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Energy recovery from municipal solid waste in Mauritius: Opportunities and challenges

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ABSTRACT

Energy recovery from Municipal Solid Waste in Mauritius is considered as a solution to enhance the country's energy security and tackle imminent waste management issues. This study applies an Analytical Hierarchy Process model for identifying the best waste to energy technology, which can be set up in Mauritius while taking into consideration technical as well as sustainability indicators. Incineration, gasification, pyrolysis and anaerobic digestion, were considered for the purpose of this study. As a result of the analysis, anaerobic digestion was ranked as the prioritised technology when social acceptance indicator, identified as the critical criterion, was attributed a high weight. When the effects of the critical criterion was either attenuated or eliminated during the sensitivity analysis, incineration emerged as the preferred technology. A critical analysis revealed that higher environmental and economic gains are expected to be generated as a result of implementing incineration for energy recovery in Mauritius. Finally, a review of the barriers hampering the implementation of an incineration plant in Mauritius demonstrated that the uptake of this technology is constrained by social acceptability. However, if proper awareness is conducted, energy recovery from municipal solid waste using incineration technology can become an interesting project for the Mauritian economy.

1. Introduction

Solid waste generation in Mauritius is estimated to be approximately 510,000 tonnes by 2034 (Bundhoo et al., 2016). Any waste generated needs to be collected, transported and managed. Landfilling is the only waste management system in Mauritius and the country's sole sanitary landfill is expected to reach saturation by 2019 (Third National Communication (TNC), 2016). As a Small Island Developing State (SIDS), Mauritius is limited in land resources, implying that continued landfilling is not a viable option for solid waste management (SWM). Wastes that are being disposed of in landfill are not valorised at all and represent a huge loss of materials and resources that could have been reused, recycled or transformed into energy sources so as to enhance the country's energy security. In view of tackling the country's immediate issue regarding the upcoming saturation of its sole sanitary landfill, the Government of Mauritius (GoM) has settled on the strategy to reduce the amount of Municipal Solid Waste (MSW) landfilled. Further, as communicated in the Long Term Energy Strategic plan (LTES) 2016–2030 report, GoM plans at integrating 4% of electricity from waste-to-energy (Wte) technologies in the national grid by 2025, in order to reinforce the country's energy security. As such, waste is no longer considered as an unsought product of progress, but rather as a valuable energy resource. Nevertheless, it has been noted that the energy strategy in Mauritius is silent on the type of Wte technology that can be implemented.

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Waste is no longer only an unwanted product but a valuable and exploitable energy resource which can be integrated in the energy production mix in view of satisfying increasing energy demands. However, different factors influence the generation of MSW namely; the economic status of a country, its level of industrialisation, its population growth and habits as well as its local climate amongst others. In Mauritius, the total amount of MSW being directed to the landfill was reported to be 448,476 tonnes in 2015 as compared to 417,478 tonnes in 2014, representing a 7.4% increase. The waste sector in Mauritius has the highest contribution to methane emission by source with 40 ktonnes emitted in 2015 (Statistics Mauritius, 2017). Methane emissions from the decomposition of organic wastes at landfill sites are the third greatest contributor to global methane concentrations (Environmental Protection Act (EPA), 2017). Consequently, one of the most challenging issues of present and future generations is to understand and master how to manage large quantities of waste in a sustainably acceptable manner. Indeed, the Solid Waste Management Strategy (2011–2015) (SWMS) for Mauritius, had the policy objective of encouraging the reduction, reuse and recycling of waste produced in the country (Third International Conference on Small Island Developing States, 2014). However, a consumption-driven economic growth has resulted in extensive waste generation outstripping any strategy for waste reduction, reuse and/or recycling. Consequently, a larger fraction of undesired end-products and wastes are still being landfilled. New cells of capacity 14.84 ha and 4.3 ha have recently been added to the only sanitary landfill on the island of Mauritius. At the current solid waste generation rate, the landfill is expected to be filled by 2021. Given the smallness of the island of Mauritius, the apparent solution in the face of increasing waste generation is the volume reduction of waste.

Accordingly, other more fruitful alternatives need to be envisaged in order to tackle the looming problem of waste management and disposal. Consequently, Wte has been proposed as a generic means to achieve volume reduction, while at the same time recovering energy in the form of electricity. Through its dual objective of simultaneously reducing the amount of waste being landfilled and substituting fossil fuels in power generation, the conversion of waste to energy sources serves to bridge the gap between energy supply and sustainable environment and alleviate the above mentioned twin problems (Lausselet et al., 2016).

A significant problem that has not been addressed in any policy document is the type of Wte that would be most appropriate in the context of Mauritius in order to meet the twin objectives of solid waste volume reduction and electricity generation. Since the amount of energy produced is technology-dependent, it remains unknown whether the stated policy of integrating 4% of electricity from waste-to-energy (Wte) technologies in the national grid by 2025 is realistic or not. The resulting discussions will show that the adoption of a sound analytical method for analysing the solid waste problem in Mauritius can provide an evidence-based approach for more meaningful and coherent policy decision making. The absence of such a sound scientific approach is framed as a policy-science gap, and is further discussed below.

1.1. Energy status of Mauritius

Today Mauritius ranks in the upper middle income countries with a gross domestic product (GDP) per capita of 9627.60 USD (World Energy Council, 2016). The combined population and gross domestic product growth inevitably results in a general increase in the total primary energy requirement of the country from 1428 kilo tonne equivalent in 2012 to 1550 kilo tonne equivalent in 2016. This high reliance on imported fuels renders the country vulnerable to a vast array of supply related complications such as the volatility of fossil fuel prices and supply chain issues (Wolf et al., 2016). Treading on this pathway not only makes it more difficult for Mauritius to achieve the Government's intention of increasing its share of renewables for power generation to 35% by 2025 (ROM, 2016), but also makes the country vulnerable to oil price shocks. The answer is that, the country has to use mix of alternative energy sources, including solid waste, to reduce its energy dependence on imported fuels. Moreover, given that Mauritius has taken the commitment in its Nationally Determined Contribution (NDC) to reduce it its greenhouse gas (GHG) emissions by 30% relative to the baseline scenario by 2030 and given that 60% of all emissions arise from the power sector, thus power generation sub-sector has the challenge to contribute to most of the pledged emission reductions whereby implementing solid waste in the mix will be the perfect solution. In Mauritius, 1200 tonnes of solid waste is generated on a daily basis out of which 60% is organic waste and the majority of the rest consists of paper, plastic, textile waste, wood and cardboard.

2. Materials and methods

This paper examines and compares the opportunities and challenges associated with the process of energy recovery from MSW in Mauritius. Since the current energy strategy of Mauritius does not propose any specific Wte technology to achieve the proposed 4% contribution of Wte towards the 35% renewable energy target in electricity generation in 2030, it is therefore important to rationalise between different technology options. Consequently, four Wte technologies, namely incineration, gasification, pyrolysis and Anaerobic Digestion (AD) have been investigated in view of identifying the most suitable and economically feasible technology to be implemented. Even though gasification is an established technology, its deployment for treatment of MSW is quite limited (Tanigaki et al., 2015) with only around a hundred facilities operating worldwide (Wong and Tam, 2014). Pre-treatment is also crucial for the efficient waste to energy conversions which involves shredding to reduce the size of highly heterogeneous waste, and drying to decrease the moisture content (Arena, 2012) and entails some considerable costs. AD is a well-established technology for the treatment of domestic sewage and organic waste, but its application for MSW treatment is only just maturing (Mallapaty, 2011). For Anaerobic digestion, the most important parameters which dictate a plant's efficiency is its organic degradation rate to produce biogas (Lindorfer et al., 2007), the yield of biogas per tonne of organic fraction of MSW (OFMSW) and the lower calorific value of methane gas (Gebrezgabher et al., 2010). The possibility of translating the associated technology barriers, with regards to the prioritised technology, into measures was also explored. The technology prioritisation process then enables an informed discussion of

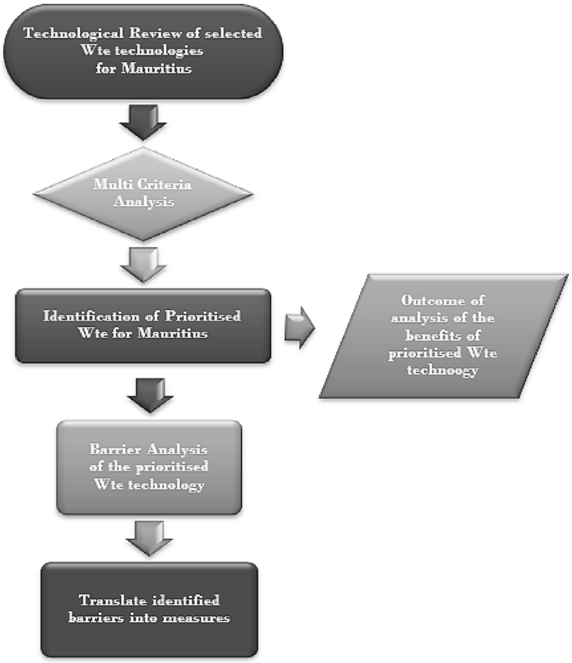

Fig. 1. Methodology flowchart.

the feasibility of the proposed electricity generation target of 4% by 2030 from Wte. Alternatively, the study shows under which conditions the proposed target can be met. In so doing, this paper provides an important contribution in achieving evidence-based policy-decision making by bridging the policy-science gap. In this case, it is shown using a robust scientific method that the energy-to-waste policy proposed at the national level may not be achieved due to a lack of sound analytical process underlying policy formulation.

2.1. Methodology

In view of prioritising the four Wte technologies, a methodological approach based on a Multi-criteria decision-making (MCDM) model was adopted (Fig. 1). The approach took into account the country's unique socio-economic, environmental and technological landscape, as well as the judgements of key experts in SWM and power generation. Decision making criteria which are incumbent for the model and relevant for the assessment of the different Wte technologies were determined. A review of the four identified technologies and data collection were carried out based on the chosen decision making criteria. The data gathered from the technology as well as literature review were plugged into the model and the different Wte technologies for Mauritius were compared. The outcome was the identification of the prioritised Wte technology for Mauritius. The environmental and economic benefits arising from the prioritised technology were further investigated in terms of avoided methane emissions, net CO_2 equivalent emissions, annual electricity generation and the economic savings resulting from the avoided combustion of heavy fuel oil (HFO) at thermal power plants. The barriers pertaining to the chosen technology were identified and recommendations for translating these barriers into measures were formulated. The flowchart of the methodology adopted for the purpose of the study is represented in Fig. 1.

2.2. Multi-criteria decision-making (MCDM)

Owing to the vast array of available technologies to tackle waste management issues and the trade-offs that exist between these technologies, decision makers usually turn towards MCDM models, a tool which unambiguously takes into consideration these conflicting criteria for decision making purposes (Astrup et al., 2015). MCDM embodies quantitative as well qualitative variables during the analysis of complex situation (Panepinto et al., 2015), and is not only an attractive means to aid decision-makers in opting for the best compromise among Wte technology alternatives, but also helps in gaining the acceptance of the public with regards to the optimal waste management strategy (Astrup et al., 2015). The MCDM exercise has been carried out by using the free-access software SuperDecisions® which has proven to be a reliable software and has been used in numerous previous studies (Yap and Nixon, 2015; Saracoglu, 2015; Atmaca and Basar, 2012; Banar et al., 2007).

2.3. Analytic hierarchy process (AHP)

The AHP, which is a MCDM technique, is regularly used to evaluate several conflicting criteria during complex decision making

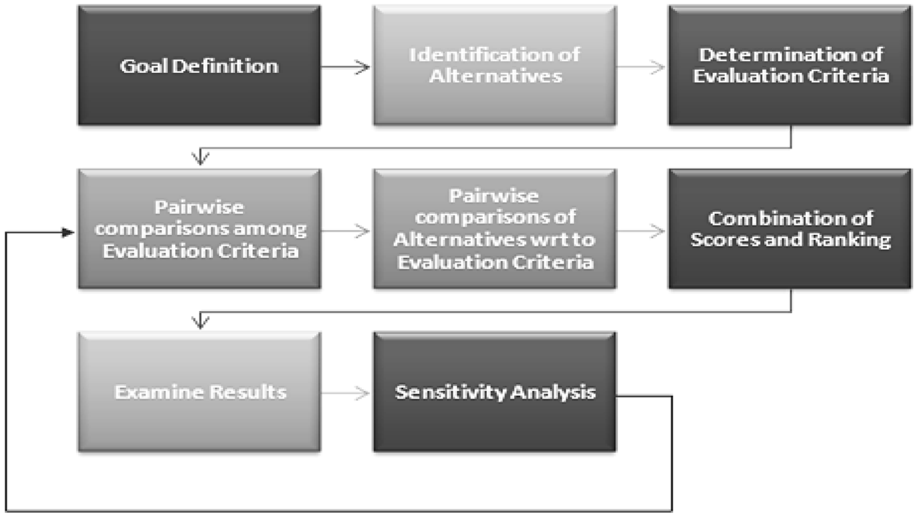

Fig. 2. Steps for the analytical hierarchy process.

process (Atmaca and Basar, 2012). AHP which is based on mathematics and judgement, serves to set priorities among the various criteria concerned, and eventually helps in making the most appropriate decision. The general idea of the AHP technique consists of breaking down a complex decision or goal into a set of hierarchical levels of criteria and alternatives. The set of selected alternatives are then assessed with regards to a set of pre-defined evaluation criteria. The best option is the one achieving the most acceptable trade-off among the criteria being considered as shown in Fig. 2.

2.4. *Pairwise comparison of evaluation criteria*

The pairwise comparisons of each evaluation criterion are conducted with the aim of allocating a weight to each criterion by using the Saaty and Sodenkamp recommended weighting scale from 1 (equal importance) to 9 (extreme importance) (Saaty and Sodenkamp, 2008). The significance of each weight is as shown in Table 1.

The ranks of the evaluation criteria were determined through pairwise comparisons of each criterion with respect to the remaining criteria by using SuperDecisions®. Likewise, pairwise comparisons of the different Wte technologies with respect to a selected criterion were carried out. The relevant data collected through the technology review of the four alternatives helped in allocating the different scales in the pairwise comparisons. The technology generating the highest score will have the highest impact on the assessment of the set of selected alternatives. Pairwise comparisons of the set of selected alternatives with respect to each evaluation criterion is thereafter conducted by assigning a score to each alternative for the considered evaluation criteria. The alternative with the highest score is considered to demonstrate better performance with respect to the criterion. The evaluation criteria weightage and the alternative scores are thereafter combined to determine a global score for each alternatives as well as an ensuing ranking. The technology with the highest global score was the prioritised technology for energy recovery from MSW in Mauritius and was considered as the best choice for the decision making process (Saaty, 1980).

2.5. *Sustainability and technical indicators*

The implementation of Wte in Mauritius is aimed at leading the country on a sustainable development pathway through clean energy generation, volume reduction of waste landfilled, and eventually greenhouse gas emissions reduction. Hence, sustainability

Table 1
Significance of weightings.

Weighting	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the activity under study
2	Weak	
3	Moderate importance	One criteria is slightly favoured over another
4	Moderate plus	
5	Strong importance	One criteria is strongly favoured over another
6	Strong plus	
7	Very strong importance	One criteria is very strongly favoured over another-its dominance is demonstrated in practice
8	Very, very strong plus	
9	Extreme importance	Unquestionable importance of one criteria over the other

indicators and technical indicators, namely economic, social and environmental indicators have been utilised. The choice of evaluation criteria and indicators were validated by the national experts.

2.5.1. Economic indicators

Capital and investment cost (CIC) and Operation and maintenance cost (O&MC) were the economic indicators considered. When it comes to the construction and implementation of Wte technologies, the extent of capital investments highly influences the decisions in choosing the most suitable alternative. The initial capital cost is generally very high, but also vary according to the chosen technology and its production capacity (World Energy Council, 2016). The cost to operate and maintain a Wte plant is also technology-dependent. However, O&MC has a lesser impact on the total expenses of the plant and vary mostly according to the amount of waste treated (World energy council, 2013).

2.5.2. Environmental indicators

Greenhouse gas Emissions: Climate change is a growing worldwide concern. Considering its direct relations to global warming and climate change (Panepinto et al., 2015), CO_2 emissions was closely scrutinised for each Wte alternative. This indicator is of national relevance in the context of tracking greenhouse gas emission target reported in the Mauritius Nationally Determined Contributions (ROM, 2016). It is highlighted that no other atmospheric pollutants have been considered in the present study except CO_2 emissions.

Volume reduction of MSW: The key objective of implementing a Wte is to reduce the volume of MSW landfilled. According to the mitigation scenarios developed in the TNC (ROM, 2016) for Mauritius, 500 tonne/day of MSW will be diverted from the landfill for power generation as from 2019.

2.5.3. Social indicators

Social acceptance by local community is critical and is an important prerequisite for the successful implementation and effective functioning of any MSW management scheme, especially when it comes to Wte alternatives (Kikuchi and Gerardo, 2009). Wte technology stigmatisation and the Not-in-my-Backyard (NIMBY) syndrome should be taken into account (Bosmans et al., 2013). Consequently, the opposition of the local community to a projected setting up of a Wte can lead to major delays or eventual withdrawal of the project, as has been the case in Mauritius concerning the La Chaumière incinerator project, the CT Power project and more recently, the oil refinery and onshore storage facilities project at Albion (CSO, 2016).

2.5.4. Technical indicators

Overall System Efficiency: Given that a technology with a superior efficiency has greater electricity yield from a known mass of MSW, this indicator is useful in prioritising the most suitable Wte technology.

Compatibility with local MSW: The different characteristics of the local MSW such as organic composition, moisture and ash content as well as its chemical composition have an impact on the energy performance of the plant.

Maturity of technology: A technology which has been successfully deployed, established and in operation on a commercial scale presents several advantages. The reduced technology risks associated with a mature technology eases access to capital acquisition programs. Furthermore, the commercial establishment of the technology on the market reduces the capital costs involved.

2.5.5. Sensitivity analysis

Given that the AHP analysis relies on expert judgement, a sensitivity analysis was carried out to examine the impact of different opinions on the final result. The criteria weightings were modified and the impact on the resulting prioritised technology was observed. The results of the AHP are considered to be robust if they do not vary drastically following an alteration of the criteria weightings (Ishizaka and Labib, 2009).

2.6. Evaluation of the environmental and economic benefits of prioritised technology

Once the prioritised technology was identified, the energetic, environmental and monetary gains attributed to the said technology were examined.

Total Volume Reduction in Landfill: Since GoM has stated the implementation of Wte plant by 2019 (Budget speech 2016/2017), the amount of final waste being landfilled was considered as from year 2019. Waste generation per annum for 2019 is projected to be 485,445 tonnes and was estimated by using a 2% year-on-year increase as reported in the TNC (ROM, 2016). According to the TNC, 500 tonnes of waste would be directed towards the Wte plant/day. Thus, the total volume reduction in MSW is expected to be:

$$MSW_l,\text{tonnes} = MSW_g - ((500 \times \alpha) \times 365) \tag{1}$$

where.

$\boldsymbol{MSW_l}$:Total MSW landfilled in 2019, tonnes;
$\boldsymbol{MSW_g}$:Total MSW generation/annum in 2019, tonnes;
$\boldsymbol{\alpha}$:volume reduction (%)

Total avoided Methane from Waste Disposal: Methane emission in landfills can be quantified by two methods (IPCC, 2000) –a simple mass balance calculation or the First Order Decay (FOD) method. The FOD takes into consideration the time required for the biodegradation of organic carbon to estimate the annual methane emission.

Annual Electricity Generation from incineration: The following assumptions were made:

- Overall waste to electricity conversion efficiency of 19% (Astrup et al., 2015);
- The power plant runs for 24 h continuously for 333 days/year;
- The plant receives 500 tonnes of MSW on a daily basis (ROM, 2016);
- The net calorific value of mixed MSW on wet basis is 8.55 MJ/kg (Surroop and Juggurnath, 2011).

The amount of electricity generated/annum was calculated from equation (2):

$$\text{Electricity, MWh} = \dot{m}_{MSW} \times \text{LHV} \times ŋ \times \text{T} \tag{2}$$

where.

$\dot{m}_{MSW}$:Mass flowrate of MSW, kg/s;
LHV:Lower Heating Value, MJ/kg;
ŋ:Efficiency of power plant, %
T: Operation time of plant.

Biogas combustion from AD: The following assumptions were made:

- thermal plant uses a gas engine to generate power from combustion of biogas;
- efficiency of the gas engine is 33% (Bove and Lunghi, 2006);
- biogas consists of 60% methane (Surroop, 2010);
- biogas yield is 150 m^3/tons of the OFMSW (Fricke et al., 2005);
- biogas has a LHV of 37.5 MJ/kg (Bove and Lunghi, 2006);

The amount of biogas produced from the OFMSW is estimated using equation (3):

$$\dot{m}_{biogas} = \dot{m}_{OFMSW} \times \text{Y} \tag{3}$$

where.

$\dot{m}_{biogas}$: Mass flowrate of biogas, m^3/s;
$\dot{m}_{OFMSW}$: Mass flowrate of organic fraction of MSW, kg/s;
Y: Biogas Yield, m^3/kg

The total amount of power generated/annum through the combustion of biogas from AD is calculated using equation (4) (Surroop and Mohee, 2012):

$$\textbf{\textit{Electricity}},\ \textbf{\textit{MWh}} = \dot{m}_{OFMSW} \times \text{Y} \times \delta \times \rho_{CH4} \times \textbf{\textit{LHV}}_{CH4} \times (1.16 \times 10^{-5}) \times ŋ \times \textbf{\textit{T}} \tag{4}$$

where.

$\dot{m}_{OFMSW}$: Mass flowrate of organic fraction of MSW, kg/s;
Y: Biogas Yield, m^3/kg
δ: Methane fraction of biogas, %
ρ_{CH4}: Density of methane, kg/m^3
LHV_{CH4}:Lower Heating Value of methane, MJ/kg
ŋ:Efficiency of power plant, %
T: Operation time of plant

Total Annual Avoided Heavy Fuel Oil (HFO) Combustion: In this study, it was assumed that electricity produced from Wte will substitute power generated at the margin, which in the case of Mauritius is done using the thermal combustion of HFO. Given the high dependence on HFO, and from the perspective of balance of trade, it is useful of estimate the amount of HFO that would be avoided (equation (5)) by implementing the prioritised Wte technology. The specific yield of HFO was taken to be 4.89 MWh/tonne (fuel) (ROM, 2016).

$$\textit{Mass of avoided } \textbf{\textit{HFO}},\ \frac{\textbf{\textit{tonnes}}}{\textbf{\textit{year}}} = \frac{\textbf{\textit{P}}}{4.89} \tag{5}$$

where.

P: Electricity generated by Wte, MWh/year.

Total Annual Savings on HFO Imports: The annual economic savings on the country's import bill is calculated using (equation (6)):

$$\boldsymbol{Economic\ Savings,\ MUR} = \boldsymbol{m_{HFO}} \times \boldsymbol{C} \tag{6}$$

where.

$\boldsymbol{m_{HFO}}$: mass of avoided coal combustion per annum, tonnes;
$\boldsymbol{C}$: cumulative savings in Mauritian Rupees (MUR) between 2019 and 2030 HFO per metric tonne (Statistics Mauritius, 2017).

Total (net) CO_{2e} Emissions Avoided: Total (net) CO_{2e} Emissions Avoided: Apart from economic savings, Wte is expected to result in global environmental benefits in terms of greenhouse gas emission reductions. These accrue from the avoided combustion of HFO from thermal generation in the counterfactual baseline and the avoidance of methane emissions at the landfill when MSW is diverted to the Wte plant. Methane emissions have been converted to equivalence of CO_2 (i.e. CO_{2e}) using a CH_4 global warming potential (GWP) of 25 as it has a much higher heat trapping ability. This factor was 21 but has been reported as 25 recently in the Third National Communication report due to an increase in the amount of CH_4 gas in the atmosphere. It is also estimated that if this trend continues, the GWP of methane will increase to a value between 28 and 36 over the next decade (United State Environment Protection Agency, 2017). The net CO_{2e} emissions avoided for 2020 were calculated using equation (7) whereby:

$$\boldsymbol{Net\ CO_{2equivalent}\ avoided,\ Gg} = (25.\ \boldsymbol{CH_{4landfill}} + \boldsymbol{CO_{2HFO}}) - \boldsymbol{CO_{2MSW}} \tag{7}$$

where.

$\boldsymbol{CH_{4\ landfill}}$: Mass of CH_4 equivalent avoided at the landfill, Gg;
$\boldsymbol{CO_{2\ HFO}}$: Mass of CO_2 avoided from combustion of HFO, Gg;
$\boldsymbol{CO_{2MSW}}$: Mass of CO_2 emitted from combustion of MSW, Gg.

Mass of CO_2 avoided from combustion of HFO, CO_{2HFO} is given by:

$$\boldsymbol{CO2HFO,\ t} = \boldsymbol{m_{HFO}} \times 0.829 \times 3.7 \tag{8}$$

where.

$\boldsymbol{CO_{2\ HFO}}$: Mass of CO_2 avoided from combustion of HFO, Gg;
$\boldsymbol{m}$HFO: mass of avoided HFO combustion per annum, tonnes
0.829: the carbon emission factor of HFO in tonnes C per tonnes HFO
3.7: the ratio of atomic masses of CO_2 and C respectively that is, 44/12 used to convert weight of C into equivalence of CO2.

Mass of CO_2e avoided at the landfill site: As from 2019, it is expected that 500 tonnes per day of MSW will be diverted from the landfill. Thus, the amount of CO_{2e} emission avoided at the landfill site for year 2020 is estimated to be **155,000 tonnes**, as calculated by the FOD method and as reported in the TNC using a double exponential decay (ROM, 2016).

CO_2 emitted from incineration of MSW, CO_{2MSW} is:

$$\boldsymbol{Mass\ of\ CO_2\ emitted\ from\ incineration\ of\ MSW,\ t} = \boldsymbol{m_{MSW}} \times 0.3015 \times 3.7 \tag{9}$$

where.

mMSW: mass of municipal solid waste, tonnes
0.3015: carbon emission factor of biomass in tonne C/tonne(MSW),
3.7 : ratio of atomic masses of CO_2 and C respectively

CO_2 emitted from combustion of biogas from MSW is:

$$\boldsymbol{Mass\ of\ CO_2\ emitted\ from\ combustion\ of\ biogas,\ t} = \boldsymbol{\dot{m}_{biogas}} \times \rho_{CH4} \times 0.6 \times 2.75 \tag{10}$$

where.

$\boldsymbol{m_{biogas}}$: mass of biogas in tonnes
0.6: fractional content of CH4 in biogas
2.75: ratio of the percentage of carbon by weight for HFO (82.9) to percentage of carbon by weight for MSW (30.15)

The following assumptions were made:

- percentage of carbon by weight for HFO is 82.9 (Morvay and Gvozdenac, 2009);
- percentage of carbon by weight for MSW is 30.15 (Surroop and Juggurnath, 2011);
- 1 kg of methane releases 2.75 Kg $CO_{2;}$
- 1 kg of carbon releases 3.7 Kg CO_2;

Table 2
Summary of technology review.

Indicator	Wte Technologies			
	Incineration	Gasification	Pyrolysis	Anaerobic Digestion
Overall System Efficiency	18–30%	18–22%	15%	10–12%
Compatibility with Local MSW	High Compatibility	Low Compatibility	Low Compatibility	Medium Compatibility
Prominence and Establishment of Wte Technology	High Prominence	Low prominence	Emerging	High Prominence
Capital and Investment Cost	400-600S/tpa (capacity of 100–200 ktpa)	620 - 850$/tpa (capacity of 100–200 ktpa)	650$/tpa (capacity of 17,5 ktpa)	240 $/tpa (capacity of l00ktpa)
Operation and Maintenance Cost	40-60$/tpa	70 - 90$/tpa	38$/tpa	18$/tpa
Air Emissions	220 g CO_2/kWhe	114 g CO_2/kWhe	Insufficient data	200 CO_2/kWhe
Pre-treatment cost	None	High (Shredding and Drying)	High (Sorting. Shredding and Drying)	Medium
Volume Reduction of MSW	Up to 95%	90–95%	90%	75% of OFMSW
Social Acceptability	Low Acceptability	Low Acceptability	Low Acceptability	High Acceptability

*ktpa – kilo tonnes per annum.

- All carbon present in HFO, methane or MSW is converted into CO_2 during combustion and there are no losses.

3. Results

3.1. Comparison of the four technical options

The comparison of the four identified Wte technologies with respect to the local context and the selected evaluation criteria is displayed in Table 2.

3.2. Pairwise comparisons of evaluation criteria

The evaluation criteria selected for the WTE were thereafter allocated a weighting in order to determine the impact that they will have on the assessment of the Wte alternatives. For that purpose, a pairwise comparison was carried out with each evaluation criteria

Table 3
Pairwise comparisons of evaluation criteria.

Weighting Scale	Evaluation Criteria		Weighting Scale
	Overall System Efficiency (OSE)	Compatibility with Local MSW (LMSW)	5
	OSE	Maturity of Technology (MoT)	6
	OSE	Capital and Investment Costs (CIC)	3
	OSE	Operation and Maintenance Costs (O&MC)	3
7	OSE	GHG Emissions	
5	OSE	Volume Reduction	
	OSE	Social Acceptability	7
	Compatibility with LMSW	MoT	3
1	Compatibility with LMSW	CIC	1
1	Compatibility with LMSW	O&MC	1
7	Compatibility with LMSW	GHG Emissions	
5	Compatibility with LMSW	Volume Reduction	
	Compatibility with LMSW	Social Acceptability	7
2	MoT	CIC	
2	MoT	O&MC	
7	MoT	GHG Emissions	
5	MoT	Volume Reduction	
	MoT	Social Acceptability	6
3	CIC	O&MC	
8	CIC	GHG Emissions	
6	CIC	Volume Reduction	
	CIC	Social Acceptability	4
8	O&MC	GHG Emissions	
6	O&MC	Volume Reduction	
	O&MC	Social Acceptability	4
	GHG Emissions	Volume Reduction	6
	GHG Emissions	Social Acceptability	5
	Volume Reduction	Social Acceptability	7

Note: weightage appearing on both side means that equal weightage is assigned to both criteria.

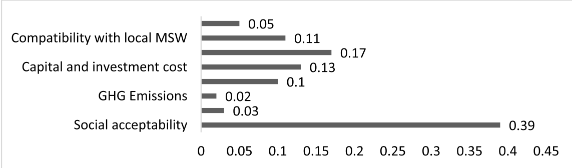

Fig. 3. Ranking of evaluation criteria following pairwise comparisons.

respectively to determine the most preferred technology. The attributed weighting scales of each evaluation criterion are summarised in Table 3.

To rank the evaluation criteria in terms of the impact that they will have on the assessment of the Wte alternatives, a pairwise comparison was carried out, whereby the allocation of weightings was conducted by taking into consideration the local economic, energy, environmental as well as social context. The validation of the weights allocated for pairwise comparison took place through a three-step process, namely: (1) by analysing the allocation of weights to indicators in similar studies reported in the literature; (2) then contextualising the weights to represent the decision-making context in Mauritius through our understanding of the local waste management context, and (3) in-depth discussions with two experts who are highly-placed public officials in the positions of (i) Director of the Waste Division in the Department of Environment, Ministry of Environment and Sustainable Development, and (ii) Manager Planning and Generation, Central Electricity Board to confirm the selected weights. The evaluation criteria validated were: the local municipal solid waste (LMSW), overall system efficiency (OSE), maturity of technology, capital investment cost, Operation and Maintenance Costs, greenhouse gas emission and volume reduction. The compatibility of each criterion was compared with remaining criteria to identify the WTE technology which will be favoured in the local context.

3.3. Ranking of the evaluation criteria

Following the pairwise comparison of the various evaluation criteria, the rankings have been reported as in Fig. 3.

3.4. Pairwise comparisons of the Wte technologies

With the aid of the data collected through the technology review of the four alternatives and discussions with stakeholders, the AHP analysis identified AD as the preferred technology for power generation from MSW in Mauritius (Fig. 4).

A priority ranking of the Wte technologies with respect to each evaluation criteria was thereafter conducted as shown in Fig. 5(a)-(h).

3.5. Sensitivity analysis

The sensitivity of the AHP results was investigated to study any change in the overall results according to three different scenarios described in chapter 3. The visual representation of the different variations of the model resulting from the sensitivity analysis are elaborated in Figs. 6 and 7.

3.6. Environmental and economic benefits of the prioritised technology

Following the AHP analysis, the amount of power generated by AD and the resulting environmental and monetary gains were examined. The results are tabulated in Table 4 as follows:

3.7. AD vs. incineration – the energy policy considerations

As per the LTES plan, the Government has demonstrated a strong intention of integrating 4% of electricity from Wte technologies to the local grid by 2030 which cannot be met by AD. Hence, the second prioritised technology, incineration, is considered. The amount of power generated by incineration and the resulting environmental and monetary gains are represented in Table 5.

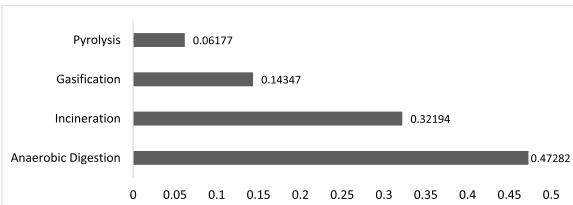

Fig. 4. Ranking of Wte technologies.

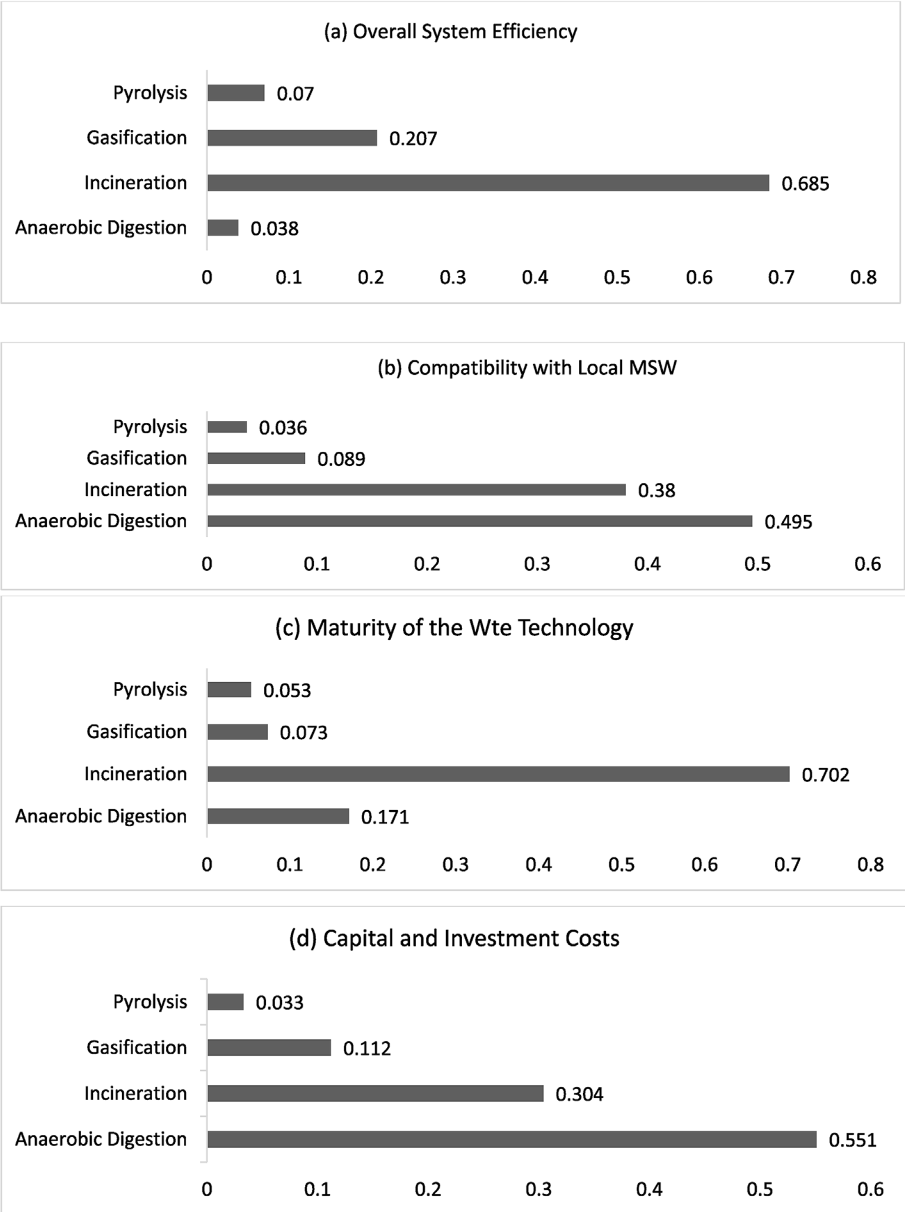

Fig. 5. Priority Rankings of Wte technologies with respect to each evaluation criteria.

4. Discussions

4.1. Comparison of the four technical options

Incineration, gasification, pyrolysis and anaerobic digestion were the selected Wte technology and were compared with various criteria (Table 1) to determine the most appropriate technology for the local context. As per the “Decision Maker's Guide to MSW Incineration, 1999” report, the net calorific value, on a wet basis of local MSW must on average be 7 MJ/kg without ever dropping below 6 MJ/kg. According to the Tanner Diagram, combustion of MSW in an incinerator can be self-sustained without the use of any secondary fuel if the MSW, on a wet basis, has an ash content $\leq$60%, a water content $\leq$50% and a combustible organic content $\geq$25%, (Komilis et al., 2014). The MSW in Mauritius has an ash content of about 9%, a water content of 38% and a combustible organic content (paper, plastic and textile) of 34% (Mohee et al., 2016). As such, the local MSW falls in the area of self-sustained combustion and is compatible with the incineration technology. Consequently, it can be observed that no pre-treatment (pre-drying) is required for the local MSW. The ISWA report (2013), “*Guidelines: Waste-to-energy in low and middle income countries*” suggested a capital investment cost (CIC) neighbouring 400–600 USD/yearly tonne for plants of capacity ranging from 100 to 200 ktpa (UNEP

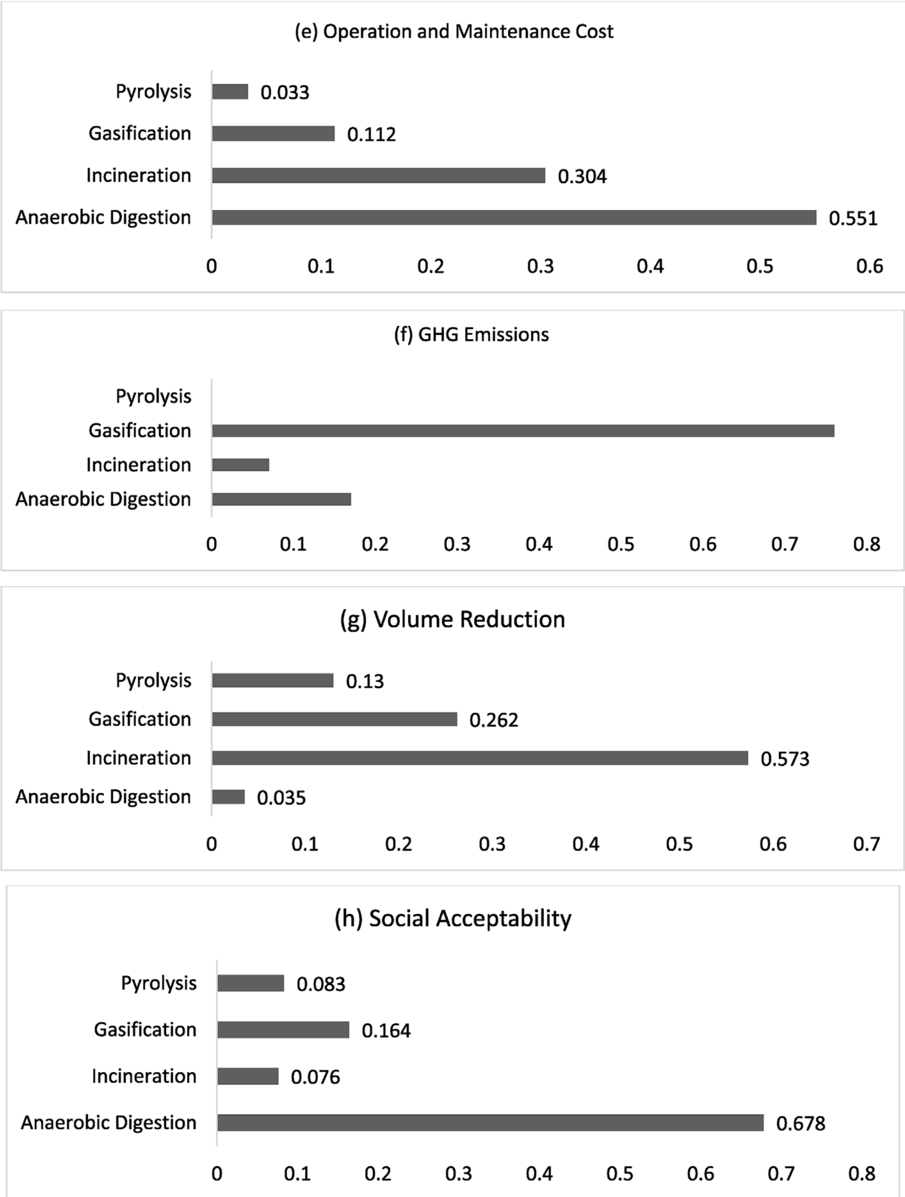

Fig. 5. (*continued*)

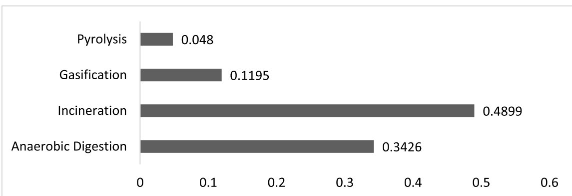

Fig. 6. Ranking of technologies when eliminating critical criterion.

and ISWA, 2015). Finally, the implementation of a mass burn Wte plant can reduce up to 95% of the amount of MSW being landfilled (Wong and Tam, 2014).

With regards to the gasification technology, it has an overall waste to electricity conversion efficiency of 18–22% (Yap and Nixon, 2015). However, it has been reported that the greatest challenge for commercialising this technology is the costly cleaning process of the syngas produced before its combustion for power generation (World Energy Council, 2016). CIC for gasification plants of

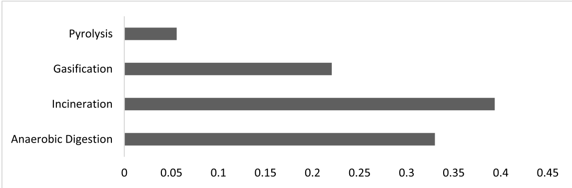

Fig. 7. Ranking of Wte technologies when all criteria are allocated equal weightings of 0.125.

Table 4
Output of anaerobic digestion.

Parameter	Results
Total volume reduction in landfill per annum	73, 912.5 tonnes
Total final MSW landfilled for 2019	411, 532.5 tonnes
Total avoided methane emission from solid waste disposal in landfill	155 Gg CO2e
Power output	2.5 MW
Total annual electricity generation	20 GWh
Total annual avoided heavy fuel oil combustion at thermal power plant	4, 086 tonnes
Total annual economic savings on heavy fuel oil imports	1,569,269 Euro
Total(net) carbon dioxide equivalent emissions avoided	151.6 Gg CO_2e

Table 5
Output of incineration plant.

Parameter	Results
Total volume reduction in landfill per annum	173, 375 tonnes
Total final MSW landfilled for 2019	312, 070 tonnes
Total avoided methane emission from solid waste disposal in landfill	155 Gg CO_2e
Power output	9.4 MW
Total annual electricity generation	75 GWh
Total annual avoided heavy fuel oil combustion at thermal power plant	15, 365 tonnes
Total annual economic savings on heavy fuel oil imports	5,900,946 Euro
Total(net) carbon dioxide equivalent emissions avoided	16.4 Gg CO_2e

capacities ranging from 100 to 200 ktpa are between 620 and 850$/yearly tonne (DEFRA, 2013). Given that the operational processes are more complex than incineration, the resulting operations and maintenance costs are also higher. Noteworthy environmental gain of MSW gasification is the total volume reduction of 90–95% of MSW being landfilled (Wong and Tam, 2014).

MSW pyrolysis technology is still in a development stage, hence, there is limited track record concerning commercial scale MSW pyrolysis power plants. Currently, there are only about 25 MSW pyrolysis power generation plants worldwide most at research or pilot level (Lombardi et al., 2015). The net electricity efficiency of this technology is about 15% when employing conventional incineration energy recovery systems (Astrup et al., 2015). MSW fractions subjected to pyrolysis consist of paper, textile, plastics and yard wastes. Fractions with high moisture content, are recommended to be either removed from the MSW, or pre-dried before pyrolysis to reduce the amount of heat that needs to be input to the reactor (Chen et al., 2015). Pyrolysis has the potential to reduce the volume of waste being landfilled by 90% (Wong and Tam, 2014).

For anaerobic Digestion (AD) technology, the overall waste to electricity conversion efficiencies range from 10 to 12%. The combustion of methane efficiencies in gas engines have been reported to be 33–37% (Bove and Lunghi, 2006). MSW comprising of high moisture and organic content are suitable for AD (Singh et al., 2011). On the other hand, since only the OFMSW can be utilised, a pre-sorting is required (Yap and Nixon, 2015). As such, it is observed that the local MSW is compatible with AD technology, provided that the organic fraction is adequately segregated and shredded in view of increasing the yield of biogas. CIC for AD are considerably lower than thermochemical processes which is around 240 $/yearly tonne for a 100 ktpa plant (Murphy and Mckeogh, 2004). However, this technology allows only a reduction of 75% of the OFMSW being landfilled (Yap and Nixon, 2015). Consequently, if a high reduction in volume of MSW is required, incineration, gasification as well as pyrolysis can be implemented however, all have a low social acceptability which is not the case for AD technology.

4.2. Justification of weightage allocated to the evaluation criteria

Each criterion was compared with the remaining criteria and a weightage was assigned based on specific judgement and information. For example, when comparing the compatibility of LMSW (weightage 5) with Overall system efficiency (OSE), it is noted that, the characteristics of MSW in terms of its organic content, moisture and ash content, lower heating value among others are parameters which drive the OSE and impact on final power generation (Kumar et al., 2014). With respect to Maturity of Technology

(MoT) (weightage 6), it has been reported that, a technology which is still at pilot/research scale, despite demonstrating attractive OSE, poses certain disadvantages like lack of availability of data on the associated technology risks and the running operations. The overall efficiency of a Wte plant is its economic driver where the financial investment is driven by the scale of profits generated through the sale of electricity; which is directly related to the efficiency of the plant. Alternatively, market growth of Wte technologies in developing countries has been deterred by their large initial costs (World Energy Council, 2016). Hence, being a developing economy, CIC (weightage 5) is a moderately more important factor for Mauritius to consider. The Operation and Maintenance costs (O&MC) are derived from the plant's revenue. Even though the profits generated through the sale of electricity are very dependent on the performance of the system, it is important to select a technology where the O&MC are not too high to ensure the economic feasibility of the plant, hence the O&MC (weightage 3) criteria was slightly favoured over OSE. OSE, which is the parameter which drives the profit generation of the plant, is considered to be very strongly more important. Furthermore, the generation of power at Wte plants result in GHG emissions being displaced at a thermal power plant for the same amount of power being produced. A weightage of 7 was therefore allocated to OSE when compared to GHG emission criteria. Even if the amount of waste being landfilled is a serious issue, the primary reason for setting a Wte plant in the country is to exploit the potential for power generation rather than volume reduction (VR). Consequently, the OSE was strongly favoured (weightage 5) over VR. Mauritius witnessed during the past 10 years, strong oppositions of the local community to WTE projects, which had to be dropped ultimately due to public outcry and community activism. Consequently, public acceptance should not be overlooked in Mauritius and is allocated the highest weightage of 7.

4.3. Ranking of the evaluation criteria

Following the weightage assigned to each evaluation criteria, a ranking of these criteria were performed using pairwise comparison using SuperDecisions®. In this case, each criterion is compared with respect to the remaining criteria in pairwise comparisons using the allocated weights. As a result (Fig. 3), social acceptability was the criterion generating the highest score and will thus have the highest impact on the assessment of the set of selected alternatives in the local context. Given the history of Wte plant, thermal power plant and oil refinery – petroleum hub projects withdrawals in Mauritius, the criterion Social Acceptability was given higher importance with respect to remaining criteria. This explains the computed preferential ranking for Social acceptability as compared to the other evaluation criteria.

4.4. Pairwise comparisons of the Wte technologies

With the aid of the data collected through the technology review of the four alternatives, the pairwise comparisons of the different Wte technologies with respect to each selected criterion were conducted. As shown in Fig. 5(a)–(h), the AHP analysis of Wte technologies for power generation from MSW in Mauritius identified AD as the preferred technology. This validates that AD has the highest ranking for compatibility with LMSW, CIC, O&MC and social acceptability. Mauritius has to date two reference projects on AD for electricity generation, at St Martin wastewater treatment plant where approximately 100 MWh units of electricity are generated per month and at Omnicane Ltd which has recently launched a new AD project to generate electricity from biogas produced from vinasse. The positive results for AD reflect the potential of this technology in Mauritius.

4.5. Sensitivity analysis

4.5.1. Weightings set to zero

With the exception of social-acceptability, setting the weightings of the remaining criterion individually to zero did not impact on the final Wte alternatives ranking, that is the preferred technology was AD. However, when social acceptability was set to zero, incineration was prioritised as the most appropriate Wte technology for Mauritius. It was also found that only when weighting of social acceptability was increased to 0.356, AD emerged as the prioritised technology. This demonstrated that Social Acceptability was the critical criteria of the model.

4.5.2. Eliminating the critical criterion

When the critical criteria (social acceptability) is attributed a weightage of zero (Fig. 6), it was observed that once again, incineration had the preferential ranking over the other Wte technologies, thus validating the results obtained whereby proving that social acceptability is the critical criteria of this model.

4.5.3. Equal weighting for all criteria

When all the eight criteria were attributed an equal weighting of 0.125, incineration remained the prioritised technology (Fig. 7). This demonstrated the robustness of the model's result with respect to incineration when social acceptability was either eliminated or given equal preference. Thus, the outcomes of the sensitivity analysis revealed that social acceptability was the critical criterion which drastically altered the final results of the analysis. This can be explained by the high importance weightings which were systematically allocated to this criterion due to the fact that some projects meeting public opposition have been withdrawn in the recent past. Hence, AD is maintained as the prioritised Wte technology. However, if incineration is to be implemented, following recent controversies witnessed by the country, there might be opposition to this project from the population. In order to avoid such a situation, an awareness campaign on the methods available to treat flue gases emanating from the incineration system should be done prior to implementation of such a technology.

4.6. Environmental and economic benefits of the prioritised technology – AD

The estimations presented in Table 4 were derived based on the Wte climate change mitigation scenario elaborated in the Third National Communication (TNC) report, whereby 500 tonnes of waste would be expected to be directed towards the Wte plant per day as from 2019. Following this scenario, 2.5 MW of power could be produced from OFMSW, which represented 222 kWh per tonne of the OFMSW. Following this scenario, 2.5 MW of power could be produced from OFMSW, which represents 222 kWh per tonne OFMSW amounting to 0.007% increase in the energy share. This will result in a total annual economic savings on heavy fuel oil imports of 1,569,269 Euro with a total (net) of 151.6 Gg carbon dioxide equivalent emissions avoided.

4.7. AD versus incineration – the energy policy considerations

Following the LTES report, the Government intends to integrate 4% of electricity from Wte technologies to the local grid by 2025. The AD technology causes a gain of only 0.007% of 3042 GWh, which is the total electricity generated for 2016 (Statistics Mauritius, 2017). Considering that social acceptability cannot be overlooked, and that AD remains the prioritised technology, it is observed that the set target will not be met. Thus, incineration which is the second prioritised technology has been considered assuming that social acceptability will not be an issue.

It has been projected that, if 500 tonnes of MSW is incinerated daily, the total annual power generated will amount to 75 GWh, which represents 2.5% of the total power generated for 2016 (Statistics Mauritius, 2017). However, the set target is still not met. Thus, a different scenario is considered, whereby all MSW generated in 2025 (projected value of 549,000 tonnes) are combusted and the annual power generation would be 181 GWh. This represents 5% of projected total annual electricity generated for 2025. As such, it can be observed that energy recovery from waste by incineration in Mauritius is a means of attaining the target of integrating 4% of electricity from Wte technologies in the local grid. Likewise, the amount of waste landfilled to be avoided is more attractive compared to AD, with a reduction of 357,148 tonnes out of 485,445 tonnes of MSW expected to be generated by end of 2019. This will in a way solve the issue of the accelerating rate of reaching saturation of the sole landfill in Mauritius. It has also been reported that power generation from incineration produces relatively higher total annual economic savings on HFO import bill of 5,900,946 Euro. On the other, it can be argued that an incineration plant has higher upfront CIC as well as O&MC than AD. Moreover, the cost of disposal of one tonne of waste is Rs 2200 (Statistics Mauritius, 2017). Hence, considering that an incineration plant reduces the total amount of waste landfilled by up to 95%, considerable savings are expected to be made on the cost of waste disposal, which can also be utilised to support the plant. Notwithstanding all the benefits arising from the incineration of waste for power generation, the strong opposition of the local community regarding the setting up of an incineration plant in Mauritius, as supported by historical events, remains a substantial barrier impeding its implementation in the country.

Nevertheless, if the same scenario is considered, whereby all the MSW generated in 2025, are subjected to AD, the total annual electricity generation will be 53 GWh which is still very far from the set target. In parallel, the implementation of a Wte technology for power generation is part of the SWMS of the GoM to reduce the amount of waste being landfilled. Yet, the total amount of volume reduction of MSW landfilled brought about by AD amounts to only 73,912.5 tonnes when the Wte climate change mitigation scenario of the TNC is employed. Likewise, if all the MSW generated in 2019, is subjected to AD, the total amount of waste reduction amounts to 152,258 tonnes/annum. Considering that the landfill is expected to reach saturation by 2019, the amount of volume reduction is not considered to be satisfactorily enough. Hence, despite being the prioritised technology, AD does not meet the targets set by the Government to reinforce the country's energy security and to tackle the current issue of waste management.

This is supported by a study conducted in the Canary Islands where it is reported that, in isolated environments that comprise the SIDS, energy recovery through incineration is a good and sustainable alternative to landfill (Uche-Soria and Rodríguez-Monroy, 2019). Following parallel analogy, a report by UNEP on the Directory of Environmentally Sound Technologies for the Integrated Management of Solid, Liquid and Hazardous Waste for Small Island Developing States (SIDS) in the Pacific Region, observed that, incineration of MSW may offer an alternate to other forms of disposal when land appropriate for landfilling is scarce which is the case for most SIDS. It has been furthermore reported that, given many SIDS already have oil powered generators, they may be adapted in some cases to take up some of the MSW (UNEP, 2002).

Noteworthy, sanitary landfills are the final waste disposal method in many SIDS in the Indian Ocean and are under development in numerous Caribbean island States. In the South Pacific region, some SIDS are improving their existing landfills. Various countries such as Barbados, Belize, Jamaica, Trinidad and Tobago and Maldives have safeguarded support from donor for advancement in waste management infrastructure. Given that, SIDS having limited land area, which limits their use of conventional technologies requiring large areas of land; thus, SIDS have no option but to adopt appropriate technologies, to deal with waste disposal (CARICOM, 2015) whereby incineration could be a good option if the aim is to export a considerable amount of firm power to the grid.

5. Conclusion

This research demonstrates that in order to reach the 4% target of electricity generation from Wte technology, incineration is the preferred technology. However, to achieve this, the critical criterion social acceptability was either reduced or assumed to have zero effect on the implementation. The critical analysis revealed that an incineration plant would be more beneficial for the country in terms of environmental, energetic and economic gains whereby the technology would generate 55 more GWh of annual electricity than AD. The reduction in volume of waste landfilled following incineration treatment would be 99,462.5 tonnes more than AD on an annual basis. Finally, incineration lead to a greater amount of avoided HFO combustion amounting in higher savings on HFO import bills by 4,331,677 Euro as compared to AD. Nevertheless, given that social acceptability can be an issue in the local context, the proposed measure to overcome the social acceptability barrier could be specific site isolation far from residential areas for the setup of the incineration plant. Furthermore, in order to determine the strength of these two variables and to identify the pre-dominant root cause of the social acceptability barrier, empirical analysis through sociological research, needs to be carried out. This can be done through surveys, polling exercises and interviews of the local community. Moreover, given that only two experts validated the evaluation criteria, it is recommended that involvement of stakeholders from different Ministries, academia, private sector, and NGOs is done which is strategic to ensure that all key aspects pertaining to the pairwise comparisons of the evaluation criteria are covered. This exercise will ensure a fair and justified scoring of the selected criteria, thus strengthening the validity of the final result. This can further be enhanced by the vulgarisation of the incineration technology, higher public participation at early project stages, accrued political will and Government's commitment at enhancing the waste management system of the country, coupled with working in concert with private investors so as to settle on attractive revenue packages, comprising of remunerative feed-in-tariffs and tipping fees, are proposed measures to enable the implementation of incineration plants in Mauritius.

CRediT authorship contribution statement

Nirvana Neehaul: Investigation, Software, Data curation, Validation, Writing - original draft. **Pratima Jeetah:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing, Visualization. **Prakash Deenapanray:** Conceptualization, Methodology, Supervision, Resources, Validation, Writing - original draft, Writing - review & editing, Visualization.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2019.100489.

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