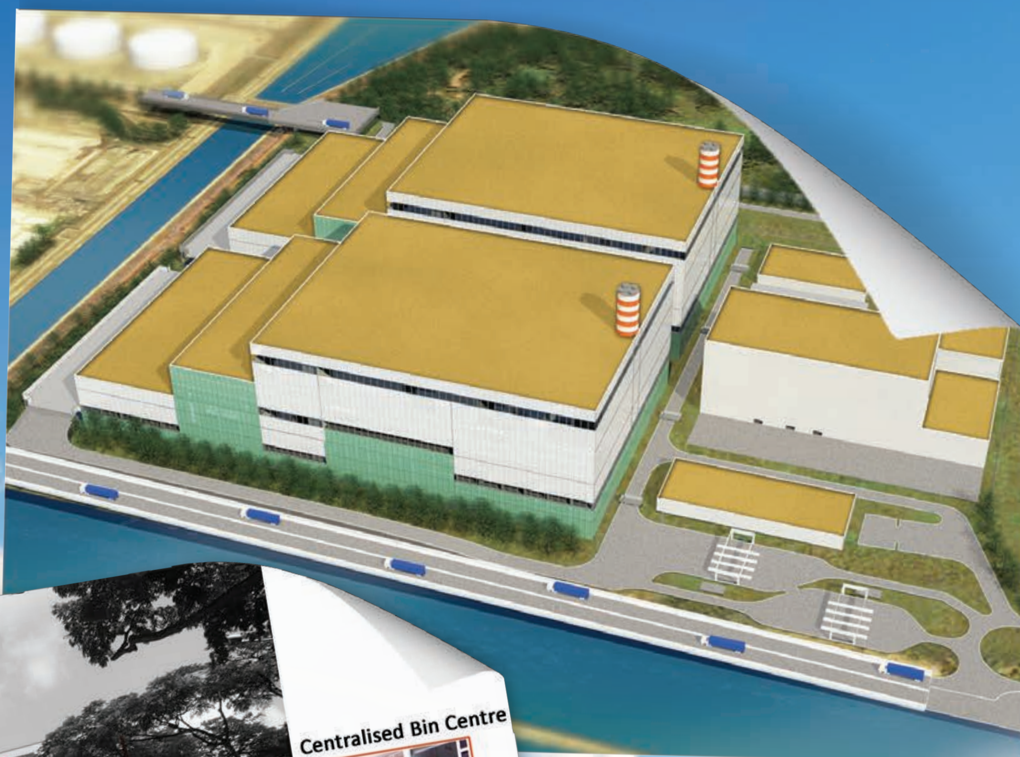
SOLID WASTE MANAGEMENT
Technology Roadmap



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EXECUTIVE SUMMARY

Golder Associates Singapore Pte Ltd. (Golder) was commissioned by the National Environment Agency (NEA) to develop a Waste Management Technology Roadmap ("Project") that establishes pathways addressing Research, Development, Demonstration and Deployment (RDD&D) to achieve 2030 vision goals, which include minimising land footprint and environmental impacts for waste management activities, maximising manpower productivity while maintaining high standard levels of public health, keeping the cost of waste disposal affordable, maximising energy recovery from standard waste (waste as a resource) and maximising recycling in meeting the national recycling target of 70% by 2030.

The approach to the roadmapping exercise included a review of current and best practices, developing and emerging trends in the waste management technologies internationally addressing various waste sectors covering collection, sorting, upcycling and treatment.

Significant in addressing the requirements of the Waste Management Technology Roadmap are the implications of implementing the recommended technologies in Singapore. To address the specific items identified and their consequential aspects and impacts, a set of technological pathways pathway was proposed.

Waste Collection

Waste collection technologies were screened to achieve the following:
To increase manpower productivity

- To continue rolling out Pneumatic Waste Conveyance System (PWCS) for high rise buildings in selected estates and neighbourhoods;
- To roll out pilot sensor-based bin at kerbside, bin centres and centralised refuse room and a unified route optimisation software to be used by all Public Waste Collectors (PWCs) and General Waste Collectors (GWCs).

Separation of dry recyclables and mixed waste fractions

- To facilitate public education and community promotion of waste prevention, waste minimisation, source segregation and recycling;
- To encourage waste reduction measures to be put in place.

Usage based charge system

- To test a RFID tracking system for high rise residential buildings together with incentives (e.g. rebates in monthly utility bill, etc.) to encourage proper recycling habits and to support a usage based charge system;

Integration

To initiate Research & Development (R&D) on using autonomous vehicles for waste collection.
Waste Sorting
Materials Recovery Facilities (MRF) and Mechanical Biological Treatment (MBT) options have been reviewed as waste sorting / segregation technologies.

MBT configurations that were screened and assessed were as follows:

- MBT A – Mechanical separation with production of Solid Recovered Fuel (SRF).
- MBT B – Waste to biogas and fertiliser via Anaerobic Digestion (AD).
- MBT C – Waste to biofuel and renewable energy via gasification and fermentation.

Waste Upcycling

The review of recycling/upcycling technologies are focused on the three waste streams of food, plastic and paper wastes, due to their high volume and low recycling rates.

Food Waste

- Option A – Anaerobic Co-Digestion of Food Waste and Wastewater Sludge
- Option B – Hydrothermal Carbonisation
- Option C – Enzymatic conversion of food wastes

Plastic Waste

- Option A – Plastic waste to Carbon nanotubes (CNT)
- Option B – Plastic waste to Fuel
- Option C – Plastic waste to Polyhydroxyalkanoate (PHA)

Paper Waste

The following recycling technologies are shortlisted for review and assessment:

- Option A – Paper waste to cellulose aerogels
- Option B – Paper waste to butanol
- Option C – Paper waste to Pro-fibre

Waste Treatment

Thermal technologies dealing with Municipal Solid Waste (MSW) are referred as waste treatment technologies. Because of its ability in volume reduction, mass burn Waste-to-Energy (WTE) technology is applied as the primary waste disposal method in Singapore.

The following alternative thermal treatments are shortlisted for further analysis against the base case of mass burn WTE technology:

- Pyrolysis and Gasification
- Slagging Gasification
- Plasma Gasification

1.0 CURRENT WASTE MANAGEMENT SYSTEM AND ITS CHALLENGES

Singapore has a population of 5.54 million as of 2015 and with an expected increase in population, waste generation is expected to increase correspondingly.

Within the entire waste management process, there are two general areas which may be targeted to deal with the increased amount of waste. The first is to increase the recycling rates and second is to reduce the volume of waste generated.

Since the launch of the National Recycling Programme (NRP) in 2001, the total recycling rate has increased from 40% in 2000 to 61% in 2015. A breakdown of the key waste streams has been provided in Table 1.

Table 1: Breakdown of Top 5 Waste Streams Generated in 2015 (from NEA statistics)

Rank	Waste Stream	Waste Generated (tonnes)	Waste Disposed (tonnes)	Percentage of Total Waste Generated	Percentage of Total Waste Disposed	Recycling Rate
1	Construction Debris	1,411,800	8,900	18.4%	0.3%	99%
2	Ferrous Metal	1,348,500	15,200	17.6%	0.5%	99%
3	Paper / Cardboard	1,192,200	588,500	15.5%	19.5%	51%
4	Plastics	824,600	766,800	10.7%	25.4%	7%
5	Food	785,500	681,400	10.2%	22.5%	13%

The top five waste streams made up more than 72% of the total waste generated in Singapore. The top two waste streams, namely, construction debris and ferrous metal achieved high recycling rates of 99%. Conversely, the next three waste streams, namely, paper, plastic and food had low recycling rates. These streams contributed to the total waste disposal rates of 19.5%, 25.4% and 22.5%, respectively.

The primary method of dealing with non-recycled waste in Singapore is incineration, which significantly reduces the volume of waste and harnesses its calorific value to recover energy in the form of electricity. The waste management process flow in Singapore is illustrated in Figure 1.

Figure 1: Waste Management Process Flow in Singapore

1.1 Waste Collection

In Singapore, depending on the geographical areas and type of premises, general waste is collected either by the Public Waste Collectors (PWCs) or individual General Waste Collectors (GWCs) licensed by the National Environment Agency (NEA).

High-rise buildings including public housing estates, private condominiums, and /or shopping and commercial complexes are typically equipped with a refuse chute system. Individual households either have a refuse chute each that feeds directly to a common bin chamber at ground level or have a centralised refuse chute system on each floor located at the lift lobbies. Waste from the common bin chambers have to be transferred by workers to compactors located at bin centre for collection. Waste is collected directly from the centralised refuse chute via a fixed dust-screw system by trucks.

Current methods of collection and transportation of waste may result in sanitary, odour and pest problems, as waste spillage can occur during the transferring process. Regular washing of the waste receptacle areas are required to keep the estate clean. Landed properties including residential premises, shop houses, and trade premises are each provided with a bulk bin (volume ranging from 120 to 1,100 litres depending on the refuse output) located in front of each premises along the roadway. These refuse bins are emptied into a collection truck that is generally staffed with two collection crew moving from door to door.

The removal of wastes in a timely and hygienic manner is challenging in Singapore's warm and humid weather. General waste, include household organic waste requires timely removal for treatment and disposal. Hence, general waste is collected and disposed of daily as the temporary storage of such waste could poses odour nuisance and vector problems to those living within the vicinity of bins, bin centres and refuse rooms.

In summary, the waste collection method and process consists of the following:

- Usage of single chute or bulk bin system;
- Storage of mixed waste prior to collection; and
- Daily collection by truck and crew.

The challenges identified with the current situation include:

- The daily collection frequency required due to a warm and humid climate;
- The high labour intensity and low efficiency;
- Difficulty to hire and retain manpower;
- Limitation of the single chute system to allow for source segregation;
- Odour and pest nuisance caused by improper maintenance of refuse bins and collection trucks; and
- High public expectation in hygiene and cleanliness.

Potential solutions include:

- Adoption of a dual / multiple chute system;
- Mechanising the refuse collection process through Pneumatic Waste Conveyance System (PWCS);
- Optimisation of truck collection routes; and
- Adoption of collection trucks with features to minimise manpower and fuel consumption.

1.2 Waste Sorting and Segregation

Separating different types of waste streams is essential for enabling recovery of useful and valuable materials as well as minimising the waste sent for incineration at Waste-to-Energy (WTE) plants. Under the NRP, commingled recyclables are collected by the PWCs and sorted at MRFs. Such facilities are generally small scale with processing capacity less than 50 tonnes per day. Their operations are manpower intensive and incurring a high operating cost. In addition, odour and hygiene issues are also of concern.

In summary, the waste sorting and segregation processes consist of the following:

- Obtaining commingled recyclables from PWCs under the NRP;
- Occur at mostly small scale MRFs; and
- Require manual sorting of recyclables.

The challenges identified with the current situation include:

- High labour intensity and low efficiency;
- High land uptake by MRFs;
- Cannot take in wet recyclables or recyclables contaminated with organic waste; and
- Exposure of workers to odour, grime and potential health risks associated with handling of wastes.

Potential solutions include:

- Increased automation of MRFs with higher productivity and recovery yield;
- Utilising MBT to sort and/or treat MSW; and
- Building multiple-tiered sorting facilities to minimise land footprint.

1.3 Waste Recycling

Based on statistics in 2015, paper/cardboard, plastic, and food waste made up about 67% of the total waste disposed of (Figure 2). To achieve the national recycling target of 70% by 2030, better recycling and upcycling methods of these three dominant waste streams could be pursued through technology innovations.

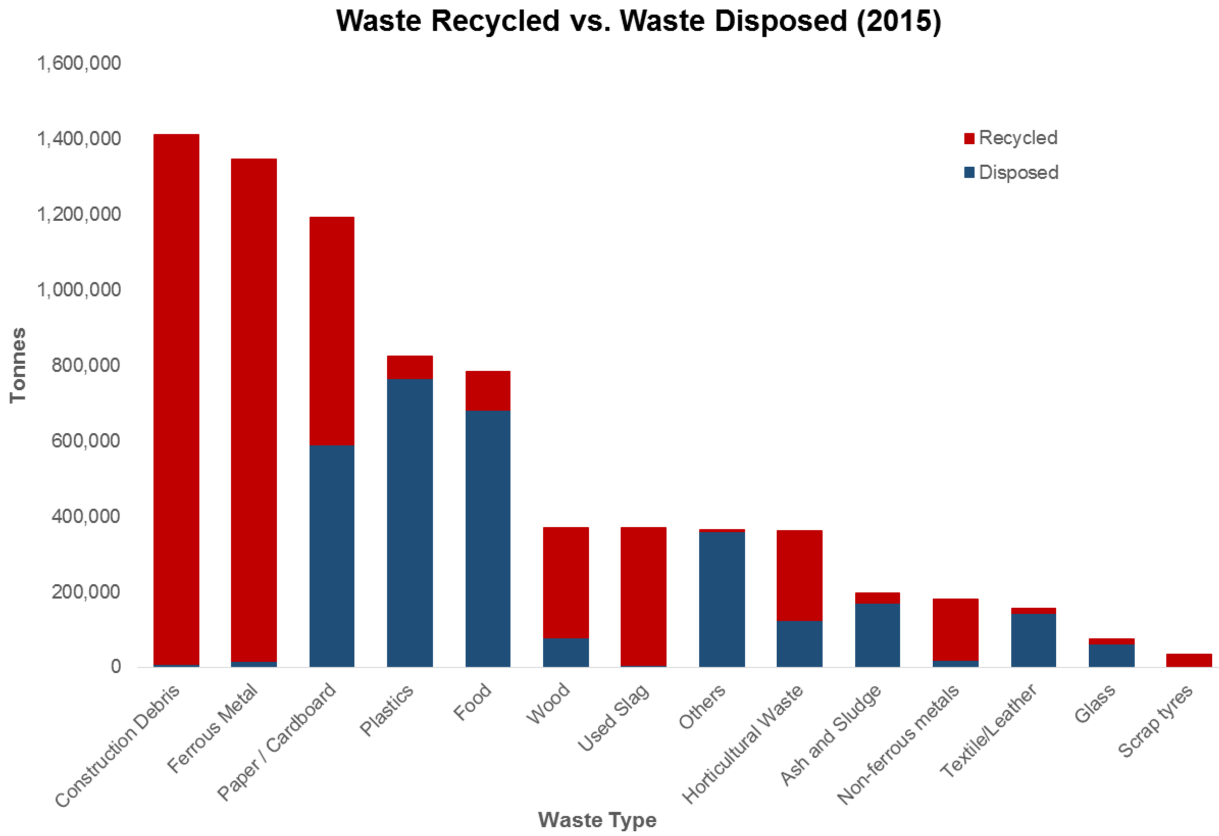


Figure 2: Waste Recycled and Disposed in 2015 (based on Singapore Waste Statistics 2015)

Other than commercial and demolition waste and ferrous metals, paper is among the most commonly recycled stream with approximately 51% out of the 1.19 million tonnes generated being recycled. Paper is sorted, baled, and exported overseas for recycling.

Only 7% of plastic waste was recycled out of the 0.82 million tonnes generated. Plastic waste is usually mechanically processed via sorting, shredding and washing as secondary raw material for making products with equivalent or similar properties. However, technological advancements could allow their upcycling into higher-value products such as depolymerisation of waste plastics into chemical constituents or conversion into fuel.

Only 13% of the food waste out of 0.79 million tonnes generated was recycled. The high costs involved in separate collection of food waste for recycling pose great challenges to increase their recycling rate. Although a small amount of food waste is processed into animal feed, there is also a low demand for turning it into compost due to scarcity of agricultural land. To encourage food waste recycling, the effective source segregation of organics from inorganic waste will need to be carried out.

The challenges identified with the current situation include:

- Lack of public participation in recycling;
- Low value of and / or lack of market demand of recovered materials; and
- Promote recycling of specific waste streams (e.g. plastics, food waste).

Existing potential solutions include:

- Food waste segregation and onsite/offsite treatment; and
- Upcycling waste to new materials or products with higher values.

1.4 Waste Treatment

Singapore has adopted waste incineration as the treatment method due to land scarcity, among other factors. Incineration reduces waste volume by 90%. The mass burn WTE technology remains the dominant method to treat MSW as it allows the recovery of energy.

Singapore has four WTE or Incineration Plants that treated 2.88 million tonnes of waste and generated 2 – 3% of total electricity in 2015 (Figure 3). A new WTE plant is planned to start operation in 2019. The electrical efficiency of a WTE plant is largely dependent on the net calorific value of the waste, size and design of the plant. The efficiency of existing WTE plants range from 15% to 20%. The efficiency of new generation mass burn WTE plants could achieve 23% and higher.

Figure 3: Current WTE IPs in Singapore

Singapore faces the following challenges on waste treatment:

- Building new WTE plants with bigger capacities to cater to the projected increase in waste generation;
- Limited land available for the construction of new WTE plants; and
- Lowering the carbon and other gaseous emissions from WTE plants.

With the current situation, the following opportunities are identified:

- Adopting cost effective treatment technologies with higher resource and energy recovery;
- Developing alternative thermal treatment technologies to produce high value products; and
- Incorporating advanced flue gas cleaning system to minimise environmental impacts.

1.5 Waste Disposal

Singapore's only landfill is located at Pulau Semakau, an island to the south of the main island. The status quo of waste disposal at this landfill is as follows:

- 0.19 million tonnes of waste was landfilled in 2015[1] (2% of total waste generated);
- Only incineration ash and non-incinerable waste are landfilled; and
- Based on the current rate of waste landfilled per year, the Semakau Landfill space is expected to be fully filled up by 2035.

The major challenge is to minimise residual waste sent to the landfill and thereby prolong the lifespan of Semakau Landfill. An identified opportunity lies in the use of Incineration Bottom Ash (IBA), after recovering of metals present in IBA. A facility to recover both ferrous and non-ferrous metals from IBA has started operation in mid-2015.

1 Waste Statistics and Recycling Rate for 2015

2.0 2030 VISION OF A SUSTAINABLE SOLID WASTE MANAGEMENT SYSTEM

Singapore aims to achieve a 70% overall recycling rate by 2030 set out in the Singapore Sustainability Blueprint 2015. Singapore has implemented numerous waste recycling programmes and achieved an overall recycling rate of 61% in 2015. In order to achieve the 70% recycling target, emerging technologies will have to be adopted and developed to further convert residual waste streams into resources. In addition, advanced technologies embedded in the municipal waste management infrastructures will make a difference to people's lives in terms of raising the productivity and efficiency, in line with the principles of the Smart Nation Programme.

The following challenges have been identified towards pursuing the 2030 vision of a more sustainable waste management system:

- Increasing the manpower productivity in waste collection and sorting activities;
- Increasing the yield of materials recovery via highly automated MRF;
- Increasing the recycling rates of the top three disposed waste streams, i.e. paper, plastic and food;
- Facing land constraint for waste management activities including building of WTE plants and landfill;
- Ensuring the cost effectiveness and affordability of new and emerging technologies; and
- Maintaining high standards of public health and minimising environmental concerns arising from waste management activities.

2.1 Vision

The vision is to establish Singapore's global leadership in utilising leading-edge technologies in solid waste management while addressing our inherent challenges and achieving the following:

- Maintaining a high level of public health;
- Minimising land footprint and environmental impacts;
- Maximising manpower productivity;
- Maximising energy recovery through improving existing and alternative WTE technology options;
- Maximising resource recovery to achieve the 70% overall recycling target; and
- Keeping the cost of waste disposal affordable.

3.0 APPROACH AND METHODOLOGY

The approach and methodology utilised in this Project is premised on the concepts of sustainability. The first priority is to identify technologies with the potential to realise the envisaged goals and targets befitting the 2030 vision. The identified technologies are then evaluated using a multi-criteria analysis framework (GoldSET©) that allows the systematic comparison of options. The multiple evaluation criteria are grouped into environmental, social, economic and technical dimensions, which provide the relative strengths and weaknesses of each option and inform on the RDD&D strategy. The four steps in the assessment approach are outlined in Figure 4.

Step 1: Exploring Waste Management Technology Options

This step includes listing and defining the possible waste management technology options that may be relevant to Singapore. The options have been developed into four categories:

- Waste collection;
- Waste sorting and separation;
- Waste recycling; and
- Waste treatment.

This list created was based on literature review and Golder's global network of professional experience in waste management project executions.

Step 2: Priority Assessment

The options were put through a priority assessment that is designed to shortlist options that can significantly contribute to the 2030 vision.

Table 2: Focus of Study – Screening Criteria for Priority Assessment

Waste Collection	• Enhance manpower productivity • Facilitate dry and wet waste separation • Encourage recycling by individual • Suitability for Singapore's predominantly high-rise residential buildings
Waste Sorting and Separation	• Enhance land productivity • Enhance manpower productivity • Improve resource recovery
Waste Recycling	• Sustain recycling business • Ensure market demands of by-products • Create high value products
Waste Treatment	• Improve energy and resource recovery • Minimise residues send to landfill • Minimise environmental impacts

Upon completion of the priority assessment, technologies that meet these conditions were subjected to the multi-criteria analysis under Step 3.

Step 3: Sustainability Evaluation - GoldSET©

The options that are identified through the initial priority assessment were further evaluated using Golder's sustainability framework tool GoldSET©. This tool evaluates each option on the basis of environmental, social, economic and technical criteria. GoldSET© further prioritise the options based on the Roadmap objectives including; maintaining high levels of public health, minimising emissions and land footprint maximising recycling, and maximising resource and energy recovery. The options are ranked based on a scoring system and graphical output that shows how the score of each option relative to the others.

Step 4: Research, Development, Demonstration & Deployment (RDD&D) Strategy

The fourth step is to formulate the RDD&D strategy that forms the basis of the technology roadmapping exercise. Technology opportunities and barriers were summarised and the potential research and development activities were recommended. These recommendations take into consideration the potential policy changes and other control measures in proposing the technology roadmap with timeline extending to 2030.

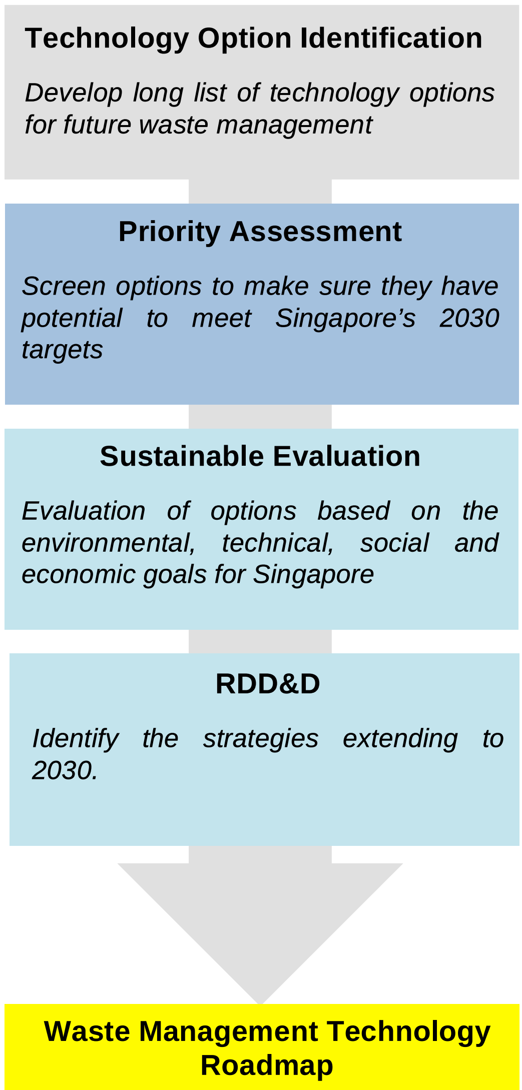


Figure 4: Technology Roadmap Evaluation Approach

4.0 SHORTLISTED TECHNOLOGIES AND THEIR RELEVANCE FOR RDD&D OPPORTUNITIES IN SINGAPORE

4.1 Waste Collection

4.1.1 PWCS

The PWCS is an automated waste collection system which uses vacuum to convey waste via a network of underground pipes to a container in a centralised bin centre. The container when filled will be transported by truck for disposal. The entire waste collection process is automated, thereby reducing manpower requirements and increasing productivity. The PWCS also serves to mitigate the environmental and hygiene issues associated with open collection methods.

4.1.2 Single-Chute Based Separation System

A dual-chute system is installed in newer HDB blocks and private condominiums to boost recycling by households through deposition of recyclables at the designated chute. However for existing single-chute system in older high rise buildings make it difficult to separate dry recyclables and mixed waste at source. Technology has been developed to modify the single chute for segregation of different waste streams, and such system could be a convenient and yet a cost-effective option to implement source segregation. This modification of existing chute system avoids the costly construction of additional chute for the dry recyclables.

Direct separation through control panels and multiple containers

A single-chute based separation system consists of a control panel with buttons for selected waste types at the chute door and provision of multiple waste containers at the refuse room of the building. The chute hopper will open when a waste selection button is pressed. The PLC (Programmable Logic Controller) controlled separator head at the discharge point will direct the waste to the desired bin position.

Indirect separation through colour bags and optical sorting

In South Korea, waste disposal service fee is charged through the sale of colour-coded bags designated for collection of different type of waste. The users are required to separate their waste into the right colour coded bags which allow the waste collectors to easily identify and reject bags filled with the wrong type of waste. The bags are priced according to their colours (i.e. waste type) and sizes (volume). Fines are imposed on those caught not segregating their waste properly and/or not using the correct coloured bags.

4.1.3 PAYT (Pay-As-You-Throw) / SAYR (Save-As-You-Reduce) Scheme by Use of RFID Tracking System

PAYT is a usage-pricing model in which users are charged based on how much waste they throw away. This gives incentives to individual household to reduce the amount of waste to be disposed. Faced with a direct form of unit pricing for the waste they produced, households are motivated to recycle as much of their waste so that less waste need to be disposed through conventional disposal route. In this way, waste disposal resembles more closely to other utilities, where the customer pays the amount for the services provided.

Three key components need to be in place for effective implementation of a PAYT / SAYR scheme are: 1) user identification system; 2) measuring the volume of waste generated; and 3) provision of a publicly acceptable charging scheme.

Advertised under the technical synonym ‘waste lock’ or ‘lockhopper’ by their producers, chamber waste storage systems require users to pass their waste through a special feeding chamber. Access to this chamber is allowed by means of a smart card or electronic key and the amount of waste deposited is recorded. The responsible authority can either bill the user or the system deducts a corresponding amount from prepaid credits. Devices on the market range from simple to fully automated mechanised or even solar-powered electro-mechanical systems.

4.1.4 Bin-fill Wireless Sensor Technology

Waste collection has been traditionally done using fixed routes and regular schedules regardless of whether the bins are filled to its capacity. The bin-fill sensor system uses smart wireless sensors to gather fill-level data from waste containers and use data analytics to generate the schedules and optimise the waste collection routes while taking into account an extensive set of parameters (future fill-level projections, truck availability, traffic information, road restrictions etc.).

4.1.5 Improved waste collection truck fleet – clean energy

Clean fuels for refuse trucks include Compressed Natural Gas (CNG), electric hybrid, and biodiesel.

Hybrid (Hydraulic / Electric) – Hydraulic hybrid system captures about 70% of the kinetic energy that would otherwise be lost during braking. This energy drives a pump, which transfers hydraulic fluid from a low-pressure reservoir to a high-pressure accumulator. When the vehicle accelerates, the fluid in the high-pressure accumulator drives a motor, which provides the extra torque.

Electric hybrid systems also capture energy from braking of the vehicle and store it in a battery pack. The batteries are largely used to drive a motor to provide additional power during acceleration. This reduces the amount of fuel used and produces less emission.

Biodiesel – Biodiesel refers to vegetable oil or animal fat-based diesel fuel consisting of long-chain alkyl esters. It can be used alone or blended with diesel.

4.1.6 Automated Collection Trucks (Unmanned)

As of 2013, four US states have enacted laws addressing autonomous vehicles. In 2011, driverless haul trucks were reportedly used by Rio Tinto for haulage of ore material and waste at its mining operations in Western Australia. Experts at the Institute of Electrical and Electronics Engineers have estimated that up to 75% of all vehicles will be autonomous by 2040.

Waste collection trucks with automated functions are able to transfer waste from bins at roadside into the truck’s hopper without the need for driver and collection crew.

4.1.7 Collection route optimisation software

Geographic Information System (GIS)-based modelling software is able to provide optimised collection routes for high density residential areas; point-to-point commercial premises; and collecting special waste. It can balance route times; service days; optimises travel paths; and reduces the time and cost associated with planning and updating the routes.

4.2 Waste Sorting & Separation –MRF

A review of advanced MRFs was conducted on their overall performance especially for facilities that incorporated advanced auto-sorting technologies. While local sorting facilities are heavily dependent on manual separation efforts, modern MRFs in Europe and North America have shown to have higher land productivity, material recovery yield and manpower productivity.

In the US, MRFs are designed either for processing single stream or mixed MSW. The former refers to commingled dry recyclables including paper, plastic, metal and glass while the latter is for mixed municipal waste including recyclables and non-recyclables with the presence of organic compounds. Depending on the purpose of the MRF, whether it is to process single-stream recycling or mixed MSW, an advanced MRF usually combines a series of disc screens, air classifiers, optical sorters, glass sorters, metal separators (ferrous and non-ferrous) in various orders. In addition, it would likely to have pre-sorting and QA/QC work being performed manually by workers prior to packaging and baling of sorted recyclables for further processing. Biological treatment can be added to an advanced MRF to treat organic compounds as required, which is discussed in the section below.

4.3 Waste Sorting & Separation –MBT

MBT technologies present an alternative treatment solution for reducing the amount of MSW send to the WTE plants or landfill. MBT comprises a series of separation and sorting technologies to separate the organic fractions and recover recyclables and the processes are integrated with biological treatment of the organic fractions.
The possible MBT options are in production of: 1) biogas and other resources; 2) compost; and 3) Solid Recovered Fuel (SRF). With regard to Singapore’s context, composting may not be a viable option due to its need for large land footprint as well as the limited demands for compost.

4.4 Waste Upcycling – Food

Only 13% of food waste out of 0.79 million tonnes generated was recycled in 2015. The costs of food waste recycling pose great challenges and there is lack of demands for compost, which minimises the recycling options. However, food waste upcycling may be viable for Singapore if segregation of organic materials can be effectively carried out.
The different food waste upcycling technology options were reviewed and compared against the incineration of food waste. Three broad types of technological options are: Option A - co-digestion of food waste and used water sludge, Option B - hydrothermal carbonisation (HTC) of food waste to hydro-char, and Option C - enzymatic conversion of food waste to produce succinic acid and bioethanol.

4.4.1 Option A – Anaerobic Co-Digestion of Food Waste and Wastewater Sludge

Anaerobic co-digestion of food waste and used water sludge may offer a viable solution to converting these waste streams to fertilisers (which may be exported if there is a lack of demand in Singapore) and biogas to produce electricity. Evidence has shown that the AD of food waste alone may be unstable due to a lack of trace elements essential for methanogenesis. A lab-scale study on food waste and used water sludge co-digestion by the Nanyang Environment and Water Research Institute (NEWRI) in the Nanyang Technological University (NTU) was initiated to determine the technical feasibility and the optimal operational conditions for the co-digestion process.

4.4.2 Option B – HTC of Food Waste to Hydro-Char

This lab-scale technology uses HTC to convert MSW (including food waste) into sterilised value-added hydro-char. During HTC, the feedstock is heated to subcritical water temperature (from 180 – 350°C) at autogenous pressures. As a result, the feedstock is decomposed via simultaneous reactions including hydrolysis, dehydration, decarboxylation, aromatisation, and recondensation in which hydro-char and wastewater are generated as by-products. Possible uses of hydro-char include adsorbent for environmental remediation, solid fuel and soil augmentation.

4.4.3 Option C – Enzymatic Conversion of Food Waste

Enzymatic conversion of food waste to value added products has been demonstrated in lab-scale studies. One approach is to use source-separated food waste for the production of bio-ethanol at high dry materials content (45% Dry Matter, DM) via microbial fermentation process. The final ethanol yield was about 108 g/kg dry material.

4.5 Waste Upcycling – Plastic

In 2015, only 7% of plastic waste of the 0.82 million tonnes generated was recycled. Plastic waste is usually recycled through mechanical processes including sorting, shredding, and washing. Generally, waste plastic can be processed or converted into products with equivalent or similar properties.

Three different types of plastic waste upcycling technologies were reviewed and compared against the incineration of plastic waste. These options are: Option A - Plastic to Carbon Nanotubes (CNT), Option B – Plastic to Fuel, and Option C – Plastic to Polyhydroxyalkanoate (PHA).

4.5.1 Option A – Plastic Waste to CNT

This lab-scale technology utilises a nanotechnological approach to convert non-degradable grocery plastic bags into carbon nanotube membranes with tuneable molecular transport properties. In this process, plastic bags are the carbon source and the CNTs are produced by a catalyst/solvent-free Chemical Vapour Deposition (CVD) which take place at temperature of 850°C for 30 minutes. CNTs are grown inside nanoporous anodic alumina membranes (NAAMs), which enable control over the nanotubes’ organisation and geometry. Possible applications of CNT include filtration, sensing, energy storage and a range of biomedical innovations.

4.5.2 Option B – Plastic Waste to Fuel

This technology converts batches of shredded and densified different types of plastic to synthetic crude oil under heat. The plastic feedstock is placed in an airtight processing vessel which is heated to temperatures ranging from 300°C to 600°C. The plastic depolymerise as it transforms from a solid to liquid and to a gaseous phase. Through a combination of temperature and vacuum, the gases are cooled in a condensing system into synthetic crude oil. Feedstock impurities are separated out into char and the synthetic crude oil is transferred to an exterior tank ready for transport to a refinery to be refined into valuable products.

4.5.3 Option C – Plastic Waste to PHA

This lab-scale technology comprises a two-step process. In the first step, plastic wastes are subjected to high temperature ranging from 400 to 900°C under anaerobic conditions using a pyrolysis system. The polymer is broken into gaseous hydrocarbon products and condensed into a hydrocarbon-rich oil mixture. In the second step, the oil mixture is fed to a fermenter with microorganisms that utilise the oil mixture to produce PHAs. PHA can then be extracted from the accumulating microorganism for the production of biodegradable PHA polymers which can be used to produce plastic films for bags, containers and paper coatings, in disposable articles (personal care products, surgery clothes), upholstery, packages, medical implants, sutures, etc.

4.6 Waste Recycling – Paper

Paper is one of the most common waste streams recycled in Singapore. Approximately 51% of paper waste was recycled out of 1.19 million tonnes generated in 2015. Most of the paper waste is sorted, baled, and exported overseas for recycling.

The different paper waste recycling technology options were reviewed and compared against incineration of paper waste. Three types of technological options are: Option A – Paper waste to cellulose aerogels, Option B – Paper waste to butanol, and Option C – Paper waste to pro-fibre.

4.6.1 Option A – Paper Waste to Cellulose Aerogels

The National University of Singapore (NUS) has developed technology to recycle cellulose fibers from paper waste as raw materials to produce cellulose aerogels. The aerogels were prepared using a sodium hydroxide/urea treatment method (includes sonication) followed by freeze-drying the aerogels without destroying their structure and preventing the porous structure from collapsing. This technology has been successfully demonstrated at lab-scale in producing cellulose aerogel with high water and oil absorption capacities. The aerogels possess the flexibility and potential to be further processed for use in thermal and acoustic insulation, as well as absorbent media, opening the possibilities of manufacturing a broad spectrum of high value-added products.

4.6.2 Option B – Paper Waste to Butanol

For this lab-scale study, recycled cellulose from newspaper is utilised as feedstock for microbial production of butanol in the presence of oxygen. While other bacteria have been found to produce butanol in the past, they have all required an oxygen-free environment, which increases production costs.

4.6.3 Option C – Paper Waste to Pro-fibre

The technology transforms non-recyclable fibers (e.g. paper and cardboard) into pulp product named 'Pro-Fibre' that can be used in insulation material, packaging products, and construction materials such as plaster boards. The technology uses a five-step process involving identifying and capturing the non-recyclable fiber fragments, pulping, cleaning, screening and mechanical pressing.

4.7 Thermal Treatment

4.7.1 Thermal A – Pyrolysis + Gasification

Pyrolysis is a thermochemical process that converts the organic fraction of waste into biofuel, char and gaseous compounds in the absence of air or oxygen. It is considered an attractive alternative to mass burn for MSW as pyrolysis has the potential to provide resource recovery in addition to energy.

Pyrolysis for MSW can be utilised alone or in combination with other thermal technologies. A review of existing systems shows that most pyrolysis facilities are coupled with gasification or a combustion stage. The output products from most commercial systems are mainly in the form of power or heat, reformed syngas and/or char.

Pre-treatment which include the separation of undesirable materials, size reduction, drying to reduce moisture content, etc. is necessary for MSW pyrolysis technology. Additional processing or treatment is required if the products are intended for immediate utilisation (e.g. gas scrubbing prior to feed in a combustion chamber or a gas engine) or char quenching to ensure quality of such products for industrial uses.

The features of the Pyrolysis process are described in outline below.

1) Low emission of dioxins and generation of fly ash – generated gas is held at 1200°C for 2 seconds or longer, followed by quenching to approximately 70°C in an oxygen-free condition to suppress the generation of dioxins, and is recovered as syngas.

2) High levels of recycling of wastes is possible – waste input is converted into purified syngas or recovered in the form of granulated slag, metals, metal hydroxides, sulphur, mixed salts, and other substances which can be used effectively as resources, resulting in minimised landfill disposal.

3) Syngas can be recovered by gas reforming – since the main components of the recovered syngas are H_2 and CO, the gas can be used as a fuel for power generation and also as a chemical feedstock. The fuel gas is applicable to a wide range of power generation methods including gas engine, fuel cell, gas-fired boiler, and gas turbine combined-cycle power generation. This broad use profile allows selection of an optimum generation method from the viewpoints of equipment scale and site variables.

4) The process offers suitable economic performance – the process utilises the energy contained in waste to perform melting and eliminates the need for separate treatment processes for dioxins and fly ash with high heavy metal contents. As a result, the cost is advantageous compared to conventional "incinerator ash melting". The process minimises the need for landfill disposal.

Figure 5 below presents a Pyrolysis cum Gasification process configuration. In the process, waste is compacted, dried and then pyrolysed by indirect heating in a degassing channel. The pyrolysed waste product is then charged into the high temperature reactor, where it is gasified and the ash is melted at high temperature by reaction with oxygen. This gas passes through the quenching and purifying process as clean syngas.

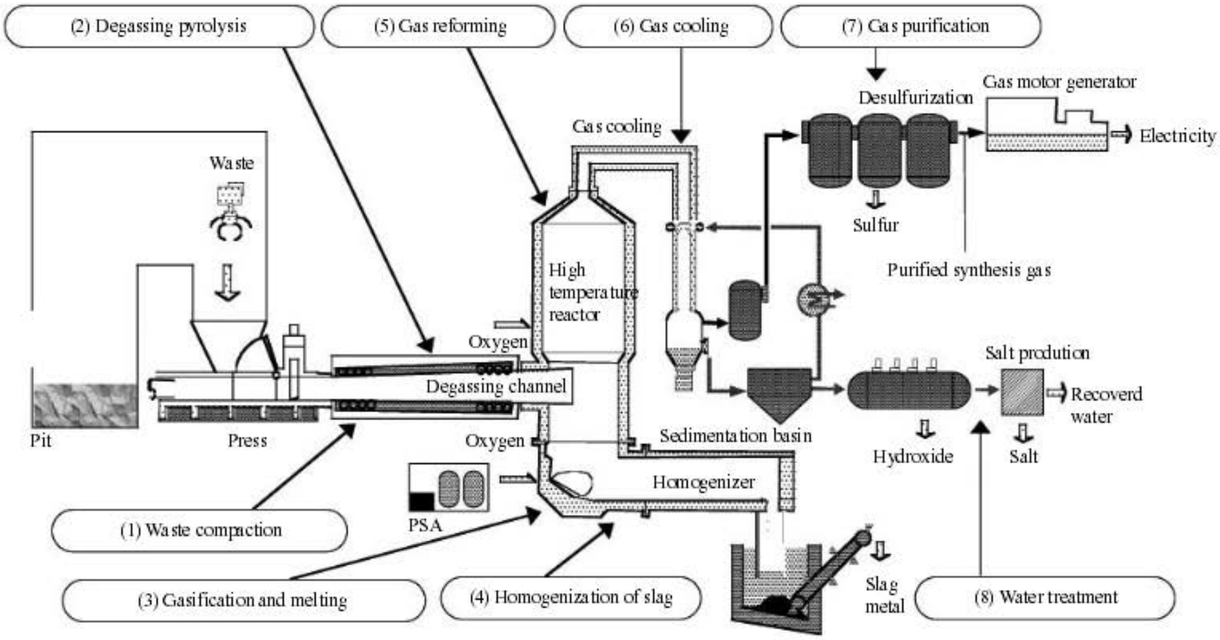


Figure 5: Pyrolysis + Gasification Process

4.7.2 Thermal B – Slagging Gasification / Shaft Type

In order to prolong the lifespan of the Semakau Landfill, it is necessary to look at waste treatment technologies with the potential to reduce residues generation that need to be landfilled. Slagging gasification was developed in Japan can significantly reduce the volume of waste residues that needs to be landfilled. The technology was also driven by the regulations for dioxin emission control and detoxifying ash. The Japanese experience has demonstrated that slags from the process can be safely used as aggregates and the metals recovered are recycled. The volatile metals and fly ash captured through the flue gas treatment will still require treatment prior to its safe disposal at landfills.

As indicated in Figure 6 below, the shaft type system has a gasification and melting furnace where combustible organics in waste will be gasified and the syngas is fed into the combustion chambers, while non-combustible metals and minerals will be melted in the high temperature molten slagging layer at the bottom of the furnace. The molten layer that flows out of the furnace is quenched in water or air to form granulated slag and metals.

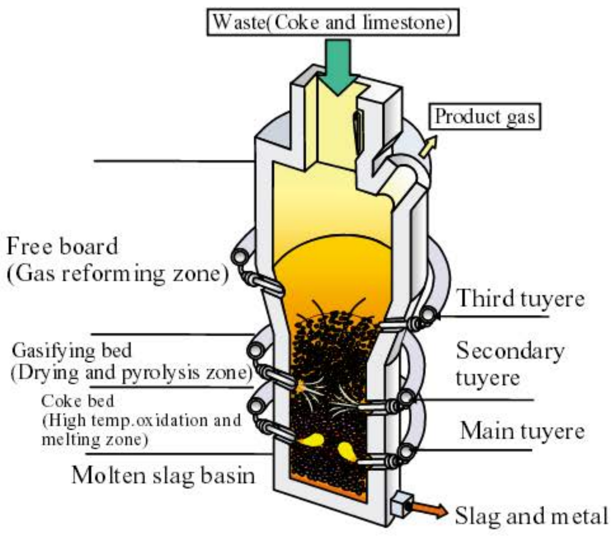


Figure 6: Slagging Gasification - Shaft Type

4.7.3 Thermal C – Gasification + Plasma

Plasma gasification uses electrical energy to create high temperature (>2,000°C) plasma arc for waste gasification. The plasma arc effectively breaks down the waste material into elemental molecules and produces syngas and inert vitreous slag as outputs. The plasma gasification process has the potential to recirculate some hazardous fly ash back into gasifier for vitrification into a non-hazardous glassy slag. For example, slag generated from the Mihama-Mikata plasma gasification plant in Japan is used as aggregate for concrete products. This slag has the potential for use as rock wool, landfill cover, reclamation purposes, base material for construction, landscaping blocks, asphalt road and pavement aggregate among other possible applications.

However, the downside of plasma systems is the high capital cost and operational expenses of the technology. Plasma gasification process is extremely energy intensive and the wear on the plasma chamber is high, subsequently requiring high quality materials, frequent maintenance and replacement.

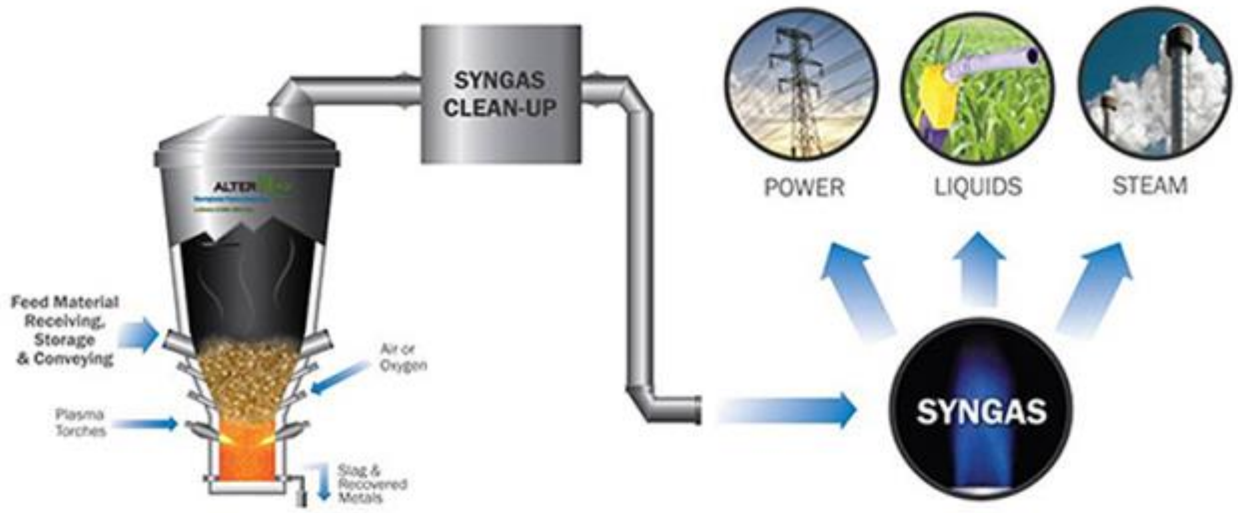


Figure 7: Gasification + Plasma Process

4.7.4 Thermal D – Slagging Gasification / Fluidised Bed Gasification

The fluidised bed gasification and melting process consists of partial combustion of debagged and shredded MSW in a fluidised bed reactor at temperatures between 500 - 600°C followed by a second furnace where flue gas and carbonaceous particles, both produced in the fluidised bed reactor, are combusted at temperatures between 1350-1450°C by the addition of secondary air. The ash overflow from the fluidised bed is separated from the sand used in the reactor for fluidisation. Separation is by means of an inclined vibrating screen with 3-4 mm openings. The sand passes through the screen while glass and metal particles are trapped at the screen and vitrified as they proceed through the furnace. The molten slag is quenched in a water bath to form granulate that can be potentially utilised for construction purposes. The gasifier and ash melting furnace operate at atmospheric conditions without consumption of added fossil fuels (except for start-up) and oxygen.

This technology is able to process mixed MSW, SRF, automobile shredder residue (ASR), waste plastics, sewage sludge and medical wastes. It combines energy and material recovery as well as destruction of organic contaminants. Removal of large items and shredding of MSW are required to ensure homogeneity of the waste feed.

One such facility using this technology is located in Kawaguchi city, Japan. The gasification/ ash melting system at the Kawaguchi City, Asahi Clean Centre is able to process 420 tonnes/ day MSW (3 x 140 tonnes/day modules operating 24 hours). The plant produces 12MW of energy from a steam boiler and power cycle process. The net energy efficiency is reported to be approximately 15%.

Slag is sold for USD 2 per tonne as construction aggregate while recovered iron and aluminium are sold into the commercial commodities market. The facility operates with a tipping fee of USD 150 per tonne of MSW.

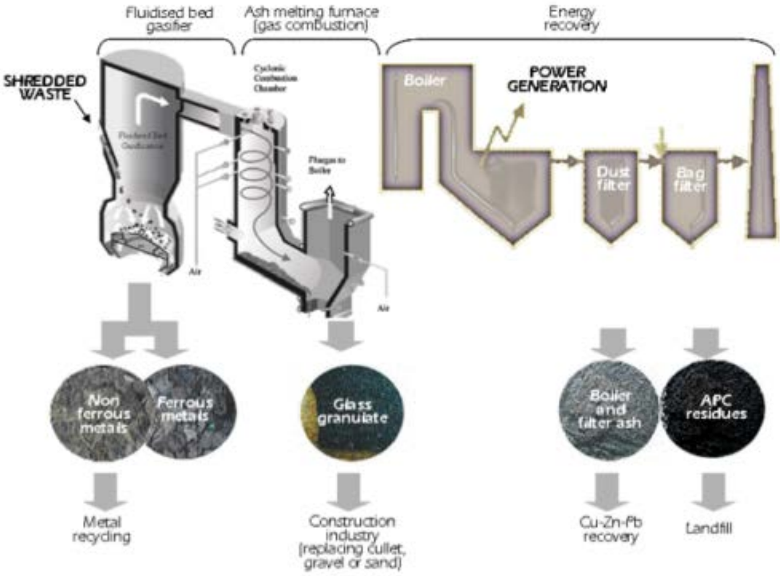


Figure 8: Slagging Gasification / Fluidised Bed Gasification Process

4.7.5 Base Case – Mass Burn

Mass burn technology refers to incineration of MSW as received while generating energy (power and heat).

Waste is tipped into a holding area (1) where it is picked up by a hoist and dropped into a hopper (2). The waste is pushed gradually into the incinerator (3) which runs at a temperature of approximately 750 °C (or over). Heat from burning waste is used in a boiler (4) and steam from this is piped to a *turbine generator* to create electricity. The heaviest ash falls into a collection point (5) and is typically passed over with an electromagnet to extract metal content for recycling. Flue gas containing fine ash then passes through a scrubber *reactor* (6) to treat acid pollutants such as SO2 and to treat *dioxins. The exhaust gases then pass through a fine particulate removal system (7) and are released through the chimney stack (8).*

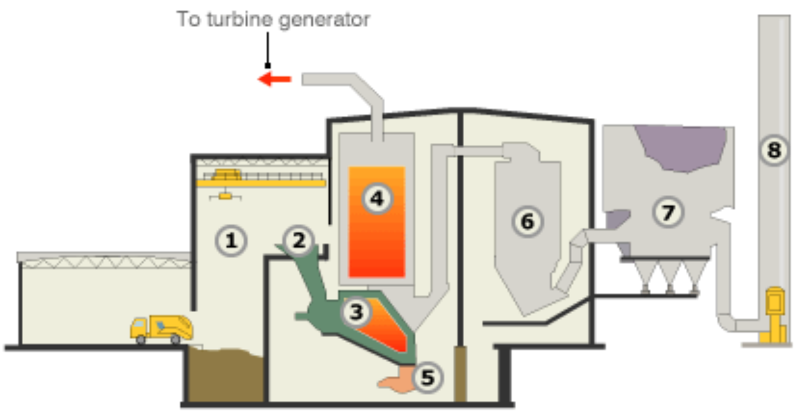


Figure 9: Mass burn process

Mass burn is a mature technology which has been around for more than 70 years. Though technological developments have taken place in terms of advanced pollution control equipment and better energy recovery efficiency, much of their adoption will depend on the policy and legislation specific to each country. For example, modern pollution control technologies have reduced air emissions from waste incinerators to very low levels . Continuous process development is on-going to lower operating costs, improving process and environmental performances. The challenge for this technology is the generation of IBA and IFA which will require further processing and treatment for utilisation in applications or to be disposed of at landfill.

Given these on-going improvements, there are still a number of areas that can be considered for improvements including energy efficiency in mass burn WTE facilities. A WTE plant built by the Afval Energie Bedrijf (AEB) in the Netherlands is an example of how incinerators can attain both high energy and materials recovery. The plant processes 530,000 tonnes of waste per year and the net electrical efficiency is reported to be more than 30%, which is one of the world's highest . With an average caloric value of 10 GJ/tonne of MSW, the plant with a set steam turbine generator can generate a total of 57 MW electricity. The high energy efficiency is accomplished by a number of design features including; reheating steam cycle, low excess air ratio with flue gas recirculation, high steam temperature (440°C) with inconel cladding, and pre-heating of boiler feed water.

Another approach to boost the electricity efficiency from waste combustion is to employ external superheating. This could involve combining natural gas fired power plant operating on Combined Cycle Gas Turbine (CCGT) where hot exhaust gases are used to further increased the "superheated" steam from the boiler of WTE plant to boost the steam turbine power cycle. For the Mainz WTE plant in Germany, steam from waste-fired boilers is piped to the water-steam circuit of a neighbouring 400 MW combined cycle power plant where the steam is further superheated to 550°C to be fed into the steam turbine. Similarly, the Zabalgarbi WTE plant in Bilbao, Spain, where the steam at 100 bar pressure from the waste-fired boiler is superheated to 540°C that operate as an integrated combined cycle power plant, results in overall net electrical efficiency exceeding 40%.

5.0 IMPACT OF POTENTIAL TECHNOLOGY AND RDD&D STRATEGY ON VISION

GoldSET© provides a systematic evaluation technology alternatives through the application of qualitative and quantitative indicators covering environmental, social, economic and technical dimensions. The proposed indicators and the scoring scheme are established through Golder's past experiences and have gone through a series of internal consensus, reviews and revisions based on comments from stakeholders.

The evaluation is to assess individual technology options under each area of the study (i.e. collection, sorting, recycling and treatment). The GoldSET evaluation is not to present a conclusion for the best solution, but to explore and analyse the potential benefits and constraints from adopting the individual solution.

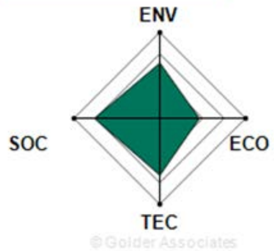
5.1 Waste Collection

The two key targets for waste collection technologies are to: 1) improve manpower efficiency; and 2) facilitate separation of dry recyclables and mixed waste.

5.1.1 Transportation

PWCS

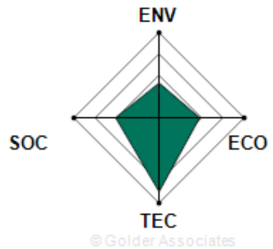
Environmental	64%
Social	75%
Economic	45%
Technical	66%



Overall Score: 63

Route optimization

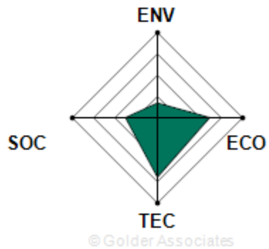
Environmental	41%
Social	50%
Economic	48%
Technical	85%



Overall Score: 56

Automated driverless truck collection

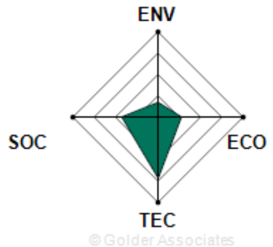
Environmental	17%
Social	37%
Economic	61%
Technical	69%



Overall Score: 46

Base case - Conventional collection trucks

Environmental	17%
Social	42%
Economic	27%
Technical	71%



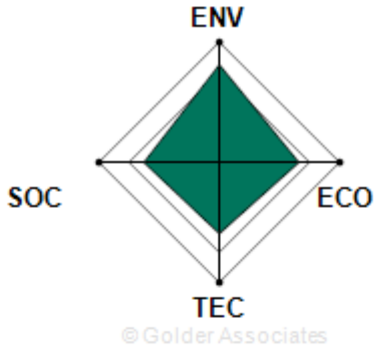
Overall Score: 39

PWCS gives better overall performance compared to the other collection and transportation technologies. In the areas of energy requirement, technology potential, manpower efficiency, odour and pest nuisances, each of the option provides RDD&D opportunities in the Singapore context.

5.1.2 Chute-based Separation System

Single-chute based separation system

Environmental	80%
Social	62%
Economic	66%
Technical	59%

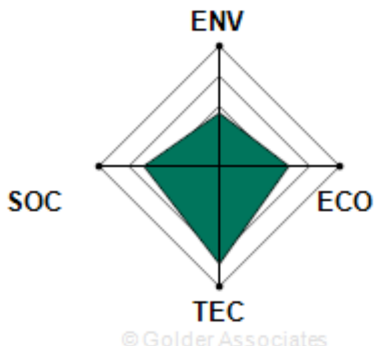


- **Moderate to highly beneficial environmental outcomes,** associated with the low energy requirement and reduction in air emissions/odours as it is likely to be contained within building. Source segregation of recyclables will result in high recovery yield from the subsequent sorting facilities.
- **Moderately beneficial social outcomes,** associated with moderate public acceptance to behavioural change to separate the waste.
- **Moderately beneficial technical outcomes,** associated with high technological development potential and moderate flexibility of waste types due to the limited space of the bin room of the block.
- **Moderately beneficial economic outcomes,** associated with moderate CAPEX and OPEX and high resource recovery potential. The system presents a low level for manpower efficiency as the amount of waste collected per trip will likely be reduced due to waste segregation space inefficiencies requiring additional trips to empty bins of segregated wastes.

5.1.3 Bin System

Bin-fill wireless sensor

Environmental	44%
Social	62%
Economic	57%
Technical	81%

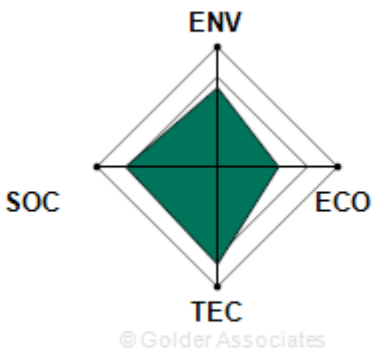


- **Neutral environmental outcomes,** with moderate reductions in air emissions due to reduction in collection truck trips.
- **Moderately beneficial social outcomes,** associated with little effect on the public compared to the current system. The system presents moderate score results considering level of odour and other pest nuisances as the bins will only be removed once the pre-determined threshold levels are exceeded.
- **Moderate to highly beneficial technical outcomes,** associated with high flexibility in expansion and in waste types and high technological potential. Minimum service disruption is expected as only maintenance of the sensor accuracy and internet connectivity will be required.
- **Neutral economic outcomes,** with moderate capital costs for retrofitting the current conventional bins. The OPEX is low for the bins and fuel/labour is expected to be reduced as fewer collection trips will be needed.

5.1.4 Pricing Scheme – PAYT / SAYR

PAYT / SAYR by RFID Tracking System

Environmental	66%
Social	75%
Economic	51%
Technical	81%



- **Moderately beneficial environmental outcomes,** associated with high waste diversion from incineration plants. Fuel consumption of waste hauling vehicles is reduced as fewer vehicles will be needed.
- **Moderate to highly beneficial social outcomes,** associated with high behavioural change driven by the system in making the public more aware and responsible for managing their own waste.
- **Moderate to highly beneficial technical outcomes,** associated with high technological potential, and high flexibility in expansion and waste types.
- **Neutral economic outcomes,** with high capital costs for chute retrofitting, supporting IT facilities and RFID equipment to all households.

5.1.5 Recommendations

PWCS

PWCS has already been installed in some existing and new residential high rise buildings in Singapore. It helps to minimise odour, traffic congestion, hygiene concerns and other social impacts. The initial feedback of concern in using this system had been that the pipes can occasionally get blocked and there were some difficulties rectifying them.

Research and planning are required for its implementation over a large area as transfer of waste over longer distances requires higher suction pressure. Distances may be a technical constraint as the maximum suction distance reported by technology provider Envac, is limited to 2 kilometres from the furthest inlet to the collection terminal.

Through technology revolution for longer term, PWCS may be aimed as a potential solution for fully automated waste collection and transportation system that can transfer waste from source, i.e. the households all the way to disposal facilities.

Route optimisation software

This technology can be integrated with other collection technologies to improve waste collection. This system would be optimal to work along with automated driverless trucks, and bin-fill wireless sensor technologies. Co-ordination among the waste collection companies (e.g. PWCs) would be needed so as to ensure a common platform exists among different waste collectors via the use of unified route optimisation software. Modelling simulation on traffic conditions and emissions can be done and factored into the route optimisation.

A data centre would be required to house all the data in a centralised location. The data centre can be managed by either the authorities or a third party company, as observed in the overseas experience.

Automated collection truck (Unmanned)

Driverless vehicles are something to look forward to in the near future. Numerous automobile companies have developed working prototype of autonomous vehicles. Members of the Institute of Electrical and Electronics Engineers have estimated that up to 75% of all vehicles will be autonomous by 2040.

R&D in automation for waste collection function using autonomous vehicles can be pursued.

Single-chute based separation system

Segregation at the source is not implemented in Singapore, although voluntary based recycling programmes are available. Communications and public education on the benefits and importance of source segregation of recyclables may help to reduce pre-processing requirements.

As a number of technologies are available to facilitate waste segregation in single chute-based system in buildings, it is recommended to initiate a pilot project to test the performance. Public education and promotion on the proper use of such separation system need to be conducted prior to and during the implementation of the pilot.

Upon successful implementation of the pilot projects and proof of performance of selected technologies, authorities may consider formulating policies and legislative standards to support source segregation.

Bin-fill wireless sensor technology

This technology would integrate well with the route optimisation software system where the trucks can be assigned to collect waste from bins that are near filled in an efficient planned route. This avoids unnecessary waste collections when it is not required. However, the threshold for collection should be set in consideration of the potential odour or pest issues arising from the waste not being collected.

Training for the workers and technical support team would be needed if such a system is to be implemented.

PAYT/SAYR scheme by use of RFID tracking system

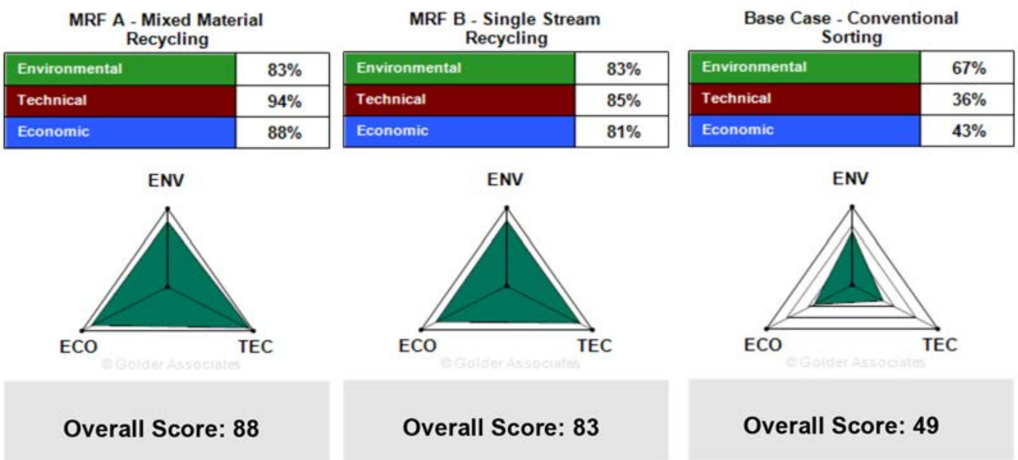
Motivation for waste reduction and recycling can be further strengthened through such a scheme. RFID system is able to provide a platform to support the PAYT/SAYR scheme.

5.2 Waste Sorting & Separation

5.2.1 MRF

Based on the review of case studies, advanced MRFs are reportedly able to achieve a sorting efficiency of as high as 95% for recycling of single stream and 75% for MSW. The processing capacity for some facilities can be as high as 120 tonne per hour. High land efficiency is achievable through options to stack up conveying lines and sorting facilities. Manpower productivity can be significantly increased using highly automated sorted equipment and advanced control system.

Advanced automated MRFs: MRF A – mixed material recycling and MRF B – single-stream recycling were reviewed and compared against the base case of a conventional manual sorting facility.



Both MRF A and MRF B show significantly better performance than the base case of conventional manual sorting facility. MRF B has similar results as MRF A with moderate to high beneficial environmental, technical and economic outcomes.

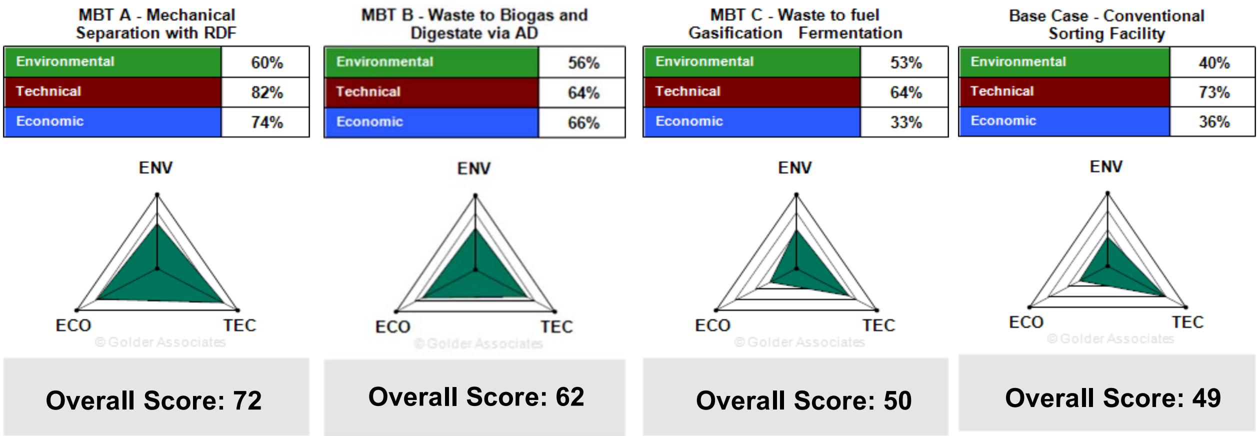
Singapore is currently adopting the commingled recycling system and generally manual sorting of commingled dry recyclables including paper, plastic, glass and metal is done at the MRFs. An advanced single-stream MRF would have been the most suitable configuration for adoption for commingled recyclables.

MRF B showed similar analysis results as MRF A as compared to the base case.

5.2.2 MBT

The MBT technologies are desired to maximise resource and energy recovery and to minimise residual waste being sent to the WTE plants or disposed of at landfill.

MBT technologies can vary depending on the preferred processes or products in the local context. The different combined mechanical and biological processes that are able to deal with the organic fraction of the waste streams have been reviewed and compared against the base case of a conventional manual sorting facility with residual waste being incinerated at a mass burn plant.



The MBT options are ranked well as compared to the base case of mass burn incineration. In the areas of waste diversion and expansion diversity, each of the MBT option provides RDD&D opportunities in the Singapore context.

5.3 Recommendations

MRF

A customised design would have to be made for each MRF based on targeted recycling of waste streams for best overall performance. Workers are generally required to hand pick bulky items or incompatible items from the conveyor belt, and workers are also needed for QA/QC purpose. With an advanced SCADA system, the entire MRF system or individual components can be controlled at the main control panel in which the manpower for site supervision and operational control can be greatly reduced.

It is recommended that a detailed waste characterisation study is warranted in order to facilitate in the design and configuration of advanced MRF to increase sorting efficiency, recycling rate and manpower efficiency in the future. R&D can be on developing technologies to facilitate additional automation through use of robotic picking arms and sorters to further increase manpower efficiency.

MBT

The technology development focus should be on producing a modular, scalable and compact design of the MBT facility in order to minimise land footprint.

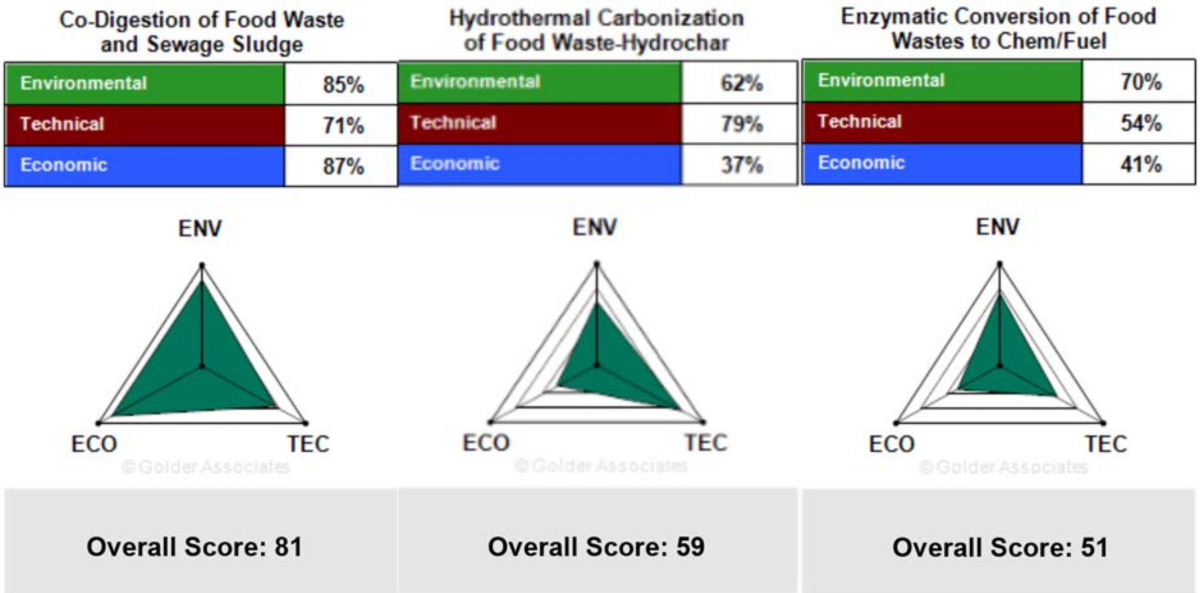
MBT A – Mechanical Separation with Production of SRF

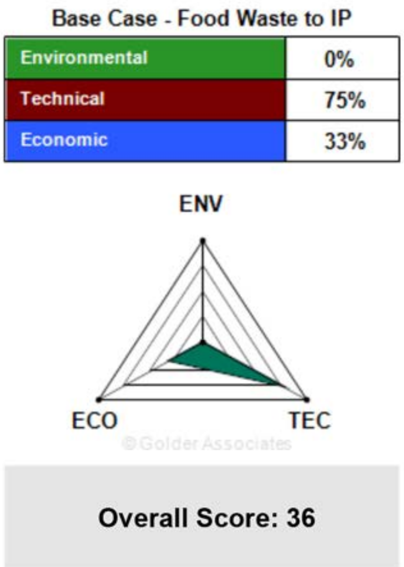
Detailed waste composition studies are required so that SRF facility operators are able to plan processes and equipment required based on the waste composition.
Establishment of SRF quality standards or specifications/guidelines (by ISO) may potentially help to ascertain SRF product quality.

[MBT B – Waste to Biogas and Fertiliser via AD]
Market survey may be conducted to establish the demand. Research on mesophilic systems may be conducted as a wider diversity of bacteria thrives at mesophilic temperatures. These bacteria are generally more robust and adaptable to changing environmental conditions.

[MBT C – Waste to Biofuel and Renewable Energy via Gasification and Fermentation]
Research could be carried out on more efficient and cost effective means of converting low-grade syngas to value added chemicals. For example, research on more efficient biocatalysts, lower cost catalysts or other means of conversion in order to reduce OPEX can be conducted. In addition, development of an alternative pre-processing method which is less energy intensive than the current method (i.e. drying) will be beneficial.

5.3 Waste Recycling – Food





Each of the alternative food waste treatments is ranked better than the base case of mass burn incineration. In the areas of technology potential and CO_2 emissions, each of the treatments provides RDD&D opportunities in the Singapore context. Option A demonstrates the highest potential for RDD&D due to its favourable scores in the environmental, technical and economic dimensions.

5.3.1 Recommendations

The technology development focus could be on producing more modular, scalable design of the facility and constructing the plant vertically or underground in order to minimise land footprint.

Option A - Co-Digestion of Food Waste and Sewage Sludge

R&D focus can be on optimising conditions in the digester. In addition, public education on the benefits and importance of source segregation of food waste would facilitate the successful implementation of this technology.

Option B - HTC of Food Waste to Hydro-Char

R&D is required to reduce the high energy requirement and costs associated. After which, efforts on upscaling and commercialising the technology can then be explored.

Option C - Enzymatic conversion of food wastes

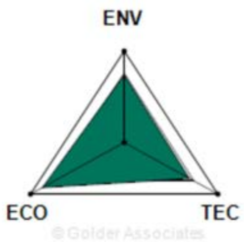
R&D efforts could focus on optimising operating conditions for optimal enzymatic reactions and improving the robustness and flexibility of the enzymes to maximise the process performance and yield.

A detailed food waste characterisation study could be carried out to identify certain chemical species (e.g. aromatic compounds, oil and grease) or microbes which may inhibit or destroy the catalytic activities of enzymes.

5.4 Waste Recycling – Plastic

Plastic Waste to CNT

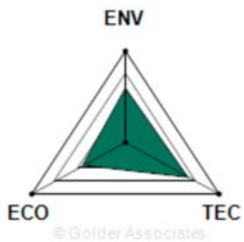
Environmental	73%
Technical	69%
Economic	87%



Overall Score: 76

Plastic Waste to Fuel

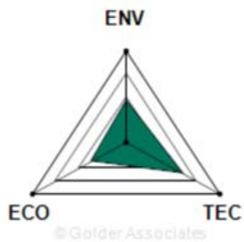
Environmental	59%
Technical	66%
Economic	45%



Overall Score: 57

Plastic Waste to PHA

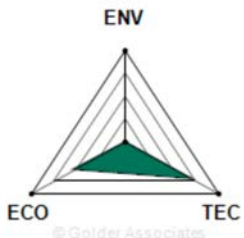
Environmental	46%
Technical	59%
Economic	37%



Overall Score: 47

Plastic Waste to IP

Environmental	0%
Technical	69%
Economic	54%



Overall Score: 41

Each of the proposed treatments is ranked similar or better than the base case of mass burn incineration. In the areas of recovery of value-added products, technology potential and CO_2 emissions, each treatment provides RDD&D opportunities in the Singapore context. Option A demonstrates the highest potential for RDD&D due to its favourable scores in the environmental, technical and economic dimensions.

5.4.1 Recommendations

Option A - Plastic waste to CNT

One of the major challenges in upcycling plastic waste to CNT is a lack of consistent quality supply of carbon feedstock. Feedstock from recycling streams is typically mixed plastic types. Research and studies on emerging technologies such as (tribo) electrostatics, laser-induced plasma spectroscopy, laser-induced breakdown spectroscopy, X-ray fluorescence, infrared (IR) and Raman methods, density media, and artificial neural networks (for spectral data analysis) in separating and sorting plastic to ensure its consistency and quality.
Research could focus on producing single-walled CNT instead of multi-walled CNT as they are of higher value and demand. In addition, single-walled CNT is generally more challenging to synthesise from plastic waste as compared to multi-walled CNT.

Option B - Plastic waste to fuel

Preliminary consultation with technology providers may help to understand the BAT and the feasibility of utilising this technology in Singapore's context.

Research could be carried out on more efficient and cost effective means of converting waste plastics to transportation fuel and other chemicals (e.g. lubricants) by optimising the pyrolysis process (e.g. temperature) in order to reduce the high energy requirement and costs.

Option C - Plastic waste to PHA

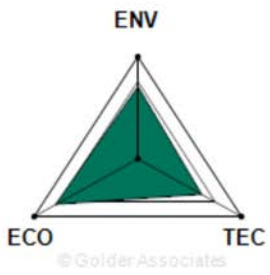
The yield and speed of PHA production will determine the commercial viability of this technology. This is dependent on the microorganisms which may require more in depth studies such as genetic engineering and synthetic biology. Research could be on optimising operating conditions for optimal microbial fermentation process and improving on the robustness and flexibility of the process to achieve control over process performance and yield.

As literature has shown that short-chained PHAs can be synthesised from plastic waste, research could focus on producing mid-chained PHAs that have more uses as compared to the short-chained PHAs.

5.5 Waste Recycling – Paper

Paper waste to cellulose aerogels

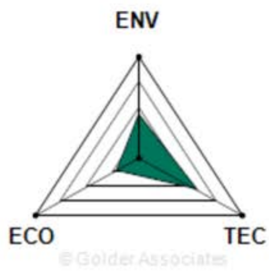
Environmental	70%
Technical	61%
Economic	79%



Overall Score: 70

Paper waste to butanol

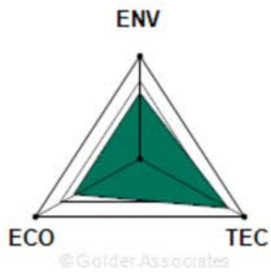
Environmental	43%
Technical	54%
Economic	21%



Overall Score: 39

Household paper waste to Pro-fibre

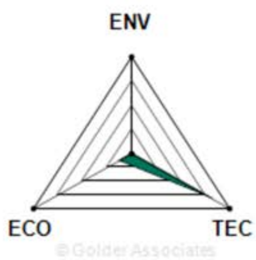
Environmental	63%
Technical	84%
Economic	62%



Overall Score: 69

Base Case - Paper waste to IP

Environmental	0%
Technical	69%
Economic	12%



Overall Score: 27

The proposed technologies are ranked well than the base case of mass burn incineration. In the areas of technology potential and CO_2 emissions, each option provides RDD&D opportunities in the Singapore context. Option A demonstrates the highest potential for RDD&D due to its favourable scores in the environmental, technical and economic dimensions.

5.5.1 Recommendations

For the implementation of all these options, communication and education of the public on the benefits and importance of source segregation of paper waste is essential to help in the downstream conversion process.

Option A - Paper waste to cellulose aerogels

R&D efforts could focus on reducing the energy requirements from freezing and freeze-drying. In addition, reducing the processing time for the conversion and use of chemicals would be beneficial for the commercial scale application of this technology.

Option B - Paper waste to butanol

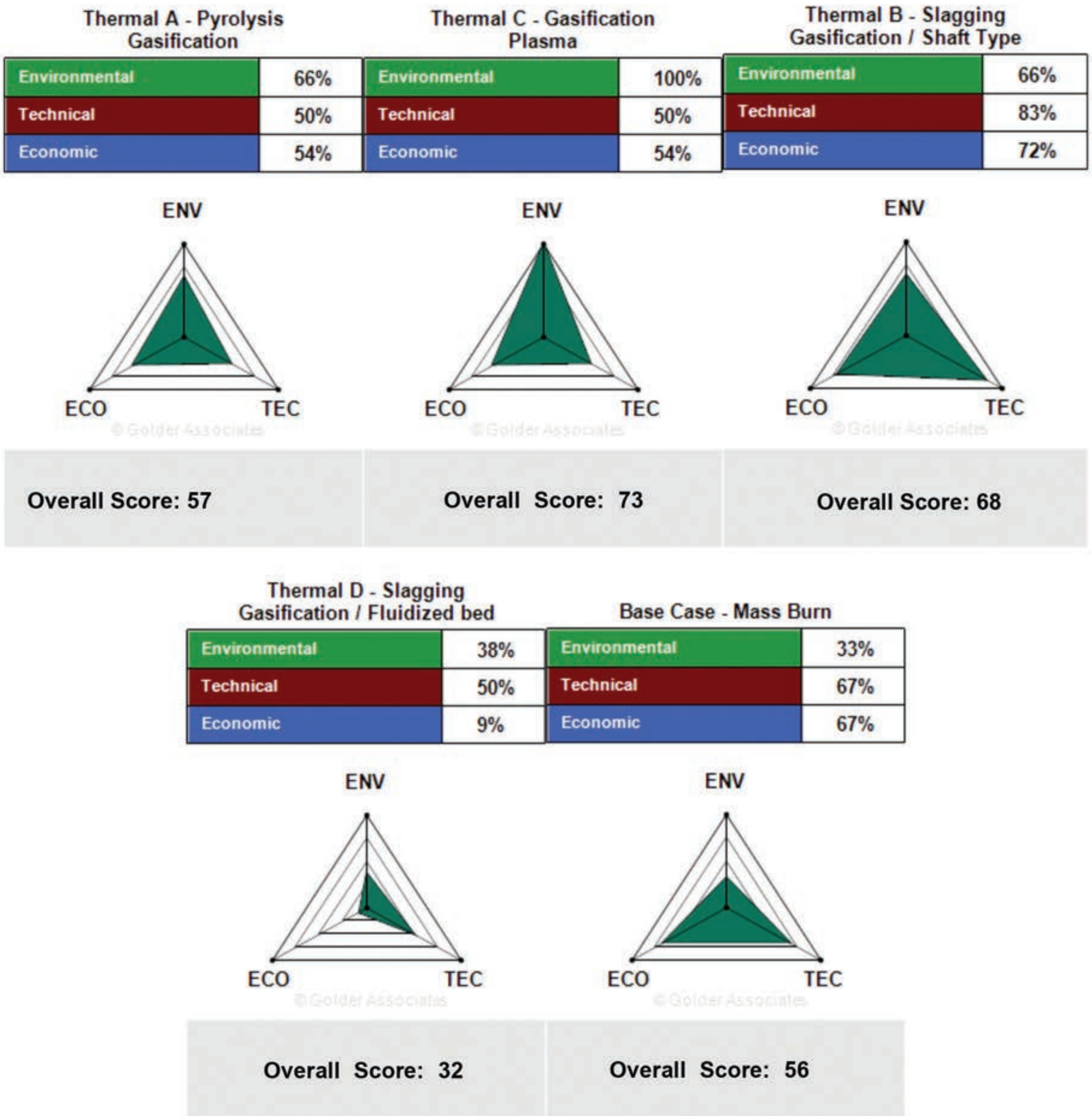
R&D efforts could focus on optimising the microbial fermentation process (acetone–butanol–ethanol (ABE) fermentation) and improving the robustness and flexibility of the process to achieve process performance and yield. The commercial viability of this technology is dependent on the microorganism, which requires more in depth studies in genetic engineering and synthetic biology.

As this technology has been demonstrated to convert newspapers thus far, R&D efforts could focus on ensuring that the technology is effective towards complex, mixed or contaminated paper waste streams.

Option C - Paper waste to Pro-fibre

Technological developmental efforts are required in optimising the process flow to reduce the CAPEX and OPEX during its operational phase.

5.6 Thermal Treatment



Each of the alternative thermal treatments is ranked similar or better than the base case of mass burn incineration. In the areas of MSW volume reduction, energy recovery, technology potential and CO_2 emissions, each of the alternative thermal options provides RDD&D opportunities in the Singapore context. Thermal B demonstrates the highest potential for RDD&D due to its favourable scores in the environmental, technical and economic dimensions.

5.6.1 Recommendations

Thermal A – Pyrolysis + Gasification

Combined pyrolysis and gasification technology can be a treatment option for MSW if the identified constraints and challenges can be overcome via R&D in the future. The technology is still at lab scale research and more R&D is required before a demonstration scale project on combined pyrolysis and gasification can be embarked on.

Thermal B & D – Slagging Gasification

The capacities of slagging gasification facilities are of small scale as it is difficult to maintain the temperature at the centre of the gasifier. The largest module is 150 tonnes/day/furnace. Compared to mass burn WTE plants which are able to process 500 or more tonne/day for each line, a slagging gasification could be an option to supplement existing WTE plants. The technology providers are carrying out R&D to double the treatment capacity of the gasifier. In addition, R&D efforts on the use of alternative substitutes for coke that will not result in an increase in CO_2 emission over mass burn incineration.

Based on Golder's literature review, most slagging gasification processes recover energy from the heat of the combustion of syngas using a steam cycle. But the challenge is in cleaning up the syngas for use in a gas engine or gas turbine which could reap higher thermal efficiency.

Thermal C – Gasification + Plasma

To keep tabs on the market assessment for development trends in plasma gasification as it could have potential for producing various types of fuels and chemical feedstock.
Plasma gasification facilities if proven to be feasible can be co-located with or located near industrial facilities that require the end products. Infrastructure to handle the products such as pipelines, road transportation or electric interconnection distance needs to be considered for the location of the plant.

Advanced Mass Burn

High energy efficiency is desired for WTE plants to reap its economic benefits. However, there is a need to balance the benefits of additional energy generated against the higher costs incurred in the operation and maintenance of the plant. For example, corrosion protection is of key concern for plant operating on high steam temperature and pressure to increase its energy efficiency. The expense of installing infrastructure for sustaining heat/high pressure steam needs to be justified against the desired capital cost as well as operating and maintenance costs.

6.0 SUPPORTING POLICY AND NON-POLICY MEASURES TO REALISE THE WASTE TECH ROADMAP

More integration of the value chain may help to provide greater resilience within Singapore's economy that is heavily dependent on imports. The OECD programme on sustainable materials management cautions that the successful introduction of policies requires support that cut across several policy fields. [2] Government departments such as environment, energy, climate, innovation and economics need to work together on inculcating resource efficiency.

6.1 Public Education and Policy on Separation of Dry Recyclables and Mixed Waste at Source

The NRP is a voluntary-based programme for collection of dry commingled recyclables. The NRP needs to be strengthened with public education and promotion activities to improve the recycling rate. Proper source segregation is the most effective means to resolve feedstock contamination problem and reduce pre-processing steps (e.g. drying and sorting) regardless of them being send to MRF, MBT, or for upcycling. This also reduces energy and labour (operational) costs. Communication and public education on the benefits and importance of source segregation of food waste also need to be encouraged.

6.2 Detailed Waste Composition Study

It is recommended that a detailed waste composition study be conducted as a starting point for the design of a customised advanced MRF that suits Singapore context. This includes the potentials for recovering different types of recyclables such as PET, PE, PP, PVC, newspaper, cardboard, glass, organics, residue etc. This can be done either via waste collection contracts awarded to the PWCs or consulting firms with relevant experience. Such a study can be conducted every five years to capture changes in the waste streams and modifications to the MRF processes may be required to accommodate the changes.

6.3 Consultation with Technology Providers and Baseline Studies

For alternative technologies, preliminary consultation with technology providers that are based overseas is recommended to understand the feasibility and their applicability in Singapore context.

Baseline studies can be carried out for new technologies which are still in pilot scale stage to identify their advantages over existing technologies. The studies also facilitate the identification of tailor-made technological solutions for Singapore to meet its desired goals.

[2] OECD: Organisation for Economic Co-operation and Development. 2012. Sustainable Materials Management. Green Growth Policy Brief. Brussels: OECD Environment Directorate. Available online at http://www.oecd.org/env/waste/SMM%20synthesis%20-%20policy%20brief_final%20GG.pdf

6.4 Regulations and Standards for Implementation of Advanced Technologies

Relevant regulations and standards have to be formulated to facilitate and regulate the implementation of technologies such as the use of autonomous waste collection trucks on roads, utilisation of IBA and slag. Pilot scale and demonstration scale projects shall be carried out before the adoption of new technologies.

6.4.1 Standards for gasification slag

There are no local regulations on the use of slag from slagging gasification process. Hence, the study on the unknown long-term effects and product quality will be required to support the offtake of slag from the MSW slagging gasification plants if they are to be built.

6.4.2 Regulation on autonomous vehicles

The regulations for the post-testing deployment of autonomous vehicles are under development in the US. The manufacturers must meet these regulations and certify that their autonomous vehicle has been successfully tested to meet safety requirements, and is operationally ready to run on public roads. Further to this, it is also important to engage and consult the public in setting the regulations for autonomous vehicles from the viewpoint of public safety.

7.0 WASTE MANAGEMENT TECHNOLOGY ROADMAP FOR SINGAPORE

The Waste Management Technology Roadmap establishes the RDD&D pathways to achieve the 2030 vision. The roadmap address the technology options for collection, sorting, recycling and treatment and recommends solutions to meet the desired goals. It is recommended that the roadmap is to be reviewed and adjusted to technology advancement, changes in policies, waste conditions and public expectations.

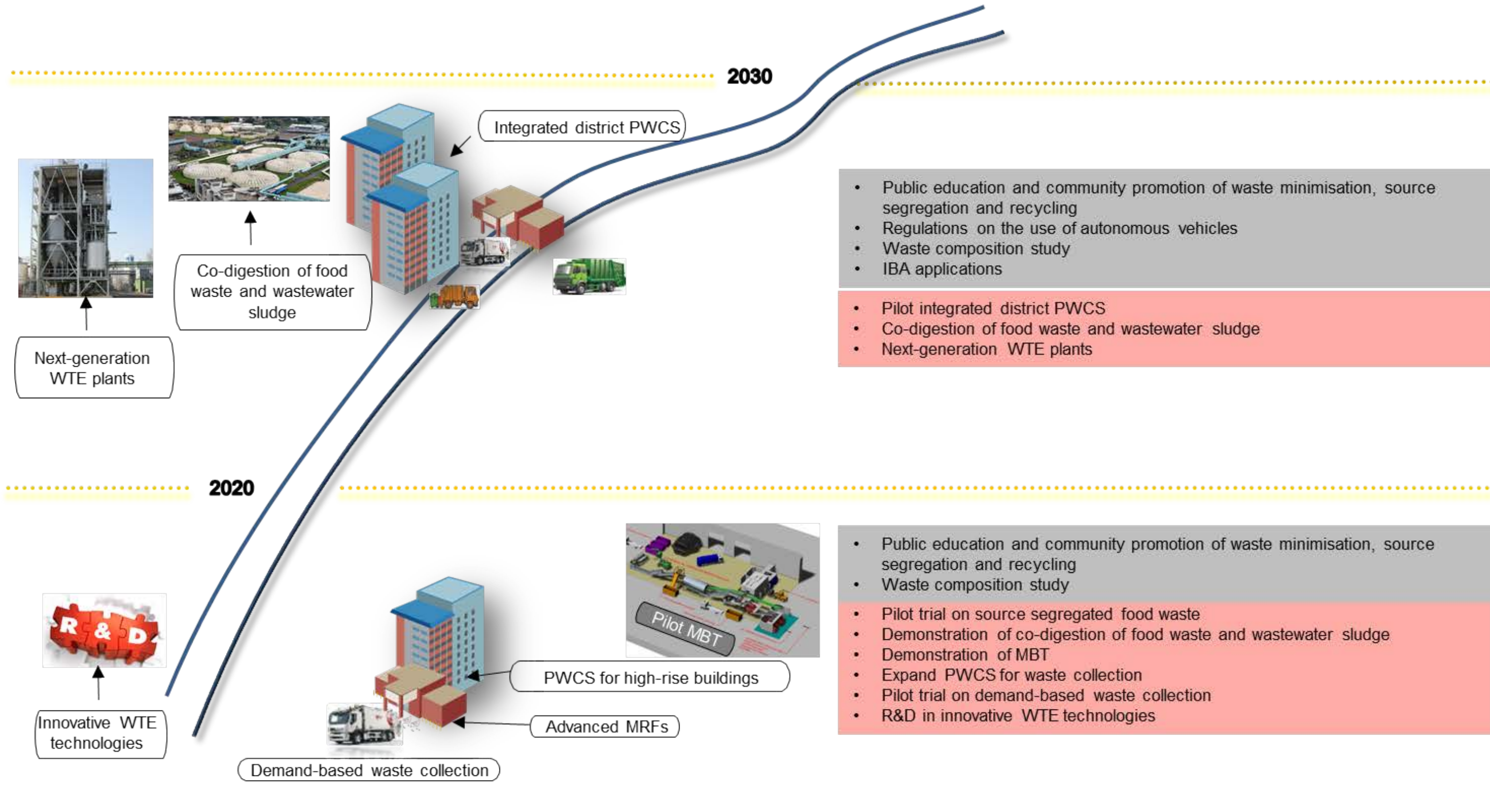


Figure 10: Proposed Technology Roadmap on Waste Management

APPENDIX A – VARIOUS MBT CONFIGURATIONS

MBT A – Mechanical separation with production of SRF

This process requires a mechanical sorting facility. After the waste has undergone size reduction, screening, magnetic separation, and density separation at the mechanical sorting facility, the waste is further processed through aerobic drying, crushing and pelletising into SRF. In order to reduce the water content, the refuse is dried to approximately a 10% moisture level in a dryer. Coarse incombustibles are rejected in the air separator, crushed again and then formed into a pellet by pelletising machine. A typical process flow diagram is presented as below:

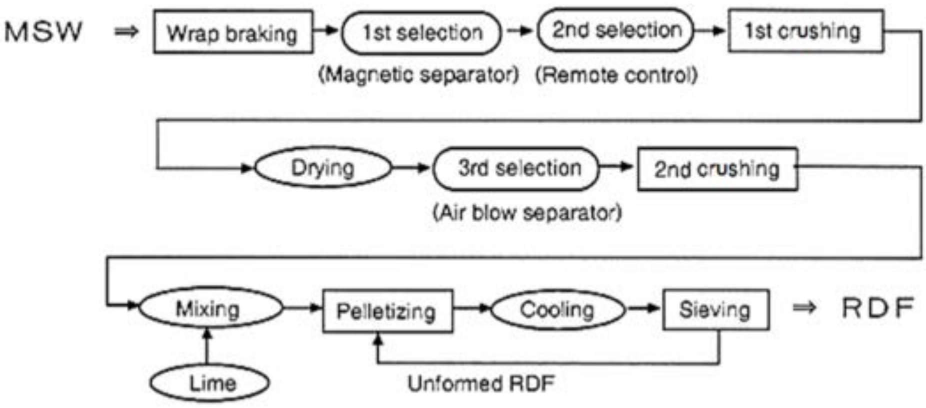


Figure 11: Typical MBT A Process Flow Diagram

The SRF produced from this process is suitable for a wide range of applications, including substituting fossil fuel for power generation and cement production where SRF can offsite a portion of other fuels such as coal, oil or natural gas. Based on the waste composition study carried out by Golder for a client, the gross calorific value or Higher Heating Value (HHV) of SRF materials such as mixed paper, plastics, textiles, wood, food waste and other organics on a ground and dried basis can range from 4,145 kcal/kg to 6,548 kcal/kg.

MBT B – Waste to biogas and fertiliser via AD

In this process, organic materials such as food scraps and yard debris are tipped into an enclosed receiving area. Operators then use front loaders to mix and stack the waste materials into tunnels called hydrolysis percolators. Inside the hydrolysis percolators, the doors are shut tight to create a gas-tight anaerobic environment. This is the first stage of the AD process. Liquid is then percolated through the materials, biochemically degrading the carbohydrates, fats and proteins into hydrolysate. The hydrolysate is then pumped into methane digesters where biogas is produced through naturally occurring methanogenic bacteria consuming the organic content of the hydrolysate. After two weeks in the hydrolysis percolators, the digestate is removed and composted. Below is a process flow diagram:

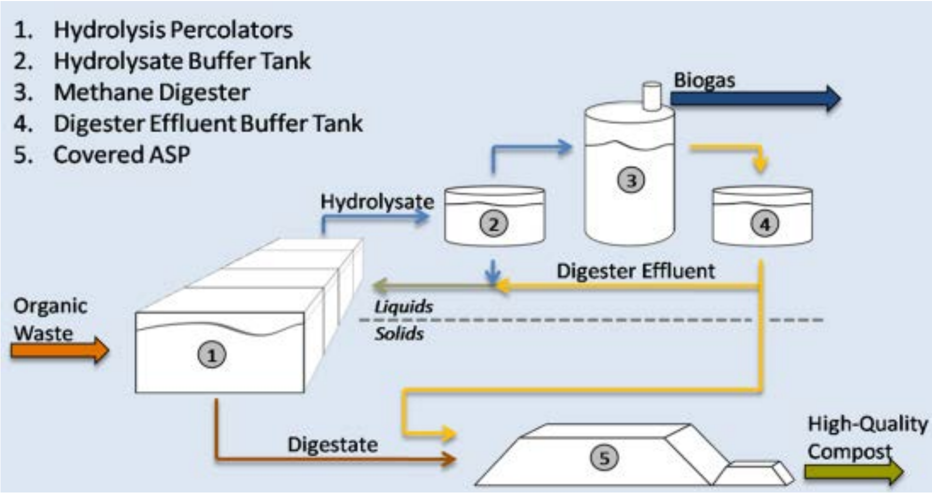


Figure 12: MBT B Process Flow Diagram

This process also recovers biogas which can be used to fuel generators to produce electricity, or upgraded to CNG for injection into a natural gas pipeline, or used to fuel vehicles.

MBT C – Waste to biofuel and renewable energy via gasification and fermentation

This process employs gasification to convert biomass to syngas followed by fermentation to bioethanol. Bioethanol is a renewable fuel and it has less GHG emissions compared to petrol.

During the gasification stage, the prepared organic carbon material is gasified using a controlled amount of oxygen to produce syngas, a mixture of principally carbon monoxide and hydrogen. The hot syngas is then quenched and cleaned and the heat is recovered to generate power for use in the process.

The cleaned cooled syngas is passed into a fermentation process, where it is converted into ethanol by naturally occurring anaerobic bacteria (the biocatalyst). The fermentation environment, containing the right quantity and type of nutrients, is maintained at controlled conditions. The off-gas from the fermenter can be used to generate additional power and heat. The ethanol solution is then purified and refined to make anhydrous bioethanol (>99.7% ethanol). This can be blended into gasoline as required for the local road transport fuel market.

The process flow diagram is presented below.

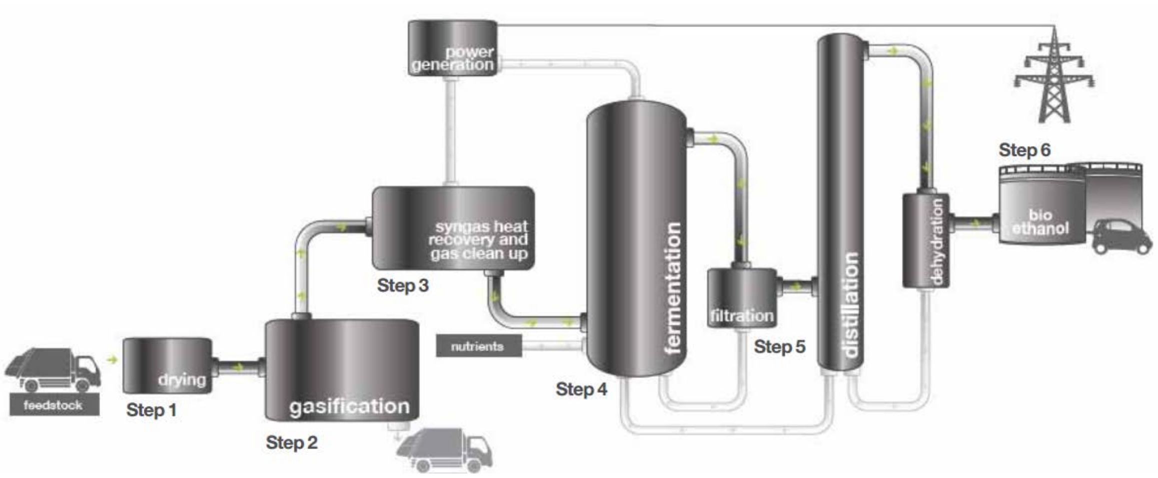


Figure 13: MBT C Process Flow Diagram

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