WASTE TO ENERGY IN THE AGE OF THE CIRCULAR ECONOMY

BEST PRACTICE HANDBOOK

NOVEMBER 2020

ASIAN DEVELOPMENT BANK

ADB

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On the cover: Municipal garbage truck brings about 3,500 tons of garbage daily from a waste transfer station to a waste-to-energy plant in the People's Republic of China (photos by Lu Guang, 12 February 2014).
Waste-to-energy plant in the People's Republic of China (photo by: Lu Guang, 11 February 2014)

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The report is a result of the team effort led by Stephen Peters, senior energy specialist (waste to energy), Energy Sector Group, Sector Advisory Service Cluster (SDSC-ENE), Sustainable Development and Climate Change Department (SDCC) with support and guidance from Yongping Zhai, chief, SDSC-ENE, SDCC; and Kee-Yung Nam, principal energy economist, SDSC-ENE, SDCC. We are also grateful to contributions provided by the consultants including Chih-Ting Lo, Fely Arriola, Patrick Co, Sasank Goli, Keshan Samarasinghe, and Elmar Elbling.

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This handbook has been prepared so that a nontechnical reader can be presented with the best available technologies, an explanation of the science and engineering involved, the policies needed, and the commercial outcomes leading to social and environmental needs. It does not supplant the work of expert consultants in feasibility, design, implementation, and operations of waste-to-energy facilities. We hope this guide empowers the reader to understand the current state of development and how best transition to a circular economy while resolving the sanitation and pollution challenges facing our civilization.

FOREWORD

This handbook is one of a series of reference materials on advanced energy and low carbon technologies. This series aims to achieve the following objectives: (i) support the Asian Development Bank's (ADB) developing member countries in adopting and deploying advanced technologies, (ii) scale up the ADB Clean Energy Program that prioritizes energy efficiency and renewable energy, and (iii) increase the energy sector's contribution to climate finance in mitigation and adaptation.

Waste to energy is one of the circular economy solutions that can have economic, social, and environmental co-benefits through efficient use of natural resources, reduced emissions, job creation, and fostering innovation. As such, the emergence of the circular economy has changed the way governments think about waste. While advanced thermal technologies provide a high level of sanitation and baseload energy, two-thirds of common municipal waste can be converted to other forms of energy, fuels, chemicals, and fertilizers for higher economic and social impact.

In this context, this handbook outlines the types of waste suitable for transformation by waste to energy technologies and provides insights into the planning scenarios to make appropriate technology choices. Rightsizing waste to energy infrastructure investments is the key message from this handbook. The handbook also presents case studies in an attached compendium of technologies provided from the industry. The case studies present the project fundamentals including financial, technical, and operational aspects of each deployment.

It is hoped that this handbook will be a useful reference for ADB operations and its developing member countries as they seek to achieve a prosperous, inclusive, resilient, and sustainable Asia and the Pacific.

Yonping Zhai
Chief of Energy Sector Group
Sustainable Development
and Climate Change Department
Asian Development Bank

ABBREVIATIONS AND UNITS AND MEASURE

ADB	–	Asian Development Bank
ASTM	–	American Society for Testing Materials
BioCNG	–	compressed biomethane
CHP	–	combined heat and power
CIGAR	–	covered in-ground anaerobic reactor
CNG	–	compressed natural gas
COD	–	chemical oxygen demand
DMC	–	developing member country
DME	–	dimethyl ether
EFB	–	empty fruit bunch
EfW	–	energy from waste
EPA	–	environmental protection agency
EPR	–	extended producer responsibility
FAME	–	fatty methyl ester
FMCG	–	fast-moving consumer goods
GGCS	–	green gas certification scheme
GHG	–	greenhouse gas
HFO	–	heavy fuel oil
LCOE	–	levelized cost of energy
LNG	–	liquefied natural gas
LSFO	–	low sulfur fuel oil
MBT	–	mechanical biological treatment
MOE	–	Ministry of Environment
MOF	–	Ministry of Finance
MGW	–	municipal green waste
MSW	–	municipal solid waste
NEF	–	networking existing facility

NGV	–	natural gas vehicle
NPK	–	nitrogen, phosphorous, potassium
ODS	–	organic dry substance
PLC	–	program logic controller
PLF	–	plant load factor
POME	–	palm oil mill effluent
PPP	–	public–private partnership
PSA	–	pressure swing absorption
PRC	–	People's Republic of China
RDF	–	refuse-derived fuel
SDG	–	sustainable development goal
TRL	–	technology readiness level
UNFCCC	–	United Nations Framework Convention on Climate Change
WACS	–	waste characterization study
WtE	–	waste to energy

UNITS AND MEASURES

GW	–	gigawatt
ha	–	hectare
hr	–	hour
kCal	–	kilocalorie
kg	–	kilogram
kJ	–	kilojoule
kWh	–	kilowatt-hour
m3	–	cubic meter
Mt	–	metric ton
MWe	–	megawatt electrical
MWh	–	megawatt-hour
MWt	–	megawatt thermal
Nm^3	–	normal cubic meter
ppm	–	parts per million
T	–	tonne*
wt	–	weight

* T is referred to as tonne (metric) which is equivalent to 1,000 kilograms. In the US, ton is used, which is equivalent to 0.907185 tonne or 907.185 kilograms.

EXECUTIVE SUMMARY

Waste-to-energy (WtE) technologies provide a convenient solution to both environmental loading and energy production, especially in distributed energy models. Business models are based on the availability and type of waste, energy needs, and technology solutions. However, care should be taken in applying off-the-shelf solutions to particular projects—each project should be evaluated on a stand-alone basis.

Several technology solutions for WtE applications are available depending on the forms of energy needed. The selection of technology becomes simpler if the waste characteristics are well understood. It is also critical to secure access and control of the waste stream to ensure that waste as feedstock is available all throughout the project life.

The determination of the capacity of a particular technology solution should be given extra consideration. This is especially so for municipal WtE plants. These solutions should be sized to cater for the nonrecyclable, nonrecoverable, and non-upcyclable materials and any landfill mining over the life cycle of the project. The solution capacity should be weighed against increases in population and waste generation versus consumer product redesigns and introduction of extended producer responsibility schemes, which will increase cost associated with waste materials.

There exist a variety of business models for WtE. A number of countries are providing electrical production subsidies as incentive for putting up WtE plants. Community-based businesses also exist for small applications while build-operate-transfer or build-operate-own-transfer schemes are being undertaken on large infrastructure projects.

The eco-industrial park business model maximizes the recycling, recovery, and upcycling of waste materials and is considered current best practice in capacity planning. Deploying these businesses in eco-industrial parks or in distributed locations is considered an ideal approach. Development of supply chains with discovery mechanisms for quantities and pricing is required. The involvement of public and private sectors in shaping solutions and operating the supply chain is essential. The public sector sets the wider infrastructure agenda by creating defined collection and operations areas. The private sector enters to build and operate infrastructure and downstream recycling, recovery, and upcycling activities within these defined areas.

Creation of sorted, homogeneous streams of waste at source is the gold standard of best practice. This creates opportunities for distributed recycling and upcycling activities. Digitization of waste collection and trading of these sorted materials allows for greater community participation in the waste collection process and discovery of actual quantities and types of waste. It also provides greater opportunity for marginalized persons in the supply chain.

The move toward a circular economy requires rethinking the supply chains currently used for waste. Landfilling a vast majority of waste generated unfairly defers this problem to future generations.

A proactive mix of 25% WtE treatment for municipal waste; 8% landfill of inert materials; and combustion products with the remaining 67% being recycled, reused, or upcycled constitutes current best practice in Asian countries.

As we move toward more livable cities and increased rural development, we should consider how to clean up our legacy and ongoing generation of waste, extract the maximum value from our waste, and engage with residents and businesses to create sustainable supply chains with community involvement.

Some cities have achieved 80% landfill diversion with no waste-to-energy facilities. This requires extensive engagement and cooperation with the city residents and a functioning recycling and/or upcycling market.

Value can be created through new business models, technology combinations, digitization, and policy support.

Care should be taken in piloting newer technologies without adequate track record. Assistance should be sought when assessing these technologies. A section on new technologies and the use of technology readiness levels to assess suitability has been included.

As the world becomes more aware of the environmental challenges from our consumer lifestyles, the companies underpinning the lifestyles patterns will change the delivery mechanisms and specification of their products and services. This will have significant impact on waste quantities and character. Using a business-as-usual planning approach is no longer tenable.

This handbook sets out the waste side of the circular economy transition and a way forward.

1 INTRODUCTION

In 2016, the world generated an estimated 2.01 billion tons of municipal waste and this is projected to reach 3.4 billion tons by 2050. Around 44% of global waste are categorized as food and green waste while the other 38% are dry recyclables such as paper, cardboard, plastic, glass, and metal. The other 18% includes rubber and leather, wood, and others. It is expected that the amount of waste being generated will continue to increase due to economic development, population growth, and degree of urbanization. However, at least 33% of the waste is openly dumped and not managed in an environmentally safe manner. Especially in low-income countries, about 93% of the waste is burned or dumped on road easements, open lands, or waterways.[1]

However, waste cannot be dealt with in isolation in a sustainable energy ecosystem and the fast-developing circular economy future. The source, composition, and value of waste streams vary geographically and will continue to change with the region's economic growth, policies, and regulations; education; and technological advancement.

In particular, waste to energy (WtE) has a role to play in achieving the transformation to a sustainable energy ecosystem as a renewable energy source to reduce greenhouse gas (GHG) emissions, a clean demand response option, a design consideration of eco-industrial parks, and sometimes the only option for end-of-life waste treatment.

The Asian Development Bank (ADB) has recognized the importance of WtE in the Asia and Pacific region and has facilitated and supported projects for more than 12 years. The first initiative started as early as 2007 with the approval of the project, Development of Biomass Power Generation in Rural Areas, in the People's Republic of China (PRC). As of December 2018, a total of 27 WtE projects have been proposed, of which six are active and three already approved. With nearly half of the projects in the proposed stage, there is great potential of WtE in the ADB portfolio in the coming years.

ADB is continuing to support its developing member countries (DMCs) through assistance in de-risking and managing private–public partnerships in the WtE sector, investments and/or loans to emerging developers in DMC markets, and inclusion of WtE-related projects in its sovereign operations.

1 S. Kaza et al. 2018. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Washington, DC: World Bank. https://olc.worldbank.org/system/files/What%20a%20Waste%202.0%20Overview.pdf.

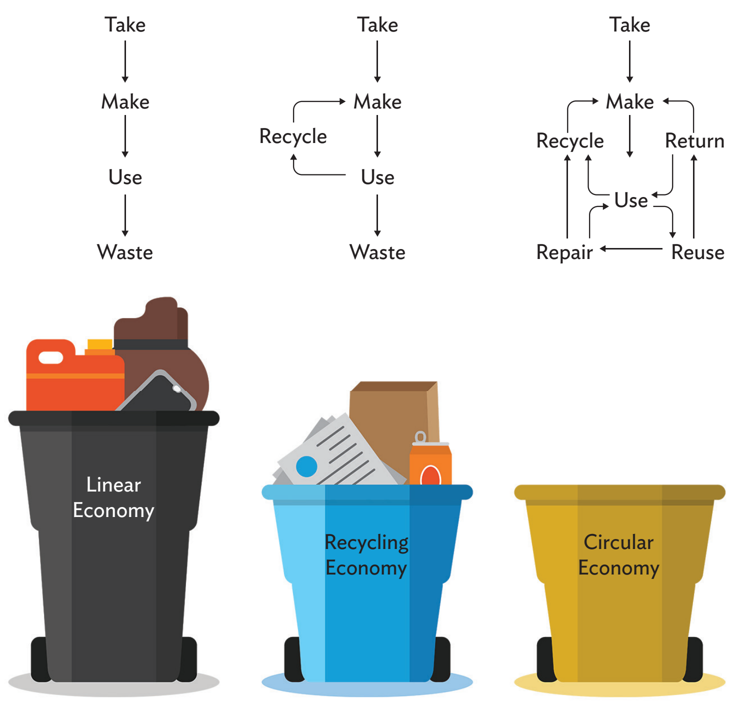
WtE is often considered as a costly option for waste disposal and energy generation when compared with other fossil fuel-powered generation alternatives. There is a disconnect as the environmental and social benefits of WtE are not valued in comparison with more established renewable alternatives such as wind and solar energy. The business models for WtE are usually more complicated than established alternatives. Considerations such as availability and steady supply of feedstock, choice of technology, and appropriate policy framework, among others, should be given extra consideration in WtE development.

Electrical energy accounts for 25% of the total revenues in waste-to-energy plants in the European Union. The remainder is for environmental treatment fee (gate fee) and the sale of ancillary products including heat, bottom ash, and slag. The current models being proposed in ADB's developing member countries is closer to 50% of revenues from electrical energy.

Thought leadership on human civilization provides a framework to consider alternate approaches to waste-related problems, namely the circular economy.

The circular economy describes emerging policies, business models, investment foci, and community behavior on less pollutive, resource-prudent, and efficient activities underpinning our global civilization. These concepts can be simplified to explain the differences between our current throwaway (linear) culture, the recycling economy, and the circular economy.

Figure 1: The Circular Economy Simplified



Source: Asian Development Bank internal training material.

The circular economy will require extensive product and business process redesign. Major multinational companies are playing catch up due to consumer demand. DMCs are currently transitioning from the linear (throwaway) economy to a recycling economy. The circular economy is infiltrating the recycling economy and will become the dominant economic model over the coming decade(s).

This means conversion from the current linear thinking model with large set-piece infrastructure to a distributed model using the circular economy thinking. By creating smaller circular steps closer to the source of waste generation, more expensive end- of-life solutions can be rightsized due to higher resource recovery rates (from 10% moving closer to 80% recovery).

This *Waste to Energy in the Age of the Circular Economy: Best Practice Handbook* has been prepared to serve as a reference guide to ADB staff and consultants, as well as ADB DMCs. The objectives are to help the reader understand waste as an evolving resource, the approach to develop a strategy, and if WtE is elected as an appropriate next step, assist the reader in reviewing technology options. This handbook focuses on various waste stream including municipal solid waste (MSW), and industrial and agricultural waste. Hazardous waste may be further discussed in future ADB handbooks.

A collection of 18 case studies and a summary of 11 emerging WtE technologies are detailed in the accompanying compendium. The emerging technologies are provided at high level, knowing that new technologies are being developed and it can take time to move the new technology to commercialization. As much as possible, concepts are presented in simple terms to achieve a thorough understanding of the subject and to encourage access by a wider audience.

The handbook is divided into different sections:

(i) An overview of waste:
   a. waste section describes various wastes, their composition, and characteristics;
   b. the WtE section discusses its various components such as feedstock, energy conversion technologies, applications, and outputs and residues.
(ii) An overview of WtE technologies
(iii) A WtE planning and strategies section highlights the 12 pathways to waste management, key considerations, and processes in developing WtE projects.
(iv) A hypothetical case is presented in the Waste Infrastructure and Planning Example section providing key proposals for a WtE project.
(v) The conclusion section condenses the findings of the report and how it can be related to ADB's DMCs given their waste management practices and WtE development potential.

The handbook also includes a compendium of existing project case studies and emerging technologies:

(i) Detailed and actual WtE project examples section includes existing projects using simple to complex technologies with varying degrees of implementation, i.e., from village to industry levels are compiled in one section of this report. Each case study includes the technology used and narrates the lessons learned while implementing the individual projects.
(ii) A high-level summary of emerging technologies and their current stage of maturity accordingly to the technology readiness level (TRL) assessment.

2 WHAT IS WASTE?

Waste is anything we want to get rid of. There are many definitions of waste. The United Nations Statistics Division defines waste as materials that are not prime products (that is, products produced for the market) for which the generator has no further use in terms of his/her own purposes of production, transformation, or consumption, and of which he/she wants to dispose. Wastes may be generated during the extraction of raw materials, the processing of raw materials into intermediate and final products, the consumption of final products, and other human activities. Not included in this definition are residuals recycled or reused at the place of generation.[2]

TYPES OF WASTE

There are different types of wastes[3] and they can be classified according to their state, i.e., solid, liquid, and air. Solid waste can be both organic and inorganic. Mud, sludge, effluents, and other liquid forms of waste need special means of collection and transportation and commonly these materials can be toxic and harmful to the environment. Effluents include sewage and wastewater from industries such as agricultural processing and many types of manufacturing. Gaseous waste should not be confused with air pollution. This handbook focuses on common forms of waste where energy or value can be extracted, not only MSW. Other waste streams may be reviewed further in future handbooks.

Municipal Solid Waste

MSW can be both organic (e.g., food waste, paper and rubber products, fabric, plant matter, plastics) and inorganic (e.g., glass, metal, construction debris). MSW is generated at households, offices, shops, schools, hospitals, hotels, and other institutions. The major components are food, paper, rags, metal, tires, construction debris, glass, and hazardous waste such as light bulbs, batteries, chemicals, etc. Majority of the MSW goes to landfill in jurisdictions where a collection system is developed and implemented. Municipal waste can be further classified into different types depending on their point of generation.

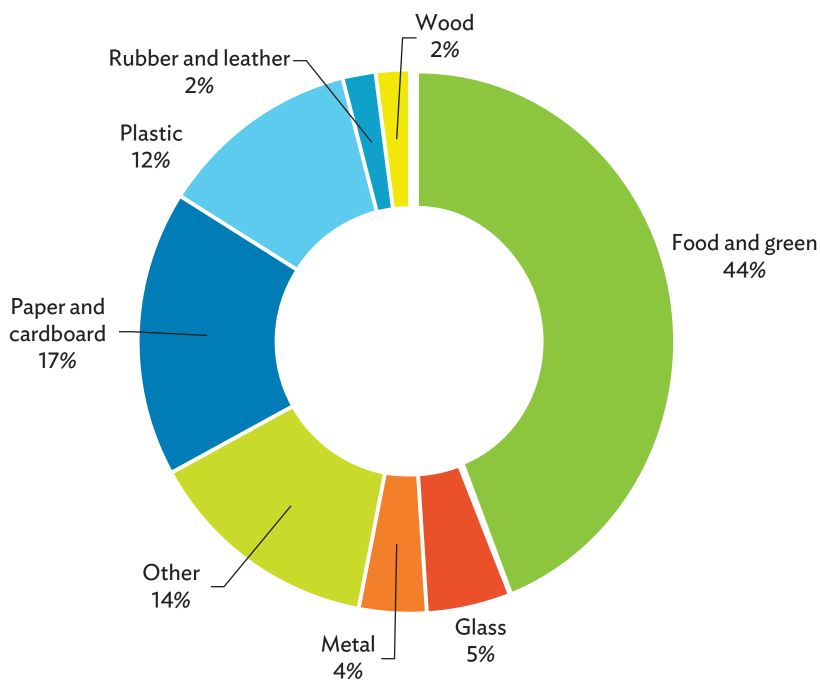
(i) **Household waste** is generated in the operation of household activities.
(ii) **Commercial waste** consists of waste from areas where business or trade is conducted. This may include business relating to sports, recreation, education, or entertainment excluding household, agricultural, and industrial sectors.

[2] E. Baker. 2004. *Vital Waste Graphics.* United Nations Environment Programme, Division of Environmental Conventions. Nairobi.
[3] D. Arpad. 2013. Engineering and Environmental Geology. Eger, Hungary: Eszterházy Károly College. https://www.tankonyvtar.hu/en/tartalom/tamop412A/2011-0038_37_david1_en/ar01s11.html.

(iii) **Construction and demolition waste** is generated from the building industry. The debris range from insulation, electrical wiring, rebar, wood, concrete, and bricks.
(iv) **Hazardous waste** contains scheduled items such as lead, asbestos, or other hazardous materials. These are often intermingled with other types of waste. It requires separate handling and disposal. (Please note that detailed technical information on hazardous and medical waste handling and disposal are not foci of this handbook).
(v) **Inert waste** includes materials which do not chemically or biologically decompose such as metal, sand, and concrete, among others.

If all MSW is monitored, sorted, and categorized, humanity could recover more energy and recycle more materials. Food and green waste is the largest waste category, which constitute 44% of the global waste. Other recyclables, e.g., paper, cardboard, plastic, glass and metal, follow at 38% (Figure 2). The composition varies by level of income; generally, the percentage of organic matter decreases as the level of income rises among countries (footnote 1).

Figure 2: Composition of Municipal Solid Waste



Source: World Bank. 2018. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.

Industrial Solid and Liquid Waste

Waste under this category includes paper, waste from food processing, packaging materials, paper, glass, stones, ceramics, metals, rubber, plastics, leather, wood, cloth, abrasives solvents, resins, paints, and oils.

Agricultural Waste and Residues

Agricultural waste and residues are those are left during agricultural production. Some of the wastes are used as fertilizer while a substantial amount remains unused. Agricultural wastes are often disposed through uncontrolled burning in the fields or dumped in the open area or in waterways. This is a major contributor to air pollution in many countries. This type of waste is discussed thoroughly in the next section.

WASTE DISPOSAL

Globally, a large percentage of waste (40%) goes to landfill and about 19% is either recycled and composted. An estimated 11% goes through modern thermal treatment. However, around 33% of waste is still openly dumped especially among low-income countries of which about 93% practices burning and dumping. Waste is dumped in open land, roads, or waterways. Meanwhile, only 2% of waste in high-income countries is openly dumped.

The development of engineered and/or sanitary landfill is a first step of progression from open dumping toward sustainable waste management. About 54% and 3% of waste are disposed in suitable landfills among middle-income and low-income countries, respectively. High-income countries, on the other hand, place greater attention on materials recovery through recycling and composting. The typical waste disposal methods within this income category are through landfill (39%), recycling (29%), thermal treatment (22%), composting (6%), and open dumping (2%).

WASTE MANAGEMENT PRACTICES

This section describes general waste management practices for solid waste, wastewater, and radioactive waste.

Municipal Solid Waste

Waste management practices vary based on the country, location, and type of waste being collected. Waste collection usually constitutes the major solid waste management costs in cities and municipalities (footnote 1). Household waste is disposed of in plastic bags, old cans, and baskets for curbside/gate collection; waste cans collected from designated locations for community dumping in bins, dumpsters, or simply piled up by the roadside. In some cases, skip bins or communal bins are placed near markets or populated centers.

In high-income industrialized countries, waste collection rate is almost 100%. Compactor trucks and highly mechanized vehicles and transfer stations are commonly used. Collection of recyclable materials is usually regulated and waste segregation is done at source and facilitated through color-coded garbage bins.

In the low- and middle-income countries, collection rate is between 50% and 80% and is done through larger vehicle fleet. Waste collection and transfer require higher labor inputs. In many low-income countries, waste is collected by those directly hired by the municipal authorities. Often the initial collection or aggregation of waste is undertaken by the informal sector, which removes recyclables and high-value items. Waste collection uses basic equipment such as handcarts and tractor-trailers to gather waste from communal bins and dumping areas.[4]

Management of wastes is usually decentralized and done by city or municipal governments. The local governments either handle waste collection from communal areas or private sector waste collection firms usually haul the remaining waste to a designated location outside the city or town area.

Open Dumping

Open dumping is the most common method of solid waste management especially in low-income countries. This practice involves improper waste disposal without consideration to its environmental implications. Waste is often openly burned at the dumpsite itself and in coastal areas, or dumped along the shoreline or into the sea. In most cases, waste is stacked at high levels, risking slope slippage that has resulted in fatalities. There is a risk of fire due to the buildup of methane in uncontrolled circumstances. Adverse health effects on workers and residents nearby include rodents, diseases from stagnant water, and toxic gases from open fires.

Landfilling

Landfills are the burial grounds of MSW. Landfills are often established in abandoned areas. If properly designed and well managed, it can be considered as an effective and inexpensive method of waste disposal. However, poorly designed or poorly managed landfills can have adverse effect on the environment such as production of liquid leachate, vermin attraction, and generation of GHGs including methane. Modern landfills are engineered to eliminate effluent leakage, odors and gaseous emissions, litter, and vermin. Many landfills install gas extraction systems to capture the landfill gas for useful purposes such as generation of electricity.

Composting

In low-income countries, organic materials constitute over 50% of the daily mass of waste. Composting is a viable option where there is sufficient land and organic materials are well sorted. Commercial-scale composting plants have been unsuccessful in some locations due to lack of market, cost efficiencies, and plastics contamination. Small-scale composting projects at the community level are sometimes more sustainable.

[4] Economic and Social Commission for Asia and the Pacific and Asian Development Bank. *State of the Environment in Asia and the Pacific 2000.* New York: United Nations. https://www.unescap.org/resources/state-environment-asia-and-pacific-2000.

Thermal Waste Treatment

The historical development of thermal waste treatment facilities have been affected by a number of factors including high capital and operating and maintenance costs, community objections, and governments' regulations on emissions. "Incineration" is a term associated with technology from the 1960s, which was highly pollutive. Incineration should not be confused with modern thermal treatment facilities, which treat air pollutants and are being developed in ADB member countries. Critics considered these facilities inappropriate in low- and middle-income countries as a high percentage of their waste have high organic and moisture contents. Direct cost of thermal waste treatment is typically more expensive than landfilling. This is due to the additional capital and operating costs for air pollution controls on modern thermal waste treatment facility. These facilities are often called WtE plants, energy-from-waste (EfW) plants and, incorrectly, incinerators. Some references continue to use the term "incineration" to associate historical environmental performance with modern facilities. We will use the term EfW to show modern thermal treatment unless it has been referenced in publications as such.

Industrial Solid Waste

Nonhazardous industrial solid waste is disposed of in a similar manner to MSW. However, the disposal of potentially hazardous industrial solid waste is done either through hazardous landfills or high-temperature thermal treatment. Countries with lack of or without waste management facilities dispose their industrial waste on private lands or bury them in dump pits on-site or in nearby areas. Further discussion may be included in a future handbook.

Agricultural Waste and Residues

Agricultural waste is applied directly to the soil or composted to serve as fertilizers. In some countries, agricultural waste is used as feedstock to produce biogas through anaerobic digestion (this is thoroughly discussed in the succeeding section). Biogas can be used for cooking, heating, and lighting, and produces slurry, which can be used as liquid fertilizer. Some agricultural residues are upcycled and fabricated into bricks and other usable materials. Biomass such as bagasse is commonly combusted to produce power and heat for remote factories and provide area heating in winter months. Further discussion may be included in a future handbook.

Wastewater

Wastewater[5] has varying characteristics as this is discharged from different sources such as households, commercial establishments, industries, or agricultural facilities. Some liquid wastes contain nontoxic inorganic substances or toxic organic substances. Households generally produce wastewater from flush toilets, sinks, dishwashers, washing machines, bathtubs, and showers. Wastewater is usually conveyed to a sewer. A sewerage system comprises of pumps, screens, pipes, and channels that carry the waste from its origin to point of treatment or disposal. It can also be transported through a combined sewer

5 U.S. Geological Survey (USGS). Wastewater Treatment Use. https://www.usgs.gov/special-topic/water-science-school/science/wastewater-treatment-water-use?qt-science_center_objects=0#qt-science_center_objects.

consisting of stormwater[6] runoff, and industrial wastewater. After undergoing treatment, wastewater is discharged into a water body. The treated wastewater can be used for other purpose or discharge to the environment. Without appropriate treatment, discharge water is a source of water pollution. Further discussion may be included in a future handbook.

Radioactive Waste

Radioactive wastes can come from hospitals, universities, research institutes, and private companies. These are by-products of nuclear power generation or nuclear technology. Radioactivity diminishes over time; thus, waste is stored and isolated for a certain period until it no longer poses any hazard. Waste with low-level radioactivity per mass must be stored for only a few hours while high-level waste must be stored for a year or more. Timeframe of radioactive waste management solutions can range from 10,000 to millions of years. Further discussion may be included in a future handbook.

SOLID WASTE MANAGEMENT GLOBAL SCENARIO

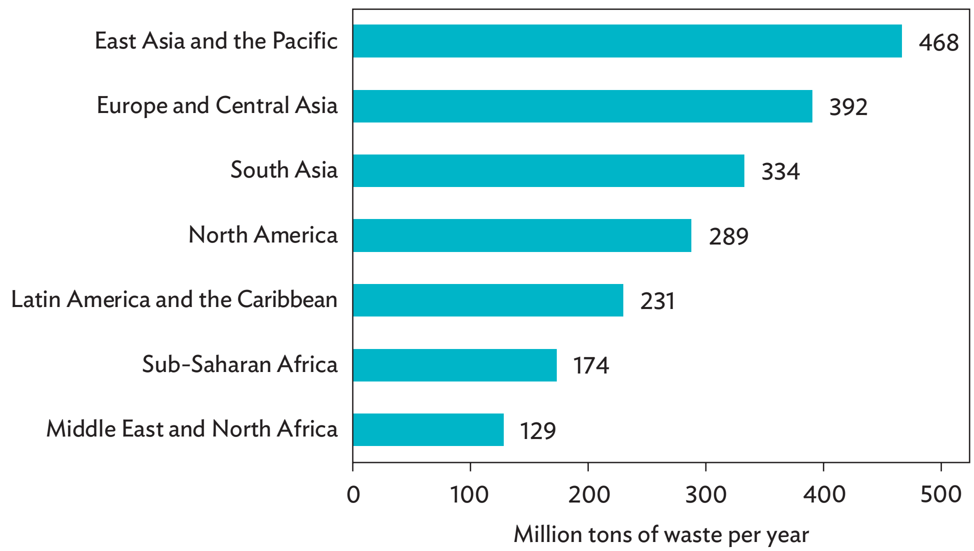
As mentioned previously, 2.01 billion tons of MSW were generated in 2016. By 2030, it is projected to reach 2.6 billion tons and will eventually increase to 3.4 billion tons in 2050. Close to half of the world's waste (43%) came from East Asia and the Pacific, Central Asia, and Europe. East Asia and the Pacific has the highest contribution among the world's regions generating a total of 468 million tons or 23% (Figure 3). Meanwhile, the Middle East and North Africa region produce the least, having a share of only 6% (footnote 1).

Waste generation is correlated with economic development and population growth. Countries in the regions belonging to the low-income and middle-income countries, specifically in Sub-Saharan Africa and South Asia regions, are expected to have a substantial increase in waste generation. Their waste levels will approximately triple and double in the next 3 decades. Higher-income regions, on the other hand, such as Europe, North America, and Central Asia are anticipated to have a gradual increase in their waste accumulation levels.

The world has an average waste generation of 0.74 kilograms (kg) per capita per day with individual countries' waste generation ranging from 0.11 kg to 4.54 kg per capita per day. As the income increases among countries, waste composition will change. Low- and middle-income countries generate around 50% of food and green waste while high-income countries produce only 32% of this waste. Organic waste constitutes only 32% in high-income economies. Recyclable wastes such as paper, cardboard, plastic, metal, and glass are significant among high-income countries constituting 50% of their waste as compared to only 16% in low-income countries. As a country's income increases, the quantity of recyclables in its waste stream also increases. As expected, more than a third of waste in high-income countries is recovered through recycling and composting.

[6] Stormwater is the general term for the rainfall runoff collected from roofs, roads, and other surfaces before flowing toward low-lying land. It is the portion of rainfall that does not infiltrate into the soil. Source: E. Tilley et al. 2008. *Compendium of Sanitation Systems and Technologies*. Dübendorf. Swiss Federal Institute of Aquatic Science and Technology (Eawag). https://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/schwerpunkte/sesp/CLUES/Compendium_1st/Compendium-Final.pdf.

Figure 3: Waste Generation by Region, 2016



Source: World Bank. 2018. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.

The method of waste collection also differs per income category. Waste collection rates in higher-income countries is nearly 100%. In lower middle-income countries, collection rate is about 51%. The rate of waste collection in cities is more than two times higher than in rural areas in low- to middle-income countries. Meanwhile, collection rate in low-income countries accounts to only 39%. Uncollected household waste may be burned or openly dumped and composting is not commonly practiced among households. The waste collection rate is higher in urban areas.

Landfill is still a common method of waste disposal accounting for 37% of waste disposed. Thirty-three percent is openly dumped and 19% goes to materials recovery facility through recycling and composting. The other 22% is treated through modern thermal treatment. High- and upper middle-income countries utilize adequate waste disposal or treatment using controlled landfills. The majority of lower-income economies (around 93%) generally dump their wastes in the open.

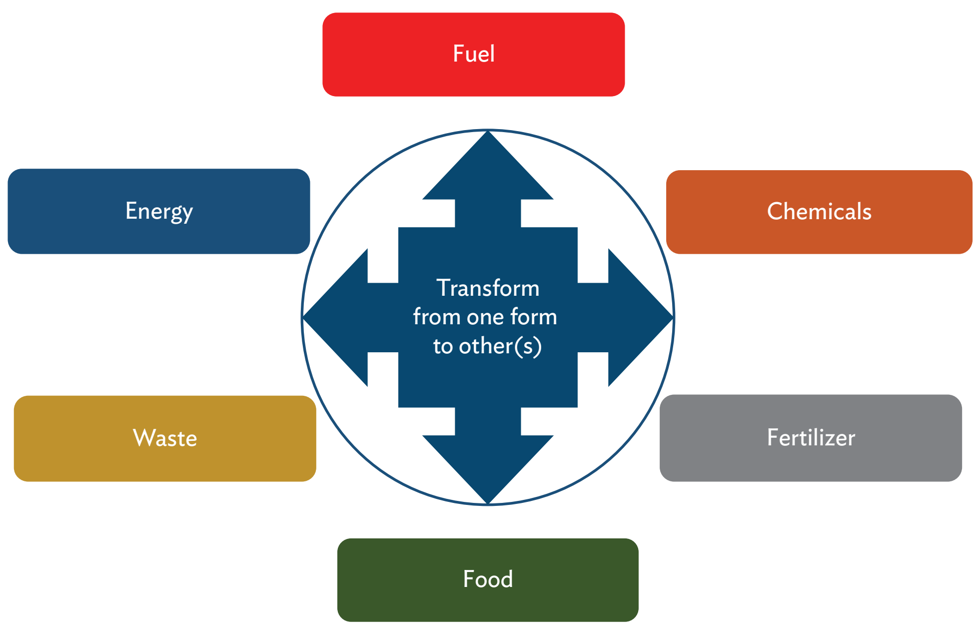
The next section discusses how waste can be used for energy generation.

3 WASTE TO ENERGY

Waste to energy can be more broadly described as taking something someone does not want and transforming it into something someone else needs or wants. Transforming our overall energy use, by decarbonizing and distributing, is a critical step in meeting the Paris Accord commitments according to the International Energy Agency.[7] WtE processes offer part of this transformation.

A simple way to conceptualize WtE is to categorize the feedstock as end-product, not the process itself. The utility of the processes or technologies can be compared based on outcomes.

Figure 4: Relationship between Waste and Other Forms of Products



Source: Asian Development Bank internal training material.

[7] International Energy Agency (IEA). 2017. *Deep Energy Transformation Needed by 2050 to Limit Rise in Global Temperature.* Paris: IEA.https://www.iea.org/newsroom/news/2017/march/deep-energy-transformation-needed-by-2050-to-limit-rise-in-global-temperature.html.

The large incinerator burning solid MSW is the process that comes to mind when WtE is mentioned. However, a similar public utility need can be met by making biogas from the organic fraction of municipal solid waste, which is mostly food; refuse-derived fuels (RDF) from combustible materials; and repurposing inert materials as fuel. Further utility can be provided by converting biogas to compressed biomethane fuel (BioCNG).[8] BioCNG can be bottled to provide a solution to cooking, light industry, or even transport.

Rural gasifiers,[9] powered by rice husk, have been displacing diesel with syngas fuel in rural microgrids for over a decade. The use of liquid wastes to create biogas[10] has met the challenges of poor quality electrical and heating energy for agricultural processing factories for a similar period. The solids recovered after the biogas process have been used as a low-grade fertilizer, subject to some controls.

This supply chain is increasingly being disrupted. Enerkem's announcement[11] of a major solid municipal waste to chemicals and fuels plant in Rotterdam is an example of the innovation in technology and business models. WtE project capital costs vary from $1,000 to $1 billion. Opportunity is the key project attribute—feedstock, process, market, funding, and implementation must all be aligned.

As well as financial returns, there are co-benefits to health, urban landscapes, transport impacts, energy access, agricultural production, and energy security, among others, resulting from WtE projects. These co-benefits depend on the project circumstances and the business model and is addressed in Section 3.3.3. These co-benefits can be directly measured against the United Nations Sustainable Development Goals (SDGs).[12]

The enduring success of a WtE project is measured by the energy produced, the reduction of the concentration of pollutants and/or nutrients created by our civilization, and its response to the SDGs. These pollutants and/or nutrients need to be reduced to a level that our biosphere can re-absorb them using its own ecosystem services. Ocean plastic litter[13] and ocean acidification[14] are two good examples where these ecosystem service limits have been exceeded. This is underlying case for intervention with WtE solutions.

8 Gas Malaysia. Bio-CNG. http://www.gasmalaysia.com/index.php/our-services/new-technologies/bio-cng.

9 IRRI Rice Knowledge Bank. Gasification of Rice Husk. Los Banos, Laguna.http://www.knowledgebank.irri.org/step-by-step-production/postharvest/rice-by-products/rice-husk/gasification-of-rice-husk.

10 ScienceDirect. 2016. Biogas reduces the carbon footprint of cassava starch: a comparative assessment with fuel oil. https://www.sciencedirect.com/science/article/pii/S0959652615008719.

11 Waste Management World. Enerkem to Lead Consortium to Develop Waste-to-Chemical Project in Rotterdam. Online magazine of the International Solid Waste Association (ISWA). https://waste-management-world.com/a/enerkem-to-lead-consortium-to-develop-waste-to-chemical-project-in-rotterdam.

12 UN General Assembly. 2017. http://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_71_313.pdf.

13 C. Groden. 2015. Report: Plastic Pollution in the Ocean is Reaching Crisis Levels. Fortune. http://fortune.com/2015/10/01/ocean-plastic-pollution/.

14 Pacific Marine Environmental Laboratory (PMEL). *What is Ocean Acidification?* PMEL Carbon Program. https://www.pmel.noaa.gov/co2/story/What+is+Ocean+Acidification%3F.

Table 1 shows the interrelationship of waste and other uses.

Table 1: Relationship between Waste and Other Forms of Products

Waste	Food	Fertilizer	Fuels	Energy	Chemicals
Solid – Rice Husk, Food Scraps, EFB, Fiber, MSW, Offal, Spent Grain, Ash, **Liquid** – POME, Process Waste, Sewerage, Sludge, **Gas** – Waste Gases, Waste Heat, Emissions, Fly Ash, Radiant Heat	**Crops** - Corn, Cassava, Palm, Sweet Sorghum, Sugar, Wheat, Rice, Edible Oils, Fruits, Algae, Grasses, Trees etc. **Livestock** – Chicken, Beef Cattle, Dairy, Duck, Sheep, Deer, Fish, Seafood etc.	NPK, Urea, Silica Phosphate, Soil Conditioners, Biochar, Ash	**Solid** – Briquettes, Pellets, Biochar **Liquid** – Bioethanol, Biodiesel, DME, FAME, LPG, LNG **Gas** – NG, CNG, BioCNG, Hydrogen, Syngas	Thermal, Electrical, Stored, Transportable, Distributed/ Microgrid, Centralized Grid, Emerging DC/ Nano	C5, C6, C7… Upward Bags, Plates, Cutlery, Biochemical Industry

BioCNG = compressed biomethane, CNG = compressed natural gas, DC = direct current, DME = dimethyl ether, EFB = empty fruit bunch, FAME = fatty acid methyl ester, LNG = liquefied natural gas, LPG = liquefied petroleum gas, MSW = municipal solid waste, NG = natural gas, NPK = nitrogen, phosphorous, potassium, POME = palm oil mill effluent.

Source: Asian Development Bank internal training material.

The succeeding sections provide simple discussion on various components that are part of the WtE process: types of feedstock, conversion technologies, energy and non-energy outputs, and co-benefits.

FEEDSTOCK

Woody organic matter has been burned for cooking and heating since ancient times. Even as modern agriculture and forestry operations have expanded and become industrialized to meet growing demand, utilizing the by-products directly as fuel remains a cost-efficient solution in many cases. The energy from the waste materials from harvesting and processing can be converted into heat, and subsequently into electricity and process steam as well.

Chapter 2 gives a full account of the different types of waste that are produced. Without proper management, waste can be detrimental to the environment. However, majority of the waste can be converted into useful energy. Below are the different types of waste that can be used as feedstock using different types of energy conversion technologies:[15]

[15] Committee on Climate Change. 2011. *Bioenergy Review*. United Kingdom. https://www.theccc.org.uk/publication/bioenergy-review/.

Food

These are edible crops developed and grown to produce food for humans and animals but can also be used as energy crop. Food crops being used for fuel include sugar cane, corn, wheat, sugar beets, sweet potatoes, sorghum, soya, and palm oil, among others.

Agricultural Residues

Agricultural residues include all wastes coming from crops such as bagasse, rice husk, straw, stem, leaves, shell, stover, peel, and pulp. Significant amounts of these waste materials are left in the fields. Some crops produce multiple types of waste. Rice produces both straw and husks. Coconut produces husk, shell, fronds, and coir dust. Corn stover often remains in the fields when corn is harvested.

The current farming practice is to plow back these residues into the soil, or they are burned, left to decompose, or grazed by cattle. These residues could be processed into liquid fuels or thermo-chemically to produce electricity and heat.[16] This will reduce the air pollution from open burning.

Part of agricultural residues' classification are animal wastes. Large amounts of manure can be collected from cattle farms and piggeries, which can be used as sources of bioenergy. Chicken waste also has high nitrogen content, which makes it ideal for energy production. In the past, waste was recovered and sold as fertilizer or they were simply spread directly to agricultural plots. However, the introduction of tighter environmental controls on odor and water pollution gives opportunity to develop WtE conversion. The most popular method of converting animal wastes to energy is through anaerobic digestion. The process produces biogas that can be used as fuel for cooking, as fuel for internal combustion engines, or for running gas engine to produce electricity. Biogas can also be used for space and water heating.

Forestry, Forest Residues, and Wood Wastes

Woody materials come from existing forests as well as residues generated from wood-related operations such as thinning of plantations, clearing for logging roads, tree pruning, extracting stem wood from pulp and timber, and residues (footnote 16). Also classified as forest residues are the products from thinning in young stands or cutting in older stands for timber or pulp that yield tops and branches usable for biomass energy. Stands damaged by insects or fire are additional sources of biomass.

Wood wastes are residues coming from sawmills, plywood mills, furniture shops, and other craft industries. These residues that include saw dusts, trims, shavings, off-cuts are mostly concentrated at the processing factories. It was estimated that per 1,000 kg of wood processed in the furniture industry, waste generated is almost half, i.e., 45% or 450 kg of wood. Similarly, the same amount of wood processed in a sawmill will generate 52% or 520 kg of waste.

[16] S. Zafar. 2019. Biomass as Renewable Energy Resource. In Popular Biomass Feedstock Archives. BioEnergy Consult. https://www.bioenergyconsult.com/tag/popular-biomass-feedstock/.

Solid Waste

Solid waste includes food waste, MSW, wastewater treatment sludge, and recovered solids from sewage. Sewage usually comes from households and industries. When domestic and industrial sewage as well as runoff from roads and other paved areas are processed at a wastewater treatment facility, a mixture of water and inorganic and organic materials is removed from the wastewater, known as sewage sludge. Sewage sludge is a biomass resource that is comparable to other animal wastes. Through the process of anaerobic digestion, sewage can generate biogas. The remaining sewage sludge can produce more energy through thermal treatment and pyrolysis.

MSW in developing countries is composed mainly of organic materials with high moisture content and a substantial amount of inert waste fractions such as sand or ash. Sorting of municipal waste at source allows for value creation and energy extraction.

Energy Crops

Energy crops[17] are usually not intended for food but being grown as a low-cost and low-maintenance harvest to be used to produce biofuels such as bioethanol or combusted for its energy content to generate electricity or heat. Energy crops can be woody crops such as jatropha, willows, poplars, etc., or grasses such as elephant grass, Napier grass, miscanthus, and switchgrass, among others.

Industrial Wastes

Generally, these are wastes generated by various industries for biomass energy. The food industry produces a significant amount of residues and by-products that can be used as biomass energy sources. Meat production and confectionery industries produce biomass wastes in both solid and liquid form. Solid wastes include peelings and scraps from fruit and vegetables, food that does not meet quality control standards, pulp and fiber from sugar and starch extraction, filter sludges, and coffee grounds. Liquid wastes are composed of wastes generated by washing meat, fruits, and vegetables; cleaning and processing operations; and wine making, among others. As these wastes contain sugars, starches, and other dissolved and solid organic matter, there is a potential for these industrial wastes to produce biogas through anaerobic digestion or fermented to produce ethanol.

The airline industry produces significant amounts of waste from meals, usually plastics and food scraps. The cruise ship industry and large malls have similar waste character.

Pulp and paper industry are one of the most polluting industries. The wastewater it discharges is called black liquor. Black liquor contains compounds from woods or other raw materials, processed chemicals, as well as compound formed during processing. It can be utilized for production of biogas with some success.

17 K. Launder. 2002. *Energy Crops and their Potential Development in Michigan*. Lansing, Michigan: https://www.michigan.gov/documents/CIS_EO_Energy_crop_paper_A-E-9_87916_7.pdf.

Palm oil mill effluent (POME) is another form of industrial waste. It is an acidic, thick brownish liquid discharged from the sterilization, clarification, and separation processes that take place in a palm oil mill.[18] For every ton of fresh fruit bunch of oil palm processed, approximately 0.65 cubic meters (m^3) of POME is generated.[19] A typical palm oil mill uses a biomass power plant, fueled by palm kernel shell and mesocarp fiber, to supply electricity and process steam. This function can be replaced by a biogas plant with POME as input, which allows more of the shell and fiber to be used as boiler fuel. This reduces the amount of fuel oil that needs to be purchased, creating a net economic benefit for the mill.[20]

WASTE-TO-ENERGY CONVERSION TECHNOLOGIES

This section summarizes the available WtE conversion techniques. Eighteen case studies of WtE projects around the world (with a focus on Asian countries) are detailed in the compendium. Based on the feedstock outlined in the previous section, Table 2 summarizes the technologies employed and the outputs or residues from various feedstock options. This table also includes each case study's reference number to the specific technology. Figure 5 outlines WtE conversion technologies that are commercially available.

Table 2: Summary of Waste-to-Energy Technologies, Feedstock, and Outputs and/or Residues

Item	Technology	Feedstock	Outputs/Residues	Reference Case Studies in Compendium
Thermal	Combustion	Mixed residual MSW, RDF, agricultural residues, energy crops, wood residues	Heat, electricity, bottom ash, and fly ash	1 Baku WtE 9 Combined Heat and Power facility 12 CBE – Clean Energy Community
Mechanical-thermal	Mechanical Biological Treatment	Residual MSW, agricultural wastes, industrial wastes, food wastes, wood residues	Biogas, electricity, RDF, compost-like materials	2 Pilot Project WtE with Bio-drying 18 Yitong Distributed WtE Project
	Landfill gas capture	Mixed residual MSW, RDF, agricultural residues, energy crops, wood residues	Biogas, heat, electricity, combined heat and power	

continued on next page

[18] A.S. Rahayu et al. 2015. *POME-to-Biogas Project Development in Indonesia Handbook. Jakarta*: Winrock International. https://www.winrock.org/wp-content/uploads/2016/05/CIRCLE-Handbook-2nd-Edition-EN-25-Aug-2015-MASTER-rev02-final-new02-edited.pdf.

[19] Sarawak Energy. http://www.sarawakenergy.com.my/index.php/r-d/biomass-energy/palm-oil-mill-effluent.

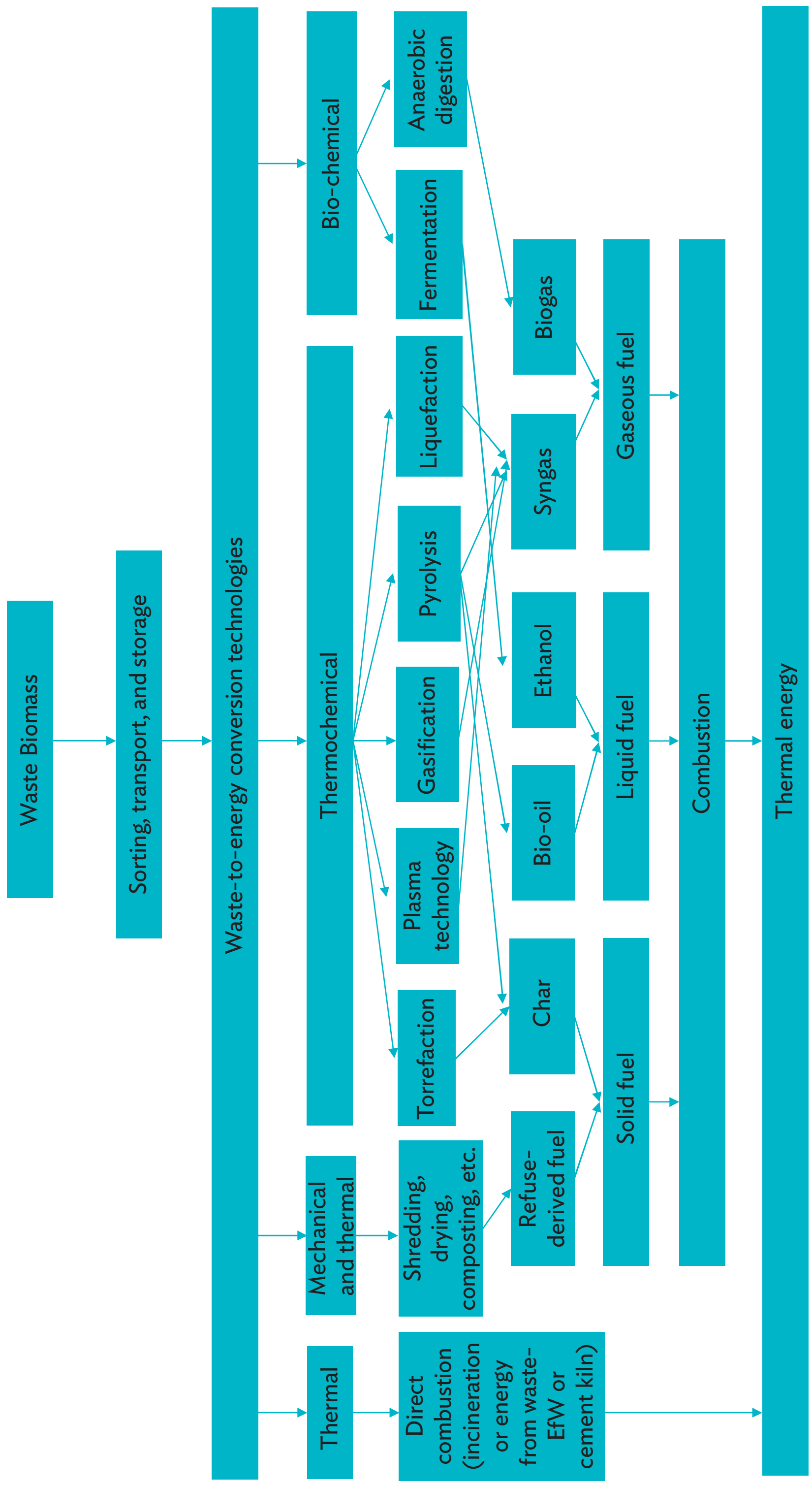
[20] M.J. Chin et al. 2013. Biogas from Palm Oil Mill Effluent (POME): Opportunities and Challenges from Malaysia's Perspective. *Renewable and Sustainable Energy Reviews*. 26 October. pp. 717–726. https://www.sciencedirect.com/science/article/pii/S1364032113003857.

Table 2 *continued*

Item	Technology	Feedstock	Outputs/Residues	Reference Case Studies in Compendium
Thermochemical-chemical	Torrefaction	Agricultural waste, wood waste, energy crop	Char, ash	11 Australian Bio Fert Small-Scale Biological Fertilizer Demonstration and Product
	Gasification	RDF, mixed residual MSW, agricultural wastes, wood wastes, energy crops	Heat, electricity, syngas, bottom ash	5 Ankur's WtE Project 10 150-kilowatt electrical Power Generation in Dual Fuel Mode 13 ID Gasifiers Coconut Shell Fueled Module—Coconut Technology Centre Development
	Pyrolysis	Homogenous feedstock from forestry/wood residues, tires, sorted residual MSW (e.g., plastics), agricultural waste	Syngas, biochar, bio-oil	3 Decentralized Plastic Pyrolysis 4 Plastic-to-Liquid Fuel 18 Yitong Distributed WtE Project
	Liquefaction	Any organic waste	Bio-oil	
Biochemical	Fermentation	Organic waste high in sugar (e.g., corn, beetroot, sugarcane), energy crops	Alcohol (e.g., ethanol), digestate	18 Yitong Distributed WtE Project
	Anaerobic digestion	Agricultural waste, industrial waste, energy crops, food waste	Biogas, heat, electricity, biomethane, digestate, compost	6 High Crest Corporation 8 Carbon Masters Koramangala plant 14 Sumilao Farm Waste to Energy 15 WtE Siang Phong Biogas 16 Kitroongruang Compressed Biomethane Gas Project 17 Rainbarrow Farm Poundbury 18 Yitong Distributed WtE Project

MSW = municipal solid waste, RDF = refuse-derived fuel, WtE = waste to energy.
Source: Author.

Figure 5: Waste Processing Methods



Source: Prescouter. October 2017. https://www.prescouter.com/2017/10/waste-to-energy-technologies-available/ (with some modifications).

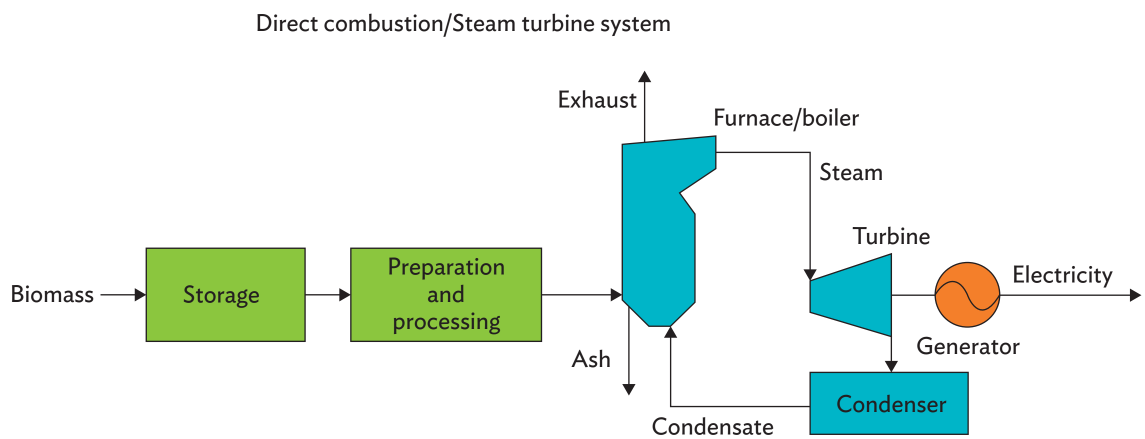
Thermal

Direct Combustion

Direct combustion is the oldest technology for biomass conversion, especially for generating heat and steam. It burns biomass in the presence of oxygen. A biomass combustion facility can produce steam, electricity, or both (combined heat and power [CHP]) through direct firing.[21] The combustion technologies to convert renewable biomass fuels to heat and electricity use similar processes if using fossil fuels. The biomass fuel is burned in a boiler to produce high-pressure steam that flows through a series of turbine blades causing the turbine to rotate. The turbine is connected to an electric generator that produces electricity.[22] The steam can also be used in district heating and cooling systems.[23] Figure 6 shows the direct combustion process schematic.

Co-firing involves the combustion of fossil fuel like coal, or natural gas with biomass feedstock. Co-firing with biomass may be an effective approach to meet the strict regulations on emissions. Biomass can also be used in co-generation or through CHP applications. CHP involves the simultaneous production of heat and electricity. Heat is a by-product of electricity generation; thus, all power plants produce heat but usually it is released to the atmosphere through cooling towers or discharged into bodies of water nearby. In the CHP process, the waste heat is recovered for use in district heating. Co-generation converts about 85% of biomass' potential energy into useful energy.[24] The CHP plant

Figure 6: Direct Combustion Process



Source: Alternative Energy Sources. Biomass Energy - The Definitive Guide. https://alternativeenergysourcesv.com/biomass-energy/.

[21] US Environmental Protection Agency. Combined Heat and Power Partnership. 2007. *Biomass Combined Heat and Power Catalog of Technologies v1.1*. Washington, DC.

[22] International Business Publications, Inc. 2015. *Malaysia Energy Policy, Laws and Regulations Handbook Volume 1* Strategic Information and Basic Laws (*World Business and Investment Library*). Washington, DC.

[23] West African Economic and Monetary Union. 2008. *Sustainable Bioenergy Development in UEMOA Member Countries*. https://www.files.ethz.ch/isn/105943/2008_10_unf_bioenergy_full_report1.pdf.

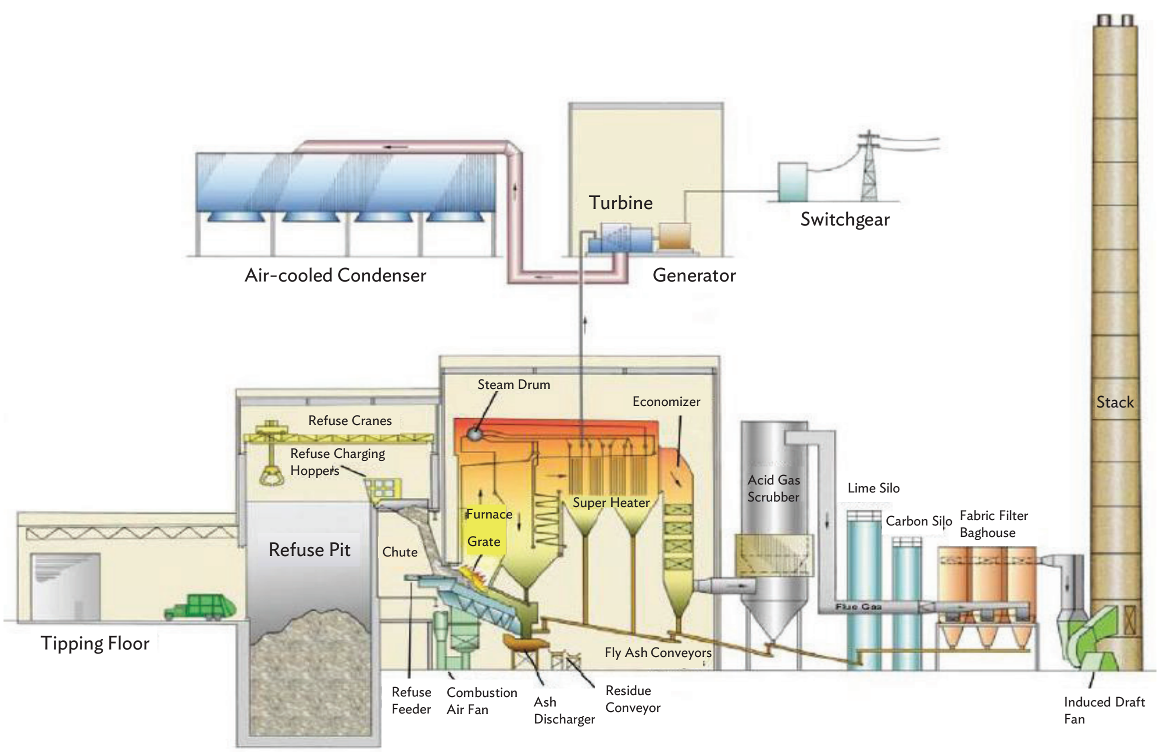
[24] S. Zhang. 2015. *All About Biofuels*. Wixsite.com http://allaboutbiofuels.wixsite.com/biofuels/thermal-conversion.

is highly resource efficient, providing higher levels of energy output per unit of biomass consumed compared to facilities that only generate electricity. For efficiency of operation, most biomass-fired plants are located in the sites that have a steady supply of biomass, e.g., sugarcane mills, rice mills, and paper mills.

One form of direct combustion is often EfW, which is the burning of waste in a controlled process to reduce the volume and mass of MSW to be landfilled, and to render it chemically inert. It also enables recovery of energy, minerals, and metals from the waste stream. EfW is designed to treat typically mixed and largely untreated domestic waste, and certain industrial and commercial wastes. A minimum calorific value of the waste is required to enable a thermal chain reaction and self-supporting combustion with no addition of other fuels. In developing countries, unsorted MSW is often close to this threshold due to a dominant organic content with high moisture, and a significant level of inert waste fractions such as ash or sand. Figure 7 shows the overview of single-stage mass burn EfW plant.

During the EfW process, gases are created, which are coursed through a pipe, or flue. These flue gases contain a mixture of combustible products to produce heat which are converted to steam and then electrical energy. The heat can be used for district heating or cooling or process steam for industry.

Figure 7: Overview of Single-Stage Mass Burn Energy-from-Waste Plant



Source: Stantec Consulting Limited. 2009. Residual Waste Study Environmental Assessment.

Types of Combustion Technologies

Three types of combustion technologies can be applied to burn MSW or RDF. RDF is produced from specific wastes otherwise destined for landfill. It has sufficient net calorific value to supplement or replace a standard fuel in an industrial process.[25] Additional information about RDF is discussed in the succeeding section. The combustion technologies include grate system, fluidized bed, and rotary kiln.

Grate

Grate technologies have two types: moving grate and fixed grate. Moving grate EfW uses grate to move the waste from the combustion chamber for an effective and complete combustion. The MSW for a moving grate EfW does not need to be pre-treated, thus it is easier to process waste with large volume and variations. Most of EfW plants have hydraulic feeders to feed received MSW to the combustion chamber, a boiler to recover the heat, an air pollution control system to clean toxins in the flue gas, and discharge units for the fly ash. The central piece in the process is the air- or water-cooled moving grate, which is made of special alloys to resist high temperature and avoid erosion and corrosion.[26] In the fixed grate system, the waste is being moved by a series of rams. The first step is a drying stage and initial combustion stage, the next phase is where the remaining combustion takes place and the third grate is for final carbon burnout.[27]

Fluidized Bed EfW

Fluidized bed EfW involves the uniform combustion of waste through a bed of sand which behaves as a fluid when heated. This type of EfW can be applied to different type of wastes like MSW, sludge, or waste liquids, and high-calorific wastes like discarded tires or waste plastic. Wastes are treated stably through agitating and shredding effect of fluidizing sand, which enables mixed firing of sludge at very high mixed combustion rates without premixing. In this process, ignition loss of incombustibles is very low and ferrous metal and aluminum can be recovered in an oxidized state (footnote 27).[28] A fluidized bed EfW has two types: bubbling fluidized bed and circulating fluidized bed. The bubbling fluidized bed EfW delivers the materials onto a bed with air blowing from underneath to create a bubbling effect. It allows for more efficient air access to combustible materials. Heat is transferred to a boiler tubes filled with water to run a steam turbine. The circulating fluidized bed is a more efficient combustion design as the circulation of materials reduces operating temperature and generally provides lower nitrous oxides emissions. This uses higher airflow and the flue gas carries out the particles out of the combustion chamber. The solid materials are captured and then circulated back to the bed (footnote 27).

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25 Government of Australia, Environmental Protection Agency. https://www.epa.sa.gov.au/environmental_info/waste_management/solid_waste/refuse_derived_fuel.

26 R. Lew. 2020. Moving Grate Incineration: Preferred WTE Technology. *BioEnergy Consult*. https://www.bioenergyconsult.com/moving-grate-incineration/.

27 Department for Environment Food and Rural Affairs. 2013. Incineration of Municipal Solid Waste. http://www.WtErt.co.uk/content/Defra%20report.pdf.

28 Ebara Environmental Plant Co. Ltd. n.d. Technologies and Products. http://www.eep.ebara.com/en/products/incineration.html.

Rotary Kiln

Rotary kiln is another type of EfW technology that is widely used in municipalities and industries. The system has a two-stage process comprising kiln as the primary combustion chamber and a separate secondary chamber. The rotation moves the waste through the kiln thereby exposing it to heat and oxygen (footnote 27). Rotary kilns require emissions monitoring when using heterogeneous fuels, especially those containing chlorine. Adequate gas cleanup is required for safe operations to meet emissions standards.

Combined (Mechanical and Thermal)

Mechanical Biological Treatment

Mechanical biological treatment (MBT)[29] involves the combination of various processes such as mechanical (e.g., sorting, shredding, milling, separating, or screening) and biological components (drying, composting, or anaerobic digestion) to create solid recovered fuel or RDF and divert organic materials for fertilizer and energy. This fuel can be further processed as pellets or briquettes and can be used as feedstock in energy facilities as replacement to fossil fuels.

MBT has positive environmental impacts such as the improved landfill efficacy due to the positive modification of leachate and landfill gas production and quality. MBT can also recover a larger percentage of recyclables from the mixed waste streams. MBT consists of different treatment processes and has four types of outputs:

(i) RDF – has high calorific value due to high paper and plastic content;
(ii) stabilized organic waste – produced from the biological treatment of the organic portion of the waste;
(iii) ferrous and non-ferrous metals – for potential recycling; and
(iv) inert wastes – scraps/residues that are disposed of in landfills.

Landfill Gas Capture

In the course of operating an engineered or a sanitary landfill, landfill gas, which consists of 35%–55% methane, is generated by the anaerobic digestion of organic matter in the landfill body. To capture the methane generated, a landfill gas recovery plant is installed consisting of extraction system and flaring system.[30]

Extraction System

Gas is extracted from landfills using different components such as vertical perforated pipes, horizontal perforated pipes, and ditches. Membrane is sometimes used to cover the landfill under which the gas produced is collected. The most common method of active gas collection is through vertical perforated pipes that are injected to the waste mass to collect gas while avoiding the entry of air and water into the system.

[29] F. Fe, Z. Wen, and S. Huang. 2018. Mechanical Biological Treatment of Municipal Solid Waste: Energy Efficiency, Environmental Impact and Economic Feasibility Analysis. https://doi.org/10.1016/j.jclepro.2018.01.060.

[30] H. Terraza and H. Willumsen. 2009. Guidance Note on Landfill Gas Capture and Utilization. Technical Notes 108. Inter-American Development Bank. http://www.resol.com.br/textos/guidance_note_on_landfill_gas_capture-idb.pd.

Flaring System

In cases where the use of landfill gas for energy purposes is not economically feasible, the gas has to be flared off. Flaring is done to reduce methane emissions that can affect local air quality and contribute to greenhouse effect. Flaring also reduces odors and the risk of fire and explosion. Flares can be open or enclosed. Usually, open flares do not meet emission standards, but they are inexpensive and simple to operate. The enclosed system consists of a single burner or array of burners in a cylindrical enclosure lined with refractory material. Such construction results in more uniform burning and lower emissions.

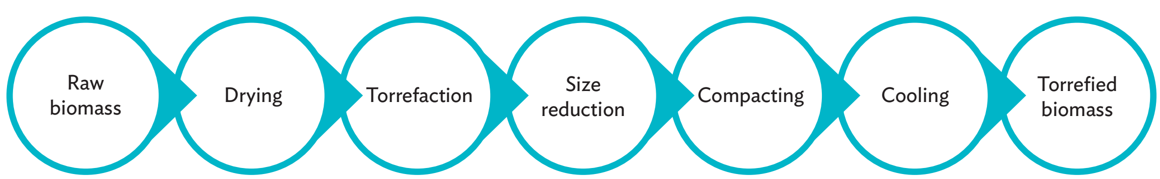
Thermochemical

Compared with fossil fuels, biomass has some limitations that makes it difficult to use on large scale. Raw biomass possesses limitations such as low bulk density, high moisture content, and low calorific value that impacts on logistics and final energy efficiency. Because of its low energy density, large volumes of biomass are needed, making storage, transportation, and handling logistically challenging. The high moisture content of biomass also reduces the efficiency of the process, which increases the fuel production costs. Raw biomass has irregular shapes, which is also an issue especially during feeding and co-firing or gasification system. It has more oxygen than carbon and hydrogen making it less ideal for thermochemical conversion process. To overcome these challenges, raw biomass must be reprocessed to make it suitable for energy applications.

Torrefaction

Torrefaction technology is a thermal pretreatment process that alters the physical and chemical composition of raw biomass.[31] Torrefaction involves the process of heating the biomass to a temperature of between 200°C–400°C in the absence of air. When biomass is heated at the said temperature levels, the moisture evaporates and low-calorific components or volatiles present in the biomass are driven out. During this process the hemicellulose in the biomass decomposes, transforming the biomass from a fibrous low-grade fuel into a product with excellent fuel characteristics. Figure 8 shows a simple torrefaction process.

Figure 8: Simple Flow Diagram of Torrefaction Process



Source: J. S. Tumuluru et al. 2011. A review on biomass torrefaction process and product properties for energy applications. *Industrial Biotechnology*.

[31] J. S. Tumuluru et al. 2011. A Review on Biomass Torrefaction Process and Product Properties for Energy Applications. *Industrial Biotechnology*. https://www.liebertpub.com/doi/pdf/10.1089/ind.2011.7.384; Biomass Technology Group. http://www.btgworld.com/en/rtd/technologies/torrefaction.

The process reduces the biomass weight to about 20%–30% but the energy loss is only 10%–15%. Torrefaction converts biomass into a coal-like substance, which has a better fuel characteristic than the original biomass. Biomass if torrefied is more brittle, making it easier to grind and less energy intensive. Torrefied biomass is not bulky as biological degradation and water uptake is minimized thereby making the storage easier.

The raw biomass once torrefied becomes a high-grade biofuel that can be used as a replacement of coal in electricity and as input for gasification processes.

Gasification

Gasification is the conversion of the carbon in organic waste into a synthetic gas (syngas) comprising largely of carbon monoxide and hydrogen with the help of air or steam at 800°C–1,000°C. Syngas can subsequently be burned to produce heat energy. Gasification takes place through partial oxidation by controlling absence or very low amounts of oxygen.[32]

Reaction Zones

Producing gas from biomass consists of the following zones that occur inside a biomass gasifier: (i) drying, (ii) pyrolysis, (iii) combustion, and (iv) reduction.

The drying process involves the removal of surface water through filtration, evaporation, or a combination of both. Waste is typically used to do the evaporation. Pyrolysis is essentially the process of charring. The char is reacted with steam or burned in a restricted quantity of air or oxygen to produce further combustible gas. During the pyrolysis stage, biomass rapidly decomposes with heat once the temperature reaches above around 240°C. The biomass breaks down into solid, liquid, and gas. The solid component is commonly called charcoal while the combination of gas and liquid that are released are collectively called tars. The breaking down of large molecules such as tar into lighter gases through exposure to heat is called cracking. The process is vital in the production of clean gas that is compatible with an internal combustion engine as tar gases formed into sticky tar that will clog the valves of an engine. Cracking is also critical to ensure proper combustion. Complete combustion only occurs when combustible gases are thoroughly mixed with oxygen. The next stage is reduction or removal of oxygen from waste products at high temperature to produce combustible gases. All the heat that drives drying, pyrolysis, and reduction comes either directly from combustion or is recovered indirectly from combustion by heat exchange processes in a gasifier. Tar gases or char from pyrolysis can serve as fuel during combustion.

[32] Alternative Fuels from Biomass Sources. https://www.e-education.psu.edu/egee439/node/607; BioEnergy Consult. Biomass Gasification Process.https://www.bioenergyconsult.com/biomass-gasification/; All Power Labs. Gasification as incomplete combustion. http://www.allpowerlabs.com/gasification-explained; N. Nwokolo, S. Mamphweli, and G. Makaka. 2017. Analytical and Thermal Evaluation of Carbon Particles Recovered at the Cyclone of a Downdraft Biomass Gasification System. Sustainability. p.645; Food and Agriculture Organization of the United Nations (FAO). 1986. Wood Gas as Engine Fuel. FAO Forestry Department. http://www.fao.org/docrep/t0512e/T0512e0a.htm.

Types of Gasifier

Downdraft

A downdraft gasifier has an advantage as it produces gas with a relatively low tar content. The primary gasification air is introduced at or above the oxidation zone of the gasifier. The syngas is removed at the bottom of the gasifier so the fuel and gas move in the same direction. On the way down, the acid and tarry distillation products from the fuel must pass through a glowing bed of charcoal and are converted into permanent gases: hydrogen, carbon dioxide, carbon monoxide, and methane. Depending on the temperature of the hot zone and length of stay of the tarry vapor, a complete breakdown of the tars is achieved. Thus, this design has an advantage of low tar production, which makes it suitable for engine applications. The downdraft gasifier has positive features such as low power requirements, short start up period, and quicker response time. However, the design is more complex and its major drawback is its inability to operate on unprocessed fuels giving rise to flow problems and excessive pressure drop. The feedstock must be pelletized or briquetted before use.

Updraft

In updraft gasifier, air enters at the bottom and the gas stays on the top. The combustion reaction occurs at the bottom, which is followed by reductions reaction. Heating and pyrolysis of the feedstock occur as a result of heat transfer by forced conventional and radiation from lower zones. The resulting combustible producer gas is rich in hydrocarbons (tars) and, therefore, has a higher calorific value, which makes updraft gasifiers more suitable where heat is required such as in industrial furnaces. If it is used for electricity generation, the producer gas needs to be thoroughly cleaned. The tars and volatiles produced during the gasification process will be carried in the gas stream. Ashes are removed from the bottom of the gasifier.

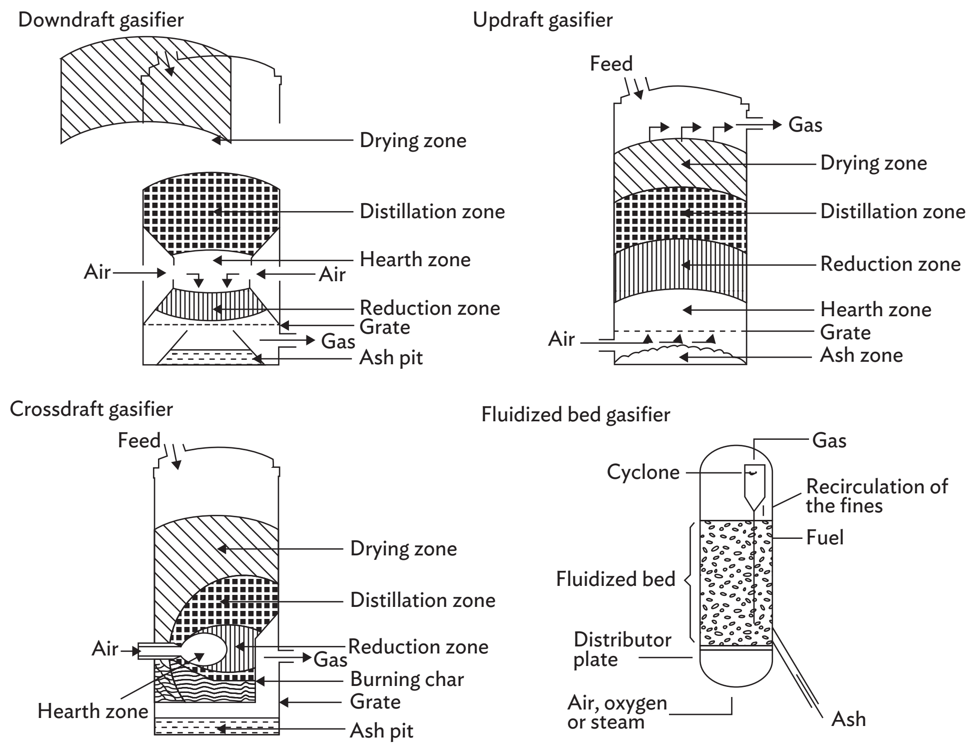
Cross Draft

In a cross-draft gasifier, air enters from one side of the gasifier reactor and leaves from the other. Grate is no longer needed as the ash falls to the bottom and this does not affect normal operation. The cross-draft gasifier design is also complex and cannot use high-mineral-containing fuels. One advantage of this type of gasifier is its size. The system is small-scale at which installations below 10 kilowatts (kW) can still be economically feasible. This is due to the very simple gas cleaning train consisting only of a cyclone and a hot filter, which can be easily coupled with small engines. One disadvantage, however, is its minimal tar-converting capabilities and the need for high quality (low volatile content) charcoal.

Fluidized Bed

In a fluidized bed gasifier, the biomass is sent into an inert bed of fluidized material, e g., sand, and char. The designed process is similar to boiling of water except the air (and other gas) pass through the fines, e.g., sand, forming bubbles as in boiling water. The design allows for feedstock flexibility resulting in better temperature control and the ability to deal with fine grain material (e.g., sawdust) without need of pre-processing. These features of the fluidized bed gasifier present some drawbacks, which include higher capital costs, higher power requirements, and high tar content of the producer gas. The different types of gasifiers are illustrated in Figure 9.

Figure 9: Schematic Diagrams of Different Types of Gasifiers



Source: Food and Agriculture Organization of the United Nations (FAO) Forestry Department. FAO 1986. Wood gas as engine fuel. http://www.fao.org/docrep/t0512e/T0512e0a.htm.

Plasma Gasifier

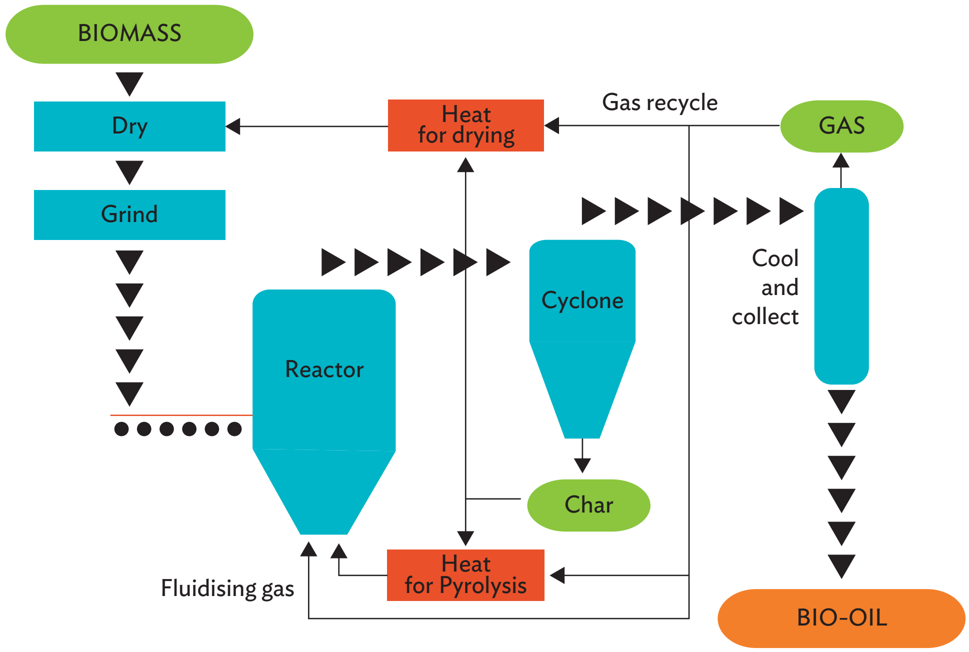
Plasma gasifier uses extremely high temperatures, around 2,000°C–5,000°C to break down waste material into small molecules and atoms to form a syngas, which is primarily made of hydrogen and carbon monoxide. A plasma torch powered by an electric arc is used to ionize gas and catalyze organic matter into syngas with the remaining slag as the by-product. Plasma gasification is used commercially as a form of waste treatment, e.g., for MSW and medical and hazardous waste.

Pyrolysis

Pyrolysis is a thermochemical process conducted at a temperature between 400°C–600°C in the absence of air. As there is no oxygen present, the organic material does not combust but chemical compounds such as cellulose, hemicellulose, and lignin decompose into combustible gases and charcoal. Depending on factors such as temperature, pressure, and heating rate; pyrolysis produces three products—solid, liquid, and gas in the form of biochar, bio-oil, and syngas (Figure 10).[33]

[33] Student Energy. Pyrolysis. https://www.studentenergy.org/topics/pyrolysis; Biochar for Carbon Capture. Slow and Fast Pyrolisis. http://biocharforcarboncapture.com/research/fast-and-slow-pyrolisis; BioEnergy Consult. Biomass Pyrolysis Process. https://www.bioenergyconsult.com/tag/pyrolyzer/; AZO Cleantech. What is Pyrolysis? https://www.azocleantech.com/article.aspx?ArticleID=336.

Figure 10: Biomass Pyrolysis Cycle



Source: Bioenergy Consult. 2018. Biomass Pyrolysis Process. https://www.bioenergyconsult.com/tag/pyrolyzer/.

Pyrolysis Methods

The variation in the composition of solid, liquid, and gas products from pyrolysis depends on the methods that will be employed. Pyrolytic reactions are categorized into three types: (i)) slow pyrolysis, (ii) fast pyrolysis, and (iii) ultra-fast/flash pyrolysis.

Slow pyrolysis modifies solid material while minimizing the oil produced. Slow pyrolysis is conducted at low to moderate temperatures (around 300°C) at long reaction times (up to days). The technology has been used for thousand years particularly for conversion of wood into charcoal. The main product of this process is biochar. Biochar can be used as soil conditioner and for carbon sequestration.

Fast pyrolysis involves a rapid thermal decomposition of carbon-based materials in moderate to high heating rates. The major product is bio-oil comprising about 30%–60% of the total output. Bio-oil can be used as low-grade diesel oil. Other products produced from fast pyrolysis are syngas constituting 15%–35% and biochar which is about 10%–15%. Syngas is comprised of carbon monoxide, hydrogen, methane, carbon dioxide, and light hydrocarbons.

Ultra-fast or flash pyrolysis involves the rapid heating of biomass at temperature up to 1,000°C at a short reaction time. The major product is syngas (about 60%–80%). Syngas can be used as replacement for natural gas or converted with catalysts to ethanol. Liquid condensate represents 10%–20% of the yield while the biochar is around 10%–15%.

Pyrolysis presents several benefits. It is a simple technology for processing a variety of feedstock. The products of the pyrolysis such as biochar, bio-oil, and syngas have the potential to reduce the country's dependence on imported energy resources and harnessing locally available resources. Pyrolysis can also be done in small scale and thus can be applicable even in remote locations where biomass resource is available thereby reducing transport and handling costs.

To some extent pyrolysis does have higher costs associated costs and its viability mainly depend on the price of biomass. The quality of bio-oil is also low grade and typically requires further refining to be substituted for fossil fuel-powered applications.

Liquefaction

Hydrothermal liquefaction[34] is a thermochemical conversion process to convert organic material into liquid bio-crude and co-products. Liquefaction occurs at a moderate temperature from 300°C to 400°C with added reducing agent, usually hydrogen or carbon monoxide. Biomass is relatively wet and is thus processed through hydrothermal processing which involves the heating of aqueous slurries. Bio-oil is produced through hydrothermal liquefaction. During this process, long carbon chain molecules are thermally cracked and oxygen is removed through dehydration or decarboxylation. These reactions produce high hydrogen/carbon ratio bio-oil.

The conversion of biomass to bio-oil is influenced by factors such as temperature and heating rate, solvent, pressure, feedstock composition, residence time, and catalysts. While any biomass can be converted to bio-oil through hydrothermal liquefaction, the amount of bio-oil yield and quality are dependent in the organic components in the feedstock, (i.e., cellulose, hemicellulose, protein, and lignin). Temperature plays a major role in the conversion process. Temperatures higher than the ideal can cause higher char formation and finally increased gas formation whereas temperatures lower than the ideal can reduce depolymerization and bio-oil yields. Hydrothermal liquefaction is a fast process. Residence times, which are measured in minutes (15–60 minutes) are dependent on a number of reaction conditions such as temperature, feedstock, and solvent ratio. Water acts as a catalyst in the reaction, but in order to optimize the conversion, other catalysts can also be used in the reaction vessel.

Production of biofuels through hydrothermal liquefaction has an advantage as no net carbon emissions are produced.

BioChemical

Fermentation

Fermentation is an anaerobic process that breaks down the glucose within organic materials. Through a series of chemical reactions, sugar is converted to alcohol or acid. Yeast or bacteria are added to the biomass material, which are fed on the sugar to produce ethanol and carbon dioxide.[35] Corn and sugarcane are the most common agricultural wastes that are purposely grown for industrial ethanol production; however, some advanced processes are under development, which use lignocellulosic waste materials (e.g., corn stover, sugarcane bagasse, straw, and saw mill and paper mill discards) as

[34] e-Education Institute. Direction Liquefaction of Biomass. https://www.e-education.psu.edu/egee439/node/676.
[35] European Biomass Industry Association. Fermentation. https://www.eubia.org/cms/wiki-biomass/fermentation/.

feedstocks.[36] Bioethanol has to undergo distillation process to achieve the required purity so it can be used as transport fuel. The residue from the fermentation process can be used as animal feed while bagasse (the residues from sugarcane) can be used as fuel for boilers.

India, the People's Republic of China (PRC), and Thailand are among the world's major ethanol producers, and primarily make use of corn, wheat, cassava, and molasses as feedstock. Process water is introduced during the liquefaction of the feedstock, and then extracted as a by-product of the distillation and dehydration of the ethanol. This water can serve as an input to a biogas reactor and then recycled. The resulting biogas is commonly combusted to heat the boiler in the liquefaction stage.

Anaerobic Digestion

Anaerobic digestion is a process of decomposing organic wastes in an oxygen-free environment to produce biogas. Fermentation is one step in the anaerobic digestion process, and biogas plants make use of either wet or dry fermentation.[37] In wet fermentation, which is more common, a liquid biomass slurry (i.e., with a water concentration of 85% or greater) is held within the reactor for anaerobic digestion to progress over a period of several weeks. For organic inputs to become suitable for wet fermentation, it may need to be pre-treated, and/or liquid may be added for it. In addition, the feedstock in the reactor may need to be mechanically circulated for microorganisms to come into contact with the organic matter, and/or heated in order for it to be a tolerable environment for the bacteria. The biogas is usually collected in the upper section of the same tank. Wet fermentation is generally a continuous process wherein organic matter is added to and removed from the holding tank.

Dry fermentation is a batch biogas production process in which organic matter with moisture levels at 50%–80% is piled into an airtight chamber and a fluid referred to as percolate is sprayed on top. The percolate enables fermentation as it flows down through the pile.[38] Biogas created in the chamber is captured and usually stored in a separate container; the percolate is drained at the bottom of the pile and recycled. After several weeks, biogas production decreases, and the organic material is replaced with a new batch to repeat the process.

Aside from the type of fermentation, biogas plants also vary widely in terms of capacity and complexity. Different systems utilize different kinds of bacteria and so must support tolerable temperature conditions for these bacteria. The carbon-nitrogen ratio of the primary feedstock may not be optimal for biogas production, so other readily available organic matter may need to be added to create a balance.[39] The treatment of the resulting biogas, particularly the scrubbing of toxic and corrosive hydrogen sulfide, must also be considered. Biogas can be upgraded to biomethane with higher methane content of up to 98% and can be used as an alternative for natural gas.

For the creation of biogas from agri-industrial wastewater and similar by-products or effluents, the most common practice is to dig a lagoon or pond (according to appropriate design standards) that is lined with impermeable material such as high-density polyethylene. This is then covered by a similarly

[36] European Technology and Innovation Platform (ETIP). *Biofuel Fact Sheet: Ethanol*. European Biofuels Technology Platform.

[37] BioFerm Energy Systems. Dry Fermentation vs. Wet Fermentation https://uwosh.edu/biogas/wp-content/uploads/sites/63/2015/11/dry-fermentation-process.pdf.

[38] T. Fischer and A. Krieg. 2001. About Dry Fermentation in Agriculture. *Biogas Journal*. 1: Mai 2001. S. 12–16. https://www.kriegfischer.de/fileadmin/public/docs/texte/KF_2001_FvB_Dry_fermentation_English.pdf.

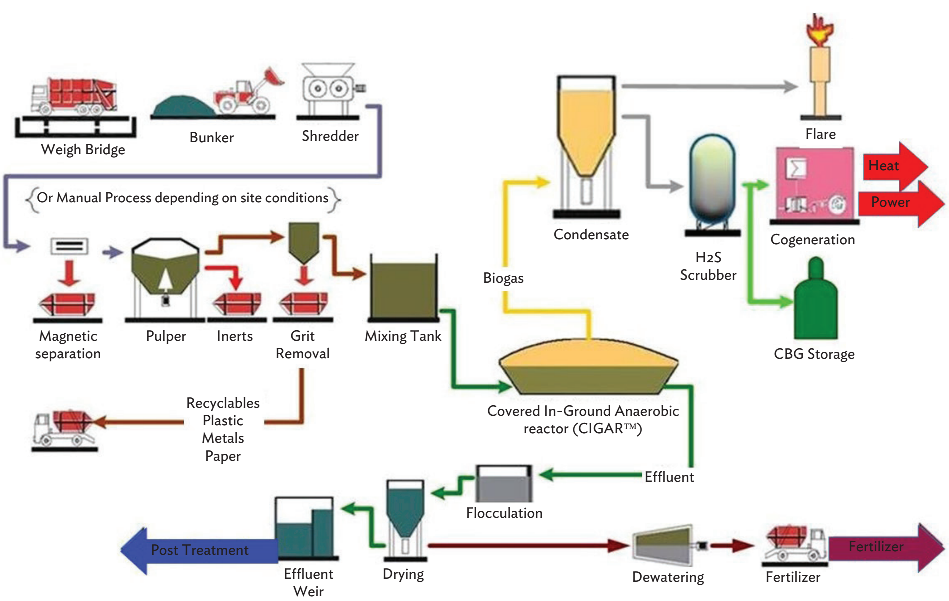
[39] E. Neczaj, A. Grosser, and M. Worwag. 2013. Boosting Production of Methane from Sewage Sludge by Addition of Grease Trap Sludge. *Environ. Protect. Eng*. 39: pp. 125–133. http://epe.pwr.wroc.pl/2013/2-2013/Neczaj_2-2013.pdf.

impermeable material and a gas-tight seal is created. Wastewater is pumped into this reactor to undergo anaerobic digestion. This design is commonly known as the covered-in-ground anaerobic reactor (CIGAR) and various other names (Figure 11).

Power quality and heating fuel supply reliability in rural areas are often issues in agri-industrial processing. Using biogas-based power on-site to help address these issues may lead to more reliable operations and more consistent demand for raw materials. This creates a "virtuous cycle" with co-benefits for local stakeholders. Large-scale projects that capture biogas from such effluents are also able to profit from schemes to reduce greenhouse gas (GHG) emissions, since minimum regulatory requirements for such effluents like settling ponds would otherwise result in the methane and carbon dioxide (CO_2) being released into the atmosphere.

Biogas has two feed methods: batch and continuous. Batch-type digester is easy to construct. The organic materials are loaded to the digester allowing it to digest. The retention time depends mainly on temperature and available carbon. When digestion is complete, the effluent is removed and the same process is repeated. The batch plant is labor intensive and a major disadvantage is the gas output is not steady.[40] Meanwhile, continuous digester is fed and emptied continuously. The material moves through the digester by the force of the new feed pushing out the digested material. In the continuous-fed digester, gas production is constant and higher than the batch type.[41]

Figure 11: CIGAR-Type Biogas Technology



CBG = compressed biogas, CIGAR = covered-in-ground anaerobic reactor, H_2S = hydrogen sulfide.
Source: Asian Development Bank internal training material.

40 energypedia. Types of Biogas Digesters and Plants. https://energypedia.info/wiki/Types_of_Biogas_Digesters_and_Plants.
41 B. T. Nijaguna. 2006. Biogas Technology. page 59. http://www.worldcat.org/oclc/1117143573.

Classifications of Anaerobic Digester

Anaerobic digester systems[42] have several classifications as presented in Table 3:

Table 3: Classification of Biogas Digester

Classification	Types	Characteristics	Advantages	Disadvantages
Temperature	Mesophilic	Operates at temperatures of 25°C–45°C	More stable operation Less maintenance required	Lower biogas production rate Does not reduce the pathogen concentrations enough to produce Class A biosolids
	Thermophilic	Requires higher temperatures of 50°C–60°C	Faster biogas production per unit of feedstock and m^3 digester Effective at clearing the digestate of pathogens	High costs Require more management than mesophilic ones
Feedstock	Wet Hydrophilic	Feedstock composition is lower than 20% total solids (maximum)	Requires lower investments and maintenance costs Greater flexibility in the materials to be treated	Need to add liquid to reduce the dry matter of the mixture Requires robust and costly mixing equipment Significant energy requirements to run pumps and agitators
	Dry Dry Fermenters	Feedstock composition is from 20%–40% total solids	Cheaper to operate More gas production per unit of feedstock Low power and heat requirements Very tolerant system for contaminants Less maintenance required	Need to manage the variation of biogas and heat production The microbial process has to start for each batch Lower methane yields
Feed	Batch	Biogas plants are filled and emptied completely after a fixed retention time	Simple to build	Requires high labor input Gas output is not steady
	Continuous	The digester is fed and emptied continuously	Costs are lower Give more biogas per unit of input Gas production is constant	Raw material needs to be diluted first

continued on next page

[42] Energypedia. Types of Biogas Digester and Plants. https://energypedia.info/wiki/Types_of_Biogas_Digesters_and_Plants; *eXtension Foundation. March 2019. Introduction of biogas and anaerobic digestion*. https://farm-energy.extension.org/introductionto-biogas-and-anaerobic-digestion/; The Eco Ambassador. Anaerobic Digestion - Mesophilic Vs. Thermophilic. https://www.theecoambassador.com/Anaerobic-Digestion-Temperature.html; Biogas World. State-of-the-art dry and wet anaerobic digestion systems for solid waste. https://www.biogasworld.com/news/drywet-anaerobic-digestion-systems/.

Table 3 *continued*

Classification	Types	Characteristics	Advantages	Disadvantages
Design	Vertical	Feedstock is fed on one side while digestate overflows through a pipe on the other side	Cheaper and simple to operate	Feedstock may not reside in the digester for optimum period resulting in possible economic losses
	Horizontal	More solid feedstock is used as a plug that flows through a horizontal digester at the rate it is fed-in	Feedstock do not leave the digester too early or stay inside the digester for an uneconomically long period	Expensive to build and operate

Sources: eXtension Foundation April 2019. Introduction of biogas and anaerobic digestion. https://farm-energy.extension.org/introduction-to-biogas-and-anaerobic-digestion/ s; Biogas Technology. https://www.worldcat.org/title/biogas-technology/oclc/1117143573; 3; The Eco Ambassador. Anaerobic Digestion – Mesophilic vs Thermophilic. https://www.theecoambassador.com/Anaerobic-Digestion-Temperature.html; Biogas World. State of the Art Dry and Wet Anaerobic Digestion Systems for Solid Waste. https://www.biogasworld.com/news/dry-wet-anaerobic-digestion-systems/.

OUTPUTS

Energy Outputs

Heat

Biomass can produce heat to provide energy for space heating, hot water, and process heating/steam. Direct combustion is the most common method of producing heat from biomass using different feedstock such as agricultural wastes, MSW, wood and forest residues, among others. Biomass heating system can be used in different scale from kW to megawatt (MW) capacities. The major markets for biomass heating are district heating systems and process heat applications for industries where biomass is produced such as sawmills, rice mills, sugar mills, alcohol plants, furniture manufacturing, and drying sites for agricultural processes. These industries usually require heat all throughout the year; thus, the use of biomass for heating can lead to substantial savings on fuel costs.[43]

Power

Biomass-based power system is an efficient substitute for fossil fuels to generate electricity. There are several ways to produce electricity from biomass. These processes include direct combustion, gasification, anaerobic digestion, and pyrolysis. Different feedstock varieties can also be used similar for heating purposes as discussed in the previous section. The capacity is also wide from kW to MW level of power generation.

[43] Energy Alternatives India. Biomass to Heat. http://www.eai.in/ref/ae/bio/heat/biomass_heat.html.

Combined Heat and Power

Biomass-fueled CHP or co-generation is one of the cost-effective methods of energy recovery. The heat that is a by-product during electricity generation is not wasted but utilized as thermal energy. The efficiency of such system ranges from 60%–80%. The feedstock used for CHP include energy crops, forest residues or wood waste, agricultural waste, food processing residues, and MSW.[44]

Transportation Fuel and Additives

Biofuels are seen as one of the most feasible options for reducing carbon emissions in the transport sector, along with improvements in fuel efficiency and electrification of the light vehicle fleet. For heavy-duty vehicles, marine vessels, and airplanes, in particular, biofuels will play an increasing role to reduce CO_2 emissions since electric vehicles and fuel cells are not feasible for these transport modes.

Biomass provides various options for manufacturing substitutes for both gasoline and diesel fuel. Some of these, such as the production of ethanol as a gasoline replacement, or processed vegetable oils (biodiesel) as a diesel fuel replacement, are well known; others, such as the gasification of biomass to produce either hydrogen for fuel cell vehicles, or synthetic hydrocarbons for conventional vehicles, are more speculative.

As climate change mitigation and air pollution reduction efforts have intensified, so have questions of the sustainability of first-generation biofuels (e.g., corn-based ethanol) meant to address these challenges. Research and development on second-generation transportation fuels from various biomass sources, including agricultural waste and MSW, have resulted in a variety of additives or substitutes to gasoline or diesel in various stages of development.

Hydrogen

Hydrogen is used in industrial applications and as a transportation fuel in fuel cells. The global demand for hydrogen has been increasing with methane reforming from natural gas as the primary source of hydrogen production, accounting for 75% of the annual global hydrogen production.[45] Hydrogen can also be produced by additional processing of methane in biogas or syngas- renewable hydrogen.

Dimethyl Ether

Dimethyl ether (DME) can be used in diesel engines and gas turbines with simple modifications. At present, a common method of producing DME is gasifying biomass, such as low-value woody by-products of agriculture (e.g., oil palm empty fruit bunch [EFB]) and forestry operations, RDF from MSW, or a by-product of paper and pulp manufacturing called black liquor—to produce syngas, which is then catalytically converted into methanol, and finally catalytically dehydrated into DME.[46]

44 Penn State, Department of Energy and Mineral Engineering. Bio-mass Fueled Combined Heat and Power Systems. https://www.e-education.psu.edu/eme807/node/714.

45 International Energy Agency (IEA). 2019. *The Future of Hydrogen*. https://www.iea.org/hydrogen2019/.

46 A. Inayat et al. 2017. Parametric Study for Production of Dimethyl Ether (DME) As a Fuel from Palm Wastes. Energy Procedia. 105(May). pp. 1242–1249 https://www.sciencedirect.com/science/article/pii/S187661021730472; European Biofuels Technology Platform. 2016. Biofuel Fact Sheet: Dimethyl Ether. http://www.etipbioenergy.eu/images/AllBiofuelFactsheets2016.pdf.

Alternatively, anaerobic digestion of agri-industrial, livestock**,** or municipal wastes will produce biogas (50%–75% methane) which is cleaned, then catalyzed into methanol through various means, and then into DME.[47]

Ethanol and Methanol

Ethanol, or ethyl alcohol, is a common additive or substitute for gasoline, which can be produced by fermenting feedstock containing sugar or starch that can be converted into sugar. While corn and sugarcane are the most common biomass sources purpose-grown for industrial ethanol production, some advanced processes are under development, which use lignocellulosic waste materials (e.g., corn stover, sugarcane bagasse, straw, and sawmill and paper mill discards) as feedstock.[48]

Methanol, or methyl alcohol, is a gasoline additive and convertible to DME, aside from being used in the production of formaldehyde and acetic acid. As described above, methanol is primarily produced through catalytic conversion of syngas (which may be formed by gasifying woody biomass), or methane (which may be formed by anaerobic digestion of organic matter).[49]

Fatty Acid Methyl Esters

Biodiesel, which is blended into conventional diesel in several countries, comprises a mixture of fatty acid methyl esters (FAME). It may be produced from oil seeds including oil palm, and also from waste cooking oil, through a process called transesterification. FAME can be produced in a small-scale, decentralized manner as transesterification is relatively simple.[50]

Bio-Butanol

Butanol, or butyl alcohol, is a gasoline additive similar to ethanol; the term bio-butanol refers to butanol made from biomass. While bio-butanol output is less than ethanol for the same amount of purpose-grown feedstock (e.g., corn),[51] recent research has presented options to effectively recover butanol from food waste, treated organic fraction of municipal solid waste, and sugar bagasse via fermentation using specific types of bacteria.[52]

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47 Q. You. 2009. Synthesis of dimethyl ether from methane mediated by HBr. Journal of Natural Gas Chemistry. 18(3). pp. 306–311. https://www.sciencedirect.com/science/article/pii/S100399530860122X; A. Chumaidi, D. Moentamaria, and A. Murdani. 2017. Mechanism Reaction of Methane-Methanol-Dimethyl Ether (DME)With Catalyst CuO-ZnO/y-Al2O3. International Journal of Engineering Research and Development. 13(10). pp. 50–55. http://www.ijerd.com/paper/vol13-issue10/Version-.

48 European Biofuels Technology Platform. 2016. Biofuel Fact Sheet: Ethanol. http://www.etipbioenergy.eu/images/AllBiofuelFactsheets2016.pdf.

49 European Biofuels Technology Platform. 2016. Biofuel Fact Sheet: Methanol. http://www.etipbioenergy.eu/images/AllBiofuelFactsheets2016.pdf.

50 European Biofuels Technology Platform. 2016. Biofuel Fact Sheet: Fatty Acid Methyl Esters (FAME). http://www.etipbioenergy.eu/images/AllBiofuelFactsheets2016.pdf.

51 US Department of Energy. Biobutanol. https://afdc.energy.gov/fuels/emerging_biobutanol.html.

52 H. T. Kennedy. 2018. Biofuels Digest. Greener, cheaper technique for biofuel production from mushroom crop residue. Florida; Wageningen University and Research. From Municipal Solid Waste to Butanol and Hydrogen. https://www.wur.nl/en/project/From-municipal-solid-waste-to-butanol-and-hydrogen.htm.

Syngas

Synthetic gas or syngas is produced through gasification and pyrolysis. Syngas is a mixture of carbon monoxide, methane, and hydrogen that can be used to run turbine for the generation of electricity. It also has the potential to replace natural gas or it can be converted into biofuel.

Biogas

Biogas is a mixture of gases, typically composed of 50%–75% methane, 25%–45% carbon dioxide, and traces of other gases.[53] A biogas plant facilitates the anaerobic digestion of organic inputs like municipal and industrial waste and agricultural and agri-industrial by-products in an airtight holding tank or reactor. The resulting biogas is burned to produce heat, which is converted into electrical energy or used for other purposes, like cooking in small-scale systems.

Compressed Natural Gas

Compressed natural gas (CNG) is methane stored in gaseous form in high-pressure tanks and used as a substitute for automotive fuels. India, Indonesia, Pakistan, the PRC, Thailand, and Uzbekistan have significant numbers of vehicles utilizing CNG. One source of CNG is biogas from anaerobic digestion of agri-industrial waste or landfill gas, which has been upgraded for this purpose by removal of impurities, which is also termed biomethane.[54]

Biochar

Biochar refers to charcoal created from pyrolysis and torrefaction of biomass that is added to soil. Biochar lowers the overall acidity of the soil as it is inherently alkaline. It also increases water and nutrient retention due to its high porosity, thus helping boost agricultural productivity. It is highly efficient at binding atmospheric CO_2. It can be used as fuel but is best as a high-surface area scaffold for microbes to fix nutrients into soils.

Bio-oil

Bio-oil is a product of pyrolysis particularly through fast pyrolysis, which involves a rapid thermal decomposition of carbon-based materials in moderate to high heating rates. Bio-oil can be used as low-grade diesel oil and as feedstock for chemical production. Compared with fossil fuels, the use of bio-oil provides some environmental advantages.

Non-Energy Outputs

Bio-fertilizer

When applied as fertilizer, the residual slurry from livestock manure-based biogas generation has been observed to produce a more pronounced short-term soil conditioning effect as compared to undigested manure, as nitrogen and other nutrients are more readily available. Using sludge has also been shown to contribute to high formation rates of stable humus, earthworm activity, and reduction

53 S. Jose and B. Thallada. 2015. *Biomass and Biofuels: Advanced Biorefineries for Sustainable Production and Distribution:* Boca Raton.

54 Clarke Energy. *Biomethane Production*. https://www.clarke-energy.com/biomethane/.

of nitrogen loss. However, while most vegetable crops and many types of fruit appear to react favorably to sludge fertilization, the fertilizing effect is plant-specific and dependent on the climate and type of soil. All bio-fertilizers must be tested for contamination in production process.

Digestate

Digestate is composed of indigestible material and dead microorganisms that are left out after the process of anaerobic digestion. It is a nutrient-rich substance and can be used as fertilizer. Although it has similar characteristics, digestate is not compost. Digestate can be used directly to the soil but another option is to separate the liquid and fiber components which have differing distributions of nutrients. The liquor can be spread easily to crops while separated fiber can be used as soil conditioner.[55]

Alcohol

The alcohol produced after fermenting the biomass is called bioethanol. Feedstock for the fermentation process include crops that are high in sugar like sugarcane, potato, beetroot, and corn. The sugars present in these crops are fermented by strains of yeast to produce bioethanol. The use of ethanol as an alternative fuel is one of the solutions to reduce emissions of greenhouse gases; however, the major obstacle at present is the high cost of production.

Ash

Ash is produced from the combustion of biomass that constitutes about 5%–15% of biomass processed. Ash utilization is limited by the presence of heavy metals and other inorganic compounds, which are formed as a result of the thermochemical reactions that the biomass undergoes when combusted. Ash can be used in different applications depending on the feedstock used.

Bottom ash can be used as agricultural fertilizers, as an additive in construction materials, or as a neutralizing and liming agent, where the feedstock is organic and homogeneous.

Fly ash from MSW combustion requires strict handling and disposal procedures. It can contain the dioxin family of compounds that are classed as likely carcinogenic. They are classed as persistent organic pollutants under the Stockholm Convention.[56]

Municipal waste fly ash has been used as road base or construction products where the allowable concentration of heavy metals and persistent organic pollutants (such as dioxins) has been proved by testing. Where the testing shows unsatisfactory levels, the fly ash must be disposed of in a hazardous waste landfill.

Research and testing are being undertaken by ADB in relation to the safe inoculation of fly ash from MSW feedstocks. ADB is investigating methods to reduce chlorine-containing materials entering

[55] The Official Information Portal on Anaerobic Digestion. Digestate. http://www.biogas-info.co.uk/about/digestate /.

[56] UN Environment Programme Stockholm Convention. The Convention Overview. http://www.pops.int/TheConvention/Overview/tabid/3351/Default.aspx#:~:text=The%20Stockholm%20Convention%20on%20Persistent%20Organic%20Pollutants%20is%20a%20global,and%20have%20harmful%20impacts%20on.

combustion zones, increase residence and other burning zone techniques, inoculation using chemical technologies, and methods to concentrate fly ash for vitrification.

Fly ash from homogenous processes may contain significant levels of silica. The use of this fly ash requires testing, which will determine its application.

Co-Benefits

WtE technologies undergo detailed technical and economic feasibility studies. On the economic feasibility analysis, cost or revenue related to the waste source and value of the product in terms of avoided cost or sales price are generally well defined. However, there are other tangible environmental benefits that should be quantified and qualified.

Air Pollutants Reduction

Globally, uncontrolled trash burning accounts for 29% of anthropogenic emissions of tiny particulate matters, 10% of mercury emissions, and 40% of polycyclic aromatic hydrocarbons.[57] Air pollution, specifically the particulate matters, is associated with a broad spectrum of acute and chronic illness and death. The World Health Organization reports that in 2016, ambient air pollution was responsible for 4.2 million deaths—16% of lung cancer deaths, 25% of chronic obstructive pulmonary disease deaths, about 17% of ischemic heart disease and stroke, and about 26% of respiratory infection deaths.[58] Methane emitted from landfills without gas capturing can also erupt into fire, such as the multiweek burning in Yangon, Myanmar in 2018.[59] To increase landfill capacity, it is sometimes common to burn solid waste in landfills. These fires also generate similar health risks. Improved waste management processes and modern WtE technologies can eliminate these emissions through properly destructing and immobilizing the toxic chemicals.

Based on the WtE technology and pathways, nonrecyclable plastic waste, such as single-use plastic bags and straws, can be turned into a low-sulfur transportation fuel to substitute for diesel or gasoline. In addition to being renewable, there is also significantly less air emissions. This type of projects should be weighed against increasing awareness and policy being developed to eliminate single-use plastic products from entering the consumer market. Emissions testing of the proposed technology should be undertaken to confirm that no toxic emissions are created in the process.

57 C. Wiedinmyer, R.J. Yokelson, and B.K. Gullett. 2014. Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants from Open Burning of Domestic Waste. *Environmental Science and Technology*. 48(16). pp. 9523–9530.

58 World Health Organization (WHO). Global Health Observatory data. https://www.who.int/gho/phe/outdoor_air_pollution/en/.

59 J. Goldberg. 2018. Yangon's two-week landfill fire raises burning questions for authorities. *The Guardian*. 17 May. https://www.theguardian.com/cities/2018/may/17/yangon-two-week-landfill-fire-raises-burning-questions-for-authorities-myanmar.

Greenhouse Gas Emissions Reductions, Carbon Market, and Sustainable Development Goals

The United States (US) Environmental Protection Agency (EPA) estimated that MSW, separating out recyclable materials, is net-negative in GHG emissions when compared to landfilling. The additional savings was estimated at 1 tonne of carbon dioxide equivalent (tCO_{2e}) per tonne of MSW combusted.[60] As per the Intergovernmental Panel for Climate Change special report (2019), human activities have already been estimated to cause approximately 1.0°C of global warming above pre-industrial levels. To maintain a global warming of 1.5°C by 2100, emission reductions through net-negative technologies must be deployed beyond net-zero emissions technologies.

While economists agree that putting a price on carbon is the most effective GHG emissions reduction policy, few countries outside of Europe and North America are committed to the carbon tax or the emission trading schemes.[61] The Republic of Korea, Kazakhstan, and select cities in the PRC have emission trading schemes covering large industrial sectors, and Japan and Singapore have legislated carbon tax. Several economies, including Indonesia; the PRC; Taipei,China; Thailand; and Viet Nam are scheduled or under consideration to implement carbon-pricing policies. WtE plants can benefit from the carbon policies and may also be recognized as a source of GHG credits under the Clean Development Mechanism and other carbon offset programs.

Figure 12: United Nations Sustainable Development Goals

Source: United Nations Department of Economic and Social Affairs website.

[60] K. Maize. 2016. Power Magazine. Energy from Waste: Greenhouse Gas Winner or Pollution Loser? https://www.powermag.com/energy-waste-greenhouse-gas-winner-pollution-loser/?pagenum=1. >

[61] World Bank. The World Bank Carbon Pricing Dashboard. https://carbonpricingdashboard.worldbank.org/map_data.

WtE technologies and pathways in the context of circular economy principles address a number of SDGs, including good health and well-being, clean water and sanitation, affordable and clean energy, industry, innovation and infrastructure, sustainable cities and communities, responsible consumption and production, climate action, life below water, and life on land.

Demand Response and Peaking Power Plants

Demand response refers to the change in utility end user's energy consumption to better match with utility power supply.[62] Typically, there is a price signal that motivates the customers to act. In a traditional centralized power generation and distribution model, baseload power plants include large hydroelectric, coal, nuclear, and bioenergy. During peak power time, peaking plants such as those powered by natural gas are turned on to meet the additional power requirements. The price of peaking power is high and the grid is under stress. In developed nations, peak power time is well understood and the cost of electricity is set high by the utility or the market. Customers change their electricity consumption behavior—a demand response—or have to pay more. Sometimes the demand response programs have additional financial benefits to motivate the customers to act. However, in developing nations, there is an increase in distributed power generation and a rapid growth of solar and wind power to the supply mix. This makes the local grid more difficult to manage and more difficult to design demand response programs.

One alternative is to incorporate WtE technologies as additional baseload power generation or peaking power plant to stabilize the grid. As a baseload facility, WtE plants can work in sync with other renewable power and energy storage technologies in a distributed or centralized grid. More importantly, biogas is the sole dispatchable renewable energy and can be used as a fuel source to peaking power plants. Additional purification of biogas to biomethane will have even wider applications, directly replacing methane and transported via pipelines for peaking power plants.

For example, Taipei,China, one of the most successful Asian economies in addressing MSW as an energy resource, incorporates the circular economy principles. Twenty-four WtE facilities have been built over the last 2 decades with an installed capacity of approximately 560 MW, generating 1.24% of the total baseload power in 2017 from more than 6.2 million tonnes of waste.[63]

Reducing Trash to Sea

Researchers at the University of Oxford published in 2018 say that annually, there are 31.9 million tonnes of mismanaged coastal plastic waste and 8 million tonnes (25% of mismanaged coastal plastic waste) will end up in the ocean.[64] More critically, 70% of the 8 million tonnes of plastic to the ocean is from Asia, particularly East Asia and the Pacific Island nations. Improving waste management in developing nations and considering WtE technologies are part of the solution to improve ocean health and reduce ocean plastics.

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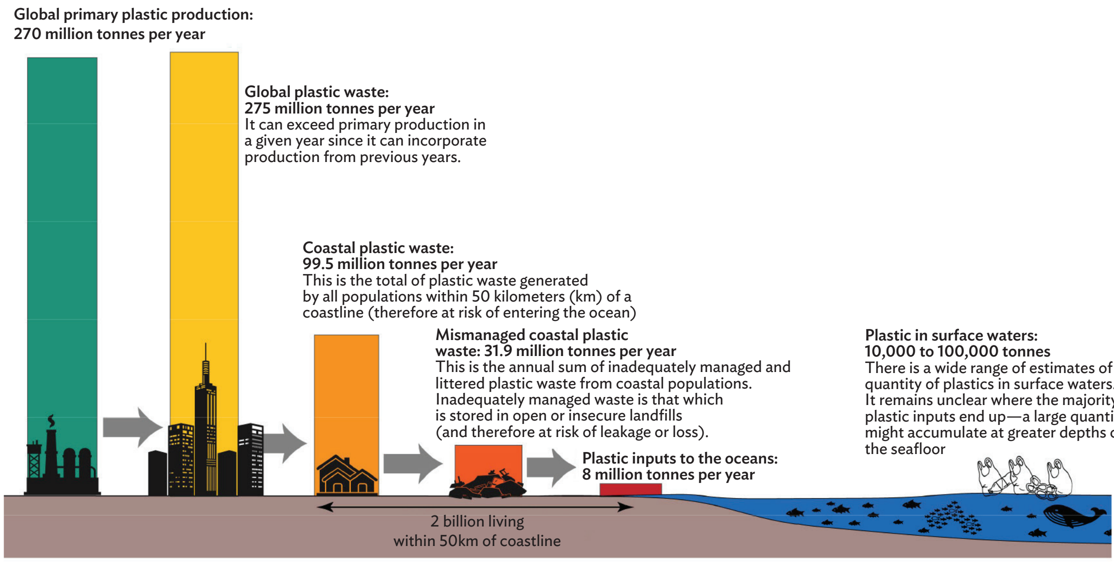
62 M. H. Albadi and E. F. El-Saadany. 2007. *Demand Response in Electricity Markets: An Overview*. 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, 2007, pp. 1-5. https://www.researchgate.net/publication/224716630_Demand_Response_in_Electricity_Markets_An_Overview

63 Team Finland. 2019. Energy Policy Shift and Its Future Aspects. *Future Watch–Strategy Brief*. 26 February.

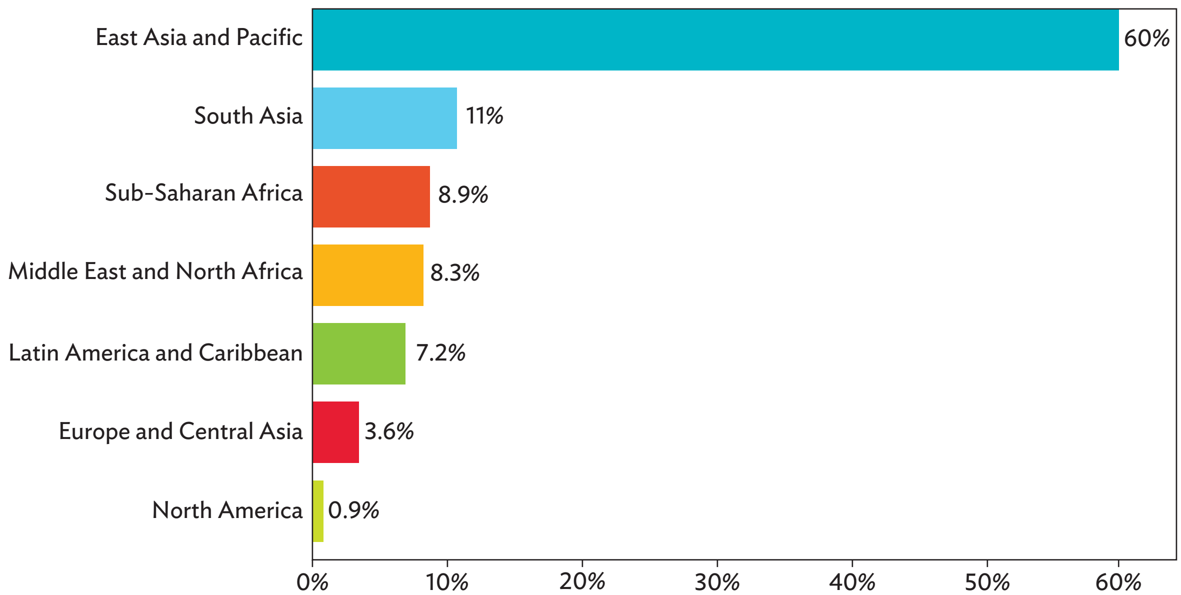
64 H. Ritchie and M. Roser. 2018. *Plastic Pollution*. https://ourworldindata.org/plastic-pollution.

Figure 13: Plastic Pollution Entering the World's Oceans



Source: Our World in Data.

Figure 14: Plastics Mismanagement by Region



Source: Our World in Data based on Jambeck et. al. (2015).

4 WASTE-TO-ENERGY PLANNING AND STRATEGIES

Each WtE strategy is unique to the project and must be developed with consideration to current and future waste characterization, impact on the local grid, local and regional economy, industrial and other activities with synergy, circular economy principles, and co-benefits of the waste feed or products. In addition, the technology and the consumer needs can change over time. For example, recent global efforts on the reduction of single-use plastics and excessive consumer product packaging and labeling can impact the waste stream in developing and developed nations alike.

This section outlines a process to develop a WtE strategy for MSW.

PLANNING AND DEVELOPMENT PATHWAYS

Before characterizing and securing the waste stream, it is important to consider the ultimate objectives of a WtE project—is it primarily to tap into the energy and co-benefits, to reduce environmental impacts, to free up land, or is it the only option left to deal with waste? Ultimately, waste needs to be incorporated in the circular economy to reduce global environmental footprint.

Often, large municipal WtE projects (over 500 tons of waste per day) are assessed in a stand-alone manner. Projections for increase in population and increases in waste generation due to increasing affluence are often used to justify infrastructure sizing. The impact on areas adjoining the proposed facility are often not considered. This is especially so if there is competition for feedstock, as in the case of a cement kiln seeking RDF.

A number of developing nations are reconsidering the incentivization of EfW plants through electrical power production subsidies. Much of the waste in these countries is organic and wet. Paying people to boil water in the organics does not make much sense. Having a more nuanced model where easily extracted wastes are treated in a more energy-efficient and sustainable manner is required.

However, the fact remains that waste has an end of life. Exactly what that amount is on an ongoing basis is the biggest question facing investors in WtE plants.

Currently, infrastructure for plastics recyclers, food to biogas, and other specialty recycling technologies are not well established in ADB DMCs. ADB is committed to support the development of these industries and infrastructure to reduce end-of-life quantities of waste. The development of these industries will accelerate over the next decade as well as changes in collection techniques, notably digitization.

In planning infrastructure, it would be prudent to offset the increases in waste generation due to population growth and affluence against the reduction in packaging and the rise of recycling and upcycling technology driven by consumer demand for sustainability.

The net change waste in the environment daily is equivalent to the amount of waste generated daily or at a wider provincial level:

(i) Minus the amount processed to usable products;
(ii) Minus the amount recycled or upcycled from daily waste stream including items collected in supply chain from source;
(iii) Minus the amount processed into EfW plants;
(iv) Plus, the ash and other materials sent to landfill daily.

The argument that end-of-life solutions encourage increase consumer production is misleading. It denies the negative impact of landfills and does nothing to address the inherent environmental cost of products. Consumers will seek the lowest cost and highest utility. The reason consumers will choose products that are poor environmental choices (i.e., single-use plastics) is that the environmental costs are not included in the price of the goods.

Twelve Pathways

One approach is to evaluate the specific problem statement and align with one or more of the following 12 pathways. These 12 pathways provide policy and technical routes to a more circular economy.

Pathway 1: End-of-Life—Waste Destruction (Provincial)

The end-of-life quantity is a reflection of how circular the waste economy actually is functioning. The end-of-life quantity in any region is defined as the daily amount processed in EfW plants plus the amount of waste mined daily from landfills or clean up and sent to EfW plants.

The total amount of end-of-life waste should ideally be 30% or less of the daily mass of MSW generated, where there is no landfill mining or clean up quantity. Where there is significant landfill clean to undertake, this threshold can be increased to closer to 60% of daily mass of MSW. On many emerging WtE projects, the average end-of-life waste within defined catchments is being proposed at 55%–100% of daily waste generation. This is not sustainable in the long term. Consideration for the circular economy is neglected in favor of a magic bullet solution of overcapacity. Experiences in more developed Asian countries have shown how this overcapacity distorts the market for waste and crowds out the smaller circular economy businesses in recycling. The reality is that both can co-exist providing complementary solutions to our waste problems. Taipei,China is a good example where several old incinerators were shut and lower capacity EfW plants installed.

At this stage of the waste life cycle, grate-based EfW plants with advanced gas cleanup are the most reliable solution for municipal waste. The creation of toxic by-products can be reduced to far below that of open burning or landfill fires, and captured. The captured materials can be inoculated and stored in safe condition. The fly ash from gas clean up requires specific attention as it is a hazardous waste. Bottom ash is generally less hazardous but still requires testing.

Pathway 2: End-of-Life Residues (Immobilization)

The safe handling and storage of the fly ash is mandatory for any WtE plant. Fly ash may contain heavy metals, dioxins, furans, and other highly materials. As a hazardous waste, it must be stored in a hazardous waste landfill, immobilized chemically (using scrubbing, chelation, or geopolymers), or vitrified (locked in a ceramic lattice).

Pathway 3: Centralized Sorting—Eco-Industrial Park Model

Siting an end-of-life facility in a larger industrial park allows for sharing of energy and heat from the process, but also allows for processes to extract higher value or to recover waste into usable products.

Eco-industrial park models being promoted in the PRC have the circular economy at their core, by law. Keeping resources in play for as long as possible and maximizing the value creation from their use is balanced against the environmental and social implications of new business models.

Pathway 4: Centralized Recycling and Upcycling

Siting these value addition and material recovery technologies with an eco-industrial park leads to simpler environmental management. It also allows for tracking of materials and sharing with industry involved in recycling and upcycling.

Pathway 5: Decentralized Sorting and Upcycling

Cities will have existing material recovery facilities and transfer stations as part of their existing waste supply chain. These sites are excellent locations to add recovery or localized solutions to reduce waste quantities for subsequent transport to centralized locations.

Pathway 6: Digitization at Source

Various apps existing for collection of waste include household truck collection, centralized community collection, and opportunistic collection of higher-value items by the informal sector. The capture of higher-value materials at source creates more secure feedstocks for decentralized recycling and upcycling technologies. The informal sector can be matched to householders and businesses using apps. The degree of digitization will reduce transport costs for cities and increase participation and efficiency of the circular economy. It does need to be well regulated.

Pathway 7: Landfill, Soil and River Cleanup

Most landfills in developing countries are not sanitary or engineered. Over the coming decade, these landfills will be mined and remediated to limit groundwater pollution. Digitization of this cleanup will allow for more efficient not-for-profit interventions through direct payment of landfill miners.

There are millions of tons of waste dumped across Asia. Much of this waste is in highly unsanitary conditions and subject to fires. These fires create highly toxic pollutants that end up in the water table, streams, rivers, and the oceans. Increasingly, communities are demanding the removal of waste from these sites. While some can be recycled, much needs to be sent to an end-of-life solution.

Planners should consider adding the landfill mined quantity to projects within 10 years of the start of operations. The character of this mined waste should also be considered in design.

Pathway 8: Regional Eco-Industrial Parks

The eco-industrial park model can be expanded to support the small island developing states and archipelagic states with extended marine or river supply chains. Creating economy of scale for recycling and upcycling of higher values items can work hand-in-hand with the destruction of harmful waste that cannot be treated in country.

Pathway 9: Digitized Extended Producer Responsibility Schemes

The success of extended producer responsibility (EPR) schemes is based on their ability to add the embedded waste management cost to materials prior to sale of product. These costs collected by EPR funds should reflect the impact of a product. This will affect consumer buying patterns. These funds cover the cost of the government underwriting environmental management and should be revenue positive.

A good example of where the EPR scheme has been addressed is in Taipei,China where the local EPA has an EPR fund for all products entering the island or made there. The fund received $2 billion in 2017, paid for the environmental cleanup including end of life and returned $400 million as revenue to the government. This EPR scheme is being studied by many countries.

By creating value through the digitized tracking, collection, trading, recycling, and end-of-life of materials, these EPR schemes can allocate the costs to encourage good environmental choices and maximize the value of waste supply chains. The EPR schemes will have an impact on the sizing and profitability of WtE projects.

Cities that have provided 100% capacity for EfW struggle to allow any circular economy growth. In a fully developed circular economy model with landfill mining and clean up, a ceiling of 45% of daily capacity is likely. This percentage may be higher for smaller cities or where there are governance issues related to financing projects.

Pathway 10: Strengthening Recycled Output Supply Chains

The challenge for many recyclers is that they are unable to sell their recycled product. Creation of supply chains, price discovery, product quality verification, and buyer identification are required to support recyclers and upcyclers.

Pathway 11: Supporting Fast-Moving Consumer Goods in Product Redesign—Recycled %

Large consumer goods manufacturers (or fast-moving consumer goods [FMCG] companies) are aware that the days of single-use plastics are numbered. Creating recognition and support for these groups in product redesign is crucial as FMCG companies have such a large impact.

An emerging issue with governments, nongovernment organizations, FMCG companies, and communities is the impact of single-use plastics and packaging waste. This issue has rapidly become mainstream. Community-based businesses spring up, which disrupt historic high-consumption models. This will have a marked impact on the long-term character of the waste.

Pathway 12: Strengthening Governance and Enforcement

The above pathways need consistent direction in policy and also strong enforcement. Strengthening enforcement capacity is a critical.

Implementing a circular economy requires changes in the whole supply chain. These changes will affect the size of infrastructure in the medium term. Understanding this change is a critical requirement for infrastructure planners and investors.

Table 4 summarizes the 12 pathways to create best practice in handling of MSW through the circular economy and broader waste management perspectives. They should be considered at the beginning of the planning process. Wherever appropriate, project examples in the compendium is referenced in various pathways in the table.

Table 4: Waste-to-Energy Pathways and Example Projects (Referencing the Compendium)

#	Pathway	Description of Critically Important Issues	Example Projects In Compendium
1	End-of-life - waste destruction (Provincial)	Building the infrastructure to deal with waste when it can no longer be recycled, reused, or upcycled, its “end of life.”	• 1 Baku WtE Plant • 12 CBE – Clean Energy Community
2	End-of-life residues (Immobilization)	Seeking long-term solutions for the end products from advanced waste-to-energy plants in pathway one.	• 1 Baku WtE Plant
3	Centralized sorting – eco-industrial park model	Clustering recycling, upcycling (value creation) and by-product users around end-of-life facilities to increase the amount of waste treated and create more value from sorted higher-value items—a mix of industrial symbiosis with the circular economy.	• 18 Yitong Distributed WtE Project
4	Centralized recycling and upcycling	Promoting the recyclers, upcyclers, and re-users at both large centralized facilities and distributed locations closer to the point-of-waste generation.	• 2 Pilot Project WtE with Bio-Drying • 18 Yitong Distributed WtE Project
5	Decentralized sorting and upcycling	Cities will have existing material recovery facilities and transfer stations as part of their existing waste supply chain. These sites are excellent locations to add recovery or localized solutions to reduce waste quantities for subsequent transport to centralized locations.	• 2 Pilot Project WtE with Bio-Drying • 3 Decentralized Plastic Pyrolysis • 4 Plastic-to-Liquid Fuel • 5 Ankur’s WtE Project • 6 High Crest Corporation

continued on next page

Table 4 *continued*

#	Pathway	Description of Critically Important Issues	Example Projects In Compendium
			• 7 Decentralized Waste Management Model • 8 Carbon Masters Koramangala Plant • 9 Combined Heat and Power Facility • 10 150-kilowatt electrical Power Generation in Dual Fuel Mode • 11 Australian Bio Fert Small-Scale Biological Fertilizer Demonstration and Product • 13 ID Gasifiers Coconut Shell Fueled Module—Coconut Technology Centre Development • 14 Sumilao Farm WtE • 15 WtE Siang Phong Biogas • 16 Kitroongruang Compressed Biomethane Gas Project • 17 Rainbarrow Farm Poundbury • 18 Yitong Distributed WtE Project
6	Digitization at source	"Uberizing" the collection, trading, tracking, and treatment of waste by extending secondhand trading to waste—valorizing low-value waste.	• 7 Decentralized Waste Management Model
7	Landfill, soil, and river cleanup	Supporting apps, which can be used to link willing donors for cleanup with actual proven cleanup activities.	• 18 Yitong Distributed WtE Project
8	Regional eco-industrial parks	The eco-industrial park model can be expanded from pathway 3 to small island developing states and green ports.	• 7 Decentralized Waste Management Model
9	Digitized extended producer responsibility schemes	Costing the impact of products as introduced into an economy, charging extended producer responsibility fee at manufacture or import and tracking via app from pathway 6.	• 7 Decentralized Waste Management Model • 18 Yitong Distributed WtE Project
10	Strengthening recycled output supply chains	Supporting innovation in post collection to upcycled product supply chain—innovative recyclers, logistics models, and technology.	• 2 Pilot Project WtE with Bio-drying • 11 Australian Bio Fert Small-Scale Biological Fertilizer Demonstration and Product • 16 Kitroongruang Compressed Biomethane Gas Project • 18 Yitong Distributed WtE Project
11	Supporting fast-moving consumer goods companies in product redesign—recycled %	Assisting product manufacturers to understand the impact of pathway 9 and supporting transitions to lower-impact products.	
12	Strengthening governance and enforcement	Supporting the ability of governments to enforce environmental legislation—creation of avoid-cost model to support pathway 9.	

WtE = waste to energy.
Source: Asian Development Bank internal training material.

WASTE CHARACTERIZATION STUDY

The most important element of any WtE activity is the waste. A waste characterization study (WACS) is needed to understand the current and future state of waste. The WACS answers questions which include but are not limited to the following:

(i) How much waste is there?
(ii) How is it disbursed and collected?
(iii) What is its character?
  a. How wet is the waste?
  b. Is it volatile?
  c. Does it produce dangerous emissions prior to treatment/processing?
(iv) Does this character change within the year and will it change next 5, 10, or 15 years?
(v) Does the quantity change within the year and will it change next 5, 10, or 15 years?
(vi) Is it homogenous or does it vary over a single day?
(vii) How much of it is segregated at source?
(viii) How much is removed along the collection supply chain?

Waste Catchment

Planning a WACS requires an understanding of where the waste is. For large municipal waste or biomass projects, it is necessary to map the locations where waste is generated and see how it is collected. This is sometimes referred to as a waste catchment. For municipal waste projects, the waste character will vary depending on the socioeconomic status of the residents in the area. Less fortunate residents in rural areas of low-income countries may produce as little as 200 grams of waste per day per person. People living in towns in low-income countries can produce between 400 grams to 850 grams per day per person. Extra caution should be observed when using average figures from reports relating to waste generation. A stand-alone understanding of the particular waste catchment is necessary.

Sampling

Sampling of the waste needs to be done to capture different parts of the waste catchment. The number of samples is determined by the following equation for heterogenous waste streams.

It is important to note the dominant waste stream will change depending on the process considered. For instance, for municipal WtE plants employing EfW, plastics would be the dominant waste stream. However, if mechanical and biological treatment is being considered, then organic waste will be the dominant sampling method.

To determine a reasonable representative sample of the waste, sampling should be carried out over a 1-week continuous period (7 days total) at the same site, preferably an existing landfill site. Similarly, to obtain a total representative sample from MSW delivered to the landfill site, random trucks from different districts and/or sub-municipalities should be selected. The form for recording these samples should be standardized with additional information about the waste load, its origins, and the journey of the truck. This data will also be used to track any samples sent for testing at the laboratory. If there is a significant change over seasons, sampling should be repeated in any different seasons to develop a reliable yearly result.

It is important to determine the number of samples tested to produce a reliable result. Waste in ADB DMCs has differing character, being usually more organic and wetter with more contaminants. The American Society for Testing and Materials (ASTM) method for sampling is based on the US waste stream and there has been some academic argument about the use of the method in developing countries. However, it is a useful guide to practitioners seeking to find the right number of samples to take.

Under ASTM D5231-92, Section 9, a calculation to determine the number of samples and vehicle loads to be tested per day to determine either a 90% or 95% confidence limit, based on mean and standard deviation of waste characterization studies undertaken at various sites within the US. With food waste as the governing component, at a 90% confidence level, then a total number of 26 composition analysis samples will be required.

Based on ASTM D5231-92, the number of sorting samples (vehicle loads [n] required to achieve a desired level of measurement precision is a function of the component [s] under consideration and the confidence level). The governing equation for n is as follows:

$$n = (t^*x/e-x)^2$$

where

- t^* = student t statistic corresponding to the desired level of confidence,
- s = estimated standard deviation (from Table 4 of ASTM D5231-92),
- e = desired level of precision; and
- x = estimated mean

As an example, the two highest components of the waste streams, food waste (and putrescibles) and plastics, are used.

Table 5: Example of Waste Sample Needed to Meet Confidence Limit

Waste	s	X	Precision (e)	t* (n=inf)	no	t*90% (Table 4)	n’	n’ within 10% of no?	n
Plastic - ALL	0.0481	0.1553	0.1	1.645	26	1.708	28	Yes	28
Food waste	0.1457	0.4819	0.1	1.645	25	1.711	27	Yes	27
Putrescibles	0.1388	0.5215	0.1	1.645	19	1.734	21	Yes	21

Source: Asian Development Bank internal training material.

To achieve a 90% confidence level, with a precision of 10% desired, 28, 27, and 21 samples needed to be tested for plastics (all), food waste, and putrescibles, respectively.

Laboratory Testing

For municipal waste projects over 500 tonnes per day of waste, developers typically investment $200,000–$300,000 in WACS including catchment studies, sampling, physio-chemical testing, and analysis.

The physio-chemical testing includes, but is not limited to, calorific value (HHV/LHV), moisture content, heavy metals, ratios of carbon, hydrogen, oxygen, nitrogen and sulfur, and other elements. Various standards exist for specific waste testing and should be used depending on the project location.

For homogenous waste streams like biomass and carbon-rich factory effluents, sufficient samples to model the changes over a standard weekly production schedule are required. These samples may include biological methane potential (or similar tests), chemical oxygen demand, biological oxygen demand, and other related physio-chemical properties.

Table 6: Waste Characterization Standards

Test	Standard or Similar
Moisture content	ASTM E 790- Standard test method for residual moisture in a refuse-derived fuel analysis sample
Bulk density	ASTM E 1109– Standard test method for determining the bulk density of solid waste fractions
Characterization plastic, fabric, paper, wood, leave, rubber, food, glass, stone, metal, electronic, hazardous, others	ASTM D 5231 - Standard test method for determination of the composition of unprocessed municipal solid waste
Ash content	ASTM E 830 – Standard test method for ash in the analysis sample of refuse-derived fuel
HHV, gross calorific value	ASTM E 711 – Standard test for gross calorific value of refuse-derived fuel by the bomb calorimeter, also calculation
LHV, net calorific value	Calculation
Chlorine content	ASTM E 776 – Standard test method for forms of chlorine in refuse-derived fuel
Sulfur content	ASTM E 775 – Standard test methods for total sulfur in the analysis sample of refuse-derived fuel
Elemental analysis, CHONS	CHN (CHN Analyzer), S (ASTM E 775,B), standard test method for forms of chlorine in refuse-derived fuel
Heavy metal content, As,Cd,Cr,Cu,Mn,Ni,Pb,Zn	EPA 3050B – Acid digestion of sediments, sludges and soils ASTM E 885 – Standard test methods for analyses of metals in refuse-derived fuel by atomic absorption spectroscopy EPA 5050 – Bomb preparation method for solid waste
Biomethane potential	Alternative Assay Test can be useful also

ASTM = American Society for Testing and Materials, Cd= cadmium, CHONS = carbon, hydrogen, oxygen, nitrogen, and sulfur, Cu = copper, EPA = US Environmental Protection Agency, HHV = high heating value, LHV = lower heating value, Mn = manganese, Ni = nickel, Pb = lead, Zn = zinc.

Source: Asian Development Bank internal training material.

Securing the Waste Stream

The next and the most important step is to secure access and control of the waste stream. Without a waste stream, there is no project. When using public–private partnership (PPP) agreement, it is essential to have well-defined conditions of control. For more information on PPP route, please refer to the ADB Working Paper Series Creating an Enabling Environment for Public–Private Partnerships in Waste-to-Energy Projects.[65] In parasitic power projects at factories, a hosting agreement with full access to waste is more appropriate.

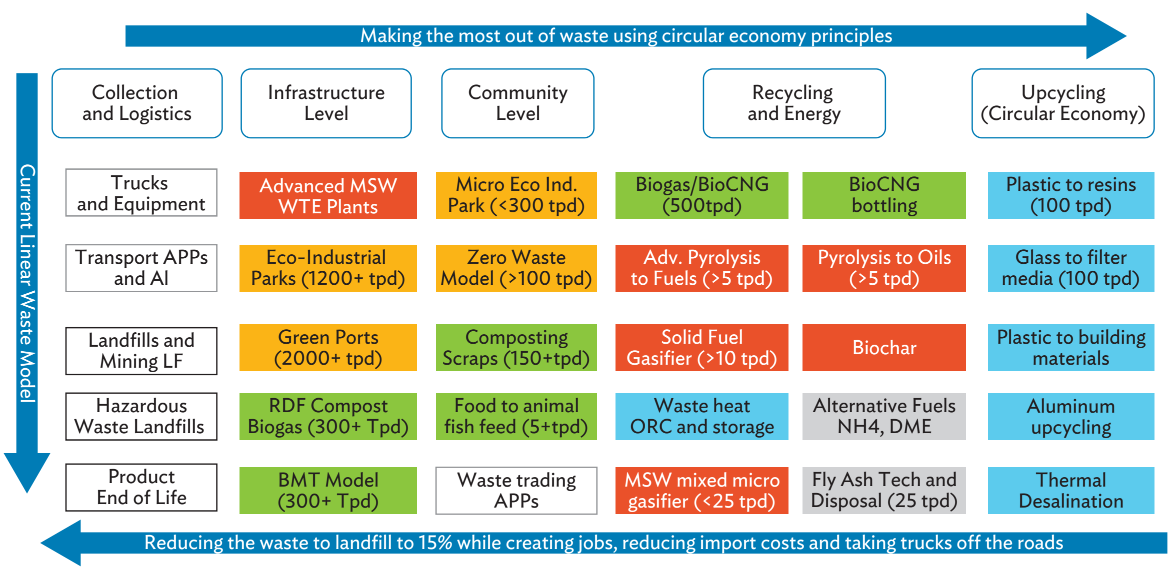
Build-own-operate-and-transfer is a commonly sought model in waste projects. This approach works well in large infrastructure projects that are well defined. This places a great deal of risk on the operator. This is not appropriate in smaller contracts as the counter party or host may not be able to meet their obligations.

Technology Choice

Making Sense of the Choices

To simplify the assessment of commercially viable technical choices and how they interact with the supply chain, the various technologies have been represented as follows:

Figure 15: Municipal Solid Waste Supply Chain and Technologies



AI = artificial intelligence, APP = application, BioCNG = compressed biomethane, BMT = biological mechanical treatment, DME = dimethyl ether, LF = landfill, MSW = municipal solid waste, ORC = organic rankine cycle, RDF = refused-derived fuel, WtE = waste to energy, tpd = tonnes per day.

Note: Red = thermal processes; Green = biological processes; Light blue = recycling/upcycling technologies; White = business-as-usual processes (including trucks and landfills); Grey = emerging technologies; Orange = operating models.

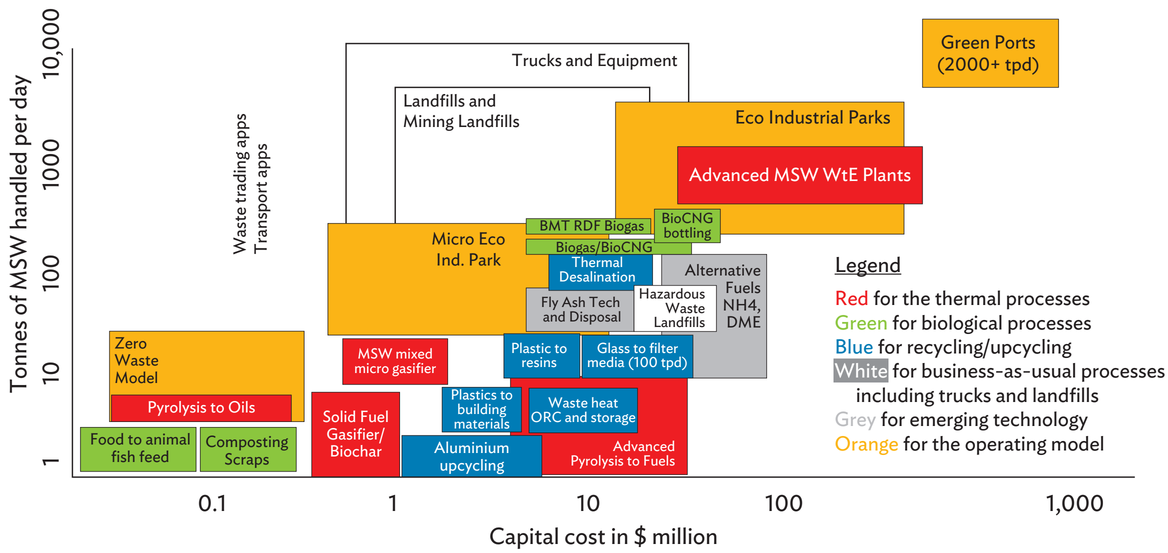
Source: Asian Development Bank internal training material.

[65] J. Huang et al. 2018. *Creating an Enabling Environment for Public–Private Partnerships in Waste-to-Energy Projects*. Manila: ADB. https://www.adb.org/sites/default/files/publication/471811/sdwp-058-ppp-waste-energy-projects.pdf.

Scale of Implementation

Understanding the relative size of investments and how they fit into the various operating models is fundamental. Many technologies are suited to the smaller distributed operating models of micro eco-industrial parks or even smaller zero waste community models.

Figure 16: Technologies and Their Capacity and Capital Cost Ranges



AI = artificial intelligence, BioCNG = compressed biomethane, BMT = biological mechanical treatment, DME =dimethyl ether, MSW = municipal solid waste, NH4 = ammonia, ORC = organic rankine cycle, RDF = refused-derived fuel, WtE = waste to energy, tpd = tons per day.

Source: Asian Development Bank internal training material.

The larger eco-industrial park and green port models can support the smaller technologies as part of their centralized response. These larger facilities can accommodate a range of other services that complement the WtE technology on-site. Examples of these configurations include:

(i) wastewater collocation with WtE,
(ii) waste oils and maritime wastes collocation at green ports,
(iii) offtake of biomethane to displace diesel or CNG for use by transport operators,
(iv) offtake of power for use by transport operators as electricity for battery operated vehicles, and
(v) offtake of power for use by transport operators to produce marine hydrogen.

All of the above configurations are in the development pipeline of ADB. Notably the technologies employed are in order of decreasing industrial readiness.

Figure 17: Technology Readiness Levels

Pre-Commercialization Gap Build in Canada Innovation Program (Levels 7–9)

Level of Readiness	Description of Level	
Actual technology proven through successful deployment in an operational setting	Actual application of the technology in its final form and under real-life conditions, such as those encountered in operational tests and evaluations. Activities include using the innovation under operational conditions.	LEVEL 9
Actual technology completed and qualified through tests and demonstrations	Technology has been proven to work in its final form and under expected conditions. Activities include developmental testing and evaluation of whether it will meet operational requirements.	LEVEL 8
Prototype ready for demonstration in an appropriate operational environment	Prototype at planned operational level and is ready for demonstration in an operational environment. Activities include prototype field testing.	LEVEL 7
System/subsystem model or prototype demonstration in a simulated environment	A model or prototype that represents a near desired configuration. Activities include testing in a simulated operational environment or laboratory.	LEVEL 6
Component and/or validation in a simulated environment	The basic technological components are integrated for testing in a simulated environment. Activities include laboratory integration of components.	LEVEL 5
Component and/or validation in a simulated environment	Basic technological components are integrated to establish that they will work together. Activities include integration of "ad hoc" hardware in the laboratory.	LEVEL 4
Analytical and experimental critical Function and/or proof of concept	Active research and development is initiated.This includes analytical studies and/or laboratory studies. Activities might include components that are not yet integrated or representative.	LEVEL 3
Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Activities are limited to analytic studies.	LEVEL 2
Basic principles of concept observed and reported	Scientific research begins to be translated into applied research and development. Activities might include paper studies of a technology's basic properties.	LEVEL 1

Source: Innovation Canada.

4.2.5.3 Technology Readiness Level

When putting together a development plan, the choice of technology becomes apparent when the waste and its use is well understood. It is a matter of linking the most desirable outcome financially and other value-added aspects with reliable technology options.

The definition of a reliable technology option should include both high technology readiness level (TRL) and in meeting or exceeding environmental guidelines and being socially beneficial.

TRL is a commonly employed approach to provide consistency in assessing the maturity of a technology, with 1 being the idea inception stage and 9 being a fully commercialization ready stage. Generally, DMCs are interested in implementing technologies with at least a TRL of 7—prototype ready for demonstration in an appropriate operational environment.

Occasionally, small-scale pilot projects (TRL 6) may be carried out for technologies with high social and environmental development potential

BUSINESS AND FINANCING MODELS

Indicative Business Models

The table below shows the various business models based on best practice from ADB's experience. The suitability for a PPP model is shown on the far right column.

Table 7: Waste-to-Energy Business Models

Business-As-Usual Activities	Indicative Project Internal Rate of Return (%)	Typical Business Model	Typical Sponsor	Typical Off taker(s)	PPP Suitability
Trucks MRFs and collection	12	Concession	Municipality	Municipality	Yes
Landfills and landfill mining	20	Concession	Municipality	Municipality	Yes
Apps for waste segregation and trading	35	Concession	Municipality	Traders	Yes
Hazardous waste landfills	25	Concession	Province/ National (Nat.)	Province/Nat.	Yes
Operations model					
Zero-waste communities	15	Nongovernment organizations	Municipality	Traders	No

continued on next page

Table 7 *continued*

Business-As-Usual Activities	Indicative Project Internal Rate of Return (%)	Typical Business Model	Typical Sponsor	Typical Off taker(s)	PPP Suitability
Micro eco-industrial park	20	SME	Municipality	Heat, power, traders, recyclers, and upcyclers	Yes, if bundled
Eco-industrial park	25	Concession	Municipality		Yes
Green port	20	Concession	Province/Nat.		Yes
Thermal technologies					
Pyrolysis to oils	25	SME	Municipality	Buyer/trader	Yes
Solid fuel gasifies and/or biochar	25	SME	Municipality	Power, trader	Yes
Mixed MSW micro gasifier	20	SME	Municipality	Heat, power, traders, recyclers, and upcyclers	Yes, if bundled
Advanced pyrolysis to fuels	25	Concession	Municipality		Yes, if bundled
Advanced MSW waste to energy	15	Concession	Municipality		Yes
Biological technologies					
Food to feed (animal/fish)	25	SME	Municipality	Buyer/trader	No
Composting of scraps	15	SME	Municipality	Buyer/trader	No
BMT biogas and refuse-derived fuels	15	Concession	Municipality	Buyer/trader	Yes, if bundled
Biogas and BioCNG	20	Concession	Municipality	CNG users	Yes, if bundled
BioCNG bottling	20	Concession	Industry	CNG users	Yes
Recycling and/or upcycling					
Aluminum upcycling	25	SME	Industry	Buyer/trader	No
Plastics to building materials	25	SME	Industry	Buyer/trader	No
Plastics to resins	20	SME	Industry	Buyer/trader	No
Waste heat, ORC and/or storage	15	SME	Industry	Heat user	No
Thermal desalination	20	Concession	Province/Nat.	User/Buyer	Yes
Glass to filter media	20	SME	Province/Nat.	Buyer/trader	Yes
Emerging technologies					
Fly ash inoculation	15	Concession	Province/Nat.	Province/Nat.	Yes
Alternative fuels (DME, NH4)	20W	SME	Province/Nat.	Buyer/trader	Yes, if bundled

BMT = biological mechanical treatment, bioCNG=compressed biomethane, CNG = compressed natural gas, DME = dimethyl ether, MRF = material recovery facility, MSW = municipal solid waste, NH4 = ammonia, SME = small- and medium-sized enterprise.

Source: Asian Development Bank internal training material.

Development Timelines

The larger a project with more financially secure stakeholders, the faster these projects move from approved concept to reality. These larger more commercially mature projects tend to have a realization period of 2–5 years depending the size and construction scope of the infrastructure.

Surprisingly, the smaller projects with a capital cost under $10 million tend to take several years as the level of due diligence for financiers is the same and the stakeholders tend to be less secured. Many of these smaller projects are not suited to project finance models, most especially build-own-operate-transfer type of arrangements. The allocation of risk is not optimal in these circumstances.

Appropriateness of the Business Model

Using an example of a rural factory powered by biogas from its wastewater, the factory owner is looking for a solution to reduce environmental operations risk and secure a power supply that is cheaper and more reliable. The owner is making a return on investment of 35%–60% in some circumstances on the underlying factory business. Biogas plants typically provide an internal rate of return of 14%–19%. From the owner's investment viewpoint, he or she will not get the same returns by building another plant. The challenge is determining a delivery model to suit the business model of the biogas technologists or developers. During the functioning of carbon markets, carbon financing provided the viability gap to these projects. Insistence on the use of build-own-transfer models is another problem facing developers who take on all the payment risks. For this reason, the small- to medium-sized WtE market segment has struggled to be profitable.

Need for Financial Innovation

Financial intermediation by local financial institutions is an ideal solution to this financing problem. Many Asian financial institutions have staff who are trained by organizations such as The Renewables Energy Academy (www.renac.de). The next step is to develop new lines of business funding the factory owners to build these facilities themselves and secure sufficient technical and commercial undertaking from the technologists and developers. A leasing or hire purchase model would be ideal. Ongoing support for the operations and monitoring of the plant can be factored into the lease cost. Financial institutions can replace technologists and developers who fail to deliver. ADB is providing support to financial institutions in this way for energy efficiency. WtE projects at the smaller to medium size could be considered as energy efficiency measures, especially when waste heat utilization or fuel substitution is included.

Small- and Medium-Sized Enterprise Financing Models

Smaller projects up to $500,000 are typically funded by inventors and the four "Fs" – friends, family, fools, and frauds. In high-risk ventures, the participants commonly do not understand the likelihood of project failure, which is over 85%. Where local financing schemes are available, these should be used. Developers and technologists should apply particular caution in the engagement of financial consultants promising funding. Working with established corporate partners with resources and a shared interest is a more successful route to delivery. Aligning these corporates as long-term customers, off-takers, partners, and even equity participants has shown to be a strategy with higher chances of success for small developers. This is because financiers are more likely not to take the better financial position of the corporate partners. This reduces realization time, which is a key to success. It is often said that 45% of $5 million is better than 100% of nothing. Seeking grants, concessional funding, and smaller investors is a possible route but it takes much longer and has a much lower chance of successful realization.

Additional Revenue Streams

WtE projects have a surprising variation in the energy component. For the examples in Chapter 3, it can be seen that energy comes in many forms and there are often a number of by-products produced. When financiers assess the value and returns of a project or technology company, often these by-products are discounted or ignored. Carbon credits are now valued below the cost of registering, verifying, and selling them. Sales of fertilizer from biogas plants is often discounted due to the location or market price fluctuations. Recyclable materials are difficult for financiers to value unless there is a direct technological line to an off-taker. This has become more pronounced since the PRC announced its Great Sword initiative, which has effectively closed the sales of most of the previously imported materials.

Energy is sometimes a minor fraction of revenues from WtE plants. In developed markets, the energy revenues from large municipal WtE plants is typically 25% of total revenue. The gate fee for the treatment of the waste is the majority of the revenues with some recycling and by-product sales. In Asia, energy for the plants tend to be a higher percentage (closer to 50%) as the landfill costs are lower and energy is often subsidized to support the growth of the industry. The cost of landfilling currently ignores the long-term implication of waste dumping. This distorts the market and underlying costs to the economy of not treating waste effectively.

Plant Availability

When assessing the viability of a project, the availability of the plant to operate is often poorly characterized. Biogas plants from cassava starch can have a 98% availability. This means the plant can operate 98% of the time when it is not under maintenance (typically 18–20 hours per day for 330 days per year). This has very high availability. Conversely, many recycling and upcycling plants have availability below 70% of the time and have higher maintenance requirement. The availability of these plants is typically 12–16 hours per day for 290 days per year. Modeling the ability to generate revenues requires a strong understanding of the technical and operational risks of the underlying technology. Financiers will often engage owners' engineers to advise on these issues.

Feedstock

Municipal WtE plants have an average availability of 22–23 hours per day for 325 days per year. The larger the plant, the lesser the impact of the heterogeneous nature of municipal waste. Conversely, smaller plants (under 300 tons per day) are negatively impacted by this issue. There appears to be a threshold for viability of municipal WtE plants based on grate or stoker technology around 500 tonnes per day. To secure feedstock in the long term, planners need to consider how to feed the beast. The catchment should be well defined for fresh waste, mined combustible waste from landfills, and industrial waste suited to the plants design. The use of makeup fuels is risk in the long term. Supplies of RDFs should be considered when calorific values fall below the plants' threshold design.

Public–Private Partnership Arrangements

For this reason, it is an expensive proposition to ask the private sector to take the risk on changes in calorific values of MSW. As the amount of plastic decreases in the waste stream, operators will need to increasingly find new fuels. Landfill mining will provide some of that fuel. The size of a plant is a key investment consideration. Quantities, growth rates, and increased affluence should be carefully considered. A more appropriate model is the use of PPPs.[66] A model where municipal WtE plant developers are paid a toll to build and operate the plant and the city taking the risk on calorific value and quantities is ideal. It allows cities to provision a fixed cost for the plant and charge a gate fee of their choosing, instead of being locked into a commercial relationship with little room to move. It also allows cities more flexibility in supporting localized recycling, upcycling, and reuse activities. Should more capacity be required, the city can grow its footprint by the siting of any new facility in a separate area to the existing plants. This distributed footprint will reduce traffic implications and collection and transport costs significantly by reducing dump trucks route lengths.

[66] J. Huang et al. 2018. Creating an Enabling Environment for Public–Private Partnerships in Waste-to-Energy Projects. *ADB Sustainable Development Working Paper Series* No. 58. Manila: ADB. http://dx.doi.org/10.22617/WPS189766-2.

DE-RISKING

Table 8 presents typical risks for the various business models.

Table 8: Risks of Business Models

	Characteristic					Commercial								Environmental					Financial/Regulatory							
Risk Matrix	Feed Stock Consistency	High Moisture Content	High Organic Content	1000 TPD threshold	Need for Segregation	Collection fee	Processing/gate fee	Diesel Price	Gasoline Price	Solid Fuel Price	Electricity Price	Water Supply Price	Land Price	Wastewater Price/Fines	Air emission Fines	Carbon Emission Price	Noise Fines	Odor Fines	Sponsor Risk	Operator Risk	Construction Risk	Offtaker Risk - PPA	Offtaker Risk - Non-PPA	Supplier Risk	Regulatory Risk	Legal Risk and Liability
Landfills and Landfill Mining	M	M	L	-	-	L	H	H	M	-	-	-	M	M	H	H	H	H	H	M	L	L	L	L	M	M
Apps for Waste Segregation and Trading	M	L	-	-	E	H	E	-	-	-	-	-	-	-	-	-	-	-	H	M	-	-	M	-	L	L
Hazardous Waste Landfills	L	L	M	-	-	H	H	H	M	-	-	-	M	M	H	H	H	H	H	M	V	L		L	V	V
Operations Model																										
Zero Waste Communities	L	L	L	-	H	M	L	M	L	L	L	L	M	M	L	L	L	L	L	L	-	L	L	L	L	M
Micro Eco-Industrial Park	M	L	L	-	-	M	M	M	M	M	H	L	M	M	M	M	H	H	H	H	M	H	M	L	M	H
Eco-Industrial Park	H	H	H	H	-	H	H	M	M	H	H	M	H	H	H	H	H	H	H	H	H	H	M	L	H	V
Green Port	H	H	H	H	-	H	H	M	M	H	H	M	H	H	H	H	H	H	H	H	H	H	M	L	H	V
Thermal Technologies																										
Pyrolysis to Oils	M	H	M	-	H	L	E	E	E	E	L	-	L	M	M	M	M	M	H	H	L	H	H	L	M	M
Solid Fuel Gasifies/ Biochar	M	H	L	-	H	M	E	E	E	E	L	-	L	M	M	M	M	M	H	H	L	H	M	L	M	M
Mixed MSW Micro Gasifier	L	M	M	-	L	H	M	L	L	L	E	-	L	-	L	L	L	L	L	M	L	L	M	L	H	H
Advanced Pyrolysis to Fuels	M	L	L	-	M	M	E	E	E	M	M	L	L	E	L	L	M	M	M	M	L	H	M	L	H	H
Advanced MSW Waste to Energy	M	M	M	M	-	H	V	M	M	M	V	L	M	M	H	H	H	H	H	H	H	H	H	L	H	V
Biological Technologies																										
Food to Feed (Animal/Fish)	L	-	-	-	M	L	E	L	L	-	-	M	M	M	M	M	M	M	M	M	L	M	L	L	L	L
Composting of scraps	L	-	-	-	M	L	E	L	L	-	-	M	M	H	H	L	M	M	M	M	L	M	L	L	L	L
BMT Biogas and RDF	L	M	L	-	E	M	H	E	E	E	E	M	M	H	H	E	H	H	M	M	M	H	M	L	M	M
Biogas and BioCNG	M	-	-	-	H	M	H	E	E	E	E	M	M	H	H	E	M	H	M	L	M	H	H	M	M	M

continued on next page

Table 8 *continued*

Risk Matrix	Characteristic					Commercial								Environmental					Financial/Regulatory							
	Feed Stock Consistency	High Moisture Content	High Organic Content	1000 TPD threshold	Need for Segregation	Collection fee	Processing/gate fee	Diesel Price	Gasoline Price	Solid Fuel Price	Electricity Price	Water Supply Price	Land Price	Wastewater Price/Fines	Air emission Fines	Carbon Emission Price	Noise Fines	Odor Fines	Sponsor Risk	Operator Risk	Construction Risk	Offtaker Risk - PPA	Offtaker Risk - Non-PPA	Supplier Risk	Regulatory Risk	Legal Risk and Liability
BioCNG Bottling	H	-	-	-	V	M	H	E	E	E	E	-	M	-	L	E	H	H	M	H	H	H	H	M	H	H
Recycling / Upcycling																										
Aluminum Upcycling	M	M	M	-	H	L	E	E	E	L	L	L	L	L	L	L	L	L	M	H	L	H	M	M	L	L
Plastics to Building Materials	M	M	M	-	H	M	E	L	L	L	L	L	L	L	L	M	H	H	M	M	L	M	M	L	M	M
Plastics to Resins	M	M	M	-	H	M	E	L	L	L	L	L	L	L	H	H	H	H	M	H	L	M	M	M	M	M
Waste Heat/ORC/ Storage	M	-	-	-	H	L	E	E	E	E	E	-	L	L	M	M	M	M	M	M	M	H	M	L	M	M
Thermal Desalination	M	-	-	-	H	L	E	E	E	E	E	E	M	M	L	L	L	L	H	H	M	H	H	M	M	M
Glass to Filter Media	M	L	L	-	H	M	E	L	L	L	L	E	L	E	L	L	L	L	M	M	M	H	M	M	M	M
Emerging Technologies																										
Fly Ash Innoculation	H	-	-	-	-	M	V	L	L	L	L	L	H	M	V	H	H	H	H	H	M	H	H	H	V	V
Alternative Fuels (DME, NH4)	H	M	M	-	-	M	H	E	E	E	E	L	M	M	M	M	M	M	H	H	M	H	H	L	H	H

BioCNG = compressed biomethane, BMT = biological mechanical treatment, DME = dimethyl ether, MSW = municipal solid waste, RDF = refuse-derived fuel, NH4 = ammonia, ORC = organic rankine cycle, PPA = power purchase agreement, TPD = tonnes per day.

Note: Putting measures in place to address these risks is critical for any waste-to-energy project. Some technologies address risks of others. These are shown in blue with the letter E – enabling condition. Low, Medium, High, and Very High as shown as L, M, H and V in the table.

Source: Asian Development Bank internal training material.

SAFEGUARDS AND OPERATIONAL EXCELLENCE

ADB has a well-developed set of safeguards standards. WtE projects have to meet these standards to receive ADB support.

Compliance to local emissions standards is often not sufficient where such standards are not fully developed or enforced. Compliance to a strict emissions regime with internationally recognized monitoring, testing, and reporting is a must.

Consideration of the siting of the facility with respect to air, and liquid discharges requires significant planning. A municipal WtE plant requires a buffer zone and stack height requirements, which also meet stringent international emissions standards. Siting the rural waste facility in protected or fragile areas such as peat bogs or high-carbon stock zones will automatically disqualify any project from funding.

The resettlement of any person living on or near the site needs to be determined and an adequate and equitable resettlement plan needs to be included in the project documentation.

Gender equality, minorities, and vulnerable groups are all parts of a WtE project. Whether it is enhancing the participation of women in the workforce, supporting skills and employment opportunities for minorities, or supporting waste pickers to transition to more secure and safe employment, WtE projects provide an opportunity to include these social advances.

For private sector funding, developers need to provide sufficient information on the project. A good starting point for what is required is located here- https://www.adb.org/site/private-sector-financing/applying-assistance.

If you would like to delve deeper in the safeguards policies, go to https://www.adb.org/site/safeguards/main. It is also helpful to look further into the publications for safeguards on the www.adb.org website.

A helpful tip is to link the thinking about complying with safeguards into the operational plans for the project. It is important to show innovation and engagement in the project.

5 WASTE INFRASTRUCTURE PLANNING EXAMPLE

This example will be based on a hypothetical case. It is assumed that Pura is the capital city of an ADB DMC. It lays out the high-level advice. More detailed assessment has not been included in this example.

BACKGROUND

Pura has a population of 2.6 million in 2016, consisting of 1.7 million people permanently residing in the city and about 900,000 in-transit from neighboring provinces. It is projected that Pura's population will reach 4 million in 2030. About 85% of the population receives basic earning, while 11% earns less than $2,000 per year. The remaining 4% earns more than $5,000.

Based on 2016 population, Pura generated a total of 2,330 metric tonnes of waste per day (MT/day), which is projected to further increase to 4,000 MT/day in 2030. The 2016 daily waste generation per person was 0.9 kg/day. This is expected to increase to 1 kg/day/person in 2030.

The Ministry of Environment (MOE) has overall responsibility for keeping the environment clean. The collection of waste is carried out by a private company called PuraBersih under a contract with the Pura city government. The city has another layer of governance with local wards, nine of which make up the city. The local power company, PuraWatt, collects fees from those households with an electricity connection for their solid and liquid waste and water supply. These fees are remitted to the Ministry of Finance (MOF) who subsequently distributes funding back to the city government.

This system worked well as the city was growing but in an age of internet and digitalization, the whole supply chain needs an overall upgrade. The residents of Pura were not happy with the performance of PuraBersih. Consequently, there is a general disregard and apathy for dumping and littering.

The new mayor of Pura has sought advice on how to turn the situation around and asked for a study completed in 2014 to be updated.

MUNICIPAL SOLID WASTE SOLUTION OPTIONS (2014 STUDY)

The previous city government was presented several solutions for the management of its MSW in 2014. These options and their drawbacks included:

(i) **Option A: Find new dumpsite.** Cost of buying land and building infrastructure without changing the way business is conducted. High trucking and low value addition with lower service quality.
(ii) **Option B: Build one large WtE facility.** High capital cost and all performance risk in one company and plant. Issues with public perception of incineration. Low civic-mindedness.
(iii) **Option C: Build multiple smaller WtE plants around the city.** Less efficient but large reduction in truck trips and flexibility if one plant is not operating.
(iv) **Option D: Build sorting machines at local level.** Locally made machines to strip off recyclable materials and encourage new companies to make fertilizer, charcoal, biogas, power, heat, or other value-added products in response to industry needs.

From the four options presented, the preferred solution was to invest in Option D by buying locally made machines and sell value-added waste to private industry. The creation of more jobs was highly regarded. It was felt that Option D would result in higher value addition. The economics would determine what will happen to food waste, recyclables, and wood waste. The 10% that cannot be sold can be dumped in the landfill. This option would have radically reduced trucking cost. The assessment was based on the following information.

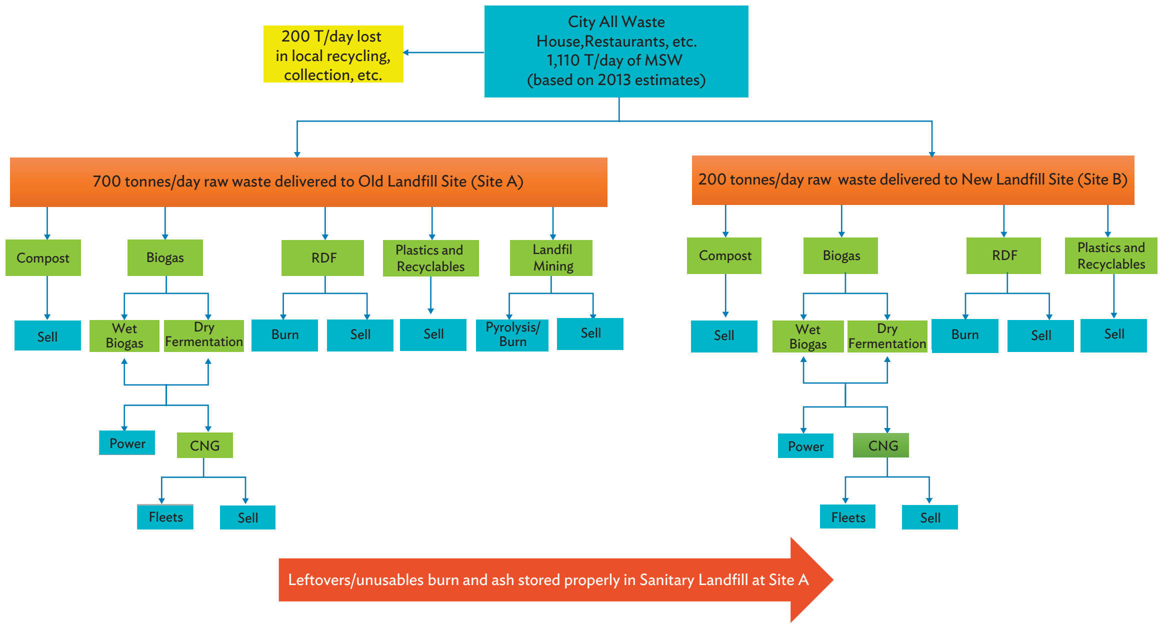
TECHNOLOGY

In 2013, it was estimated that the city generated a total 1100 tonnes of MSW per day. About 400 tonnes were lost during recycling and collection and the remaining 700 tonnes went to two landfills: 500 tonnes in an old land fill site (Site A) and 200 tonnes in a new site (Site B). Through the development of new technology solutions, both landfills were to have four by-products: compost, refuse-derived fuel (RDF), plastic and other recyclables, and biogas. The first three were to be sold for additional revenue streams while biogas would undergo two distinct processes. Wet biogas was to be scrubbed and used for power generation while biogas would be upgraded to produce BioCNG, which is sold and used in fleets. Landfill mining was to be undertaken in the old landfill site and the recyclable materials recovered were sold. The remaining waste would be processed through pyrolysis or gasified.

A large plant was to be built to process a total of 2,300 tonnes of MSW per day. Construction of the plant was proposed in two phases. The first phase involved the building of bio-methanation digester with feedstock of 1,255 MT of organic waste per day. The biogas power output was estimated at 11.86 megawatt electrical (MWe) with 10.26 MWe exportable to the grid. The other by-products of bio-methanation process would include 23 tonnes of ammonia fertilizer, 116 tonnes of low-dose urea, and 3,099 cubic meters (m_3) of processed water per day.

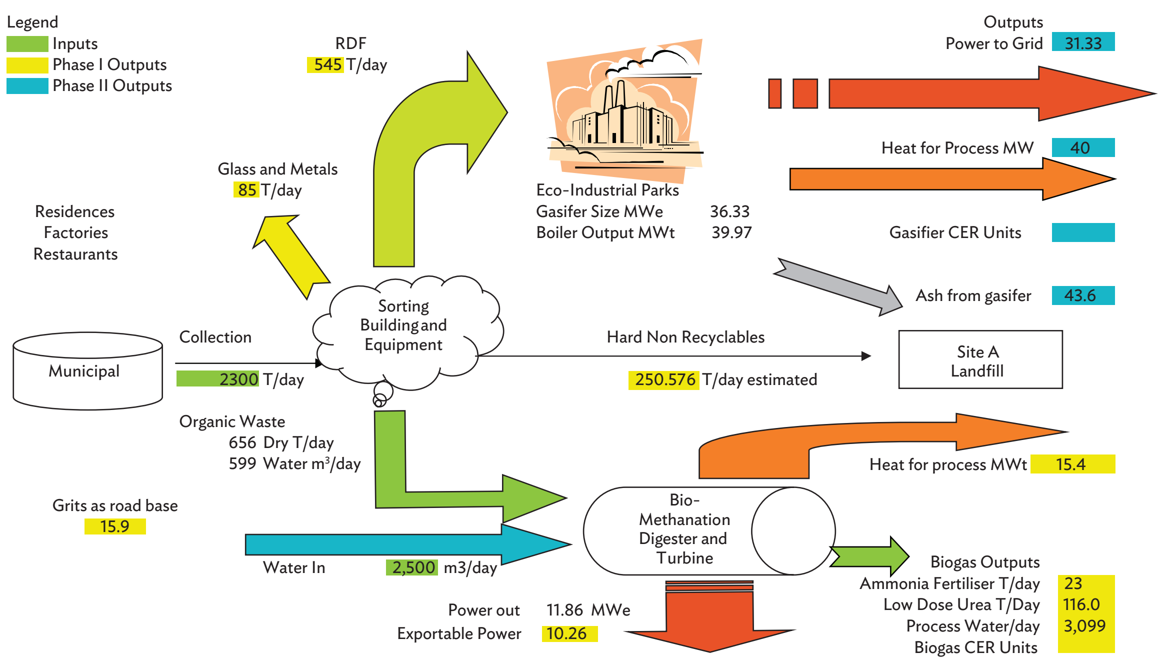
For the second phase, gasifier and boiler island was to be built with a capacity of 36.33 MWe and 39.97 megawatt thermal (MWt), respectively. The two technologies were to have a total output of 31.33 MW exportable to the grid. An estimated 40 MWt of process heat would also be produced. The gasifier was projected to produce a total of 43.6 tonnes of ash.

Figure 18: Technology Options for Pura City (2014 Study)



CNG = compressed natural gas, MSW = municipal solid waste, RDF = refuse-derived fuel, T = tonnes.
Source: Asian Development Bank internal training material.

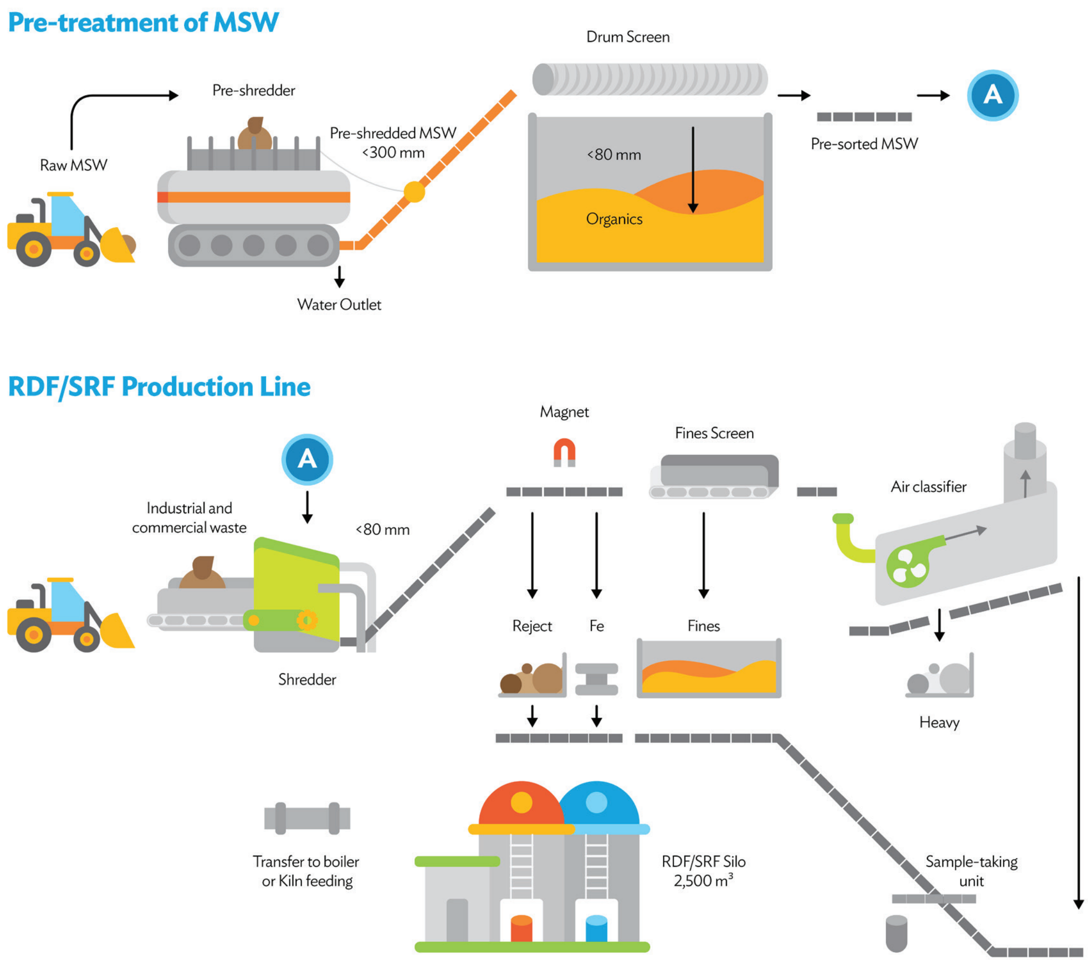
Figure 19: Large Waste-to-Energy Power Plant (2014 Study)



CER = carbon emission reduction, m^3 = cubic meter, MWe = megawatt electrical, MWt = megawatt thermal, RDF = refuse-derived fuel, T = tonne.
Source: Asian Development Bank internal training material.

A separate sorting facility using EU technology (Figure 20) was to be erected to segregate the waste. The sorting machine would segregate MSW into organic dry, organic wet, metal, glass and ceramics, plastic, sand or stone, wood, textiles or rubber, and ash, computer, heavy, and others. These wastes could be processed to produce biogas for power generation, fertilizer, road base grit, or fuel for cement plant. A significant portion of MSW was to be recovered and recycled. After going through this process, only a small amount of waste would be dumped at the landfill.

Figure 20: Sorting Technology (2014 Study)

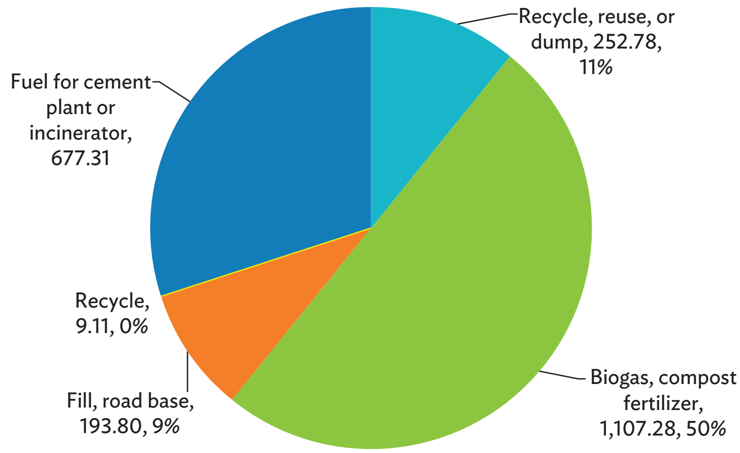


m^3 = cubic meter, mm = millimeter, MSW = municipal solid waste, RDF - refuse-derived fuel, SRF = solid recovered fuel.

Source: Asian Development Bank internal training material.

Figure 21 shows the proposed use of the wastes. The biggest portion (50%) is for biogas production including generation of compost and fertilizer. About 30% of the waste was intended for fuel for cement plant or EfW; 11% was for recycling, reuse, or dump; and 9% as road base. The amount of waste that would be purely recycled is negligible at only 9.11 tonnes/day. With this proposed waste utilization, only 59 tonnes or around 2% of the total waste generation of 2,300 tonnes/day will go to landfill.

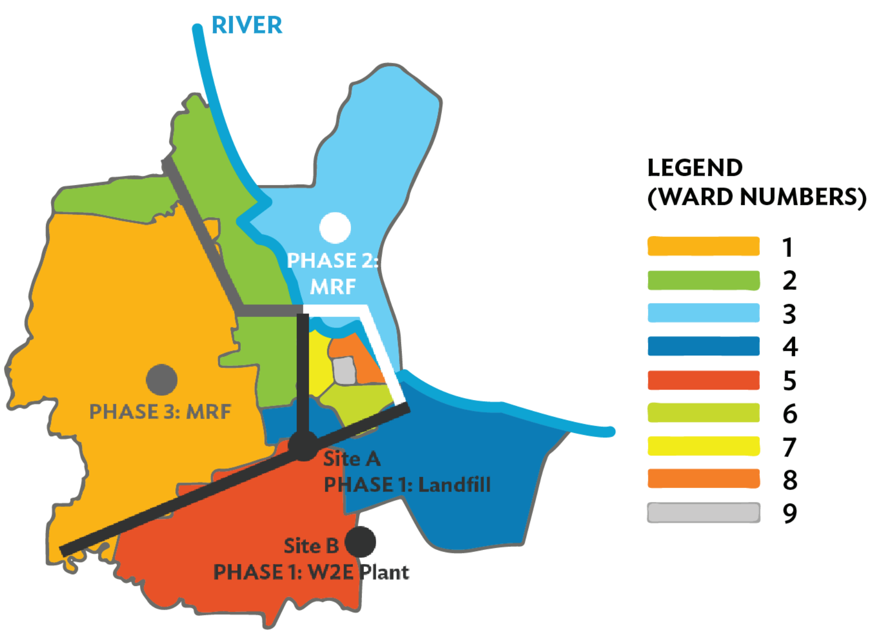
Figure 21: Composition of Waste (2014 Study)



Source: Asian Development Bank internal training material.

The area of Pura was also mapped out (Figure 22). Site B, the site where the existing landfill site is located, would be used as a WtE plant while Site A is for the extraction of landfill gas only. Two materials recovery facility sites were identified: Ward 1 and Ward 3.

Figure 22: Waste Catchments for Pura City



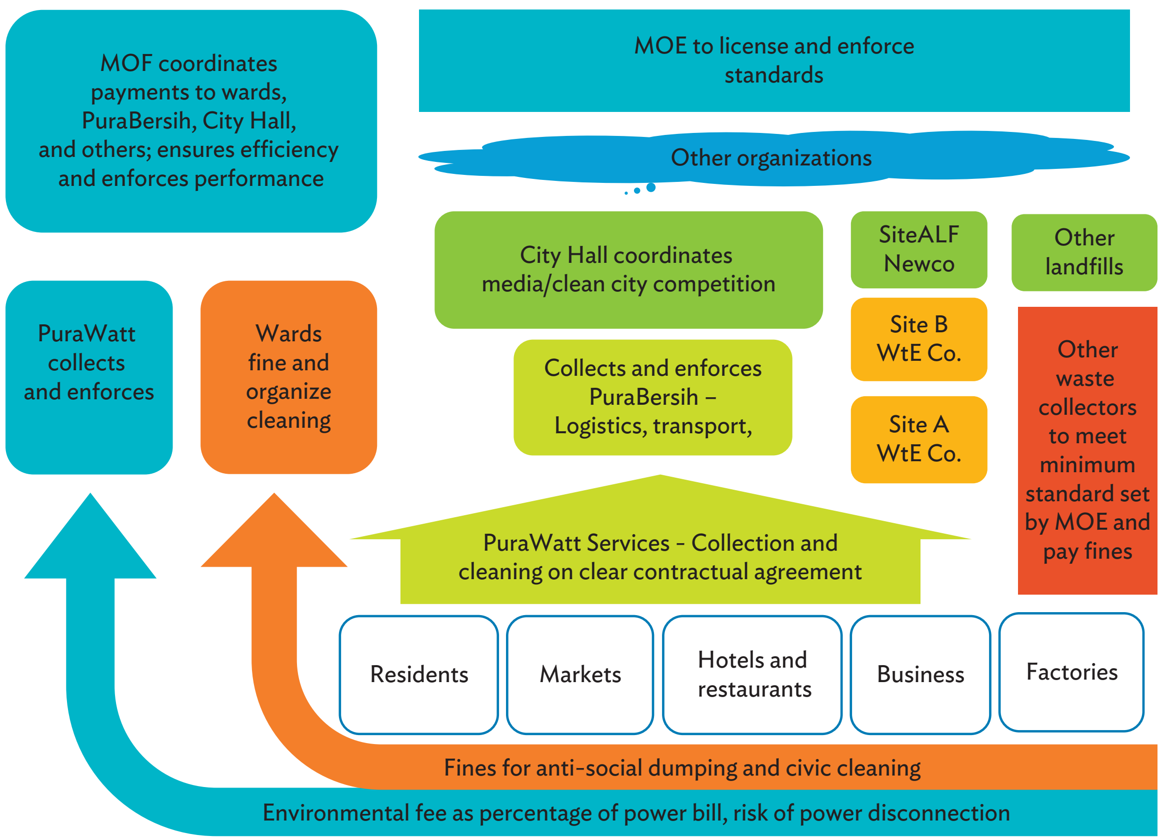
MRF = material recovery facility, MSW = municipal solid waste, WtE = waste to energy.
Source: Asian Development Bank internal training material.

INSTITUTIONAL ARRANGEMENTS

The Ministry of Environment is in charge with the issuance of license and enforcing environmental standards with regard to solid waste management. To improve waste collections services, Pura City Hall introduced a competitive market to encourage entry of other players. Currently, waste collection services in the city is dominated by PuraBersih. PuraBersih, through PuraWatt, collects payment for services through a fee charged as part of the electricity bill for each customer. Wastes collected by PuraBersih come from residents, markets, hotels and restaurants, businesses, and factories and sent directly to landfill sites and WtE facilities.

The local wards, on the other hand, work at the village level, where they liaise with the public on matters relating to collection issues, waste buildup, cleaning, fee complaints, and fines for anti-social dumping. The MOF is responsible for supporting and coordination with local wards, PuraBersih, city hall, and others to ensure efficiency of waste collection and monitor performance of those involved in solid waste management (Figure 23).

Figure 23: Relevant Waste-to-Energy Stakeholders



MOE = Ministry of Environment, MOF = Ministry of Finance, WtE = waste to energy.

Source: Asian Development Bank internal training material.

Table 9: Operations Matrix (2014 Study)

Actions	Revenues ($)	Costs and Loans ($)	Capital Cost ($)	Expanded Service Model												
Activity			Various	PuraB	MOE	CITY	PuraWat	Ward	SBCo	SACo	Residents	Business	LCEs	MOF	Others	Financing Source
Provision of Bins	0	400,000	1,200,000	C												Collections by Wards
Litter Enforcement	2,737,500	500,00	0		Issuer			Issuer								Revenue Positive
Fine Collection	0	50,000	0				Lead									Power off
Public Education and Media	0	450,000	500,000													From collection PuraWatt
Digitization implementation	0	320,000	350,000													From collection MOF
Clean Ward Competition	0	250,000	250,000													From Fines/ LCE donor
Adopt-a-Ward	0	250,000	250,000													LCE Donations
Collection of PuraWatt Fees	0	50,000	0				Lead									PuraWatt/ MOF Share
Street Cleaning	4,000,000	3,200,000	120,000	C												Collections MOF
River Cleaning	2,000,000	1,700,000	200,000	C												Fines/Share EnvFees
Waste Collection	9,000,000	6,800,000	0	C												Collections MOF
Create Eco-Industrial Park	0					Owner										Land Sale
Transport Efficiency		500,000	120,000													AF
Transfer Station Operations	50,000	40,000	0						C							ADB/IFC/ Private/PPP
Sorting	200,000	110,000	5,200,000						C							ADB/IFC/ Private/PPP

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Table 9 *continued*

Actions	Revenues ($)	Costs and Loans ($)	Capital Cost ($)	Expanded Service Model												
Organics/Food WtE	0	120,000	1,200,000						C							ADB/IFC/ Private/PPP
Recycling and RDF	2,300,000	340,000	250,000						C							ADB/IFC/ Private/PPP
Power SB Only	0	50,000	300,000						C							ADB/IFC/ Private/PPP
CNG Fuels SB Only	3,600,000	1,900,000	6,900,000						C							ADB/IFC/ Private/PPP
Transfer to SB LF	40,000	28,000	0	C												Collections
SB LF Sort incoming	80,000	40,000	1,800,000							C						Collections
SB Landfill gas	0	25,000	1,100,000							C						Unclear
SB Recycling and RDF	2,300,000	1,200,000	1,300,000													Collections
SA LF Mine	110,000	250,000	450,000							C						ADB/IFC/ Private/PPP
SA LF Gas to CNG	540,000	220,000	1,550,000							C						Gas cleaning for CNG
SA cleaned LF Sell	210,000	90,000	0							C						Collections
SA Transfer Station Ops	0		0			C										ADB/IFC/ Private/PPP
Tipping Fee	34,000	12,000	0			C										City
Totals	27,201,500	18,445,000	23,040,000													

Specific Projects	Revenues	Costs and Loans	Capital Cost
Site A Recycling	2,380,000	1,265,000	4,200,000
Site A Landfill Mining	860,000	560,000	2,000,000
Site A Waste Transfer Station	6,150,000	2,560,000	13,850,000

ADB = Asian Development Bank, AF = alternative finance source, C = collection, CNG = compressed natural gas, IFC = International Finance Corporation, LCE = local commercial enterprise, LF = landfill, MOE = Ministry of Environment, MOF = Ministry of Finance, Ops = operations, PPP = public–private partnership, RDF = refuse-derived fuel, SA = Site A, SB= Site B, SACo = Site A Company, SBCo = Site B Company, WtE = waste to energy.
Source: Asian Development Bank internal training material.

PROPOSED OUTCOMES

The proposed development of waste infrastructure in Pura was expected to result to the following:

(i) truck trips to landfill reduced to 10% of current,
(ii) more jobs created in sector with more entrepreneurs engaging in smaller business with higher competition leading to lower costs and better service levels,
(iii) increased awareness of general public,
(iv) allow space for new technologies,
(v) lower risk with multiple plants and stakeholders,
(vi) amount to landfill be reduced by 10 times, and
(vii) more options for landfill.

The proposal was supported by government. Concessionaires were approached but were unable to close financially. The project did not proceed.

REVIEW OF THE PROPOSAL AND ADVICE TO THE CITY

The mayor, through the MOF, approached the ADB resident mission and requested support. A review was undertaken with ADB's regional department supported by the Sustainable Development and Climate Change Department. In the 2014 proposal, advanced thermal oxidation was not included due to public concerns. The new mayor asked for the ADB review to comment on this in line with current best practices. Seeing the success of Japan, the Republic of Korea, and the PRC in implementing the technology, the public was more amenable to the idea after a media campaign by the city government.

In the intervening time, a cement plant was built in a neighboring province. The cement company was interested in supporting the project if it could offtake the supply of RDF. The cement factory was well capitalized and could be supported by ADB's Private Sector Operations Department. However, the amount of RDF needed would be half the amount produced at Site B (WtE Plant).

The landfill gas potential of Site A was determined to be low due to biological and saline contamination issues. The remediation of the site was required due to health impacts on the neighboring wards and it would necessitate biological treatment of the soil and ground water.

After analyzing the economic impacts of the various options, a report was presented to the city. Key proposals included:

(i) To generally keep the 2014 proposal in place for socialization measures and siting of infrastructure (see Table 9 for summary).
(ii) Adopt the proposed biogas to power instead of transport fuel proposal from 2014 study.
(iii) Include a digitization component for waste collection at source to increase the segregation level of waste streams for locally based recycling and upcycling solutions. These solutions to be sites at MRF or the eco-industrial park at Site B.

(iv) To upgrade the Site B WtE Plant to an eco-industrial park by grant of land to a concessionaire. Concessionaire granted the right to build a WtE plant on the site with preferential energy sales tariff and right to mine Site A. Government to undertake a PPP process to award the concession to be based on a flat fee to treat all end-of-life materials in the city. The concessionaire to be able to treat a minimum of 800 metric tonnes in year 2022. The concessionaire to plan for capacity to handle all end of life was to match the cities needs based on net waste remaining and landfilled waste available to be mine.

(v) To issue only one WtE concession while leaving the collection in place. The concession to be based on a flat yearly fee for treatment of waste on a take or pay basis.

(vi) A safeguards assessment of the project found no issues with the project sites and environment issues. The proposed resettlement plant was augmented with livelihood programs and retraining, especially for several at-risk families.

By using a flat fee and insisting on an eco-industrial park model, the concessionaire is incentivized to see higher value returns from the waste by encouraging technologists to co-venture or rent space at the eco-industrial park. The WtE facility will be allowed to take other waste if it processes the waste in higher value processes or the city does not have enough waste. By limiting the size of the facility to under 40% of total capacity, the concessionaire is able to implement lower capital cost technologies in distributed areas around the city.

The projected waste generation was reviewed in line with the revised activities proposed in Table 11. This included a program to digitize waste collection of sorted materials to allow for more efficient recycling at a community engagement of 20% of households in 2030.

The generation rate for 2021 was projected at 2,813 tonnes per day. Figure 24 shows the material flow rates and production per day. Seven-hundred fifty tonnes per day is to be diverted to the waste-to-energy facility with 1,550 tonnes of wet solids and 2,000 tonnes of liquid waste being diverted to a biogas plant. About 298 tonnes is to be diverted to recycling and upcycling activities. The balance was landfilled. This gives a split of 63% recycling, 26% WtE, and 11% landfilling. This is achieved by drastic change in sorting at source behaviors.

The generation rate for 2030 was 3,947 tonnes per day. Figure 25 shows the material flow rates and production per day. About 750 tonnes per day is to be diverted to the waste-to-energy facility with 2,018 tonnes of wet solids and 2,500 tonnes of liquid waste being diverted to a biogas plant. About 300 tonnes of waste is to be diverted to a RDF facility and 615 tonnes is to be diverted to recycling and upcycling activities. The balance was landfilled. This gives a split of 74% recycling, 19% WtE, and 7% landfilling.

A 19% WtE share is a low number when considering current attitudes. However, changes in packaging and consumer products will reduce the amount of plastics and increase the use of biodegradable materials. This is highly likely to occur over the next decade.

The 2030 projection does not include an allowance for emerging technologies that will change the logistics landscape for waste. It is not possible to predict which technologies will succeed but there is high likelihood of resin recycling for waste plastics. This give more credence for a smaller design for WtE capacity going forward. By producing over capacity in municipal WtE plants, newer technologies will not be able to enter the market. Experience in a number of countries has shown that initial overcapacity planning resulted in stranded assets, which were ultimately decommissioned due to feedstock and emission problems. Other countries cling to the capacity model from the 1980s, which has resulted in low recycling and upcycling rates. This project utilizes some of the 12 pathways as shown in Table 10.

Table 10: Pathways Chosen by Pura City Government

City Government No.	Pathway	Preferred Solution
1	End-of-life - waste destruction (Provincial)	✓
2	End-of-life residues (Immobilization)	
3	Centralized sorting – eco-industrial park model	✓
4	Centralized recycling and upcycling	✓
5	Decentralized sorting and upcycling	✓
6	Digitization at source	✓
7	Landfill, soil, and river cleanup	✓
8	Regional eco-industrial parks	
9	Digitized extended producer responsibility schemes	
10	Strengthening recycled output supply chains	
11	Supporting fast-moving consumer goods companies in product redesign - recycled %	
12	Strengthening governance and enforcement	✓

Source: Asian Development Bank internal training material.

The Sankey flow diagrams on the following pages show clearly the impact of a smaller-capacity plant by not crowding out the recycling and upcycling technologists and developers (Figures 24 and 25). Please note some smaller flows are excluded to provide some clarity to the diagrams. These exclusions include wastewater from the WTE plant feeder bins to wastewater treatment, evaporation losses from the WTE plant, metals and slag from the WTE plant to recycling and other miscellaneous material flows.

Table 11: Proposed Upgrade Service Delivery Model for Pura City

Item	Actions	Revenues ($)	Costs and Loans ($)	Capital Cost ($)	Expanded Service Model												
1	Activity			Various	PuraB	MOE	CITY	PuraWat	Ward	SBCo	SACo	Residents	Business	LCEs	MOF	Others	Financing Source
2	Provision of Bins	—	400,000	1,200,000	C												Collections by Wards
3	Litter Enforcement	2,737,500	50,000	—		Issuer			Issuer								Revenue Positive
4	Fine Collection	—	50,000	—				Lead									Power off
5	Public Education	—	450,000	500,000													From collection PuraWatt
6	Media Campaign	—	320,000	350,000													From collection MOF
7	Clean Ward Competition	—	250,000	250,000													From Fines/LCE donor
8	Adopt a Ward	—	250,000	250,000													LCE Donations
9	Collection of PuraWatt Fees	—	50,000	—				Lead									PuraWatt/MOF Share
10	Street Cleaning	4,000,000	3,200,000	120,000	C												Collections MOF
11	River Cleaning	2,000,000	1,700,000	200,000	C												Fines/Share EnvFees
12	Waste Collection	9,000,000	6,800,000	—	C												Collections MOF
13	Transfer Station Land	—															Land Sale
14	Transport Efficiency		500,000	120,000													AF
15	Transfer Station Operations	50,000	40,000	—						C							ADB/IFC/ Private/PPP
16	Sorting	200,000	110,000	5,200,000						C							ADB/IFC/ Private/PPP
17	Organics/Food WtE	—	120,000	1,200,000						C							ADB/IFC/ Private/PPP

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Table 11 *continued*

Item	Actions	Revenues ($)	Costs and Loans ($)	Capital Cost ($)	Expanded Service Model												
18	Recycling and RDF	2,300,000	340,000	250,000						C							ADB/IFC/ Private/PPP
19	Power SB Only	—	50,000	300,000						C							ADB/IFC/ Private/PPP
20	CNG Fuels SB Only	3,600,000	1,900,000	6,900,000						C							ADB/IFC/ Private/PPP
21	Transfer to SB LF	40,000	28,000	—	C												Collections
22	SB LF Sort Incoming	80,000	40,000	1,800,000							C						Collections
23	SB Landfill Gas	—	25,000	1,100,000							C						Unclear
24	SB Recycling and RDF	2,300,000	1,200,000	1,300,000													Collections
25	SA LF Mine	110,000	250,000	450,000							C						ADB/IFC/ Private/PPP
26	SA LF Gas to CNG	540,000	220,000	1,550,000							C						Gas cleaning for CNG
27	SA Cleaned LF Sell	210,000	90,000	—							C						Collections
28	SA Transfer Stn Ops	—		—			C										ADB/IFC/ Private/PPP
29	Tipping Fee	34,000	12,000	—			C										City
	Totals	27,201,500	18,445,000	23,040,000													

Specific Projects	Revenues ($)	Costs and Loans ($)	Capital Cost ($)
Site A Recycling	2,380,000	1,265,000	4,200,000
Site A Landfill Mining	860,000	560,000	2,000,000
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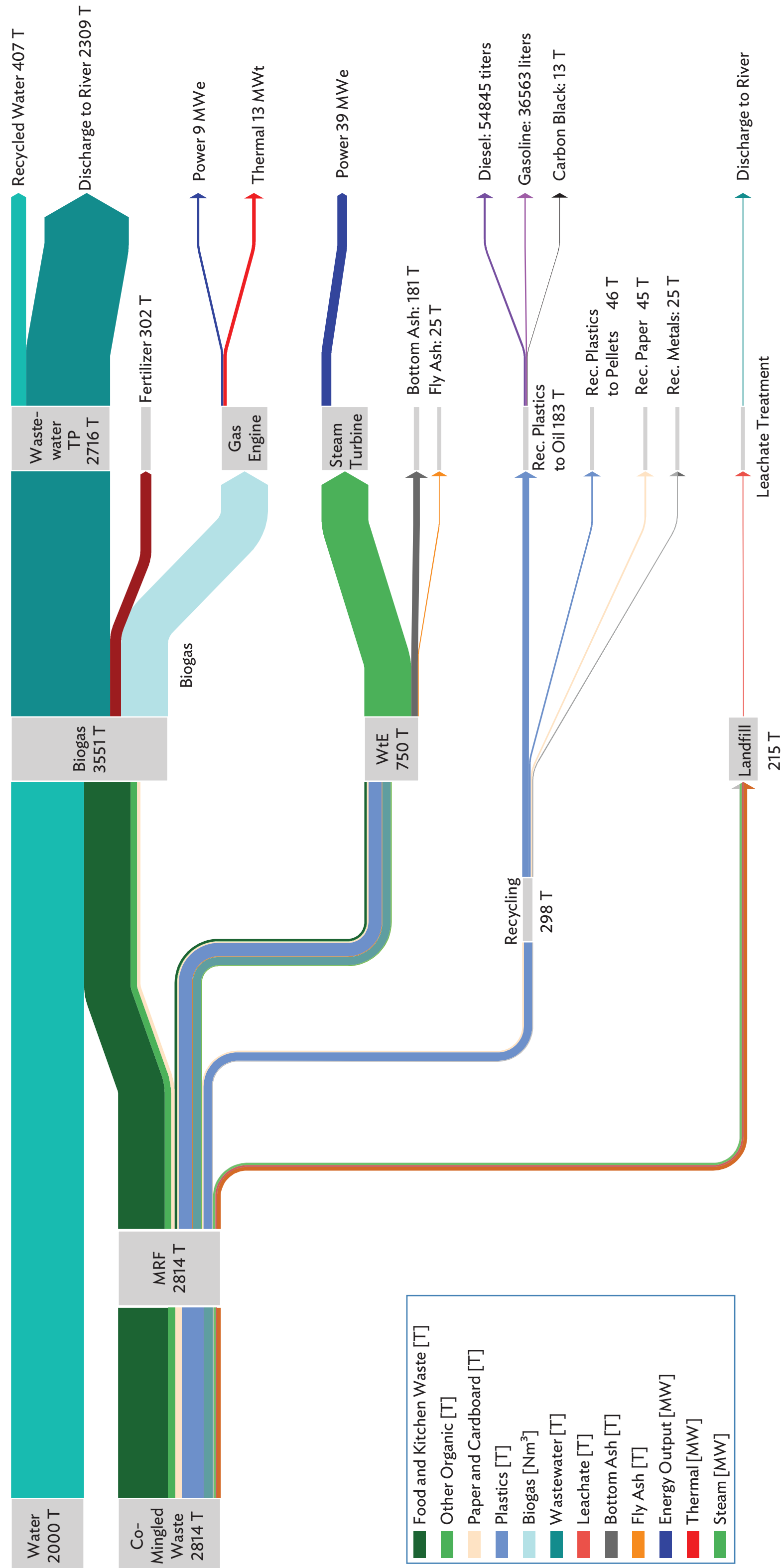
ADB = Asian Development Bank, AF = alternative finance source, C = collection, CNG = compressed natural gas, IFC = International Finance Corporation, LCEs = local commercial enterprises, LF = landfill, MOE = Ministry of Environment, MOF = Ministry of Finance, Ops = Operations, PPP = public–private partnership, RDF = refuse-derived fuel, SA = Site A, SB = Site B, SACo = Site A Company, SBCo = Site B Company, WtE = waste to energy.
Source: Asian Development Bank internal training material.

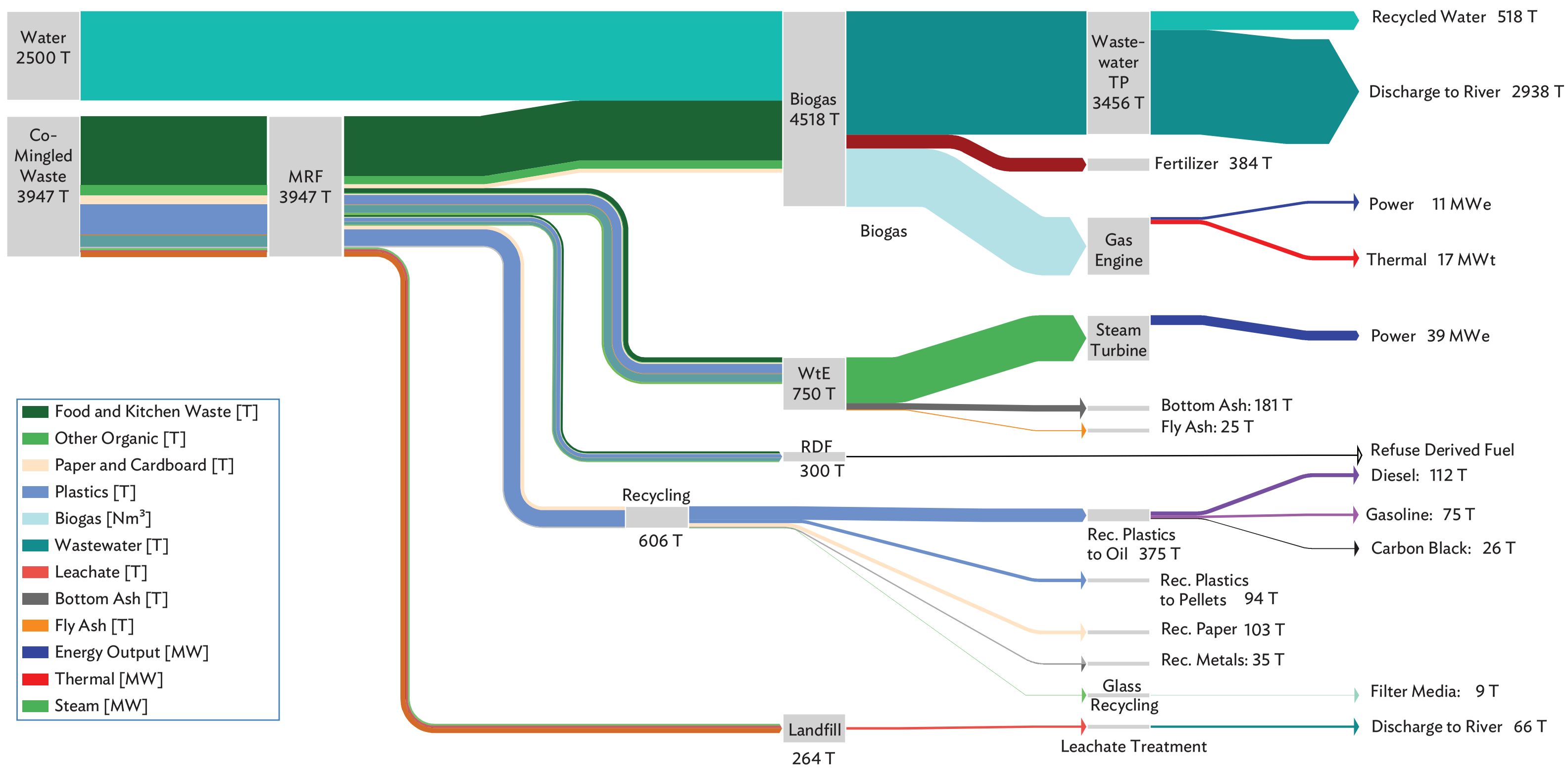
Figure 24: Optimal Waste Flows under Proposed Concession Model (2021 Projection)



MRF = material recovery facility, MWe = megawatt electrical, MWt = megawatt thermal, T = tonnes, TP = treatment plant, WtE = waste to energy.

Source: Asian Development Bank internal training material.

Figure 25: Optimal Waste Flows under Proposed Concession Model (2030 Projection)



MRF = material recovery facility, MWe = megawatt electrical, MWt = megawatt thermal, RDF = refuse-derived fuel, T = tonnes, TP = treatment plant, WtE = waste to energy.

Source: Asian Development Bank internal training material.

6 CONCLUSIONS

Waste to energy (WtE) is a set of transformational processes that can be applied in a project-specific manner to achieve outcomes for energy production, waste minimization, environmental outcomes, and can also create thriving secondary markets for reused, recycled, and upcycled materials. The technology can be used in both smart cities and thriving rural economy to promote a more circular economy.

This handbook has shown a number of examples of technologies with significant benefits to the project stakeholders. The development of the industry has been hindered by the technocratic presentation of materials and failure to elucidate an economic and developmental rationale for its adoption.

The limited number of emerging enterprises have struggled with funding and operational issues. This has created a perception of the segment being fraught with difficulty. Innovation in risk allocation and financing will shorten the journey to a realized project with positive cash flows. However, caution needs to be applied in the capacity planning and assumptions for infrastructure with a life span of 20 to 40 years.

For more information on the circular economy and how it is transformed business processes internationally, the Ellen McArthur Foundation has excellent resources.[67]

We hope this handbook has proved to be a useful resource to the reader.

[67] Ellen MacArthur Foundation. What is a circular economy? A framework for an economy that is restorative and regenerative by design. https://www.ellenmacarthurfoundation.org/circular-economy/concept.

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Waste to Energy in the Age of the Circular Economy

Best Practice Handbook

This handbook features best practices for integrating waste to energy and related technologies into the operations of various industries. It discusses current technologies, presents a conceptual example of municipal solid waste planning, and provides commentary on waste-to-energy initiatives. The importance of appropriate infrastructure as well as flexibility and openness to technologies and business models is emphasized. The handbook—and its complementary compendium of 18 projects—aim to support the efforts of developing countries in Asia and the Pacific to deploy and scale up technologies relevant to the circular economy.

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