandel et al., 2012; Murdock, 2017; Ouda et al., 2013). In KSA, GHG generation from landfills is likely to be a significant environmental issue, as more than 50% of KSA waste is food, and expected to reach 13.52 Mt by 2030. In KSA the landfill requirement in KSA is almost 3 million m^2/year (Ouda et al., 2013), where most of the landfills are mature, and are expected to reach their capacities within the next 10 years (Zafar, 2015). According to Ouda et al. (2013), continuing to manage MSW in KSA with the existing landfill management strategy will create immense environmental and economical negative outgrowths, and options such as WTE and recycling would be attractive alternatives.

Table 6-5 Landfill diversion savings from different waste reduction scenarios for KSA in 2030

Scenario	Food waste		Plastic Waste		Food+Plastic	
	Total Waste Million Ton	Total Saving Million SAR	Total Waste Million Ton	Total Saving Million SAR	Total Waste Million Ton	Total Saving Million SAR
Current practice	13.51 (50.6%)	7,665	4.64 (17.4%)	2,585	18.15 (64%)	10,251
Reduction of Food and plastic	6.75 (38.39%)	3,832	2.32 (13.20%)	1,317	9.07 (51.59%)	5,150
Reduction of Food	6.75 (33.91%)	3,832	4.65 (23.32%)	2,635	11.4 (57.23%)	6,468
Reduction of Plastic	13.51 (55.48%)	7,665	2.32 (9.54%)	1,317	15.83 (65.02%)	8,983

From Table 6-6, the highest savings from electricity sales is obtained from the current practice scenario where is no waste reduction (3,620 million SAR), with the next highest electricity savings from the scenario with 50% food reduction (3,119 million SAR) and the lowest electricity savings from the scenario with 50% plastic reduction (2,311 million SAR). The results also show that pyrolysis offers more electricity savings from plastic waste than the electricity savings from food waste via AD, due to the high energy content of plastic in comparison to food waste. Electricity production from WTE technologies would have economic advantages for KSA, since this would reduce the need to supply oil for electricity, which is the main source of energy, saving millions of SAR. As mentioned previously, KSA needs more electricity capacity in future years to meet its power demand of power, and that will cost a big portion of the country budget. For example, Electricity & Cogeneration Regulatory Authority (ECRA) calculated that KSA will need to invest 140 billion USD by 2020 in order to meet its electricity demands. There have also been recent increases in the cost of fuel used for power sector, as shown in Table 6-7, and the electricity tariff from 0.20 SAR/kWh (USD 0.05/kWh) to 0.30 SAR/kWh (USD 0.08/kWh) (Fattouh et al., 2016).

Table 6-6 Electricity savings from different waste reduction scenarios for KSA in 2030

Scenario	AD		Pyrolysis		AD+Pyrolysis	
	Food Waste (Million Ton)	Saving (Million SAR)	Plastic Waste (Million Ton)	Saving (Million SAR)	Total Waste (Million Ton)	Total Saving (Million SAR)
Current practice	13.51 (50.6%)	1,002	4.64 (17.4%)	2,618	18.15 (64%)	3,620
Reduction of Food and plastic	6.75 (38.39%)	501	2.32 (13.20%)	1,309	9.07 (51.59%)	1,810
Reduction of Food	6.75 (33.91%)	501	4.65 (23.32%)	2,618	11.4 (57.23%)	3,119
Reduction of Plastic	13.51 (55.48%)	1,002	2.32 (9.54%)	1,309	15.83 (65.02)	2,311

Table 6-7 Fuel prices in KSA used for the power sector (Fattouh et al., 2016)

Fuel	Old Prices	New Prices	% of increase
HFO	0.43	0.86	100
Gas (Methane)	0.75	1.25	67
Diesel	0.67	2.18	225
Crude Oil	0.73	1.02	40

There are several countries that have benefitted from electricity production by investing WTE technologies on waste treatment. For example, in the USA, WTE plants supplied much more energy than all other renewable energy sources excluding hydropower and geothermal energy sources, generating around 10% (9.8 GW) of the renewable electricity capacity. (National Research Council, 2010). In Malaysia, WTE technologies like Biomethanation are becoming more popular and it has been estimated that CH_4 emissions from landfills in Malaysia during 2010 are sufficient to generate 2.20×10^9 kWh of electricity worth of 219.5 million USD, with estimates of 243.63 and 262.79 million USD for 2015 and 2020, respectively (Zainura et al., 2013).

6.2.2 Makkah

Makkah city in KSA hosts many Muslim worshippers each year, thus MSW management is a big challenge for the local municipality. Unlike other studies on WTE potential that combine the MSW from Makkah, Hajj and Umrah for their analysis, this investigation examines each case separately to determine the relative impact of their WTE outcomes.

6.2.2.1 Energy produced

The results for the total energy potential for different waste reduction scenarios in Makkah predicted for 2030 are shown in Table 6-8 and Figure 6-8 The highest amount of energy produced is of 12,135 TJ from the current practice scenario where most of the energy is from pyrolysis of the plastic waste where 202.22 million kg of fuel oil generates 8,916 TJ. On the other hand, the scenario with 50% reduction of both food and plastic waste produced the lowest energy of 6,067 TJ and the scenario with 50% food reduction had the second highest energy produced at 10,526 TJ. The scenario with 50% plastic produced 7,677 TJ in total energy; it is interesting that the energy from pyrolysis of plastic waste was slightly greater (4,458 TJ) than the energy from food waste via AD (3,219 TJ), despite the reduction in plastic waste, which is similar to that reported for KSA in the previous section.

There are several studies that have investigated the potential for WTE technologies in Makkah and concluded that energy recovery would be promising given the huge amount of MSW that is produced in Makkah yearly, the high calorific values in the MSW, and large organic component. Nizami et al. (2015b) examined the potential for AD and pyrolysis, and predicted a generation of 99 million m^3 of biogas, with a total energy of 2,172 TJ, and about 224 million kg of fuel oil, with a total energy of 8,852 TJ could be achieved in 2015 if all of the food and plastic waste produced in Makkah city was converted to energy by AD and pyrolysis, respectively. In another study, Nizami et al. (2017) examined several WTE technologies for Makkah MSW, and predicted a production of 77 million m^3 of biogas, 134 thousand tons of fuel oil, 62.5 thousand tons of biodiesel, and 150 thousand tons of pellets from AD, Pyrolysis, transesterification, and RDF technologies respectively. Also, Rehan et al. (2016) projected 334,000 MWh or 8,402 TJ of energy from a total amount of 238 million tons of liquid fuel from plastic waste via pyrolysis technology (efficiency of 33%) in 2040. It should be noted that in all these energy recovery studies for Makkah city, the contribution of waste generated by visitors during Umrah and Hajj pilgrims was included with the local population of Makkah residents. In this thesis, energy produced from Makkah residents, is separated from the potential energy generated by Umrah visitors and Hajj pilgrims, so that their relative impact can be studied.

Table 6-8 Total energy potential for various waste reduction scenarios for Makkah in 2030

	AD			Pyrolysis			AD+Pyrolysis
Scenario	Total Food Waste (Million ton)	Total biogas production (Million m^3)	Total energy potential (TJ)	Total Plastic Waste (Million ton)	Total fuel oil production (Million Kg)	Total energy potential (TJ)	Total energy potential (TJ)
Current Practice	0.810	146.34	3,219	0.28	202.22	8,916	12,135
Food+Plastic Reduction by 50%	0.405	73.17	1,609	0.14	101.11	4,458	6,067
Food Reduction by 50%	0.41	73.17	1,609	0.28	202.22	8,916	10,526
Plastic Reduction by 50%	0.810	146.34	3,219	0.14	101.11	4,458	7,677

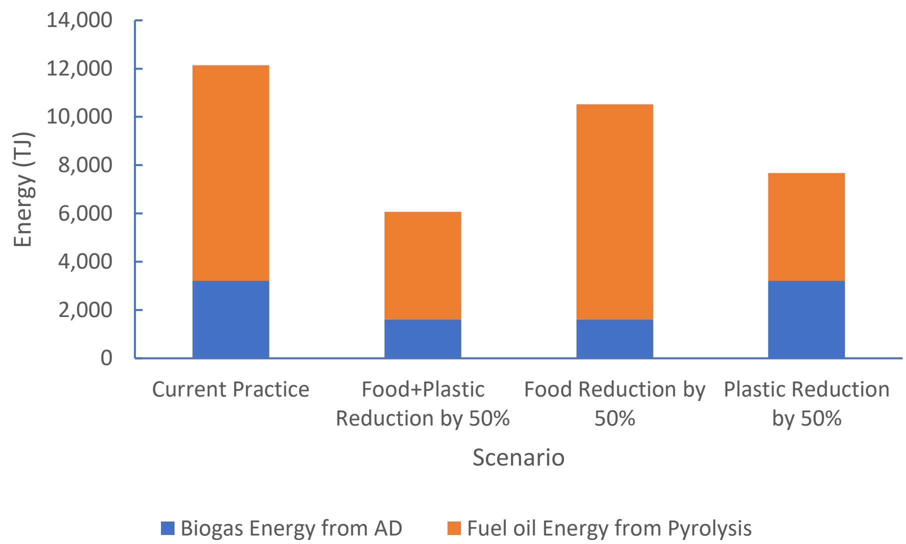

Figure 6-8 Energy from different waste reduction scenarios in Makkah in 2030

6.2.2.2 Power potential and electricity demand

Makkah city is one of greatest consumers of power in KSA, since it hosts two major seasonal mega-events: Umrah and Hajj. According to Althubaiti (2015), the power consumption in Makkah is equivalent to the power consumption of some countries in the region. Figure 6-9 shows a projected gap of 1.5 GW between the future peak demand and population power demand for Makkah in 2030. This assumed an electricity peak demand of 4,500 MW in 2016 and the future peak demand for Makkah was estimated to be 8,480 MW in 2030 using the rate of increase for peak demand in KSA, while the power demand by population was projected to reach 6,938 MW by 2030 based on the population of Makkah residents. In this section, the output power from AD and pyrolysis for different waste reduction scenarios will be compared and analyzed in relation to their contributions to the Makkah city power grid.

Table 6-9 and Figure 6-10 show that the power predicted for Makkah in 2030 is the highest for the current practice scenario at 130 MW (0.13 GW) with the greatest amount of waste, where most of the power (93.30 MW) is from pyrolysis of 0.28 million ton of plastic waste, while 35.73 MW is from AD of 0.810 million ton of food waste. The amount of power from the current practice scenario can reduce the Makkah power gap in 2030 by 8.6% (Table 6-10). The lowest energy predicted is 65 MW (0.065 GW) for the scenario with both food and plastic reduced by 50%, with most of the power from pyrolysis of the plastic waste (46.65 MW); the total power can contribute to as much as 4.3% of the Makkah power gap in 2030 (Table 6-10).

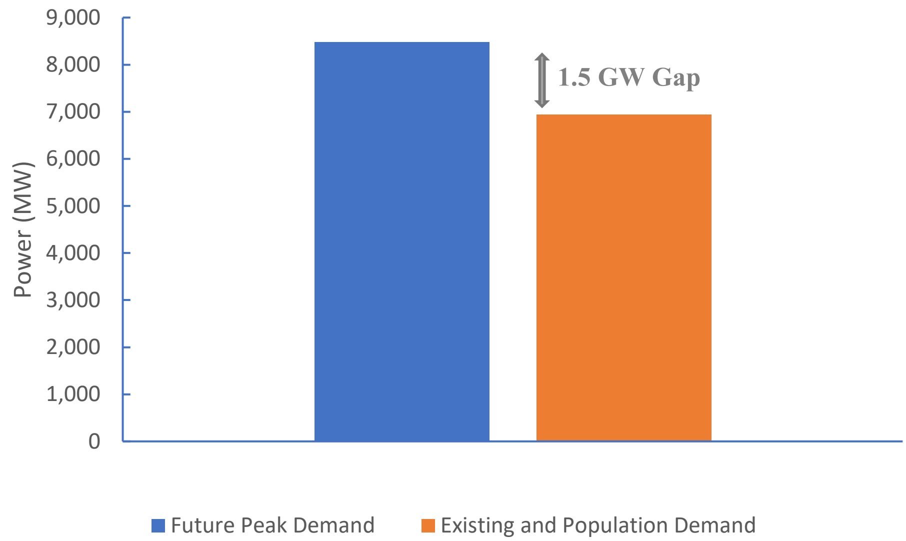

Figure 6-9 Comparison of future peak and existing (population) power demand for Makkah in 2030

In terms of the 50% reduction scenarios for either food or plastic waste, Figure 6-10 shows that the food reduction scenario generates more power (110 MW or 0.11 GW), than the plastic reduction scenario (82 MW or 0.082 GW), in spite the huge 0.405 million ton decrease in food waste. The power from the food reduction scenario would reduce the Makkah power gap by 7.3% (Table 6-10). The plastic waste reduction scenario produces less power compared with the food reduction scenario, even when the plastic waste is reduced by around 0.14 million ton. The power from the plastic reduction scenario would contribute about 5.4% of the power required to meet the 1,500 MW power gap in Makkah in 2030.

Table 6-9 Electricity and power from different waste reduction scenarios for Makkah in 2030

	AD				Pyrolysis				AD+Pyrolysis
Scenario	Total Food Waste (Million ton)	Electricity potential (MWh)	Power Potential (MW)	[1]Actual Power (MW)	Total Plastic Waste (Million ton)	Electricity potential (MWh)	Power Potential (MW)	[2]Actual Power (MW)	Total Actual Power (GW)
Current Practice	0.810	894,282	102.08	35.73	0.28	2,476,754	282.73	93.30	0.13
Food+Plastic Reduction	0.405	447,141	51.04	17.87	0.14	1,238,377	141.36	46.65	0.065
Food Reduction	0.405	447,141	51.04	17.87	0.28	2,476,754	282.73	93.30	0.11
Plastic Reduction	0.810	894,282	102.08	35.73	0.14	1,238,377	141.36	46.65	0.082

[1]After 35% process efficiency for AD technology

[2]After 33% process efficiency for Pyrolysis technology

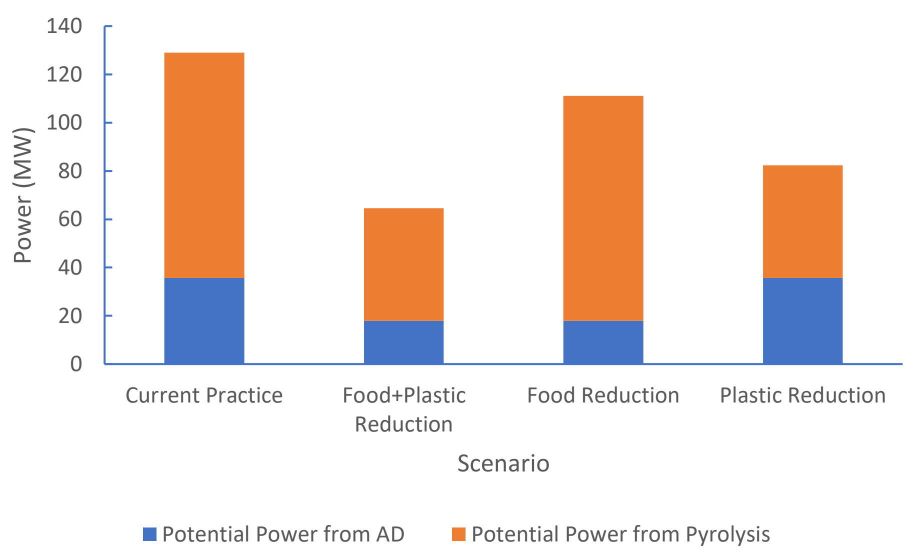

Figure 6-10 Power from different waste reduction scenarios for Makkah in 2030

Table 6-10 Potential power contributions from different waste reduction scenarios for Makkah in 2030

Scenarios	Power (MW)	Contribution % of Makkah Power Gap (1500 MW)
Current Practice	130 MW	8.6%
Food+Plastic Reduction	65 MW	4.3%
Food Reduction	110 MW	7.3%
Plastic Reduction	82 MW	5.4%

There have been some studies investigating the potential benefits of WTE technologies for Makkah. According to Nizami et al. (2017), treating MSW in Makkah via WTE technologies will create tremendous economic and environmental benefits such as the production of renewable electricity from the local waste stream. In that study, MSW fractions in Makkah were assessed independently and a suitable WTE technology was selected to predict the potential energy that could be obtained. The potential power generation from AD if all the food waste was treated was 18.77 MW and around 56.40 MW was predicted from pyrolysis of all the plastic waste generated in Makkah during 2016. In addition, 27.87 MW was predicted if all of the fat from the food waste generated in Makkah was converted to biodiesel via transesterification and 22.83 MW obtained if all of the RDF related waste in Makkah was converted to energy in the RDF process. In the present study, only AD and pyrolysis have been investigated as WTE technologies to treat food and plastic waste, respectively, and food wastes are assumed to be fully utilized in AD.

In another study by Rehan et al. (2016), the pyrolysis of Municipal Plastic Waste (MPW) in Makkah was predicted to generate around 88 MW of power in 2016, reaching about 173 MW by 2040. As well, Ouda et al. (2013) assessed incineration as a WTE technology and reported that the mass burn method could generate 138 MW from MSW in 2032 for Makkah.

6.2.2.3 Economic savings

The economic savings from the different waste reduction scenarios for Makkah are summarized in Table 6-11, where the net savings from AD and pyrolysis are compared in Figure 6-11 and comparison of landfill and electricity savings are shown in Figure 6-12. It can be seen that the greatest economic savings occurs in the current practice scenario where 834 million SAR could be added to the local economy. The scenario where both food and plastic waste were reduced by 50%

scenario has the lowest savings of 417 million SAR. Reducing the plastic waste by 50% provides 676 million SAR, which is slightly higher than the savings from the scenario with food waste reduction of 574 million SAR.

Table 6-11 Economic savings from different waste reduction scenarios for Makkah in 2030

Technology	AD			Pyrolysis			AD+Pyrolysis
Saving (million SAR)	Landfill Saving	Electricity Saving	NET Saving	Landfill Saving	Electricity Saving	NET Saving	Total Net saving
Current practice	459	60.10	519	157	156	314	834
Policy Change By 50% (Food+Plastic)	229	30.05	259	78	78	157	417
Policy Change 50% (Food Reduction)	229	30.05	259	157	156	314	574
Policy Change By 50% (Plastic Reduction)	459	60.10	519	78	78	157	676

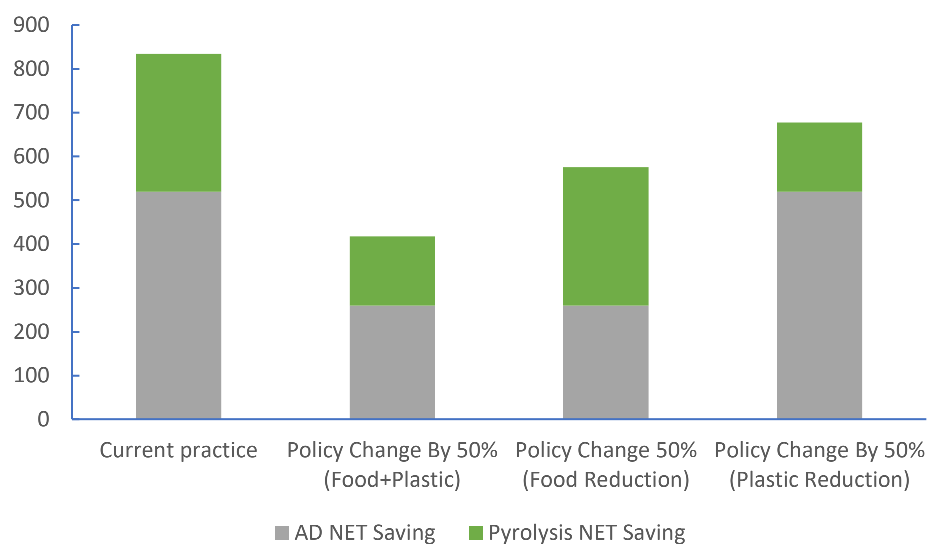

Figure 6-11 Comparison of AD and pyrolysis savings from different waste reduction scenarios for Makkah in 2030

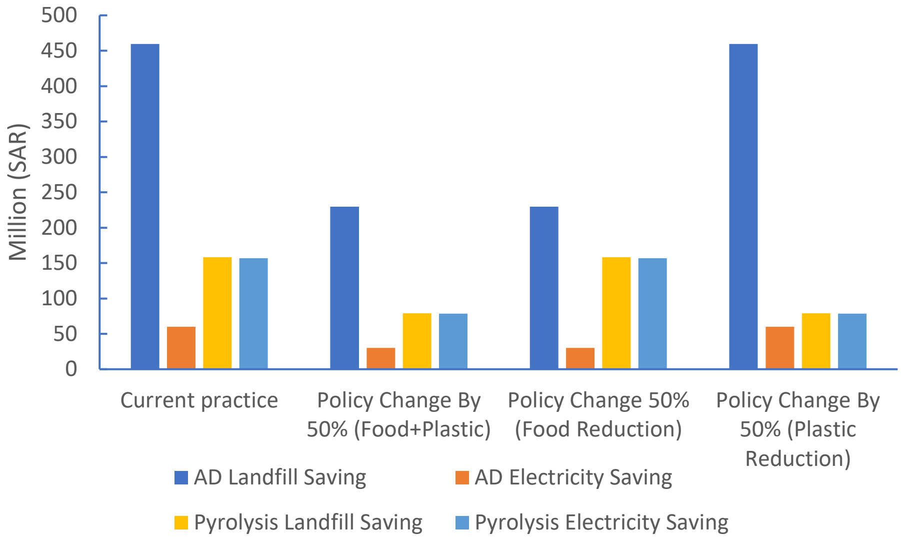

Figure 6-12 Comparison of landfill and electricity savings from different waste reduction scenarios for Makkah in 2030

Figure 6-12 shows that AD of food waste has the most savings from landfill diversion and also has the lowest savings in terms of electricity, while pyrolysis of plastic waste has the most electricity savings and lowest savings from landfill diversion in all examined scenarios. The primary reason AD had the highest landfill diversion savings is due to the food waste stream in Makkah being higher than the plastic waste stream in all scenarios. Similarly, pyrolysis was high in electricity savings as plastic waste has a high calorific content, despite the smaller quantity of plastic estimated in Makkah's MSW in 2030 compared to food.

Results showing landfill diversion savings from different waste reduction scenarios for Makkah in 2030 are presented in Table 6-12. Here, the highest landfill savings were predicted for the current practice and 50% plastic scenarios with no reduction in the food waste, resulting in savings of 617 million and 538 million SAR, respectively. Scenarios where there was a reduction in food waste resulted in similarly low landfill savings with 308 million SAR and 387 million SAR predicted for the scenario with 50% reduction of both food and plastic, and with 50% reduction of food, respectively.

Table 6-12 Landfill diversion savings from different waste reduction scenarios for Makkah in 2030

Scenario	Food waste		Plastic Waste		Food+Plastic	
	Total Waste Million Ton	Total Saving Million SAR	Total Waste Million Ton	Total Saving Million SAR	Total Waste Million Ton	Total Saving Million SAR
Current practice	0.810 (50.6%)	459	0.279 (17.4%)	157	1.089 (68%)	617
Reduction of Food and plastic	0.405 (38.39%)	229	0.139 (13.20%)	78	0.544 (51.59%)	308
Reduction of Food	0.405 (33.91%)	229	0.278 (23.32%)	157	0.683 (57.23%)	387
Reduction of Plastic	0.810 (55.48%)	459	0.139 (9.54%)	78	0.949 (65.02)	538

The electricity savings for the different scenarios for Makkah are summarized in Table 6-13. It is evident that the highest savings are for the current practice scenario and 50% food reduction scenario with no plastic reduction. The current practice scenario has a total of 311 million SAR savings from electricity sales, with the most savings from pyrolysis of plastic with 251 million SAR, and the remaining 60 million SAR obtained from AD of food waste. Scenario with plastic reduction had the lowest electricity savings, where the scenario with reduction of both food and plastic waste had savings of 155 million SAR and the scenario with 50% plastic reduction had electricity savings of 185 million SAR. It is also evident that the savings from landfill diversion (Table 6-12) are higher than the electricity savings (Table 6-13) from the food and plastic waste generated by Makkah residents.

In the study by Nizami et al. (2017), the economic benefit of AD and pyrolysis for combined waste from Makkah residents, Hajj pilgrims and Umrah visitors was investigated based on 2014 data. It was reported that AD could provide savings from landfill diversion for food waste of 243 million SAR and 42 million SAR from electricity generation. In terms of the economic savings from the pyrolysis of plastic waste, Nizami et al. (2017) reported a savings of 96 million SAR from landfill diversion and 127 million SAR from electricity savings, while the net revenue potential for transesterification of food fat and RDF technologies were 76.5 million and 117 million SAR, respectively. As well, Nizami et al. (2015b), predicted that a total savings of 405 million SAR per year might be achieved by developing an AD plant in the Makkah city and a total savings of 565 million SAR per year could be obtained by installing a pyrolysis plant in the city. In another study by Rehan et al. (2016), it was reported that savings of 150 million and 120 million SAR (total 270 million SAR) could be obtained from landfill diversion and electricity production, respectively, if all the MPW in Makkah was pyrolyzed in 2016, reaching 295 million and 236 million SAR (total 531 million SAR), respectively by 2040.

Table 6-13 Electricity savings from different waste reduction scenarios for Makkah in 2030

Scenario	AD		Pyrolysis		AD+Pyrolysis	
	Food Waste (Million Ton)	Saving (Million SAR)	Plastic Waste (Million Ton)	Saving (Million SAR)	Total Waste (Million Ton)	Total Saving (Million SAR)
Current practice	0.810 (50.6%)	60	0.279 (17.4%)	251	1.089 (68%)	311
Reduction of Food and plastic	0.405 (38.39%)	30	0.139 (13.20%)	125	0.544 (51.59%)	155
Reduction of Food	0.405 (33.91%)	30	0.278 (23.32%)	251	0.683 (57.23%)	281
Reduction of Plastic	0.810 (55.48%)	60	0.139 (9.54%)	125	0.949 (65.02)	185

6.2.3 Umrah

The following section will illustrate the energy, power production, and economic savings from Umrah waste treated by AD and pyrolysis for in 2030. The projections will use the Vision 2030 targets for visitors to predict the waste generated during the 10 days period for Umrah and the WTE outcomes for various waste reduction scenarios.

6.2.3.1 Energy produced

Since Umrah is a seasonal event that occurs within Makkah city, the composition of MSW generated by Umrah visitors is assumed to be the same as for Makkah residents, where food and plastics are the two main waste streams, since these visitors expected to follow the local population's diet and habits. Thus, the caloric value of Umrah MSW was assumed to be similar to the caloric value and energy content of the local MSW in Makkah. The results for the total energy potential for Umrah with different waste reduction scenarios in 2030 are shown in Table 6-14 and Figure 6-13 and follow the same trends as for KSA and Makkah.

Umrah visitors are estimated to produce the highest rate of energy in the current practice scenario with a total energy of 4,660 TJ, with most of the energy from plastic waste (3,424 TJ) and the remainder from food waste (1,236 TJ). The scenario with reduction of both food and plastic waste by 50% had the lowest energy (2,330 TJ). For the scenario with 50% food reduction, the energy potential is slightly less the current practice scenario, with 4,042 TJ of energy. For the scenario with 50% plastic reduction, 2,948 TJ is estimated; it should be noted that unlike the other scenarios where the energy from pyrolysis of plastic is much greater than from AD of food waste, the energy from pyrolysis is only slightly greater than from AD, which is similar to that reported for KSA and Makkah in previous sections.

Table 6-14 Total energy potential for various waste reduction scenarios for Umrah in 2030

	AD			Pyrolysis			AD+Pyrolysis
Scenario	Total Food Waste (Million ton)	Total biogas production (Million m^3)	Total energy potential (TJ)	Total Plastic Waste (Million ton)	Total fuel oil production (Million kg)	Total energy potential (TJ)	Total energy potential (TJ)
Current Practice	0.311	56.20	1,236	0.11	78.01	3,424	4,660
Food+Plastic Reduction	0.156	28.10	618	0.05	38.83	1,712	2,330
Food Reduction	0.156	28.10	618	0.11	78.01	3,424	4,042
Plastic Reduction	0.311	56.20	1,236	0.05	38.83	1,712	2,948

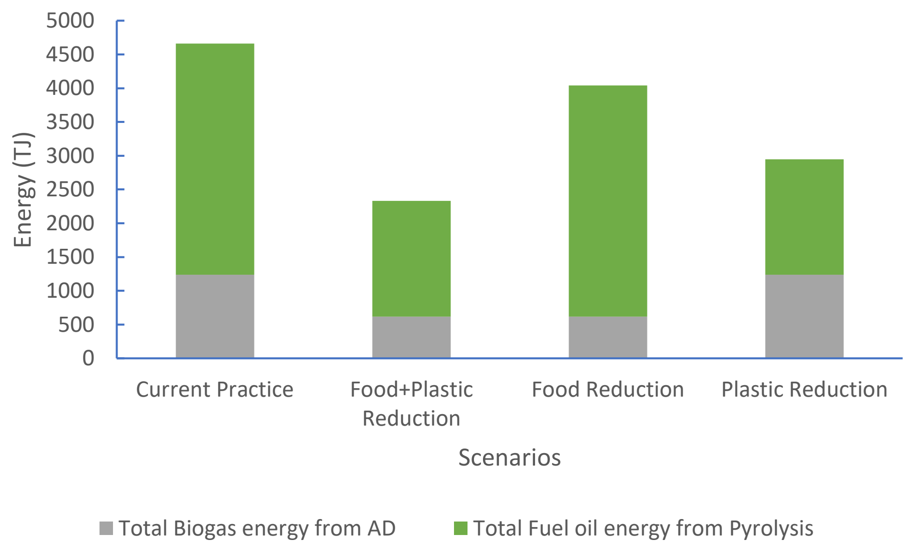

Figure 6-13 Energy from different waste reduction scenarios for Umrah in 2030

6.2.3.2 Power potential

This section reports on the results for the amount of power potential that can be provided from Umrah for the waste reduction scenarios in 2030. A waste-based biorefinery for Umrah could create enormous benefits, one of which is to generate power that can contribute to the overall electricity requirements of the host city of Makkah. The results for electricity potential from Umrah for the different scenarios are presented in Table 6-15 and Figure 6-14, and follow the same trends as those observed for KSA and Makkah. The current practice scenario produces the highest power (49.55 MW) for Umrah when compared with the other waste reduction scenarios, which would be a significant contribution to the local power needs of Makkah. Similarly, the scenario for 50% reduction in food and plastic waste generated the lowest power of 24.77 MW. Further analysis of the potential power generated from Umrah visitors in relation to Makkah is discussed in Section 6.4.

Table 6-15 Electricity and power from different waste reduction scenarios for Umrah in 2030

	AD				Pyrolysis				AD+Pyrolysis
Scenario	Total Food Waste (Million ton)	Electricity potential (MWh)	Power Potential (MW)	[1]Actual Power (MW)	Total Plastic Waste (Million ton)	Electricity potential (MWh)	Power Potential (MW)	[2]Actual Power (MW)	Total Actual Power (MW)
Current Practice	0.311	343,450	39.20	13.72	0.11	951,200	108.58	35.83	49.55
Food+Plastic Reduction	0.156	171,725	19.60	6.86	0.05	475,600	54.29	17.91	24.77
Food Reduction	0.156	171,725	19.60	6.86	0.11	951,200	108.58	35.83	42.69
Plastic Reduction	0.311	343,450	39.20	13.72	0.05	475,600	54.29	17.91	31.63

[1]After 35% process efficiency for AD technology

[2]After 33% process efficiency for Pyrolysis technology

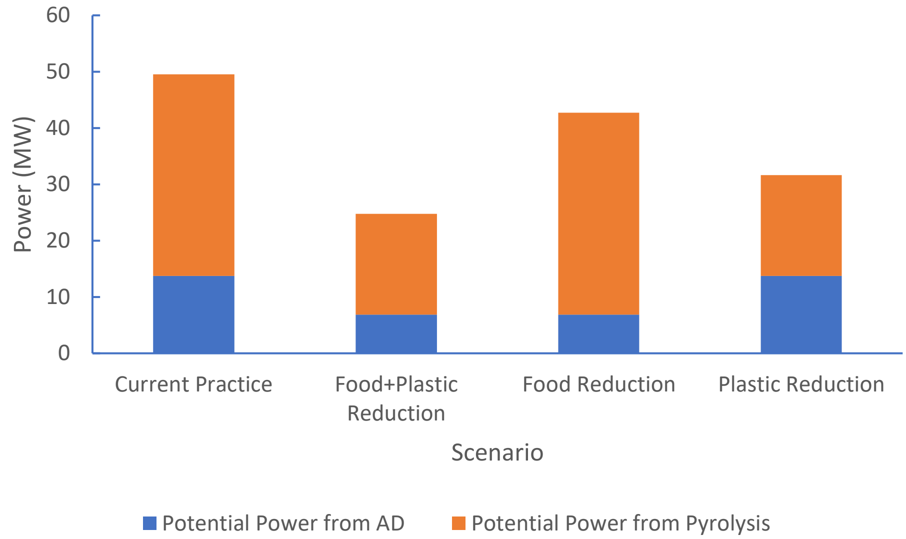

Figure 6-14 Power from different waste reduction scenarios for Umrah in 2030

6.2.3.3 Economic savings

The economic savings from the different waste reduction scenarios for Umrah in 2030 are summarized in Table 6-16, where the net savings from AD and pyrolysis are compared in Figure 6-15. Similar trends are seen as described for KSA and Makkah in previous sections. For example, the current practice scenario with the most waste resulted in the highest economic savings (320 million SAR), followed by the scenario with 50% plastic reduction (259 million SAR), the scenario with 50% food reduction (220 million SAR) and 50% of both food and plastic (160 million SAR). As well, the comparison of landfill and electricity savings (Figure 6-16) shows that AD technology provided the highest savings for landfill diversion in all scenarios. While AD technology resulted in high savings predicted from landfill diversion, low electricity savings were predicted in all four scenarios. In comparison, pyrolysis would provide high savings from electricity sales and less saving from landfill diversion comparing to that obtained from AD in all scenarios.

Table 6-17 summarizes the landfill diversion savings for Umrah in 2030 and shows that food waste has more savings compared to the savings from the plastic wastes. This is because the amount and quantity of food waste for Umrah visitors by 2030 are greater than the amount and quantity of plastic waste in almost all the scenarios. For instance, for the current practice scenario where is no reduction, the food waste savings is 176 million SAR from 0.31 million ton which is 50.6% of the total stream, while the savings from the plastic waste is 60 million SAR from around 17.4% of the total stream, resulting in the highest total savings of 237 million SAR. The lowest savings can be seen in the scenario with 50% reduction of both food and plastic, where the total savings is 118 million SAR from both food and plastic waste. Here, the savings from landfill diversion of food waste are higher with savings of 88 million SAR from 0.156 million ton (around 38.39% of the total stream) in comparison to savings from plastic waste with 30 million SAR of savings from 0.05 million ton (about 13.20% of the total waste stream).

In terms of the electricity savings summarized in Table 6-18, the current practice scenario has the highest savings of 83 million SAR, and the scenario with 50% reduction of both food and plastic had the lowest savings of 42 million SAR. The pyrolysis of plastics in the current practice and 50% food reduction scenarios resulted in the highest savings from the plastic waste of 60 million SAR. For AD technology, the savings from electricity revenue are less than the savings from pyrolysis, however the greatest savings from electricity via AD technology were predicted for the current practice and 50% plastic reduction scenarios with savings of 23 million SAR in each case.

Table 6-16 Economic savings from different waste reduction scenarios for Umrah in 2030

Technology	AD			Pyrolysis			AD+Pyrolysis
Saving (million SAR)	Landfill Saving	Electricity Saving	NET Saving	Landfill Saving	Electricity Saving	NET Saving	Total Net saving
Current practice	176	23	199	60	60	120	320
Policy Change By 50% (Food+Plastic)	88	11	99	30	30	60	160
Policy Change 50% (Food Reduction)	88	11	99	60	60	120	220
Policy Change By 50% (Plastic Reduction)	176	23.	199	30	30	60	259

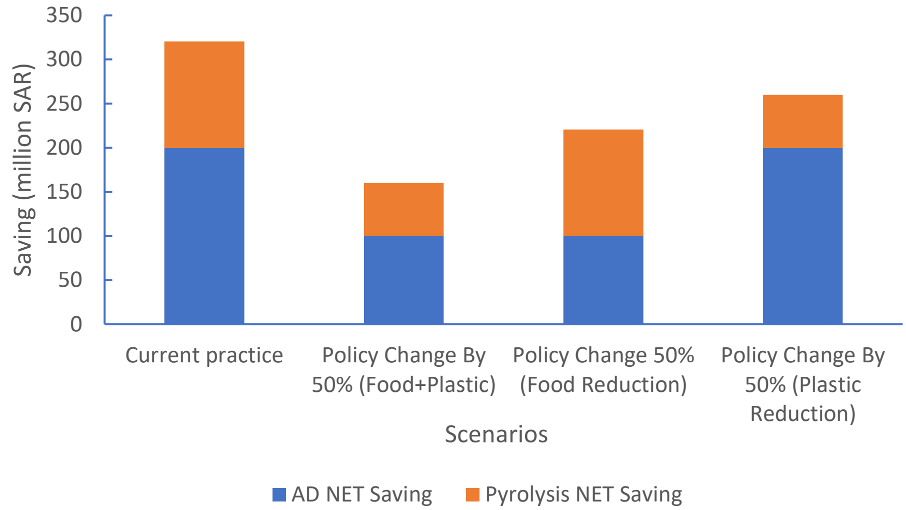

Figure 6-15 Comparison of AD and pyrolysis savings from different waste reduction scenarios for Umrah in 2030

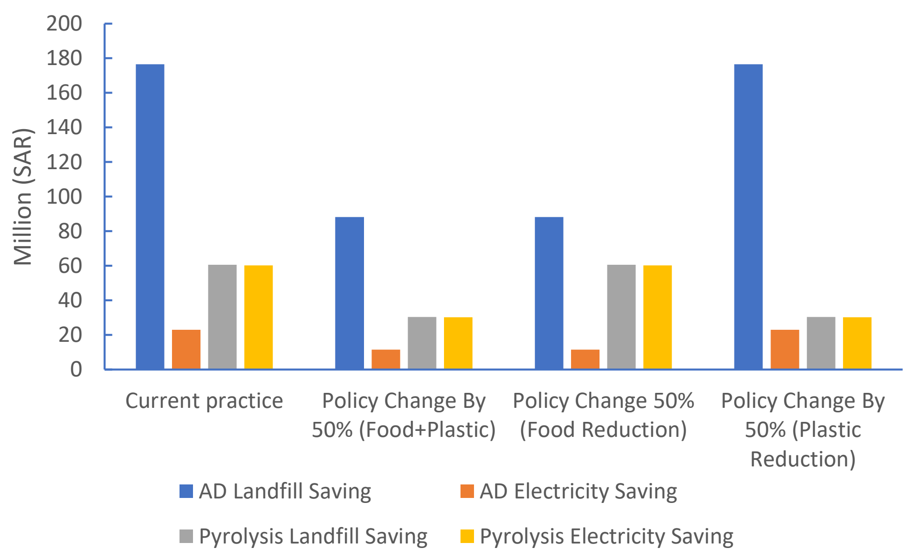

Figure 6-16 Comparison of landfill and electricity savings from different waste reduction scenarios for Umrah in 2030

Table 6-17 Landfill diversion savings from different waste reduction scenarios for Umrah in 2030

Scenario	Food waste		Plastic Waste		Food+Plastic	
	Total Waste Million Ton	Total Saving Million SAR	Total Waste Million Ton	Total Saving Million SAR	Total Waste Million Ton	Total Saving Million SAR
Current practice	0.311 (50.6%)	176	0.11 (17.4%)	60	0.421 (64%)	237
Reduction of Food and plastic	0.156 (38.39%)	88	0.05 (13.20%)	30	0.206 (51.59%)	118
Reduction of Food	0.156 (33.91%)	88	0.11 (23.32%)	60	0.266 (57.23%)	148
Reduction of Plastic	0.311 (55.48%)	176	0.05 (9.54%)	30	0.361 (65.02)	206

Table 6-18 Electricity savings from different waste reduction scenarios for Umrah in 2030

Scenario	AD		Pyrolysis		AD+Pyrolysis	
	Food Waste (Million Ton)	Saving (Million SAR)	Plastic Waste (Million Ton)	Saving (Million SAR)	Total Waste (Million Ton)	Total Saving (Million SAR)
Current practice	0.311 (50.6%)	23	0.11 (17.4%)	60	0.421 (64%)	83
Reduction of Food and plastic	0.156 (38.39%)	11	0.05 (13.20%)	30	0.206 (51.59%)	41
Reduction of Food	0.156 (33.91%)	11	0.11 (23.32%)	60	0.266 (57.23%)	71
Reduction of Plastic	0.311 (55.48%)	23	0.05 (9.54%)	30	0.361 (65.02)	53

6.2.4 Hajj

In the previous case studies, the WTE outcomes for KSA, Makkah, and Umrah assumed the same waste composition. However, the waste stream from Hajj is generated separately, and it is own waste composition is used in this section (Figure 4-1) to estimate WTE outcomes for different waste reduction scenarios in 2030, using the Vision 2030 targets for Hajj visitors.

6.2.4.1 Energy produced

For these results, the physical and chemical composition of food waste for Hajj was assumed to be similar to the host city of Makkah and KSA. In 2030, the amount of MSW during Hajj is projected to amplify due to the potential increase of the pilgrims and food waste is predicted to reach 0.036 million ton and plastic waste to reach up to 0.034 million ton. The results for the total energy potential from Hajj with different waste reduction scenarios in 2030 are shown in Table 6-19 and Figure 6-17. In comparison to KSA, Makkah, and Umrah, the same trends in total energy production are seen with the current practice scenario having the most energy (1,221 TJ) and the scenario with 50% reduction in both food and plastic having the lowest energy production as it involves the least amount of waste. However as Hajj has a reduced proportion of food waste and greater proportion of plastic waste in comparison to KSA/Makkah/Umrah (Figure 4-1), there is correspondingly a greater proportion of energy obtained from pyrolysis than AD for Hajj.

Table 6-19 Total energy potential for various waste reduction scenarios for Hajj in 2030

	AD			Pyrolysis			AD+Pyrolysis
Scenario	Total Food Waste (Million ton)	Total biogas production (Million m^3)	Total energy potential (TJ)	Total Plastic Waste (Million ton)	Total fuel oil production (Million kg)	Total energy potential (TJ)	Total energy potential (TJ)
Current Practice	0.036 (38.96%)	6.50	143	0.034 (36.48%)	23.58	1,078	1,221
Food+Plastic Reduction	0.018 (31%)	3.25	71	0.017 (29%)	12.23	539	610
Food Reduction	0.018 (24.19%)	3.25	71	0.034 (45.31%)	23.58	1,078	1,150
Plastic Reduction	0.036 (47.65%)	6.50	143	0.017 (22.31%)	12.23	539	682

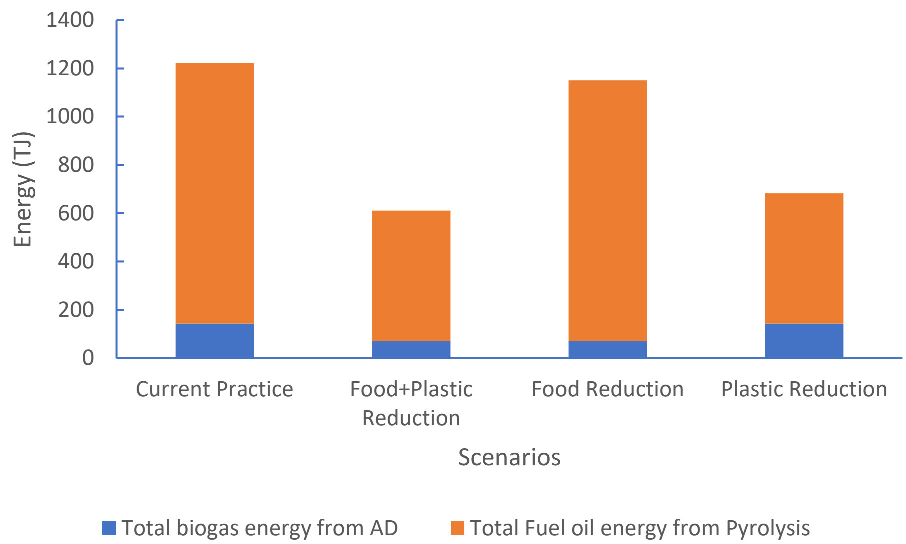

Figure 6-17 Energy from different waste reduction scenarios for Hajj in 2030

6.2.4.2 Power potential

The potential energy from Hajj's food and plastic waste could be employed as a reliable source of energy to back up the future power demand of the host city of Makkah. Therefore, the projected energy in the previous section was used to estimate the amount of potential power for the waste reduction scenarios in 2030 (Table 6-20 and Figure 6-18).

In this section the predictions are based on the Vision 2030 targets for Hajj pilgrims of 6 million by the year of 2030. In comparison to KSA (Figure 6-6), Makkah (Figure 6-10) and Umrah (Figure 6-14), the same trends in total power production are seen with the current practice scenario having the most power (12.78 MW) and the scenario with 50% reduction in both food and plastic having the lowest energy production (6.43 MW) as it involves the least amount of waste. Similarly, to the energy produced for Hajj (Figure 6-17) there is a greater proportion of power obtained from pyrolysis than AD for Hajj in Figure 6-18 than the corresponding graphs for KSA, Makkah and Umrah. This can be attributed to the Hajj MSW waste composition, which has a reduced proportion of food waste and greater proportion of plastic waste in comparison to KSA/Makkah/Umrah (Figure 4-1).

Table 6-20 Electricity and power from different waste reduction scenarios for Hajj in 2030

	AD				Pyrolysis				AD+Pyrolysis
Scenario	Total Food Waste (Million ton)	Electricity potential (MWh)	Power Potential (MW)	[1]Actual Power (MW)	Total Plastic Waste (Million ton)	Electricity potential (MWh)	Power Potential (MW)	[2]Actual Power (MW)	Total Actual Power (MW)
Current Practice	0.036 (38.96%)	39,730	4.5	1.5	0.034 (36.48%)	299,622	34.20	11.28	12.78
Food+Plastic Reduction	0.018 (31%)	19,865	2.26	0.79	0.017 (29%)	149,811	17.10	5.64	6.43
Food Reduction	0.018 (24.19%)	19,865	2.26	0.79	0.034 (45.31%)	299,622	34.20	11.28	12.07
Plastic Reduction	0.036 (47.65%)	39,730	4.5	1.5	0.017 (22.31%)	149,811	17.10	5.64	7.14

[1]After 35% process efficiency for AD technology

[2]After 33% process efficiency for Pyrolysis technology

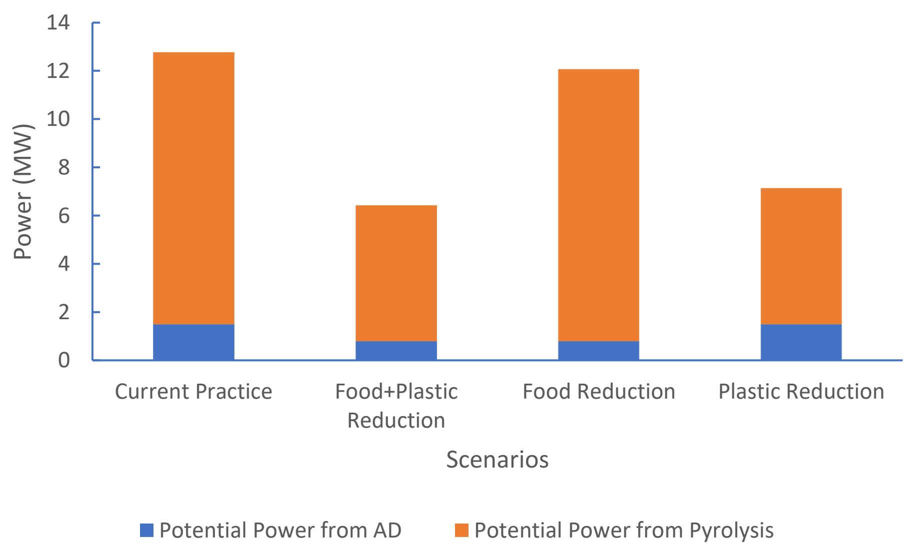

Figure 6-18 Power from different waste reduction scenarios for Hajj in 2030

6.2.4.3 Economic savings

The economic savings from the different waste reduction scenarios for Hajj in 2030 are summarized in Table 6-21, where the net savings from AD and pyrolysis are compared in Figure 6-19. A similar trend as KSA, Makkah and Umrah was seen for the different waste reduction scenarios, where the highest savings were for the current practice scenario with the most waste (61.2 million SAR), and the lowest savings were for the scenario with 50% reduction of both food and plastic (30.6 million SAR). However, the scenario with 50% plastic reduction had slightly lower savings (42.1 million SAR) in comparison to the scenario with 50% food reduction (49.6 million SAR), which was different for the savings from KSA, Makkah, and Umrah. Figure 6-19 shows that pyrolysis net savings from plastic waste is higher than the AD net savings from food waste in all scenarios, except for the scenario with 50% reduction of plastic waste where the reduction of plastic waste affects the overall savings from pyrolysis.

A comparison of landfill and electricity savings for the waste reduction strategies is shown in Figure 6-20. Here, the AD savings from landfill diversion are much higher than the AD savings for electricity savings as observed for KSA, Makkah and Umrah. Also similar to previous reports for KSA, Makkah and Umrah is the observation that the landfill diversion savings from pyrolysis are also equal to the electricity savings from pyrolysis. However, for Hajj it is evident that the savings from pyrolysis are greater in relation to the savings from AD, and for the 50% food reduction scenario the pyrolysis savings even exceed the landfill diversion savings from AD. This can be attributed to the greater proportion of plastic compared to food waste generated during Hajj.

Table 6-22 compares the landfill diversion savings for the waste reduction scenarios and shows that the current practice scenario provides the most savings from both food and plastic waste via AD and pyrolysis technologies respectively with a total saving of 39 million SAR from 0.068 Mt. The reduction of plastic waste by 50% provides savings of 29 million SAR from 0.053 Mt of food and plastic waste, with 20 million SAR from food waste and 9.5 million SAR from the reduced plastic waste. For the scenario with 50% food reduction, the total savings of landfill diversion from food and plastic waste is 29 million SAR, slightly less than the scenario with 50% plastic reduction scenario, where the main savings of 19 million SAR are from the plastic waste while the landfill diversion savings from food is 10 million SAR. The scenario with reduction of both food and plastic waste by 50% has the lowest savings from landfill diversion, totaling 19 million SAR from 0.033 Mt food and plastic waste.

Table 6-21 Economic savings from different waste reduction scenarios for Hajj in 2030

Technology	AD			Pyrolysis			AD+Pyrolysis
Saving (million SAR)	Landfill Saving	Electricity Saving	NET Saving	Landfill Saving	Electricity Saving	NET Saving	Total Net saving
Current practice	20.41	2.67	23.08	19.11	18.98	38.09	61.17
Policy Change By 50% (Food+Plastic)	10.20	1.33	11.54	9.55	9.49	19.04	30.58
Policy Change 50% (Food Reduction)	10.20	1.33	11.54	19.11	18.98	38.09	49.63
Policy Change By 50% (Plastic Reduction)	20.41	2.67	23.08	9.55	9.49	19.04	42.12

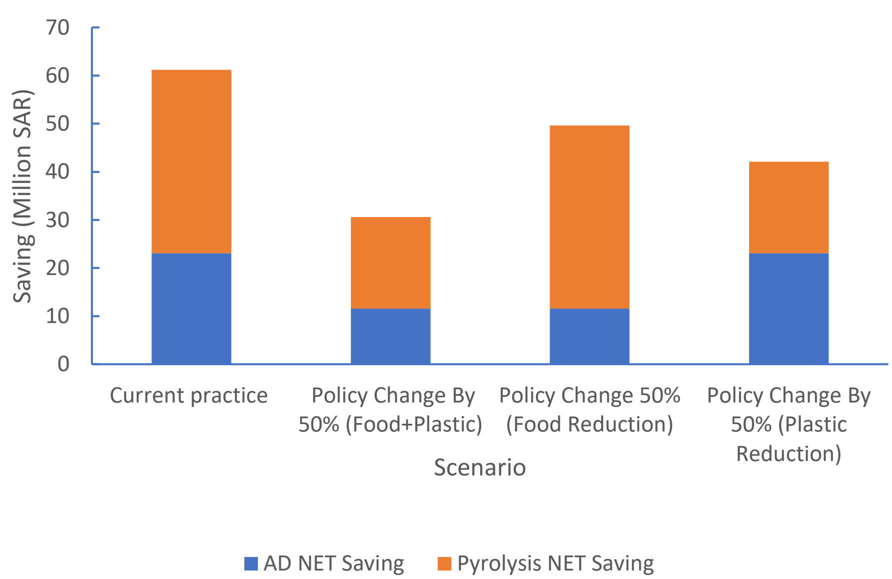

Figure 6-19 Comparison of AD and pyrolysis savings from different waste reduction scenarios for Hajj in 2030

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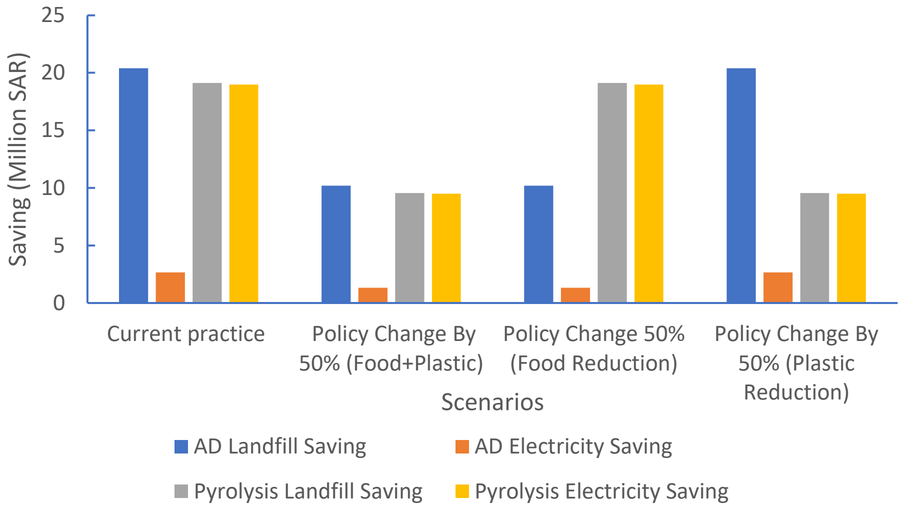

Figure 6-20 Comparison of landfill and electricity savings from different waste reduction scenarios for Hajj in 2030

Table 6-22 Landfill diversion savings from different waste reduction scenarios for Hajj in 2030

Scenario	Food waste		Plastic Waste		Food+Plastic	
	Total Waste Million Ton	Total Saving Million SAR	Total Waste Million Ton	Total Saving Million SAR	Total Waste Million Ton	Total Saving Million SAR
Current practice	0.036 38.96%	20	0.034 (36.48%)	19	0.068 (74%)	39
Reduction of Food and plastic	0.018 31%	10	0.017 29%	9.5	0.033 (60%)	19
Reduction of Food	0.018 24.19%	10	0.034 45.31%	19	0.052 (70%)	29
Reduction of Plastic	0.036 47.65%	20	0.017 22.31%	9.5	0.053 (70%)	29

Table 6-23 compares just the electricity savings for Hajj, where the current practice scenario has a total saving of 21 million SAR from 0.068 Mt of food and plastic waste. As it is high in energy, plastic waste via pyrolysis provides the most savings in this scenario with 18 million SAR, while the food waste from AD technology provides fewer savings of 2.6 million SAR. While the current practice scenario offers the highest savings from the electricity, the reduction of food by 50% scenario also provides a high level of savings despite reduction in food waste, with a total savings of 20 million SAR, slightly less than the current practice scenario. Reduction of plastic waste by 50%, on the other hand, has a total savings of 12 million SAR from 0.053 Mt of food and plastic waste, where most of the savings are from the plastic waste via pyrolysis technology with electricity savings of 9.5 million SAR. Nevertheless, the reduction of food and plastic waste by 50% has the lowest savings compared to the rest of the scenarios for Hajj, with total electricity savings of 10 million SAR.

Table 6-23 Electricity savings from different waste reduction scenarios for Hajj in 2030

Scenario	AD		Pyrolysis		AD+Pyrolysis	
	Food Waste (Million Ton)	Saving (Million SAR)	Plastic Waste (Million Ton)	Saving (Million SAR)	Total Waste (Million Ton)	Total Saving (Million SAR)
Current practice	0.036 38.96%	2.67	0.034 (36.48%)	18	0.068 (74%)	21
Reduction of Food and plastic	0.018 31%	1.33	0.017 29%	9.5	0.033 (60%)	10
Reduction of Food	0.018 24.19%	1.33	0.034 45.31%	18	0.052 (70%)	20
Reduction of Plastic	0.036 47.65%	2.67	0.017 22.31%	9.5	0.053 (70%)	12

6.3 General Impact of Waste Reduction Scenarios

Waste reduction is considered the most preferred option of waste management for it is numerous benefits such as energy savings, and reduction in greenhouse gas emissions and other pollutants.

From an environmental viewpoint, having AD technology as an option to process the rest of KSA food waste after 50% reduction (6.7 Mt) is worthwhile, considering the toxicity of methane discharge from food waste in a landfill. Similarly, having pyrolysis along with any future reduction scenario is needed to treat the rest of the plastic waste, since there is lack of the recycling in the country, and to prevent the plastic waste from ending up in the landfill. Economically, waste reduction scenarios decrease the landfill and electricity savings. For example, landfill diversion savings for KSA would drop from 10,251 million SAR to 5,150 million SAR if the food and plastic was reduced by 50% and the profits from electricity savings would decrease to 1,810 million SAR. As for the energy aspect, since one of the main reasons for a WTE plant is for energy recovery purposes, any future reduction of waste would affect the practicability of the prospective WTE industry in the country.

It seems that the benefit of WTE technologies will be reduced if the country were to adopt any of the reduction scenarios that are compliant with UN SDG goals by 2030. Nonetheless, regardless of any possible reduction, WTE will still be beneficial as an excellent environmental option to prevent the rest of the food and plastic waste from ending up at the landfill, though it would lose it is profitability as a renewable energy and alternative economic source, and may not be as competitive with other renewable sources such as wind and solar power. It is necessary for the decision-makers in KSA to recognize the viability of installing such a WTE plant, and impact of any waste reduction policy, whether for implementing WTE industries in the kingdom as an environmental solution to waste management challenges or as an of renewable energy production practice and new economic source. In addition, they should take into account the capacity and the plant scale for any future WTE installation to cope with any future reduction and consider the amount of energy that can be produced from such plant, and whether it could be relied on as a source of power to aid the national grid.

The issues experienced by Sweden should be given due consideration, as they have problems in accessing sufficient MSW to run their incineration plants to capacity due to the ban on landfilling waste that occurred in 2001 (NVV, 2016). The country currently consumes all of it is waste, with 50% of MSW going to energy recovery, around 15.5 % used for composting, and 33% for material recycling (Skarp, 2016). Consequently, Sweden imports around 1.4 Mt of waste each year from countries such as Norway, Britain and Ireland to feed their own incineration plants. However, unlike typical imports, Sweden does not make any payments for taking other countries' waste, but it is paid to do so (Skarp ,2016). According to Yee (2018), those countries pay Sweden to receive their waste because it can be more cost-effective than paying landfill taxes. However, although importing waste seems a beneficial idea to supply the waste to the incineration plants without any additional cost, it has been reported that approximately two thirds of the waste imported for incineration could have been recycled for material or composted (Skarp, 2016). Thus, such a practice is considered as a waste of resources and the EU commission has set their future environmental policy to consider the waste recovery technique as an option to treat non-recyclable materials only, considering WTE technology as a transition to the circular economy and not as an end (TÜTTŐ, 2017). The possibility of supplying WTE plants in KSA with waste from neighboring countries that have high population density, large amounts of waste and difficulties in managing their waste, such as Egypt, Lebanon, and Jordan, should be investigated. However, it would be important to consider whether the waste would contain recyclable materials since the recycling practices in those countries is at an early stage and not comparable with the European countries from where Sweden imports their waste. Further, KSA should take into consideration the sensitivity of pyrolysis and AD to mixed waste if importing waste and should only select feedstock that would be suitable for their plants.

Currently, WTE is trending worldwide as a profitable industry for waste management. Besides Sweden where they burn 50% of their waste, Japan now incinerates up to 60% of it is solid waste (Yee ,2018) and China has more than doubled it is WTE capacity from 2011 to 2015, according to a World Energy Council report (Export, 2019). Moreover, as part of a Canada-led Ocean Plastics Charter declared in 2018 that calls for cutting plastic from landfills, G7 countries consider WTE incineration part of the plastic waste solution (Chung, 2018). As well, Nova Scotia has recently opened a pyrolysis plant, primarily to convert plastic waste obtained from local MSW to fuel. The plant is considered to be small-scale with a capacity of around 15 ton/day (5,500 ton/year) of plastic waste that would be expected to be converted to fuel oil (NSE, 2018). Although the current practice is to divert plastic from landfilling by rerouting those materials via the curbside blue bag recycling collection system (Denty, 2018), it should be noted that the Halifax Regional Council in Nova Scotia is exploring a proposal to ban plastic bags (Draus, 2019).

6.4 Comparison of WTE Outputs from Umrah and Hajj: Normal Growth vs Vision 2030

As mentioned previously, "normal growth" in this study refers to the use of the historical growth rate for Umrah and Hajj for predicting the number of visitors and pilgrims in 2030. In this section, WTE outcomes from normal growth to 2030 are compared with WTE outcomes obtained using the target numbers of pilgrims and visitors for Vision 2030 for the current practice scenario with no waste reduction, and the combined results for Umrah and Hajj are summarized in Table 6-24. For normal growth, the predicted energy, power, and savings were 3,052 TJ, 32 MW and 194 million SAR respectively if AD and pyrolysis were used to treat all the food and plastic waste in 2030. In comparison, the Vision 2030 targets for increasing the number of Hajj pilgrims and Umrah visitors beyond normal growth in 2030 resulted in total energy of 5,882 TJ, 62 MW of power, and 381 million SAR in savings. These results indicate that the Vision 2030 targets will result in approximately double the WTE outcomes achieved with normal growth to 2030, which means more energy and economic benefits from WTE technologies could be obtained with the Vision 2030. Installing WTE technology to treat future MSW from Umrah and Hajj seems a practical choice toward better management of these gigantic mega-events, where the proposed technologies of AD and pyrolysis would not only provide economic savings, but would also establish a new industry of renewable energy for KSA and improve environmental sustainability by extending the life of existing landfills.

Table 6-24 WTE outcomes for Umrah and Hajj – comparison in 2016 and 2030 (normal growth vs Vision 2030) with no waste reduction

Umrah and Hajj	Visitors/Pilgrims (Million)	Food and Plastic Waste (Million Ton)	Energy (TJ)	Power (MW)	Saving (Million SAR)
2016 (Base Year)	10.5	0.139	1,751	18	94
Normal Growth by 2030	18.38	0.247	3,052	32	194
Vision 2030 Growth By 2030	36	0.489	5,882	62	381

6.5 Impact of WTE Outputs from Umrah and Hajj on Makkah

WTE outcomes for Makkah, are compared with combined WTE outcomes for Umrah and Hajj using Vision 2030 targets with no waste reduction in Table 6-25. The results indicate that food and plastic waste from Umrah and Hajj events could contribute 5,882 TJ, 62 MW, and 381 million SAR of energy, power, and economic savings, respectively, each of these being approximately half of the corresponding WTE outcome for Makkah. Therefore, if added to the WTE outcomes for Makkah, the city would have a total energy of 18,018 TJ available from WTE technologies, which could be transformed to 192 MW (0.2 GW) of power capacity to subsidize the Makkah electricity grid and reduce the power gap of Makkah city by 12%. In addition, the total revenue from landfill diversion and electricity production would reach 1,216 million SAR (324.24 million USD), and these outcomes would increase proportionally to the increase in local residents, Hajj pilgrims, and Umrah visitors each year, assuming the same MSW composition and generation rates. Generally, the MSW produced during the Hajj and Umrah is managed by Makkah Municipality, where all the collected waste is disposed of in the landfill. Thus, the predicted waste would be a burden on Makkah landfill where it has already exceeded its capacity. As well, the animal slaughter that is associated with Hajj rituals will increase in parallel with the increase in pilgrim numbers, where the intestines, stomach, and blood are thrown into the Makkah landfill without any treatment, causing severe environmental problems in the surrounding area.

Table 6-25 WTE outcomes for Makkah, and Umrah and Hajj using Vision 2030 targets with no waste reduction

	Population (Million)	Food and Plastic Waste (Million Ton)	Energy (TJ)	Power (MW)	Saving (Million SAR)
Makkah City	3.13	1.089	12,135	130	834
Umrah+Hajj	36	0.489	5,882	62	381
Makkah+Umrah+Hajj	39.13	1.578	18,018	192	1,216

The results in Table 6-25 reveal the positive impact of applying AD and pyrolysis technologies in Makkah producing renewable energy, power potential and economic savings that can be added to Makkah and the national economy. However, as the number of Umrah visitors and Hajj pilgrims to Makkah is set to rise each year, it is essential that the city's infrastructure is improved and updated, in order to enhance the overall experience for the guests. The Kingdom has spent billions of riyals over the past few years on building infrastructure in Makkah such as new roads, bridges, and tunnels, as well as crowd control consultation to manage the vast inflow of people. For instance, it was estimated that $50 billion USD would be invested in new transportation and other substructures to increase the capacity of the Hajj and Umrah by 2030 (McLoughlin, 2018). As well, the King Abdullah enlargement project of the Holy Mosques in Makkah, which is the biggest in history, when finished by 2020, will increase the capacity for worshippers to more than 5 million at the same time (Rehan et al., 2016). The Kingdom is also planning to install 600 MW of solar panels in the Makkah region as part of a large project to produce 2600 MW from renewable sources by 2023 (Hill, 2019). This source of power coupled with potential power that might recovered from the waste via WTE technologies is good step to gradually reduce the dependency on fusel fuel for power production.

One of the main goals for the KSA Vision 2030 plan is aimed at diversifying the Saudi economy, and for Makkah city to be a regional and global economic center by 2030, where the Islamic tourism business has a vital part in expanding KSA's non-oil-based economy. Indeed, the Hajj was considered KSA's primary source of revenue until the discovery of oil (Kumaraswamy et al., 2019), thus KSA is committed to further investment in tourist amenities and public services. The tourists are expected to bring high profitability to the national economy, given that they spent around 25 billion SAR (6.7 billion USD) in 2017, which was an increase of 70% although the pilgrims had increased by only 20% from the past year (France24, 2017). The Vision 2030 plan for receiving more visitors and pilgrims should not only focus on developing the city's infrastructure, expansion projects and improving guest accommodations, it should be establish an effective integrated waste management system. By applying MSW energy recovery, KSA has a good chance in making Makkah a center of for renewable energy, a safe environment and a circular economy model for the middle east region.

6.6 Recycling Outlook

In this study, the WTE technologies of AD and pyrolysis were used to manage the most significant components of the MSW, which are food and plastic waste. However, in general it is challenging for a single technology to effectively process the waste stream in its entirety or to reach zero waste goals. One approach to overcome these limitations is to establish a recycling industry in KSA in order to manage the recyclable MSW fractions. Recycling, along with WTE technology, could help the kingdom to reach its sustainability goal of reducing the amount of waste by 2030 in tandem with the UN's SDGs.

According to the hierarchy of waste management (Figure 6-21), the most preferred options for integrated MSW are waste prevention, reduction, reuse, then recycling. And although the US EPA considers WTE technologies as a source of renewable energy, the waste management hierarchy places energy recovery below recycling. Recycling is desirable as it reduces waste, saves energy, reduces landfill costs and it is related environmental problems. According to Ouda et al. (2016), recycling is recognized as a critical element of modern waste reduction practices to decrease the GHG discharges and environmental impact of MSW. Generally, waste recycling does not need highly skilled labour and sophisticated technology for the sorting and collection of recyclable materials, and it can be implemented in any urban areas.

The composition of recyclable materials (excluding food and plastic waste) is shown in Figure 6-22 for KSA and Figure 6-23 for Makkah, Umrah and Hajj. It is evident that the KSA waste stream has a significant portion of recyclable materials and energy containing elements such as glass, cardboard, paper, metals, and others. It is estimated that of the 26.7 Mt of MSW generated from 52.3 million people in KSA by 2030, around 8 Mt (30%) of the total generated waste are considered recyclable materials. Nizami et al. (2017) studied the potential of recycling in KSA, and he estimated that 45,000 TJ of energy could be saved by only recycling glass and metals. As for Makkah city, the recyclable materials are estimated to reach 0.45 Mt by 2030, and up to 0.65 Mt with the addition of recyclable materials from Hajj and Umrah. According to Nziami et al. (2017), there is a potential net revenue of more than 100 million SAR from recycling Makkah's glass, metals, aluminum, and cardboard, mostly from landfill diversion savings of close to 60 million SAR and around 40 million SAR from reselling the recycled materials and as well savings of 5,600 tons of methane with 140,000 thousand Mt.CO_2 eq of global warming potential (GWP).

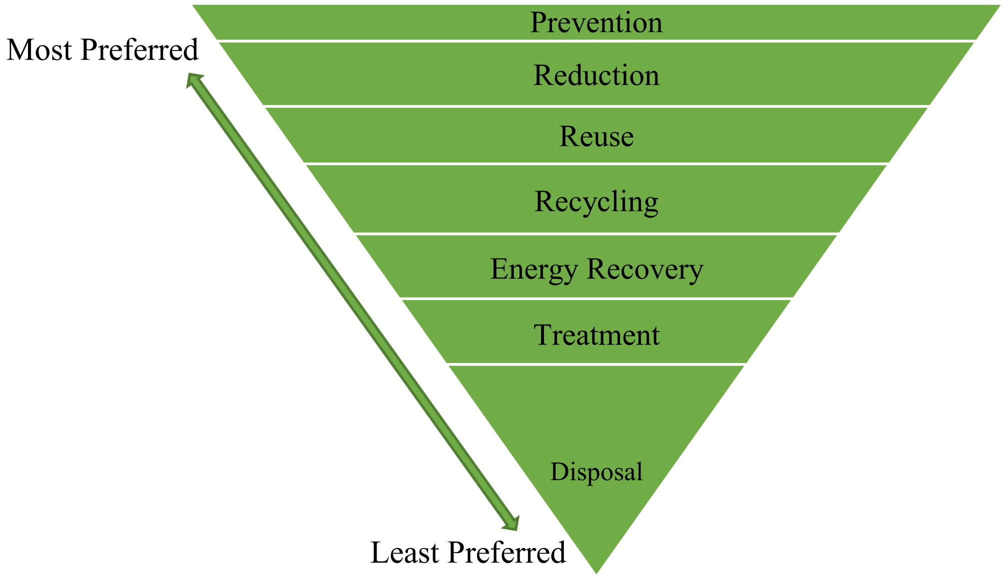

Figure 6-21 Hierarchy of Waste Management (adapted from EPA, 2017)

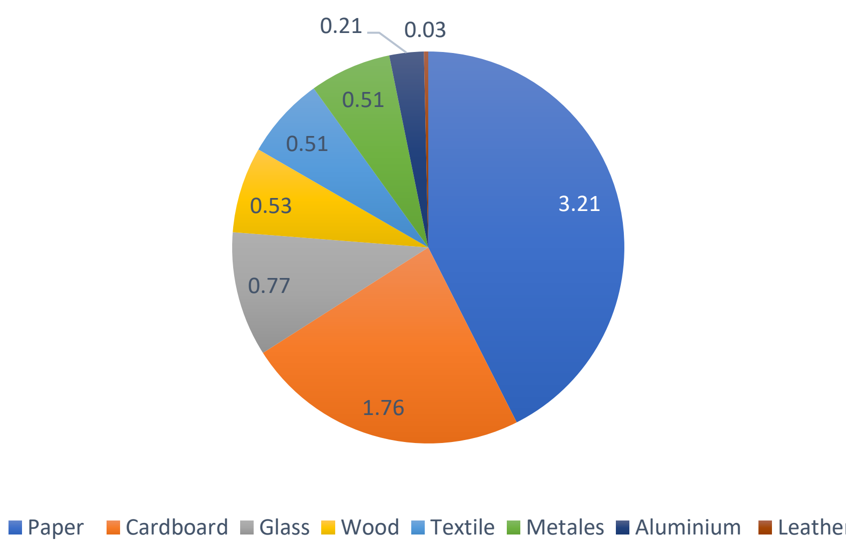

Figure 6-22 Amount (million ton) of recyclable materials in KSA in 2030, excluding food and plastic

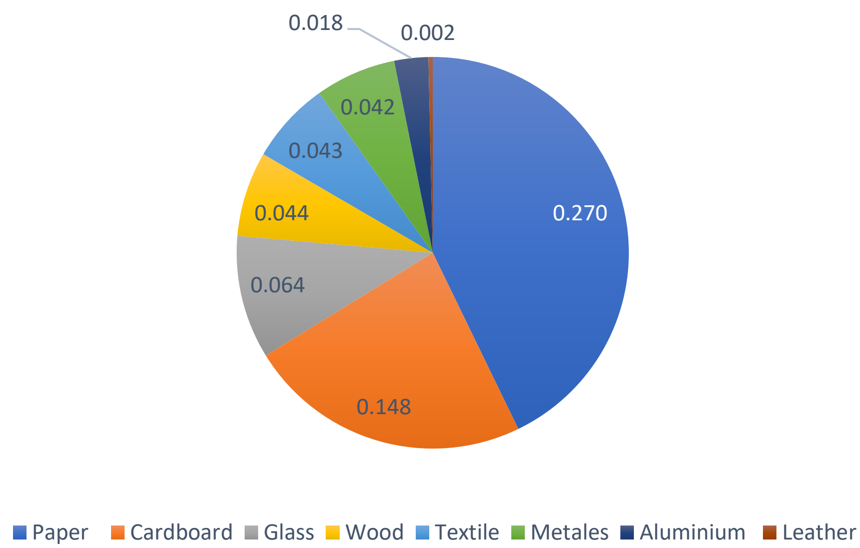

Figure 6-23 Amount (million ton) of recyclable materials in Makkah, Umrah and Hajj in 2030, excluding food and plastic waste

CHAPTER 7. CONCLUSIONS AND FUTURE WORK

The overall aim of the study was to report on the economic savings and energy produced from treating the main components of the waste streams (food and plastic), using suitable waste-to-energy (WTE) technologies. Through this work the following conclusions can be made:

1. AD and pyrolysis are the most promising WTE technologies for this study based on a comparative analysis of the economic, environment, and social aspects, as well as the waste composition and the technical requirements of the technology, and given that the major components in the MSW for KSA, Makkah, Umrah and Hajj are food and plastic wastes.
2. Increases in the population growth of KSA and Makkah by 2030 and Hajj pilgrims and Umrah visitors following the Vision 2030 plan result in increased waste generation and increased WTE outcomes. Although the targeted visitor/pilgrim numbers for 2030 are greater than the local population of Makkah residents in 2030, the waste generated by the tourists is less than the waste from Makkah residents, due to the short duration of Umrah and Hajj.
3. Policies that would result in the reduction of waste in 2030 would result in reduced WTE outcomes in terms of potential energy and power production and economic savings. In general, the highest WTE outcomes of energy, power and economic savings could be obtained from the current practice scenario (without waste reduction) and the lowest WTE outcomes were obtained from the scenario with 50% reduction of both food and plastic.
4. KSA gave the highest WTE outcomes followed by Makkah city, Umrah and Hajj. For KSA, the highest WTE outcomes were savings of 13,922 million SAR (3,711 million USD) and total energy of 202,472 TJ resulting in 2.15 GW that could subsidize the future KSA electricity demand gap.
5. AD of food waste typically had higher economic savings from landfill diversion of food waste, for cases where food waste was the major type of waste, however the savings from electricity production from biogas were relatively small. Pyrolysis of plastic waste resulted in equal savings from landfill diversion of plastic waste and electricity savings.
6. WTE outcomes for Umrah and Hajj using the Vision 2030 targets for visitors will be approximately double the WTE outcomes achieved with normal growth to 2030, which

means more energy and economic benefits from WTE technologies could be obtained with the Vision 2030 plan.

7. In relation to Makkah city, the food and plastic waste from Umrah and Hajj events in 2030 could contribute approximately half of the corresponding WTE outcomes for Makkah alone. Therefore, if added to the WTE outcomes for Makkah, the city would have a total energy of 18,018 TJ available from WTE technologies, which could be transformed to 192 MW (0.2 GW) of power capacity to subsidize the Makkah electricity grid and reduce the power gap of Makkah city by 12%.

8. Recycling, along with WTE technology, could help the kingdom to reach its sustainability goal of reducing the amount of waste by 2030 in tandem with the UN's SDGs.

From this study, it appears that using AD and pyrolysis as WTE technologies to manage the potentially increasing waste of KSA, Makkah, Umrah, and Hajj in 2030 is promising. The results revealed that processing food and plastic waste with AD and pyrolysis, respectively, not only reduces the environmental burden of landfilling practices but also generates a significant amount of energy and provides economic savings. However, waste reduction strategies would affect the performance and feasibility of WTE technologies in KSA. Another important contribution from this study is the development of a framework that can be applied to other situations outside of KSA to assess the impact of the population growth and waste reduction strategies on WTE technology outputs.

However, this study did not consider how the separation of food and plastic waste streams would occur, as currently there is no waste separation prior to disposal. It is recommended that a door-to-door or curbside collection system and mild mechanical separation for waste segregation prior to processing be investigated. Moreover, establishing an effect recycling system for the other types of waste (paper, glass, metals, cardboard and aluminum) should be established as these waste streams are not the most suitable for the proposed WTE technologies.

Furthermore, better data could be collected for waste composition and quantity from Hajj pilgrims, Umrah visitors, and the local residents of Makkah. This task could be done by monitoring Makkah landfill routinely on and off those seasonal events to determine the amount and characterization of waste for each case. Additionally, data on the historical socio-economic aspects, including local culture, practices and human behavior (pilgrimage behavior for Hajj) that might affect the future shape of waste generation and characterizations could be collected to assist authorities in the design of a commercial scale plant for AD and pyrolysis technologies as well as for recycling facilities. It would be beneficial to conduct a more extensive environmental and economic analysis using life cycle assessment (LCA) and life cycle cost (LCC) methods respectively, as well as an in-depth social and technical examination. Recommendations for future work include assessing the GHG emissions savings for the waste reduction scenarios in this study for KSA, Makkah, Umrah and Hajj. Also, the construction cost and payback period for building AD and pyrolysis plants should be determined, as well as payback period. These investigations would provide more data on the environmental and economic aspects of WTE technologies in KSA.

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APPENDIX

Table A-1 KSA: AD of food waste output in the current practice scenario

Energy and Power		
Total food waste	13.52	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	2441.49	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	53712.83328	million MJ (TJ) per year
Electricity potential	14920231.47	MWh
Time basis	8760	hours per year
Power Potential	1703.22277	MW
Process efficiency	35%	
Actual Power	596.13	MW
Landfill Saving		
Total Organic waste	13.52	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	7665.150627	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	5222081013.68	kWh
Gross saving	1671065924	SAR
Cost of waste collection, plant and operation (40%)	668426369.8	
Net Saving	1002.64	million SAR
Total net savings from AD technology	8667.79	million SAR

Table A-2 KSA: Pyrolysis of plastic waste outputs in the current practice scenario

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	4.65	million tons per year
Total oil produced	3.719	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	148760.060	million MJ (TJ) per year
Total energy from total plastic waste	148760059853.17	MJ
Electricity potential	41322238.85	MWh
Time basis	8760	hours per year
Power Potential	4717.15055	MW
Process efficiency	33%	
Actual Power	1556.659683	MW
Landfill Saving		
Total plastic waste	4.65	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	2635.84	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	13636338820	kWh
Gross saving	4363628422	SAR
Cost of waste collection, plant and operation (40%)	1745451369	
Net Saving	2618.18	million SAR
Total net savings from pyrolysis technology	5254.02	million SAR

Table A-3 KSA: AD of food waste outputs for scenario with food and plastic reduction by 50%

Energy and Power		
Total food waste	6.76	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	1220.75	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	26856.41664	million MJ (TJ) per year
Electricity potential	7460115.734	MWh
Time basis	8760	hours per year
Power Potential	851.6113851	MW
Process efficiency	35%	
Actual Power	298.06	MW
Landfill Saving		
Total Organic waste	6.76	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	3832.575314	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	2611040506.84	kWh
Gross saving	835532962.2	SAR
Cost of waste collection, plant and operation (40%)	334213184.9	
Net Saving	501.32	million SAR
Total net savings from AD technology	4333.90	million SAR

Table A-4 KSA: Pyrolysis of plastic waste outputs for scenario with food and plastic reduction by 50%

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	2.32	million tons per year
Total oil produced	1.860	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	74380.030	million MJ (TJ) per year
Total energy from total plastic waste	74380029926.59	MJ
Electricity potential	20661119.42	MWh
Time basis	8760	hours per year
Power Potential	2358.57528	MW
Process efficiency	33%	
Actual Power	778.3298413	MW
Landfill Saving		
Total plastic waste	2.32	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	1317.92	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	6818169410	kWh
Gross saving	2181814211	SAR
Cost of waste collection, plant and operation (40%)	872725684.5	
Net Saving	1309.09	million SAR
Total net savings from pyrolysis technology	2627.01	million SAR

Table A-5 KSA: AD of food waste outputs for scenario with only food reduction by 50%

Energy and Power		
Total food waste	6.76	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	1220.75	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	26856.41664	million MJ (TJ) per year
Electricity potential	7460115.734	MWh
Time basis	8760	hours per year
Power Potential	851.6113851	MW
Process efficiency	35%	
Actual Power	298.06	MW
Landfill Saving		
Total Organic waste	6.76	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	3832.575314	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	2611040506.84	kWh
Gross saving	835532962.2	SAR
Cost of waste collection, plant and operation (40%)	334213184.9	
Net Saving	501.32	million SAR
Total net savings from AD technology	4333.90	million SAR

Table A-6 KSA: Pyrolysis of plastic waste outputs for scenario with only food reduction by 50%

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	4.65	million tons per year
Total oil produced	3.719	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	148760.060	million MJ (TJ) per year
Total energy from total plastic waste	148760059853.17	MJ
Electricity potential	41322238.85	MWh
Time basis	8760	hours per year
Power Potential	4717.15055	MW
Process efficiency	33%	
Actual Power	1556.659683	MW
Landfill Saving		
Total plastic waste	4.65	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	2635.84	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	13636338820	kWh
Gross saving	4363628422	SAR
Cost of waste collection, plant and operation (40%)	1745451369	
Net Saving	2618.18	million SAR
Total net savings from pyrolysis technology	5254.02	million SAR

Table A-7 KSA: AD of food waste outputs for scenario with only plastic reduction by 50%

Energy and Power		
Total food waste	13.52	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	2441.49	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	53712.83328	million MJ (TJ) per year
Electricity potential	14920231.47	MWh
Time basis	8760	hours per year
Power Potential	1703.22277	MW
Process efficiency	35%	
Actual Power	596.13	MW
Landfill Saving		
Total Organic waste	13.52	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	7665.150627	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	5222081013.68	kWh
Gross saving	1671065924	SAR
Cost of waste collection, plant and operation (40%)	668426369.8	
Net Saving	1002.64	million SAR
Total net savings from AD technology	8667.79	million SAR

Table A-8 KSA: Pyrolysis of plastic waste outputs for scenario with only plastic reduction by 50%

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	2.32	million tons per year
Total oil produced	1.860	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	74380.030	million MJ (TJ) per year
Total energy from total plastic waste	74380029926.59	MJ
Electricity potential	20661119.42	MWh
Time basis	8760	hours per year
Power Potential	2358.57528	MW
Process efficiency	33%	
Actual Power	778.3298413	MW
Landfill Saving		
Total plastic waste	2.32	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	1317.92	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	6818169410	kWh
Gross saving	2181814211	SAR
Cost of waste collection, plant and operation (40%)	872725684.5	
Net Saving	1309.09	million SAR
Total net savings from pyrolysis technology	2627.01	million SAR

Table A-9 KSA: Population and waste generation until 2030

Year	KSA Population (million)	MSW by population (million ton)
2016	32.7	16.7
2017	33.9	17.3
2018	35.0	17.9
2019	36.2	18.5
2020	37.4	19.1
2021	38.7	19.8
2022	40.0	20.4
2023	41.4	21.1
2024	42.8	21.9
2025	44.2	22.6
2026	45.7	23.4
2027	47.3	24.2
2028	48.9	25.0
2029	50.6	25.8
2030	52.3	26.7

Table A-10 KSA power potential and electricity demand

Year	Normal Demand (MW)	Demand by population (MW)
2016	64000	54000
2018	69000	57798
2020	77000	60891
2022	80000	65124
2024	86000	69683
2026	96000	74404
2028	100000	79614
2030	112000	85150

Table A- 11 Makkah: AD of food waste output in the current practice scenario

Energy and Power		
Total food waste	0.81	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	146.34	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	3219.416266	million MJ (TJ) per year
Electricity potential	894282.2962	MWh
Time basis	8760	hours per year
Power Potential	102.0870201	MW
Process efficiency	35%	
Actual Power	35.73	MW
Landfill Saving		
Total Organic waste	0.81	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	459.4304397	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	312998803.66	kWh
Gross saving	100159617.2	SAR
Cost of waste collection, plant and operation (40%)	40063846.87	
Net Saving	60.10	million SAR
Total net savings from AD technology	519.53	million SAR

Table A-12 Makkah: Pyrolysis of plastic waste output in the current practice scenario

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.28	million tons per year
Total oil produced	0.223	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	8916.315	million MJ (TJ) per year
Total energy from total plastic waste	8916315285.96	MJ
Electricity potential	2476754.25	MWh
Time basis	8760	hours per year
Power Potential	282.73450	MW
Process efficiency	33%	
Actual Power	93.30238598	MW
Landfill Saving		
Total plastic waste	0.28	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	157.99	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	817328901.2	kWh
Gross saving	261545248.4	SAR
Cost of waste collection, plant and operation (40%)	104618099.4	
Net Saving	156.93	million SAR
Total net savings from pyrolysis technology	314.91	million SAR

Table A-13 Makkah: AD of food waste output for scenario with food and plastic reduction by 50%

Energy and Power		
Total food waste	0.41	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	73.17	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	1609.708133	million MJ (TJ) per year
Electricity potential	447141.1481	MWh
Time basis	8760	hours per year
Power Potential	51.04351006	MW
Process efficiency	35%	
Actual Power	17.87	MW
Landfill Saving		
Total Organic waste	0.41	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	229.7152198	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	156499401.83	kWh
Gross saving	50079808.59	SAR
Cost of waste collection, plant and operation (40%)	20031923.43	
Net Saving	30.05	million SAR
Total net savings from AD technology	259.76	million SAR

Table A-14 Makkah: Pyrolysis of plastic waste output for scenario with food and plastic reduction by 50%

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.14	million tons per year
Total oil produced	0.111	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	4458.158	million MJ (TJ) per year
Total energy from total plastic waste	4458157642.98	MJ
Electricity potential	1238377.12	MWh
Time basis	8760	hours per year
Power Potential	141.36725	MW
Process efficiency	33%	
Actual Power	46.65119299	MW
Landfill Saving		
Total plastic waste	0.14	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	78.99	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	408664450.6	kWh
Gross saving	130772624.2	SAR
Cost of waste collection, plant and operation (40%)	52309049.68	
Net Saving	78.46	million SAR
Total net savings from pyrolysis technology	157.46	million SAR

Table A-15 Makkah: AD of food waste output for scenario with only food reduction by 50%

Energy and Power		
Total food waste	0.41	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	73.17	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	1609.708133	million MJ (TJ) per year
Electricity potential	447141.1481	MWh
Time basis	8760	hours per year
Power Potential	51.04351006	MW
Process efficiency	35%	
Actual Power	17.87	MW
Landfill Saving		
Total Organic waste	0.41	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	229.7152198	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	156499401.83	kWh
Gross saving	50079808.59	SAR
Cost of waste collection, plant and operation (40%)	20031923.43	
Net Saving	30.05	million SAR
Total net savings from AD technology	259.76	million SAR

Table A-16 Makkah: Pyrolysis of plastic waste output for scenario with only food reduction by 50%

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.28	million tons per year
Total oil produced	0.223	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	8916.315	million MJ (TJ) per year
Total energy from total plastic waste	8916315285.96	MJ
Electricity potential	2476754.25	MWh
Time basis	8760	hours per year
Power Potential	282.73450	MW
Process efficiency	33%	
Actual Power	93.30238598	MW
Landfill Saving		
Total plastic waste	0.28	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	157.99	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	817328901.2	kWh
Gross saving	261545248.4	SAR
Cost of waste collection, plant and operation (40%)	104618099.4	
Net Saving	156.93	million SAR
Total net savings from pyrolysis technology	314.91	million SAR

Table A-17 Makkah: AD of food waste output for scenario with only plastic reduction by 50%

Energy and Power		
Total food waste	0.81	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	146.34	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	3219.416266	million MJ (TJ) per year
Electricity potential	894282.2962	MWh
Time basis	8760	hours per year
Power Potential	102.0870201	MW
Process efficiency	35%	
Actual Power	35.73	MW
Landfill Saving		
Total Organic waste	0.81	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	459.4304397	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	312998803.66	kWh
Gross saving	100159617.2	SAR
Cost of waste collection, plant and operation (40%)	40063846.87	
Net Saving	60.10	million SAR
Total net savings from AD technology	519.53	million SAR

Table A-18 Makkah: Pyrolysis of plastic waste output for scenario with only plastic reduction by 50%

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.14	million tons per year
Total oil produced	0.111	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	4458.158	million MJ (TJ) per year
Total energy from total plastic waste	4458157642.98	MJ
Electricity potential	1238377.12	MWh
Time basis	8760	hours per year
Power Potential	141.36725	MW
Process efficiency	33%	
Actual Power	46.65119299	MW
Landfill Saving		
Total plastic waste	0.14	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	78.99	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	408664450.6	kWh
Gross saving	130772624.2	SAR
Cost of waste collection, plant and operation (40%)	52309049.68	
Net Saving	78.46	million SAR
Total net savings from pyrolysis technology	157.46	million SAR

Table A-19 Makkah: population and waste generation until 2030

Year	KSA Population (million)	MSW by population (million ton)
2016	32.7	16.7
2017	33.9	17.3
2018	35.0	17.9
2019	36.2	18.5
2020	37.4	19.1
2021	38.7	19.8
2022	40.0	20.4
2023	41.4	21.1
2024	42.8	21.9
2025	44.2	22.6
2026	45.7	23.4
2027	47.3	24.2
2028	48.9	25.0
2029	50.6	25.8
2030	52.3	26.7

Table A-20 Makkah: power potential and electricity demand

Year	Normal Demand (MW)	Demand by population (MW)
2016	4500	4500
2018	5200	4788
2020	5700	5098
2022	6200	5431
2024	6800	5763
2026	7360	6140
2028	7920	6539
2030	8480	6938

Table A-21 Umrah: AD of food waste output in the current practice scenario (2030 Vision growth)

Energy and Power		
Total food waste	0.31	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	56.20	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	1236.420108	million MJ (TJ) per year
Electricity potential	343450.03	MWh
Time basis	8760	hours per year
Power Potential	39.20662443	MW
Process efficiency	35%	
Actual Power	13.72	MW
Landfill Saving		
Total Organic waste	0.31	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	176.44473	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	120207510.50	kWh
Gross saving	38466403.36	SAR
Cost of waste collection, plant and operation (40%)	15386561.34	
Net Saving	23.08	million SAR
Total net savings from AD technology	199.52	million SAR

Table A-22 Umrah: Pyrolysis of plastic waste output in the current practice scenario (2030 Vision growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.11	million tons per year
Total oil produced	0.086	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	3424.320	million MJ (TJ) per year
Total energy from total plastic waste	3424320000.00	MJ
Electricity potential	951200.00	MWh
Time basis	8760	hours per year
Power Potential	108.58447	MW
Process efficiency	33%	
Actual Power	35.83287671	MW
Landfill Saving		
Total plastic waste	0.11	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	60.67	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	313896000	kWh
Gross saving	100446720	SAR
Cost of waste collection, plant and operation (40%)	40178688	
Net Saving	60.27	million SAR
Total net savings from pyrolysis technology	120.94	million SAR

Table A-23 Umrah: AD of food waste output in scenario for food and plastic waste reduction by 50% (2030 Vision growth)

Energy and Power		
Total food waste	0.16	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	28.10	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	618.210054	million MJ (TJ) per year
Electricity potential	171725.015	MWh
Time basis	8760	hours per year
Power Potential	19.60331221	MW
Process efficiency	35%	
Actual Power	6.86	MW
Landfill Saving		
Total Organic waste	0.16	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	88.222365	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	60103755.25	kWh
Gross saving	19233201.68	SAR
Cost of waste collection, plant and operation (40%)	7693280.672	
Net Saving	11.54	million SAR
Total net savings from AD technology	99.76	million SAR

Table A-24 Umrah: Pyrolysis of plastic waste output in scenario for food and plastic waste reduction by 50% (2030 Vision growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.05	million tons per year
Total oil produced	0.043	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	1712.160	million MJ (TJ) per year
Total energy from total plastic waste	1712160000.00	MJ
Electricity potential	475600.00	MWh
Time basis	8760	hours per year
Power Potential	54.29224	MW
Process efficiency	33%	
Actual Power	17.91643836	MW
Landfill Saving		
Total plastic waste	0.05	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	30.34	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	156948000	kWh
Gross saving	50223360	SAR
Cost of waste collection, plant and operation (40%)	20089344	
Net Saving	30.13	million SAR
Total net savings from pyrolysis technology	60.47	million SAR

Table A-25 Umrah: AD of food waste output for scenario with only food reduction by 50% (2030 Vision growth)

Energy and Power		
Total food waste	0.16	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	28.10	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	618.210054	million MJ (TJ) per year
Electricity potential	171725.015	MWh
Time basis	8760	hours per year
Power Potential	19.60331221	MW
Process efficiency	35%	
Actual Power	6.86	MW
Landfill Saving		
Total Organic waste	0.16	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	88.222365	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	60103755.25	kWh
Gross saving	19233201.68	SAR
Cost of waste collection, plant and operation (40%)	7693280.672	
Net Saving	11.54	million SAR
Total net savings from AD technology	99.76	million SAR

Table A-26 Umrah: Pyrolysis of plastic waste output for scenario with only food reduction by 50% (2030 Vision growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.11	million tons per year
Total oil produced	0.086	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	3424.320	million MJ (TJ) per year
Total energy from total plastic waste	3424320000.00	MJ
Electricity potential	951200.00	MWh
Time basis	8760	hours per year
Power Potential	108.58447	MW
Process efficiency	33%	
Actual Power	35.83287671	MW
Landfill Saving		
Total plastic waste	0.11	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	60.67	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	313896000	kWh
Gross saving	100446720	SAR
Cost of waste collection, plant and operation (40%)	40178688	
Net Saving	60.27	million SAR
Total net savings from pyrolysis technology	120.94	million SAR

Table A-27 Umrah: AD of food waste output for scenario with only plastic reduction by 50% (2030 Vision growth)

Energy and Power		
Total food waste	0.31	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	56.20	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	1236.420108	million MJ (TJ) per year
Electricity potential	343450.03	MWh
Time basis	8760	hours per year
Power Potential	39.20662443	MW
Process efficiency	35%	
Actual Power	13.72	MW
Landfill Saving		
Total Organic waste	0.31	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	176.44473	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	120207510.50	kWh
Gross saving	38466403.36	SAR
Cost of waste collection, plant and operation (40%)	15386561.34	
Net Saving	23.08	million SAR
Total net savings from AD technology	199.52	million SAR

Table A-28 Umrah: Pyrolysis of plastic waste output for scenario with only plastic reduction by 50% (2030 Vision growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.05	million tons per year
Total oil produced	0.043	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	1712.160	million MJ (TJ) per year
Total energy from total plastic waste	1712160000.00	MJ
Electricity potential	475600.00	MWh
Time basis	8760	hours per year
Power Potential	54.29224	MW
Process efficiency	33%	
Actual Power	17.91643836	MW
Landfill Saving		
Total plastic waste	0.05	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	30.34	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	156948000	kWh
Gross saving	50223360	SAR
Cost of waste collection, plant and operation (40%)	20089344	
Net Saving	30.13	million SAR
Total net savings from pyrolysis technology	60.47	million SAR

Table A-29 Umrah: AD of food waste output in the current practice scenario (Normal growth)

Energy and Power		
Total food waste	0.15	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	26.79	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	589.3602515	million MJ (TJ) per year
Electricity potential	163711.181	MWh
Time basis	8760	hours per year
Power Potential	18.68849098	MW
Process efficiency	35%	
Actual Power	6.54	MW
Landfill Saving		
Total Organic waste	0.15	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	84.1053213	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	57298913.34	kWh
Gross saving	18335652.27	SAR
Cost of waste collection, plant and operation (40%)	7334260.907	
Net Saving	11.00	million SAR
Total net savings from AD technology	95.11	million SAR

Table A-30 Umrah: Pyrolysis of plastic waste output in the current practice scenario (Normal growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.05	million tons per year
Total oil produced	0.041	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	1632.259	million MJ (TJ) per year
Total energy from total plastic waste	1632259200.00	MJ
Electricity potential	453405.33	MWh
Time basis	8760	hours per year
Power Potential	51.75860	MW
Process efficiency	33%	
Actual Power	17.0803379	MW
Landfill Saving		
Total plastic waste	0.05	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	28.92	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	149623760	kWh
Gross saving	47879603.2	SAR
Cost of waste collection, plant and operation (40%)	19151841.28	
Net Saving	28.73	million SAR
Total net savings from pyrolysis technology	57.65	million SAR

Table A-31 Umrah: AD of food waste output (Base year 2016)

Energy and Power		
Total food waste	0.08	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	14.99	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	329.7120288	million MJ (TJ) per year
Electricity potential	91586.67467	MWh
Time basis	8760	hours per year
Power Potential	10.45509985	MW
Process efficiency	35%	
Actual Power	3.66	MW
Landfill Saving		
Total Organic waste	0.08	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	47.051928	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	32055336.13	kWh
Gross saving	10257707.56	SAR
Cost of waste collection, plant and operation (40%)	4103083.025	
Net Saving	6.15	million SAR
Total net savings from AD technology	53.21	million SAR

Table A-32 Umrah: Pyrolysis of plastic waste output (Base year 2016)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.03	million tons per year
Total oil produced	0.023	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	913.152	million MJ (TJ) per year
Total energy from total plastic waste	913152000.00	MJ
Electricity potential	253653.33	MWh
Time basis	8760	hours per year
Power Potential	28.95586	MW
Process efficiency	33%	
Actual Power	9.55543379	MW
Landfill Saving		
Total plastic waste	0.03	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	16.18	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	83705600	kWh
Gross saving	26785792	SAR
Cost of waste collection, plant and operation (40%)	10714316.8	
Net Saving	16.07	million SAR
Total net savings from pyrolysis technology	32.25	million SAR

Table A-33 Umrah: population and MSW generation until 2030 (2030 Vision growth)

Year	Umrah visitors (million)	MSW by Umrah visitor (million ton)
2016	8.0	0.16
2017	9.6	0.20
2018	11.1	0.23
2019	12.7	0.26
2020	14.3	0.29
2021	15.9	0.33
2022	17.4	0.36
2023	19.0	0.39
2024	20.6	0.42
2025	22.1	0.45
2026	23.7	0.49
2027	25.29	0.52
2028	26.86	0.55
2029	28.43	0.58
2030	30.00	0.62

Table A-34 Umrah: population and MSW generation until 2030 (Normal growth)

Year	Umrah Visitors (million)	MSW by Umrah visitors (million ton)
2016	8.00	0.164
2017	8.15	0.167
2018	8.35	0.171
2019	8.70	0.178
2020	9.20	0.189
2021	9.70	0.199
2022	10.00	0.205
2023	10.80	0.221
2024	11.30	0.232
2025	11.80	0.242
2026	12.30	0.252
2027	12.80	0.262
2028	13.30	0.273
2029	13.80	0.283
2030	14.30	0.293

Table A-35 Hajj: AD of food waste output in the current practice scenario (2030 Vision growth)

Energy and Power		
Total food waste	0.04	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	6.50	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	143.0313857	million MJ (TJ) per year
Electricity potential	39730.94048	MWh
Time basis	8760	hours per year
Power Potential	4.535495489	MW
Process efficiency	35%	
Actual Power	1.59	MW
Landfill Saving		
Total Organic waste	0.04	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	20.41145568	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	13905829.17	kWh
Gross saving	4449865.334	SAR
Cost of waste collection, plant and operation (40%)	1779946.134	
Net Saving	2.67	million SAR
Total net savings from AD technology	23.08	million SAR

Table A-36 Hajj: pyrolysis of plastic waste output in the current practice scenario (2030 Vision growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.03	million tons per year
Total oil produced	0.027	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	1078.641	million MJ (TJ) per year
Total energy from total plastic waste	1078640640.00	MJ
Electricity potential	299622.40	MWh
Time basis	8760	hours per year
Power Potential	34.20347	MW
Process efficiency	33%	
Actual Power	11.2871452	MW
Landfill Saving		
Total plastic waste	0.03	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	19.11	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	98875392	kWh
Gross saving	31640125.4	SAR
Cost of waste collection, plant and operation (40%)	12656050.2	
Net Saving	18.98	million SAR
Total net savings from pyrolysis technology	38.10	million SAR

Table A-37 Hajj: AD of food waste output for scenario with food and plastic reduction by 50% (2030 Vision growth)

Energy and Power		
Total food waste	0.02	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	3.25	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	71.51569286	million MJ (TJ) per year
Electricity potential	19865.47024	MWh
Time basis	8760	hours per year
Power Potential	2.267747744	MW
Process efficiency	35%	
Actual Power	0.79	MW
Landfill Saving		
Total Organic waste	0.02	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	10.20572784	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	6952914.58	kWh
Gross saving	2224932.667	SAR
Cost of waste collection, plant and operation (40%)	889973.0668	
Net Saving	1.33	million SAR
Total net savings from AD technology	11.54	million SAR

Table A-38 Hajj: Pyrolysis of plastic waste output for scenario with food and plastic reduction by 50% (2030 Vision growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.02	million tons per year
Total oil produced	0.013	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	539.320	million MJ (TJ) per year
Total energy from total plastic waste	539320320.00	MJ
Electricity potential	149811.20	MWh
Time basis	8760	hours per year
Power Potential	17.10174	MW
Process efficiency	33%	
Actual Power	5.6435726	MW
Landfill Saving		
Total plastic waste	0.02	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	9.56	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	49437696	kWh
Gross saving	15820062.7	SAR
Cost of waste collection, plant and operation (40%)	6328025.09	
Net Saving	9.49	million SAR
Total net savings from pyrolysis technology	19.05	million SAR

Table A-39 Hajj: AD of food waste output for scenario with only food reduction by 50% (2030 Vision growth)

Energy and Power		
Total food waste	0.02	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	3.25	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	71.51569286	million MJ (TJ) per year
Electricity potential	19865.47024	MWh
Time basis	8760	hours per year
Power Potential	2.267747744	MW
Process efficiency	35%	
Actual Power	0.79	MW
Landfill Saving		
Total Organic waste	0.02	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	10.20572784	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	6952914.58	kWh
Gross saving	2224932.667	SAR
Cost of waste collection, plant and operation (40%)	889973.0668	
Net Saving	1.33	million SAR
Total net savings from AD technology	11.54	million SAR

Table A-40 Hajj: Pyrolysis of plastic waste output for scenario with only food reduction by 50% (2030 Vision growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.03	million tons per year
Total oil produced	0.027	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	1078.641	million MJ (TJ) per year
Total energy from total plastic waste	1078640640.00	MJ
Electricity potential	299622.40	MWh
Time basis	8760	hours per year
Power Potential	34.20347	MW
Process efficiency	33%	
Actual Power	11.2871452	MW
Landfill Saving		
Total plastic waste	0.03	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	19.11	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	98875392	kWh
Gross saving	31640125.4	SAR
Cost of waste collection, plant and operation (40%)	12656050.2	
Net Saving	18.98	million SAR
Total net savings from pyrolysis technology	38.10	million SAR

Table A-41 Hajj: AD of food waste output for scenario with only plastic reduction by 50% (2030 Vision growth)

Energy and Power		
Total food waste	0.04	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	6.50	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	143.0313857	million MJ (TJ) per year
Electricity potential	39730.94048	MWh
Time basis	8760	hours per year
Power Potential	4.535495489	MW
Process efficiency	35%	
Actual Power	1.59	MW
Landfill Saving		
Total Organic waste	0.04	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	20.41145568	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	13905829.17	kWh
Gross saving	4449865.334	SAR
Cost of waste collection, plant and operation (40%)	1779946.134	
Net Saving	2.67	million SAR
Total net savings from AD technology	23.08	million SAR

Table A-42 Hajj: Pyrolysis of plastic waste output for scenario with only plastic reduction by 50% (2030 Vision growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.02	million tons per year
Total oil produced	0.013	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	539.320	million MJ (TJ) per year
Total energy from total plastic waste	539320320.00	MJ
Electricity potential	149811.20	MWh
Time basis	8760	hours per year
Power Potential	17.10174	MW
Process efficiency	33%	
Actual Power	5.6435726	MW
Landfill Saving		
Total plastic waste	0.02	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	9.56	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	49437696	kWh
Gross saving	15820062.7	SAR
Cost of waste collection, plant and operation (40%)	6328025.09	
Net Saving	9.49	million SAR
Total net savings from pyrolysis technology	19.05	million SAR

Table A-43 Hajj: AD of food waste output in current practice scenario (Normal growth)

Energy and Power		
Total food waste	0.02	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	4.42	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	97.23750373	million MJ (TJ) per year
Electricity potential	27010.4177	MWh
Time basis	8760	hours per year
Power Potential	3.083381016	MW
Process efficiency	35%	
Actual Power	1.08	MW
Landfill Saving		
Total Organic waste	0.02	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	13.87638795	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	9453646.20	kWh
Gross saving	3025166.783	SAR
Cost of waste collection, plant and operation (40%)	1210066.713	
Net Saving	1.82	million SAR
Total net savings from AD technology	15.69	million SAR

Table A-44 Hajj: Pyrolysis of plastic waste output in current practice scenario (Normal growth)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.02	million tons per year
Total oil produced	0.018	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	733.296	million MJ (TJ) per year
Total energy from total plastic waste	733295861.76	MJ
Electricity potential	203693.29	MWh
Time basis	8760	hours per year
Power Potential	23.25266	MW
Process efficiency	33%	
Actual Power	7.67337755	MW
Landfill Saving		
Total plastic waste	0.02	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	12.99	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	67218787.3	kWh
Gross saving	21510011.9	SAR
Cost of waste collection, plant and operation (40%)	8604004.78	
Net Saving	12.91	million SAR
Total net savings from pyrolysis technology	25.90	million SAR

Table A-45 Hajj: AD of food waste output (Base year 2016)

Energy and Power		
Total food waste	0.01	million tons per year
Typical biogas value from waste	180.6	m^3/ton
Total biogas from food waste	2.71	million m^3/year
Biogas energy potential	22	MJ/ m^3
Total energy potential of biogas from food waste	59.59641072	million MJ (TJ) per year
Electricity potential	16554.55853	MWh
Time basis	8760	hours per year
Power Potential	1.889789787	MW
Process efficiency	35%	
Actual Power	0.66	MW
Landfill Saving		
Total Organic waste	0.01	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	8.5047732	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Food waste	5794095.49	kWh
Gross saving	1854110.556	SAR
Cost of waste collection, plant and operation (40%)	741644.2223	
Net Saving	1.11	million SAR
Total net savings from AD technology	9.62	million SAR

Table A-46 Hajj: Pyrolysis of plastic waste output (Base year 2016)

Energy and Power		
Oil yield Pyrolysis	80%	weight basis
Total Plastic Waste	0.01	million tons per year
Total oil produced	0.011	million ton
Energy value of pyrolysis oil	40	Mj/Kg
Energy value of pyrolysis oil	40000	MJ/ton
Total energy from total plastic waste	449.434	million MJ (TJ) per year
Total energy from total plastic waste	449433600.00	MJ
Electricity potential	124842.67	MWh
Time basis	8760	hours per year
Power Potential	14.25145	MW
Process efficiency	33%	
Actual Power	4.70297717	MW
Landfill Saving		
Total plastic waste	0.01	million tons per year
Cost of waste dumbing	567	SAR/ton
Saving from landfill diversion	7.96	million SAR per year
Electricity saving		
Current domestic value of electricity	0.32	SAR/kWh
Total energy value of Plastic waste	41198080	kWh
Gross saving	13183385.6	SAR
Cost of waste collection, plant and operation (40%)	5273354.24	
Net Saving	7.91	million SAR
Total net savings from pyrolysis technology	15.87	million SAR

Table A-47 Hajj: population and MSW generation until 2030 (2030 Vision growth)

Year	Hajj Pilgrims (million)	MSW by Hajj pilgrims (million ton)
2016	2.50	0.039
2017	2.75	0.042
2018	3.00	0.046
2019	3.25	0.050
2020	3.50	0.054
2021	3.75	0.058
2022	4.00	0.062
2023	4.25	0.065
2024	4.50	0.069
2025	4.75	0.073
2026	5.00	0.077
2027	5.25	0.081
2028	5.50	0.085
2029	5.75	0.089
2030	6.00	0.092

Table A-48 Hajj: population and MSW generation until 2030 (Normal growth)

Year	Hajj pilgrims (million)	MSW by pilgrims (million ton)
2016	2.5	0.0385
2017	2.51	0.0387
2018	2.53	0.0389
2019	2.54	0.0391
2020	2.68	0.0413
2021	2.82	0.0434
2022	2.96	0.0456
2023	3.10	0.0477
2024	3.24	0.0499
2025	3.38	0.0520
2026	3.52	0.0542
2027	3.66	0.0563
2028	3.80	0.0585
2029	3.94	0.0607
2030	4.08	0.0628