Journal of Economic,
Administrative and Legal Sciences
Volume (6), Issue (24) : 30 Oct 2022
P: 164 - 180

ISSN: 2522-3372

مجلة العلوم الاقتصادية
والإدارية والقانونية
المجلد (6)، العدد (24) : 30 أكتوبر 2022م
ص: 164 - 180

Waste-to-energy and electricity generation: Analysis for Saudi Arabia

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Abstract: Saudi Arabia is a developing country experiencing both rapid economic growth and vast urbanization. These have led to waste disposal problems. Therefore, waste-to-energy (WTE) processes, a source of renewable energy, are expected to play an increasingly important role in sustainable management of municipal solid waste (MSW). The purpose of this paper is to estimate the energy produced from the WTE method, to assist policymakers to develop a strategy that enhances the environmental quality, through reducing energy generation in the electricity sector. This study begins by presenting Saudi's current MSW management situation and its waste disposal process as well as the major challenges associated with Saudi's WTE incineration before discussing the economic and environmental benefits of the WTE method. Since waste can be used to produce energy for electricity and heat, this study estimated energy generated from WTE technology through employing estimated baseline scenario and future scenarios. Findings indicated that future scenarios are better than the business-as-usual scenario. The paper concludes that the WTE method can produce energy for electricity generation which in turn reduces the volume and the production of greenhouse gas (GHG) emissions produced from MSW. The waste-to energy approach with supportive policies could lead the country to achieve sustainable development.

Keywords: Waste-to-energy; Municipal solid waste; GHG emissions; electricity generation.

تحويل النفايات إلى طاقة تُستخدم لتوليد للكهرباء: دراسة تحليلية للمملكة العربية السعودية

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المستخلص: المملكة العربية السعودية دولة نامية - تشهد نموًا اقتصاديًا سريعًا وتحضّرًا كبيرًا. أدّى هذا الوضع إلى مشكلات في التخلص من النفايات. لذلك، تُعَدُّ عمليات تحويل النفايات إلى طاقة ((waste-to energy (WtE) مصدرًا للطاقة المتجددة، ومِن المتوقع أن تؤدي دورًا متزايد الأهمية في الإدارة المستدامة للنفايات الصلبة البلدية (municipal solid waste(MSW)). والغرض من هذه الورقة هو تقدير الطاقة المنتجة من طريقة WTE، لمساعدة صانعي السياسات على تطوير استراتيجية تعزّز الجودة البيئية، عن طريق تقليل توليد الطاقة في قطاع الكهرباء. وتبدأ هذه الدراسة بعرض الوضع الحالي لإدارة النفايات الصلبة البلدية وعملية التخلص منها والتحديات الرئيسية المرتبطة بحرق النفايات في السعودية والفوائد الاقتصادية والبيئية لطريقة تحويل النفايات إلى طاقة. ونظرًا لأنه يمكن استخدام النفايات لإنتاج الطاقة التي تستخدم لتوليد الكهرباء، فقد قدّرت هذه الدراسة الطاقة المتولدة من تقنية WTE عن طريق استخدام سيناريو أساسي والسيناريوهات المستقبلية. وقد أعطت السيناريوهات المستقبلية نتائج أفضل من نتائج السيناريو الأساسي. وتخلص الورقة إلى أنّ طريقة تحويل النفايات إلى طاقة (WTE) تساعد في توليد الكهرباء، ممّا يقلل من إنتاج انبعاثات الغازات الدفيئة (GHG) وحجمها الناتجة عن النفايات الصلبة البلدية. وهذه الطريقة مع سياسات داعمة ستقود البلاد إلى تحقيق التنمية المستدامة.

الكلمات المفتاحية: تحويل النفايات إلى طاقة، النفايات البلدية الصلبة، انبعاثات غازات الدفيئة، توليد الكهرباء، توليد للكهرباء.

1. Introduction

The recent emphasis on conservation of resources and environmental protection has made solid waste collection and recycling necessary (Cudjoe et al., 2021). Saudi Arabia is a crude oil producing country and oil revenue has resulted in massive socio-economic development over the last four decades. By most estimates, Saudi Arabia is an emitter of GHG emissions. In the past few years, Saudi Arabia has instituted policies to slow its GHG emissions growth through launching certain initiatives. Increasing urban development paired with rapid development and an expanding population have led to increased growth of municipal solid waste (MSW) generation in Saudi Arabia at a fast rate. Therefore, the existence of an integrated waste management system in Saudi Arabia and Waste to Energy facilities are becoming a necessity (Hadidi and Omer, 2017).

Recently, Saudi Arabia launched a new policy "Vision 2030" with an ambition to produce renewable energy from indigenous sources including waste and to reduce all types of waste. The Vision planned for the development of an integrated solid waste management system to improve the financial and environmental values of waste (Nizami et al., 2017). Saudi's Vision 2030 reflects the strategy of a less oil-dependent economy through diversifying electricity sources such as generating 5.9 gigawatts of renewable energy by 2030 (Elhassan, 2021). Waste-to-Energy (WTE) is a relatively new technology with sustainable disposal of post-recycling MSW and it is a proven, environmentally sound process (ASME, n.d). Waste to Energy provides electricity or heat through preliminary treatment of municipal solid waste (Lahiraja et al., 2018). WTE technology is used in Russia, Japan, Singapore, and Taiwan and used extensively in Europe. Municipal solid waste (MSW) should be considered as a valuable source for renewable energy. The benefits from MSW are huge and may help in saving the primary energy source and for enhancing environmental quality, through employing WtE technology alongside a circular economy. WTE technology provides clean energy and produces electricity with less environmental impact than other sources by reducing emissions dramatically. MSW is a good fuel source as each tonne of combusted MSW generates 500-600 kWh of electricity. For fossil fuel, each tonne of MSW saves one to two barrels of oil (ASME, n.d).

1.1 The problem of the study

The problem of the study is that Saudi Arabia's waste causes GHG emissions, which increased from 1639 metric tonnes of carbon dioxide equivalent ($MTCO_2e$) in 1990 to 2806 $MTCO_2e$ in 2018 (see Fig. 3). Therefore, the country needs to exploit this waste to enhance environmental quality.

1.2 The importance of the study

This study tries to build a significant contribution to the existing literature by forecasting and estimating electricity generation from using the WtE method in Saudi Arabia. This in turn reduces the growth of GHG emissions in Saudi Arabia. A potential investment in the waste sector will lead to a decrease in the GHG emissions and, hence, a significantly positive impact will occur on the GDP through decreasing the amount allocated from the budget for spending on municipal services, amounting to 50.8 billion in 2021 (SAMA, 2021). Therefore, it is crucial to determine the status of MSW management, the main challenges facing the WtE industry in Saudi Arabia and its advantages. This analysis could assist policymakers to develop a strategy that helps achieve sustainable development.

1.3 Objective of the study

This study's objective is to estimate the contribution of WTE to reduce the GHG emissions produced from traditional energy resources through using the waste to energy (WtE) to generate electricity.

The rest of the study is arranged as follows: Section 2 presents a literature review. The study's methodology is presented in Section 3. Section 4 presents the study findings. Section 5 provides the conclusions and policy implications.

2. Literature review

This section reviews the studies that discuss the role of Waste-to-Energy to reduce GHG emissions. Then, it discusses the status of waste management in Saudi Arabia and the main challenges and opportunities facing the waste-to-energy industry. After that, the studies about electricity generation are presented. And finally, studies about the benefits of the waste-to-energy industry.

Waste-to-Energy (WtE) indicates technologies that treat waste to recover energy in the form of heat, electricity, or alternative fuels such as biogas and its scope is very wide. These technologies could use organic waste to produce cooking gas in household digesters and collect methane gas from landfills. It also includes co-processing of Refuse Derived Fuel (RDF) in cement plants or gasification and thermal treatment of waste in utility size incineration plants (Mutz et al., 2017). The five technologies for MSW management widely used are: incineration, plasma arc gasification, pyrolysis or gasification, refused derived fuel (RDF) and biomethanation (anaerobic digestion) (Ouda et al., 2017). Waste-to-energy processes can play a role in the transition to a circular economy if waste hierarchy (waste prevention, reuse, and recycling) is used because this is essential in order to ensure the full potential of a circular economy, both environmentally and economically. Therefore, in the future the percentage of WtE should not significantly increase as more waste is directed to recycling and improving the energy efficiency because waste prevention and recycling deliver the highest contribution in reductions in GHG emissions.

In other words, priority is given to waste prevention, reuse, separate collection, and recycling (Lohan and Pezzini, 2017). For a circular economy, Waste-to-Energy methods are important components, thus development of the WtE method can lead to suitable ecofriendly energy sources for the future which could assist in achieving the demand of clean energy in the future (Ram et al., 2021). The WtE industry can be influenced by the separate collection and recycling of municipal solid waste (MSW). This means more efficient incineration and gasification facilities will increase the electricity generation. Also, energy recovery will not be affected by achieving recycling targets (Istrate et al., 2021).

Waste-to-Energy reduces GHG emissions: the MSW can produce a significant amount of GHG emissions, incineration of waste produces CO_2 and nitrous oxide, while decomposition of MSW in landfills produces methane. WTE can curb the contribution of MSW on GHG emissions through reducing up to 1.3 tonnes of carbon equivalent per tonne of MSW (Cheng and Hub, 2010). Fossil fuel generation can be replaced by WTE incineration to achieve a reduction in the GHG emissions and avoid the discharge of landfill gases from waste in landfills (Zhang et al., 2015). Based on the European Commission, using anaerobic digestion to produce biogas and fertilisers to divert one tonne of biodegradable waste from a landfill can prevent up to 2 tonnes of CO_2 equivalent emissions (Lohan and Pezzini, 2017).

The status of waste management in Saudi Arabia: Saudi Arabia has given special support to the development of renewable energy. Vision 2030 is focused on raising the efficiency of waste management and establishing an integrated waste recycling project (Vision, 2030). The population growth coupled with an increase in the urbanization level and standard of living improvement have resulted in the rapid growth in municipal solid waste generation and electricity demand in Saudi Arabia (Ouda and Cekirge, 2014).

MSW disposal: the MSW system management governed by municipalities and disposal practices in Saudi Arabia is simply to collect and get rid of by dumping in open landfill sites. Most of these dumping sites in Saudi Arabia will reach their capacity in the coming years because a substantial amount of waste has been dumped in them. Also, the other types of waste, such as wastewater sludge are causing environmental risk like methane emissions, and other health hazards (Ouda et al., 2013). The current practices are intensively adopted due to the unavailability of advanced technologies and skilled professionals; thus, these practices are not acceptable environmentally (Radwan and Mangi, 2019).

MSW generation: in 2020, the amount of municipal solid waste generated in Saudi Arabia was more than 45 million tonnes: 25 million tonnes were household waste, and around 20 million tonnes were demolition and construction waste. The amount of waste recycled was just over 2.6 million tonnes and waste disposed by the sanitary burial method was more than 23.1 million tonnes (Ministry of Municipal Rural Affairs & Housing, 2020). Saudi Arabia waste generation is 16.13 million metric tonnes per year and its global share of MSW has reached 0.75% (Ram et al., 2021).

MSW types: there are two main components, organic waste and plastics. The main source of plastic waste comes from disposable packaging during pilgrimage. While food is the reason behind generated organic waste (Anjum et al., 2016).

In terms of waste recycling in Saudi Arabia, it is limited and carried out by an informal sector recycling paper, metals, plastics, and cardboard which form 10 to 20% of the total MSW recycling (Nizami et al., 2017). From recycling 24.21% of MSW in Madinah city, the values of revenue savings based on landfill diversion and carbon credits are estimated to be around US $32.78 and US $5.92 million respectively. Thus, every year a net revenue of US $49.01 million will be added to Saudi Arabia's economy (Nizami et al., 2017). Millions of Muslims visit Makkah every year, thus landfill receives about 2.4 thousand tonnes of MSW every day, and 3.1 and 4.6 thousand tonnes per day during the months of fasting and pilgrimage, respectively. Therefore, around 87.8% of the total MSW can be treated if WTE technologies are developed in Makkah city and the rest of MSW can be recycled (Nizami et al., 2017). Recycling is in its early stages in Saudi Arabia where the target is to increase it to 40% by 2020. Recycling is weak and almost non-existent but the waste collection is excellent (Elhassan, 2021).

Saudi government initiatives: The Saudi government is investing in solving the waste issue and is aware of the critical demand for waste management solutions. Therefore, the government allocates every year billions from the national budget to the municipal services sector. In 2021 it allocated SR 50,799 billion for the municipal services sector, which includes water drainage and waste disposal (SAMA, 2021). Recently, to ensure an integrated framework for the management of municipal waste, the Saudi government approved new regulations (Zafar, 2020). In 2023, the first plant in Saudi Arabia will be launched by the Saudi Investment Recycling Company, owned by the Public Investment Fund, to treat solid waste and convert it into energy (Mostaqbal, 2019). However, the current scenario of the management of waste in Saudi Arabia is dumping waste that causes significant environmental impacts, including GHG emissions, soil contamination and leachate production (Anjum et al., 2016). GHG emissions from waste in Saudi Arabia increased from 15.72 ($MTCO_2e$) in 1990 to 28.06 ($MTCO_2e$) in 2018 (see Fig.3). Recycling of 24.21% of MSW in one city (Madinah) could achieve up to 254,600 $MTCO_2e$. global warming potential (GWP) by saving around 10,200 tonnes of CH4 emissions (Nizami et al., 2017). Challenges facing the Waste-to-Energy industry in Saudi Arabia include the fact that WtE projects require high investments for the treatment process and for operational risks, which means WtE plant costs are considerably higher than for sanitary landfills. Therefore, it is necessary to consider additional sources of financing, plus other sources to generate income, such as waste tariffs and direct waste fees from citizens (Mutz et al., 2017). It is difficult for each WTE technology to achieve a zero waste concept and compete with present renewable-energy sources. There are limitations associated with each technology based on process efficiency, commercializing, infrastructure requirements, feedstock, and end use applications. Thus, the solution is to select conversion technologies based on waste composition and its characteristics (Nizami et al., 2015).

WTE generation electricity: waste materials can be used beneficially in producing power, transportation fuels, and chemicals by Waste-to-energy (WTE) technologies (Badgett et al., 2019). One metric tonne of municipal solid waste produces roughly the equivalent of one barrel of oil for electricity (Ouda et al., 2013). By 2032, incineration waste will produce 180, 87, and 61.3 MW of electricity in Jeddah, Makkah and Madinah respectively. Incineration and recycling produce 11.25, 5.45 and 3.84 MW; and RDF with biomethanation will generate about 87.3, 42.4 and 29.9 MW in Jeddah, Makkah, and Madinah respectively (Ouda et al., 2017). The power generation from dividing waste into two fractions or using the whole amount of waste material in biogas production is 14 to 35 million SR, and 21 to 52 million SR, respectively from 2016 till 2030 (Ali et al., 2021). If all food waste and plastic is processed through AD and pyrolysis they will produce 74.45 MW of electricity supply in Madinah for the whole year (Rehan et al., 2017).

WTE reduces dependence on fossil fuel: Mass burning shows a potential landfill area saving of about 90%, and energy demand reduction of about 9.9 million barrels of crude oil; while the mass burning with recycling shows potential landfill area saving of about 95.3%, and energy demand reduction of about 55.6 million barrels of crude oil (Ouda and Cekirge, 2014). Saudi Arabia has great potential to apply the resources approach that can be processed easily into biogas from organic waste with a large carbon content (Elhassan, 2021). Anaerobic digestion and pyrolysis add US $11696 million in total to the national economy (Rehan et al., 2017).

The Waste-to-Energy for Saudi Arabia has economic and environmental benefits. The WTE technologies will reduce the fossil fuel dependence, creating economic and environmental benefits, such as creation of jobs and new businesses, reduction in pollution, improvement in public health and achieving financial revenue (Nizami et al., 2015). The WTE approach will impact the Saudi economy positively by finding new energy sources, land saving, jobs, and training opportunity (Psomopoulos et al., 2009). In recent years, waste management has been getting widespread attention along with enabling the circular economies in Saudi Arabia. Waste to energy (WTE) plants provide a good opportunity for Saudi Arabia as the WTE with 3Rs (reduce, reuse, recycle) scenario shows a potential electricity generation reaching 254 megawatts (MW) by the year 2030 (Hadidi et al., 2020). In addition to reducing GHG emissions, there are other environmental benefits of the WTE technique:

1- reduces MSW: The Anaerobic Digestion (AD) will give a high economic and health benefit to Saudi Arabia. The AD cycle produces biogas that can be converted to electrical or thermal energy. Also, AD has been proven to be an efficient way of managing organic waste. Incineration is the process to recover energy by combustible waste, which is an effective way of reducing waste volume up to

70% by weight and 90% by volume but does require highly skilled workers and diligent maintenance (Elhassan, 2021).

2- other environmental benefits, such as complementing recycling thus reducing landfill and reducing mining operations because of recovery and recycling of metals. Also, it decreases truck traffic and emissions associated with them (ASME, n.d). Also, the WtE impacts the environment positively in terms of reducing GHG emissions, leachate production, improving air and soil quality and protecting ground water (Psomopoulos et al., 2009).

The Waste-to-Energy economic benefits: Developing the WtE in Makkah city with recycling can give a net revenue of 758 million SR generated from landfill diversion and electricity generation. Also, carbon credits can generate savings of about 87.6 million SR (Nizami et al., 2017). Some studies such as Hadidi and Omer (2017) found that WTE plants (AD and gasification) are financially profitable. The revenue obtained from dividing waste into two fractions or using the whole amount of waste material in biogas production to the national economy will be 288 million SR and 319 million SR in 2030 respectively (Ali et al., 2021). There are many studies examining the contribution of WTE to economic growth, the environment, and health for many countries (Psomopoulos et al., 2014; Psomopoulos et al., 2009; Yang et al., 2012; Tan et al., 2014; Zhang et al., 2015; Rizwan et al., 2019).

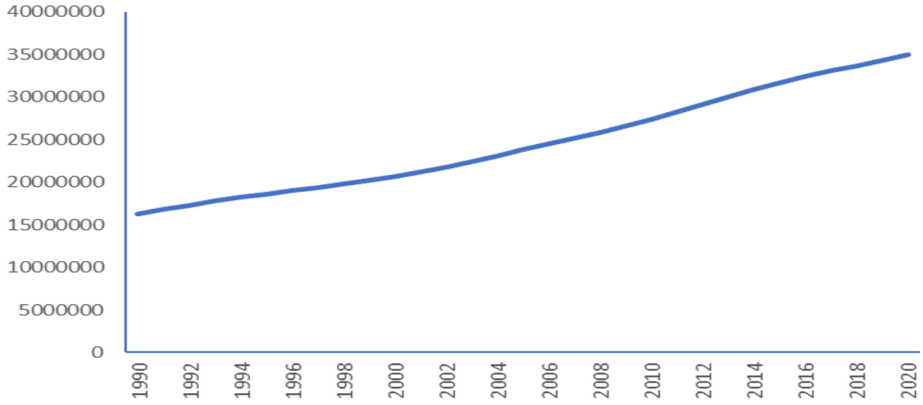
3. Methodology

Environmental policies aim to reduce pollution through employing environmental instruments, such as waste-to-energy (WtE) method. Evaluating the future WtE approach is important for policymakers to make a decision on the future strategies of sustainable development.

The mitigation emissions policy will build on reduced energy consumption in electricity generation through generating energy from MSW using the WtE approach in Saudi Arabia. Therefore, to estimate WtE empirically, future scenarios have been developed: Optimistic scenario and pessimistic scenario, and the business as usual (BaU) scenario for comparison. All scenarios will use forecast results of the population, municipal soil waste and electricity generation to estimate the WTE production potential in Saudi Arabia for the electricity sector.

3.1 Data

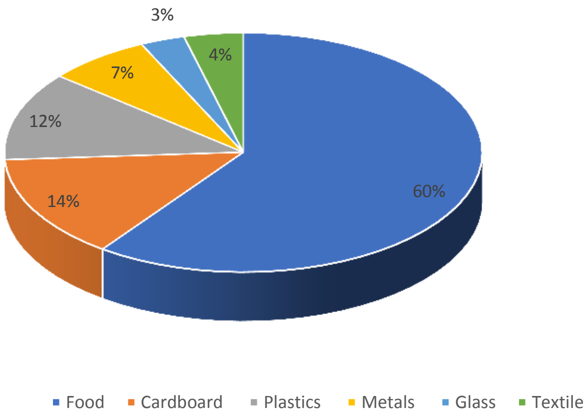
The population data used for this study was taken from the World Bank (World Bank, 2022); waste was obtained from the Annual Report Municipal Sector (Ministry of Municipal Rural Affairs & Housing, 2020), and electricity data was obtained from the U.S. Energy Information Administration (EIA, 2022). The population of Saudi Arabia in 2020 rose by 2.6 percent to 35.0 million compared to 9.6 million in 1980 (SAMA, 2021) (see Fig 1).



Source: The World Bank

Fig. 1 Population of Saudi Arabia (1980-2020)

The major ingredients of Saudi Arabian MSW are food waste, paper, cardboard, plastics, wood, glass, textile, and metals (Nizami, 2021). Fig. 2 shows that food waste is the largest MSW in Saudi Arabia at 60%, with cardboard 7%, plastics 12%, glass 3%, textile 4%, and metals at 7% (Annual Report Municipal Sector, 2020). The food waste exceeds 6 million tonnes per year in three large cities of Saudi Arabia: Riyadh, Jeddah, and Dammam (Ouda et al., 2016).

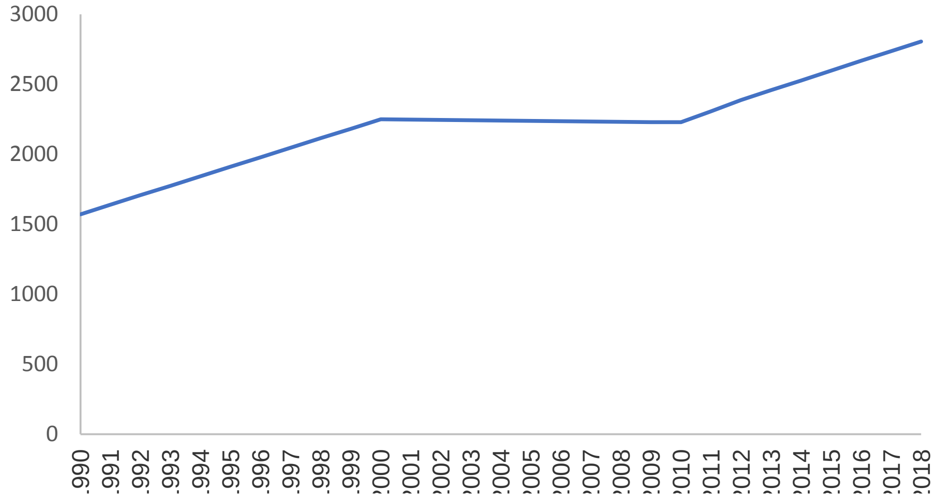


Source: Annual Report Municipal Sector, 2020

Fig. 2 Percentage of waste produced by type

Fig. 3 shows the Saudi Arabia GHG emissions from waste by $MTCO_2e$ (1990–2018), which increased from 1639 $MTCO_2e$ in 1990 to 2806 $MTCO_2e$ in 2018. Mass burning shows potential GHG emission reductions of about 4.8 million MTC_2e/year. While Mass burning with Recycling shows potential GHG emission reduction of about 15.2 MTC_2e/year (Ouda et al., 2014). In Makkah city, if developing the

WtE along with the recycling then this method can reduce the global warming potential of 1.15 million $MTCO_2e$ (Nizami et al., 2017). From the waste management employed by WtE technologies, environmental saving will be 8 to 20 million SR in the form of carbon credits (Ali et al., 2021).



Source: Ritchie et al. (2020).

Fig. 3 Saudi Arabia GHG emissions from waste by $MTCO_2e$ (1990–2018).

Table 1 shows that only five cities in Saudi Arabia applied the burning and incineration method and seven cities followed burying waste. Also, the total percentage of burning and incineration to generate energy is 0.33%. Table 2. illustrates per capita waste by (kg) and population size in Saudi Arabia from 2010-2020, which indicates a positive relationship between the two variables over time.

Table 1. Statistics of the quantities of waste and methods of disposal in 2020 (million tonnes)

Regions	MSW size	Burying waste	Burning and incineration to generate energy
Riyadh	5,197,016	5,203,692	1,000
Madinah	613,049	577,211	2,598
Makkah	608,782	608,782	0
Jeddah	2,337,693	2,350,873	563
Hail	811,672	636,589	3,941
Taif	1,778,472	1,474,085	80
Other cities	13,656,716	12,237,749	0
Total	25,003,400	23,088,981	8,182

Source: Annual Report Municipal Sector, 2020

Table 2. Per capita waste collection in Saudi Arabia from 2010-2020

Variable	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Population	27.42	28.26	29.15	30.05	30.91	31.71	32.44	33.09	33.69	34.26	35.14
Per capita daily waste	1.15	1.16	1.18	1.2	1.22	1.26	1.36	2.04	1.72	1.85	1.96

Variable	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
generation											

Source: Ministry of Municipal and Rural Affairs. Per capita generation (kg). Population from the World Bank online database.

4. Results and discussion

4.1 Forecasting results

For a sizable effect on reducing the nation's greenhouse gas emissions, new policies to encourage waste-to-energy technologies need to be employed (ASME, n.d). Rapid economic growth of Saudi Arabia during 1990–2020 led to substantial increases in per capita income, energy consumption and municipal solid waste and thus higher GHG emissions over time. This means the absence of advanced waste management can significantly increase GHG emissions and other environmental issues dramatically. Also, an important factor is population size because it raises electricity consumption and waste means more pressure on environmental quality. Thus, Saudi policymakers should give more attention to raising people's awareness and apply new policies to encourage waste-to-energy technologies.

Table 3 forecasts 2030 using the growth rate for the last ten years for population, waste, and electricity generation (electricity generation converted from billion-kilowatt hours (Bkwh) to oil barrel). Saudi Arabia's municipal solid waste will increase from 20.930 million tonnes in 2018 to 59.585 million tonnes in 2030, an increase of 184% from 2018 to 2030. This coincides with the population increase. Also, electricity generation will increase from 209.45 million oil barrels in 2018 to 442.52 million oil barrels in 2030, which reflects the impact of population size. Residential consumption accounts for the highest percentage of electricity consumption (Alajmi, 2021).

Table 3. Forecasting of the population, waste generation and electricity generation to 2030

Year	Population (million)	Total waste (million tonnes)	Electricity generation (million oil barrels)
2018	33699947	20.930	209.45
2019	34268528	23.091	222.921
2020	35144165	25.003	237.259
2021	36042177	27.271	252.519
2022	36963135	29.745	268.761
2023	37907626	32.444	286.047
2024	38876250	35.387	304.445
2025	39869626	38.598	324.027
2026	40888384	42.099	344.868

Year	Population (million)	Total waste (million tonnes)	Electricity generation (million oil barrels)
2027	41933173	45.919	367.049
2028	43004660	50.085	390.657
2029	44103525	54.629	415.784
2030	45230468	59.585	442.526

Source: calculation by author.

4.2 Scenarios results

Business as usual (BaU) scenario

As mentioned previously, analysis of mitigation emissions in Saudi Arabia will be done under the Business as usual (BaU) scenario firstly. This scenario uses the percentage of burning and incineration employed currently in the country which is 0.033% (see Table 1). Then, we will estimate how many barrels of oil are generated from the WtE method given that one metric tonne of municipal solid waste produces roughly the equivalent of one barrel of oil for electricity (Ouda and Cekirge, 2013).

Future scenarios

These scenarios aim for a reduction in GHG emissions of the waste sector. Future scenarios contain two scenarios: optimistic scenario and pessimistic scenario. These scenarios suppose to: (1) raise the waste-to-energy efficiency in the waste sector to include all cities of Saudi Arabia. Differing from the BaU scenario of the burning and incineration method to generate energy in five cities of Saudi Arabia. (2) Convert waste-to-energy at a higher percentage than the BaU scenario. Pessimistic scenario assumes to convert 10% of MSW to energy while optimistic scenario builds on transforming 50% of waste total to energy. These ratios were chosen to fit with the ambitious projects that Saudi Arabia will launch in the future; also, to be in line with what was mentioned in previous studies, that the priority will be for recycling waste (Lohan and Pezzini, 2017). And that the incineration method of waste will reduce the volume of waste up to 70% (Elhassan, 2021).

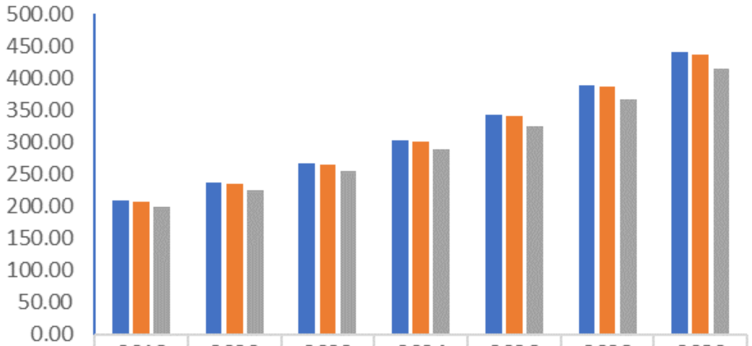
Table 4 illustrates the WtE approach under the three scenarios (BaU, optimistic and pessimistic) from 2018 to 2030. BaU scenario shows that in 2030 waste will generate 1081.10 thousand barrels of oil and under the pessimistic scenario waste will generate 5405.49 thousand barrels of oil. While under the optimistic scenario it will generate 27027.44 million barrels of oil.

Table 4. Barrels of oil from WtE technology under three scenarios

Year	BaU scenario (thousand)	Pessimistic scenario (millon)	Optimistic scenario (million)
2018	6.27	1898.74	9493.69
2019	6.91	2094.78	10473.90
2020	7.49	2268.23	11341.17
2021	8.16	2474.02	12370.08
2022	8.90	2698.47	13492.34
2023	9.71	2943.28	14716.42
2024	10.59	3210.31	16051.54
2025	11.56	3501.56	17507.79
2026	12.60	3819.23	19096.16
2027	13.75	4165.73	20828.64
2028	14.99	4543.66	22718.28
2029	16.35	4955.87	24779.37
2030	17.84	5405.49	27027.44

Source: calculation by author.

Energy reduction under the three mitigation scenarios is presented in Fig. 4. This chart shows that reduced energy under the BaU scenario and optimistic scenario is similar, but the optimistic scenario has more reduction in energy consumption.



	2018	2020	2022	2024	2026	2028	2030
BaU scenario	209.07	236.81	268.22	303.80	344.10	389.75	441.45
pessimistic scenario	207.55	234.99	266.06	301.24	341.05	386.11	437.12
optimistic scenario	199.96	225.92	255.27	288.39	325.77	367.94	415.50

Source: Author calculation.

Fig. 4 Energy reduction forecast based on mitigation scenarios in electricity generation

For the baseline scenario (BaU) of MSW, results shows that municipal solid waste will produce 17.84 thousand barrels of oil in 2030. This value forms about 0.4% of the total barrels used to generate electricity for the year 2030, which is considered a low value compared with other scenarios. Pessimistic scenario results illustrate that WtE will produce 5,405.49 million barrels of oil in 2030. This value forms about 1.22% of the total barrels used to generate electricity for the year 2030. While the optimistic scenario shows that waste-to-energy technique if it is employed for 50% of waste will produce 27,027.44 million barrels of oil in 2030 meaning 6.11% of total barrels used to generate electricity for the same year. Both future scenarios are better than the BaU scenario results. However, the BaU scenario percentage (0.033%) may rise. The proposed policy actions towards the 2030 low carbon society are improvement in energy efficiency in the residential sector by improved energy use in electrical devices such as, cooling appliances, heating appliances, cooking appliances, refrigerators, and lighting etc (Ali et al., 2019).

5. Conclusion and Policy Implications

With accelerated urbanization, a large population and economic development, Saudi Arabia's living standard has gradually improved, which has caused a growth in MSW. Saudi Arabia's main MSW disposal is currently landfill. However, this approach is unsustainable, so the adoption of waste-to-energy (WTE) technology is crucial. Thus, this study estimated the energy produced by WTE technology to use in generating electricity. This study found that the baseline scenario (business as usual) of waste -to-energy method results show that municipal solid waste will produce 17.84 thousand barrels of oil in 2030. This value forms about 0.4% of the total barrels used to generate electricity for the year 2030, which is considered a low value compared with the two future scenarios: (1) pessimistic scenario results show that municipal solid waste using the WtE approach produced 5 million barrels of oil in 2030. This value forms about 1.22% of the total barrels used to generate electricity for the year 2030. (2) Optimistic scenario results showed that the WtE technique produced 27 million barrels of oil in 2030, where this value is about 6.11% of the total barrels used to generate electricity for the same year. However, based on Saudi Arabia's current situation and types of solid waste produced, there is a great potential to use WtE technologies to make waste management practices highly effective and eco-friendly. Anaerobic digestion and pyrolysis processes could be used as waste treatment methods. The anaerobic digestion could be used for treating the organic fraction of municipal solid waste and the methane produced can be used as fuel. For plastic waste, pyrolysis is a highly suitable treatment to produce fuel oil, char, and gases (Anjum et al., 2016).

For policymakers, drawing a reliable and effective policy is important to transform the conventional disposal method into waste-to-energy method. In addition, the government must take a more active role in educating the public in the benefits of WTE, besides re-instituting the hierarchy of integrated solid waste management, which places waste-to-energy above landfill disposal. Also, the government should consider enacting legislation that would make waste-to-energy available under the definitions of green or renewable energy (ASME, n.d).

For Saudi Arabia, waste-to-energy (WTE) plants provide a golden opportunity but there are two challenges: MSW mitigation and energy production are looked at in isolation (Hadidi et al., 2020). Currently, landfilling remains the most popular waste disposal technique in the country, despite the fact that most of the landfills are expected to be saturated within the next ten years, because of the relatively low cost of land resources and the vast availability. These reasons make implementing government MSW recycling initiatives unfeasible at the moment (Hadidi and Omer, 2017). However, Saudi Arabia needs more serious efforts to improve the waste management scenario. Methodical introduction of modern waste management techniques like material recovery facilities, waste-to-energy systems and recycling infrastructure can also generate opportunities of good business (Zafar, 2020). Further, the country needs (a) to upgrade existing WTE plants, increase public participation to improve public understanding and increase WTE efficiency; (b) support policies that are reliable and effective and act as a solid foundation of MSW conversion to energy (Zhang et al., 2015); (c) focus on R&D opportunities which represent technologies that could be implemented in next generation municipal solid waste (MSW) processing facilities to increase the resource recovery potential; (d) target the markets of biofuel and bioproducts as well as develop the systems of MSW gasification, processes for direct conversion of MSW to biofuels and bioproducts and methods of decreasing the anaerobic digesters capital intensity (U.S. Department of Energy (DOE), 2019). Also, the government should consider enacting legislation that would make renewable energy credits available for WTE to expand the WTE approach (ASME, n.d). In sum, to mitigate GHG emissions while achieving economic stability, a potential option is WTE technologies (Tan et al., 2014).

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