

Beyond greenhouse gases - a natural capital-based sustainability assessment framework for the waste-to-energy approach


Chor-man Lam and Anthony Man-yin Keung

AECOM Asia Company Limited, Hong Kong, People's Republic of China

ABSTRACT

Although greenhouse gas (GHG) emissions and marine plastic reduction have been recognised as essential factors for the sustainability performance of waste-to-energy (WTE) facilities, there is a lack of comprehensive evaluation tool for quantifying the environmental, social and economic impacts caused by WTE projects. To fill the gap, this study developed a natural capital-based sustainability assessment (NCSA) framework for evaluating the sustainability of WTE projects. The merits of the NCSA framework include (1) the quantification of the benefits caused by the avoidance of marine plastic pollution by WTE projects, and (2) an inclusive sustainability evaluation framework that holistically assesses the environmental, social and economic performance associated with GHG and marine plastic reduction. The NCSA framework has been demonstrated in the case study on the Sanya WTE Project. The results showed that the Sanya WTE Project emitted 265,376 tonnes of CO₂e of GHG and prevented 28,242 - 75,312 tonnes of marine plastic during the study period, which is equivalent to a net benefit of CNY41.90 million - 464.45 million. The case study demonstrated that the NCSA framework is a comprehensive evaluation tool that provides clear and sound results for guiding decisions towards sustainable waste management and the overall sustainability of cities.

KEYWORDS Waste-to-energy; MSW management; greenhouse gas assessment; marine plastic pollution; blue economy; natural capital assessment; sustainability assessment

CONTACT Anthony Man-yin Keung  anthony.keung@aecom.com

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1. Introduction

1.1. Waste-to-energy approach for municipal solid waste management

Global municipal solid waste (MSW) generation has increased massively due to rapid population growth, urbanisation and economic development. The World Bank estimates that the global generation of MSW is 2.01 billion tonnes annually and is expected to increase to 3.40 billion tonnes by 2050 (Kaza et al., 2018). Based on the waste generation rate, waste composition and waste management approach, it was estimated that 1.6 billion tonnes of CO₂-equivalent (tCO₂e) of greenhouse gases (GHGs) were emitted from waste treatment globally in 2016 and the amount could grow to 2.6 billion tCO₂e by 2050 (Kaza et al., 2018). Waste management has evolved over the years, from treatment and disposal approaches with hygienic considerations as the prime objective, to more complex and advanced technologies aiming to achieve carbon reduction, resource recovery and energy recovery (Brunner and Rechberger, 2015; Tabata, 2013). Waste-to-energy (WTE) facilities adopting MSW incineration play an essential role in the evolution of waste management, not only by reducing the waste volumes, but also through energy recovery from waste to substitute a portion of energy consumption derived from fossil fuels (Makarichi et al., 2018). WTE is used for handling MSW primarily in high-capacity and land-constrained countries and regions. Generating more than 235 million tonnes of MSW in 2020 (MOHURD,

2021), China has become one of the world's largest waste generators (Statista, 2022). To alleviate the adverse environmental impacts from waste treatment, China is shifting towards wide application of WTE through waste incineration, and is currently one of the largest markets for WTE infrastructure. MSW treated by waste incineration in China increased from 15% in 2010 to 62% in 2020 (MOHURD, 2021).

Previous studies have revealed the adverse impacts caused by inadequate waste management, including leakage of plastic waste debris into the marine environment and GHG emissions (Jambeck et al., 2015; Ramachandra et al., 2018; Verster and Bouwman, 2020). WTE technologies not only avoid these environmental impacts, but also provide great potential for resource recovery. WTE projects could produce environmental benefits, such as GHG reduction through energy recovery (Tabata, 2013) and decreased quantities of plastic waste in the ecosystem (Evode et al., 2021), but at the same time the incineration process could cause potential adverse impacts on air pollution and human health (Beylot et al., 2018). Numerous studies have been conducted to evaluate the GHG emissions, life cycle environmental performance and sustainability of WTE incineration facilities.

1.2. Existing WTE evaluation frameworks

MSW incineration emits GHGs, while GHG reduction could be achieved through WTE energy recovery. From a carbon accounting perspective, if the GHG reductions

exceed emissions, the WTE project could be considered as a GHG reducer (Tabata, 2013). Systematic databases of detailed activity data and GHG calculation methods are critical for the sustainable management of WTE incineration plants (Lu et al., 2017). Tabata (2013) studied the carbon footprints of approximately 1,500 incineration plants in Japan and revealed that the plastic incineration and electricity savings are the two most influential factors for WTE plants to achieve net GHG reduction. The effectiveness of GHG reduction of waste incineration with energy recovery and landfill with landfill gas utilisation in China has been assessed (Wang et al., 2017). The results revealed that incineration is a more favourable option in temperate dry zones. A case study in Taiwan has been conducted to evaluate the energy recovery and GHG emission potentials of incineration of different waste types (Chen, 2018). Plastic waste generated the second-largest amount of energy and emitted the most GHGs from incineration among the different types of waste. Islam (2018) evaluated the electricity generation and GHG emission potentials of six waste management scenarios in Bangladesh, and revealed that treating all MSW by incineration with energy recovery is the most climate-friendly option in Bangladesh. Waste incineration has shown the second-highest energy recovery potential among the various WTE technologies in Korea (Yi et al., 2018).

To holistically investigate the environmental performance of WTE plants, life cycle assessments (LCAs) have been conducted to reveal the environmental impact categories other than GHG emissions. Within the 315 LCA studies on WTE technologies reviewed by Mayer et al. (2019), five impact categories were assessed on average. Most of the LCA studies investigated the impact categories of global warming, eutrophication and acidification; over half of the reviewed studies investigated toxicity, respiratory effects, and energy and resources (Mayer et al., 2019). Beylot et al. (2018) studied the environmental performance of the MSW incineration sector in France using LCA. Numerous LCA studies revealed that MSW incineration is more favourable than landfilling in terms of GHG footprint, while some studies reported opposite results (Anshassi et al., 2021). The discrepancies mainly rise due to parameters including landfill gas collection rate, portion of plastic waste in MSW composition and fuel mix of grid electricity (Anshassi et al., 2021).

Multi-criteria analysis has been used as a common tool to assess the sustainability of waste management systems and WTE technologies. An analytic hierarchy process was used to evaluate the sustainability of different MSW management alternatives, including WTE through incineration, in Serbia (Milutinović et al., 2014) and in Vietnam (Hoang and Fogarassy, 2020). Multi-criteria decision analysis was conducted to evaluate the three dimensions of sustainability, namely the economic, environmental and social aspects, of four WTE options (Khan and Kabir, 2020).

1.3. Natural capital assessment as the decision-supporting tool

Despite the numerous GHG, LCA and sustainability studies on the WTE approach for MSW management, the following research gaps were observed. Although marine debris reduction is one of the major benefits achieved by WTE approaches (Lin and Nakamura, 2019), there is a lack of tool for quantifying the consequences of marine plastic reduction regarding the overall sustainability. Also, a comprehensive sustainability assessment framework for evaluating the essential sustainability performance parameters, namely GHG emissions and marine plastic reduction (Anshassi et al., 2021; Lin and Nakamura, 2019; Tabata, 2013), is currently not available.

To fill the research gap, the natural capital framework is identified as a holistic tool to assist decision-making through linking the ecological, economic and social well-being perspectives (Bateman and Mace, 2020; Leach et al., 2019). Natural capital refers to the biotic and abiotic components of ecosystems that contribute to the generation of goods and services of value for people. The marine environment and marine ecosystem services are examples of natural capital, providing ecosystem services, such as food production, habitats for species, tourism, and recreation. To evaluate the consequences of human activities on the marine environment, the environmental, economic and social impacts shall be investigated and, where possible, quantified in monetary terms.

1.4. Aim and objectives

This study aims to develop a natural capital-based sustainability assessment (NCSA) framework to evaluate the sustainability performance of WTE incineration projects, with a particular focus on GHG emissions and marine plastic pollution. The NCSA framework is demonstrated through a case study in which the GHG emissions and natural capital benefits from the reduction of marine plastic pollution of a WTE project are quantified. The framework developed in this study is widely applicable to WTE projects worldwide and the findings will facilitate the sustainable development of the waste management sector.

2. Scope and data

A case study was conducted on the Sanya WTE Project owned and operated by China Everbright Environment Group Limited. The selection of WTE project for the case study was based on the following criteria: (1) proximity to the coastal marine environment, and (2) representativeness in terms of treatment technology and WTE operations. As the majority of land-based sources of plastic waste entering the ocean comprise MSW generated

by the coastal population, the Sanya WTE Project, as a WTE project in the coastal area, could have the potential to prevent part of the plastic waste from entering the marine environment. Given that the Sanya WTE Project has a large waste processing capacity (2,850 tonnes per day) and has been recognised as a national AAA-rated WTE project and “PPP Demonstration Project”, it was selected for this case study to demonstrate the potential benefits of WTE projects.

The scope of this case study covers the evaluation of the GHG emissions and marine plastic pollution of the Sanya WTE Project (“Project Scenario”) and the scenario without such project (“Baseline Scenario”). The evaluation was conducted to assess the performance of the Project Scenario by comparing it to the Baseline Scenario to reveal additionality.

2.1. Sanya WTE project

The Sanya WTE Project is located in the north of Sanya City, Hainan Province, and occupies a land area of 120,800 m². The Sanya WTE Project consists of three phases, with the designed capacity of 700 tonnes/day, 350 tonnes/day and 1,800 tonnes/day, respectively. With a combined designed waste treatment capacity of 2,850 tonnes/day, the Sanya WTE Project is a key waste treatment facility and the only WTE facility in Sanya City.

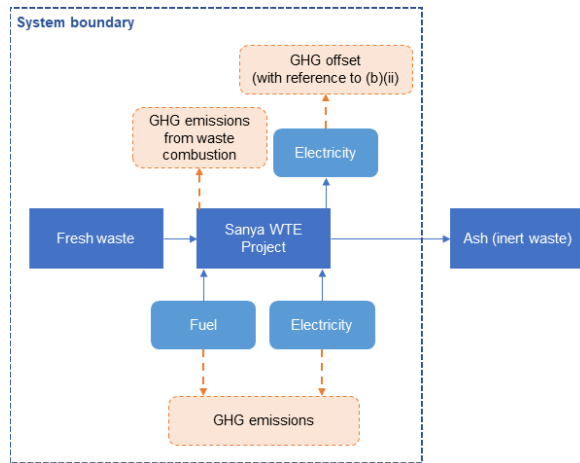
The core technologies adopted in the Sanya WTE Project include moving grate incineration, waste heat recovery, dry + semi-dry flue gas treatment systems and selective non-catalytic reduction (SNCR) systems.

2.2. Baseline Scenario and Project Scenario

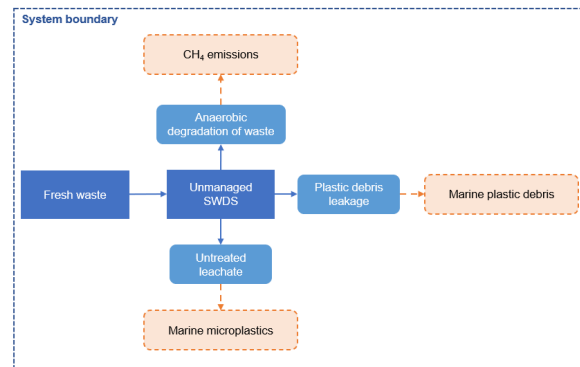
Figure 1 shows the system boundaries, which shows the processes and environmental impacts included in the evaluation scope of this study.

Figure 1(a) represents the Project Scenario, in which the MSW in Sanya is treated by the Sanya WTE Project. The MSW collection rate in Sanya is 100%, implying that there is no observable littered or illegally dumped MSW and the waste treatment by WTE projects is considered to be adequately managed; thus, the Project Scenario would not result in leakage of waste into the marine environment. The combustion of all the MSW, including plastic waste, in the Sanya WTE Project prevents the leakage of macroplastic (plastic debris) and microplastic into the marine environment. The GHG emissions from waste combustion, fuel consumption and grid electricity consumption were also evaluated. The GHG offsets through electricity generation from waste incineration were estimated as the avoided grid electricity generation from fossil fuel as used in the Baseline Scenario (Figure 1(c)).

(a) Project Scenario - waste treatment by Sanya WTE Project



(b) Baseline Scenario - waste treatment without Sanya WTE Project



(c) Baseline Scenario - grid electricity generation using fossil fuels

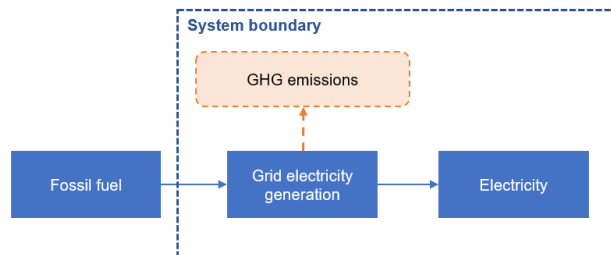


Figure 1. Project Scenario and Baseline Scenario of this study.

Figure 1(b) and 1(c) represents the Baseline Scenario, i.e. the scenario without the Sanya WTE Project. The design capacity of the Sanya sanitary landfill is 2.68 million tonnes throughout its 16-year design life from 2009 to 2025. However, the quantity of MSW disposed of at the Sanya Landfill reached 3.35 million in 2020. Considering that the capacity of the Sanya Landfill has already been exhausted, there is no spare capacity for waste disposal at the engineered landfill, and the Baseline Scenario assumes waste disposal in an unmanaged solid waste disposal site

(SWDS). It is widely recognised that land-based sources, including mismanaged MSW, contribute to a significant portion of plastic debris in the marine environment. The landfill leachate system is also one of the major pathways of microplastics entering the aquatic environment. In this case study, the plastic debris and microplastics leaking into the marine environment from unmanaged SWDS were accounted for in the Baseline Scenario. The methane emissions from anaerobic degradation of organic waste in the SWDS were also evaluated.

By comparing the Project Scenario and the Baseline Scenario to reveal additionality, the environmental impacts and benefits brought by the Sanya WTE Project were evaluated.

3. Methodology - natural capital-based sustainability assessment

3.1. Natural capital-based sustainability assessment framework

The understanding of natural capital provides a comprehensive framework for assessing the environmental effects of different policies, projects and human activities, and their externalities, such as air pollution, waste, and GHGs. The NCSA framework developed in this study is in line with the mechanisms for implementation of the natural capital approach within the UK policy framework (DEFRA, 2021; HM Treasury, 2022).

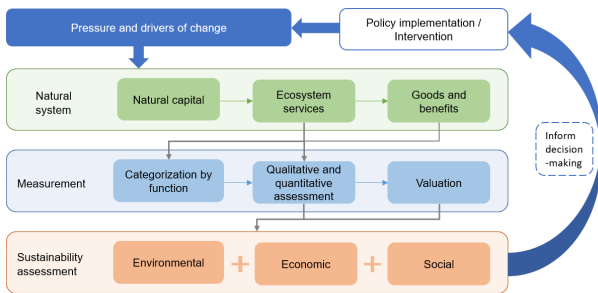


Figure 2. Framework of natural capital-based sustainability assessment.

Figure 2 presents the general framework of NCSA in this study. The NCSA framework investigates the effects of the pressure and drivers, such as increased plastic waste generation from the continuous increase in population and tourists, on the natural system. The natural system includes three key elements, namely natural capital, ecosystem services, and goods and benefits. Natural capital stocks and assets could include a broad range of components in the natural environment. This study follows the classification of the UK National Ecosystem Assessment to define the habitat types, which include the marine environment. The marine habitat supports biodiversity and aquaculture, as

well as offering opportunities for tourism and recreation. The marine environment also provides regulating functions through carbon and nutrient cycling. These goods and benefits could include edible fish, wild species, income from tourism, pleasant experience in recreational activities and other benefits to human well-being.

The two stressors caused or avoided by the WTE project in this study are GHG emissions and marine plastic pollution.

3.2. Greenhouse gas emissions

The GHG emissions of the WTE project were estimated based on the Clean Development Mechanism (CDM) *Large-scale Consolidated Methodology: Alternative waste treatment processes (ACM0022)* (UNFCCC, 2021).

The Sanya WTE Project avoids methane (CH₄) emissions associated with organic waste disposal in an SWDS and displaces electricity in a grid through electricity generation from waste incineration. The GHG emissions from decomposition of waste at SWDS and electricity generation were included in the Baseline Scenario. The GHG emissions from on-site fuel consumption, purchased electricity consumption and waste incineration were evaluated in the Project Scenario.

3.2.1. Baseline GHG emissions

The baseline emissions in this case study are determined according to Equation (1) and comprise the following components:

- Methane emissions from the SWDS in the absence of the WTE project, and
- Emissions from electricity consumed by the grid in the absence of the WTE project.

$$BE_y = (BE_{CH_4,y} + BE_{EC,y}). \tag{1}$$

Methane generation from SWDS due to decomposition of disposed waste was calculated using a first-order decay (FOD) model.

The baseline methane emissions from SWDS were calculated using Equation (2).

$$BE_{CH_4,SWDS,y} = \phi_y \times (1 - f_y) \times GWP_{CH_4} \times (1 - OX) \times \frac{16}{12} \times F \times DOC_{f,y} \times MCF_y \times \sum_{x=1}^y \sum_j (W_{j,x} \times DOC_j \times e^{-k_j \times (y-x)} \times (1 - e^{-k_j})). \tag{2}$$

The baseline emissions from generation of electricity ($BE_{EC,y}$) were calculated as follows:

$$BE_{EC,y} = EC_{BL,y} \times EF_{EF,y} \times (1 + TDL_y). \tag{3}$$

3.2.2. Project GHG emissions

The project emissions of the Sanya WTE Project from incineration were calculated as follows:

$$PE_{INC,y} = PE_{COM,INC,y} + PE_{EC,INC,y} + PE_{FC,INC,y} + PE_{ww,INC,y} . \quad (4)$$

The GHG emissions, which include carbon dioxide and small amounts of methane and nitrous oxide, from combustion in incinerators were estimated as follows:

$$PE_{COM,INC,y} = PE_{COM,CO_2,y} + PE_{COM,CH_4,N_2O,y} . \quad (5)$$

The project emissions of CO₂ associated with incineration were calculated based on the fossil carbon content of each type of sorted waste fed into the incinerators.

$$PE_{COM,CO_2,INC,y} = EF_{COM,INC,y} \times \frac{44}{12} \times \sum_j Q_{j,INC,y} \times FCC_{j,y} \times FFC_{j,y} . \quad (6)$$

The project emissions of CH₄ and N₂O from combustion in incinerators were relatively insignificant, and were estimated using the default emission factors as follows:

$$PE_{COM,CH_4,N_2O,INC,y} = Q_{waste,INC,y} \times (EF_{N_2O,INC} \times GWP_{N_2O} + EF_{CH_4,INC} \times GWP_{CH_4}) . \quad (7)$$

The project emissions from purchased electricity consumption of waste incineration were calculated using the CDM *Methodological tool (TOOL05)* as follows:

$$PE_{EC,y} = \sum_k EC_{P,j,y} \times EF_{EF,y} \times (1 + TDL_y) . \quad (8)$$

The project emissions from fossil fuel combustion associated with incineration were calculated using the CDM *Methodological tool: Tool to calculate project or leakage CO₂ emissions from fossil fuel combustion* (UNFCCC, 2017a)

$$PE_{FC,y} = \sum_i FC_{i,y} \times COEF_{i,y} \quad (9)$$

3.3. Prevention of marine plastic pollution

This study focuses on the impacts of plastic pollution on the marine environment and the ecosystem services that it provides. Marine plastic pollution is identified as the driver of changes in natural capital assets. MSW treatment by the Sanya WTE Project is recognised as the intervention to prevent marine plastic pollution. This section outlines the approach to quantify the contribution of the Sanya WTE Project to the reduction in the leakage of plastic waste into the marine environment.

3.3.1. Waste quantity

To obtain the annual quantity of MSW treated by the Sanya WTE Project, monthly monitoring data from July 2021 to June 2022 (the “Study Period”) were collected. The Sanya WTE Project treated 907,630 tonnes of MSW in the Study Period.

3.3.2. Waste sampling and waste composition analysis

Waste sampling was carried out on a quarterly basis during July 2021 to June 2022. Random sampling was conducted to collect samples from two Refuse Collection Vehicles (RCVs) entering the Sanya WTE plant. One sample was obtained from each RCV according to the following sample preparation steps (*CJ/T 313-2009: Sampling and Analysis Methods for Domestic Waste*). The waste samples were analysed for physical composition according to the *CJ/T 313-2009: Sampling and Analysis Methods for Domestic Waste*.

3.3.3. Percentage of plastic waste leakage into the marine environment

The amount of land-based plastic waste entering the ocean originates from the mismanaged portion of MSW from coastal cities, as revealed in previous scientific research studies (Jambeck et al., 2015; Law et al., 2020). Mismanaged waste investigated in this case study includes inadequately managed waste, litter and illegal dumping.

To estimate the proportion of inadequately managed waste, widely adopted waste management practices were reviewed. Waste management practices based on the World Bank’s classification include open dumping, anaerobic digestion, landfilling, incineration, composting, other advanced methods, and recycling (Kaza et al., 2018). Properly managed landfilling, anaerobic digestion, incineration, composting, other advanced methods, and recycling were considered to be “adequately managed”, while open dumping and improperly managed landfilling were considered to be “inadequately managed”. In this case study, the MSW handled by the Sanya WTE Project in the Project Scenario was considered to be adequately managed. MSW in the Baseline Scenario was considered inadequately managed as the designed capacity of the Sanya Landfill has already been used up.

The waste collection rate in Sanya is 100%, according to the “13th Five-Year Plan on the Construction of Urban Domestic Waste Harmless Treatment Facilities in Hainan Province”, thus implying that there is no observable littered or illegally dumped waste.

3.3.4. Percentage of mismanaged waste entering the marine environment

The percentage of mismanaged plastic waste entering the ocean varies and depends on multiple factors, such as topography, weather conditions and vegetation. This study does not aim to calculate the exact amount of marine plastic debris prevented by WTE facilities, but to obtain an estimate to provide a basis for the environmental evaluation of WTE projects. A range of 15% to 40%, which is consistent with previous research studies (Jambeck et al., 2015), is used in this study to obtain an approximation of marine plastic debris from land-based sources.

3.3.5. Estimation of plastic waste leakage into the marine environment

The amount of marine plastic debris was estimated using the following equation:

$$q_{MPD} = Q_{WTE} \times f_p \times f_{mw} \times p_{marine}. \quad (10)$$

The fraction of mismanaged waste (f_{mw}) is calculated as follows:

$$f_{mw} = f_{im} + f_{la}. \quad (11)$$

3.3.6. Estimation of microplastic pollution from landfill leachate

Microplastics are fragments of plastic less than 5 mm in length. Primary microplastics include intentionally manufactured microbeads in health and beauty products, cleansers and toothpastes, while secondary microplastics originate from the degradation of larger plastic debris into smaller pieces. The most essential sources of marine plastic pollution are coastal cities, landfills and dumping sites (Alfaro-Núñez et al., 2021). More specifically, landfill leachate has been identified as one of the major pathways of microplastics entering the environment (He et al., 2019; Sun et al., 2021).

In this case study, the microplastic entering the marine environment from SWDS leachate was estimated in the Baseline Scenario. The leachate generation rate from MSW disposal in SWDS was estimated based on the *Feasibility Study on the Concessions Build-Operate-Transfer (BOT) Project of the Sanya Landfill Leachate Treatment Facility*. Considering the local daily precipitation rate and the water content of MSW, the leachate generation rate was calculated as 0.24 m³/tonne of MSW. Based on sampling and laboratory tests conducted for an MSW landfill in China with similar load capacity as the Sanya Landfill, the microplastic particle and mass concentrations in the MSW landfill leachate were revealed to be 235.4 items/L and 11.4 µg/L (Sun et al., 2021).

In the Project Scenario, MSW is incinerated in the Sanya WTE Project, thus preventing leachate generation and microplastic pollution from landfill disposal of waste.

3.4. Measurement of ecosystem services

To assess the impact of changes in natural capital, ecosystem services are categorised based on their functions. Extensive review has been conducted on the ecosystem services and goods provided by the marine environment. According to the Common International Classification of Ecosystem Services (CICES) and the Green Book (EEA, 2022; HM Treasury, 2022), ecosystem services are categorised into three major sections by their function, namely *provisioning, regulation and maintenance*, and

cultural sections. Then the ecosystem services are further divided into divisions, groups and classes (DEFRA, 2019; EEA, 2022).

3.5. Sustainability assessment

The impacts of the Sanya WTE Project on sustainability, including the environmental, economic and social aspects, were evaluated in this study. The environmental impacts in terms of GHG emissions and marine plastic prevention were evaluated using the approach as described in Section 3.2 and Section 3.3. The socio-economic impacts of the changes in natural capital assets and ecosystem services were further divided into tangible and intangible impacts. The tangible impacts, such as impacts on aquaculture production and tourism, were monetised into economic values. Intangible impacts, such as effects on the level of enjoyment in regard to recreational experience and the intrinsic value of wild species, were investigated qualitatively.

This study conducted the quantification and valuation of ecosystem services based on government documents and statistical data from the Government of Sanya, Hainan, and a literature review. For some of the ecosystem services (e.g. regulation and maintenance and cultural services) which do not typically have direct market values, valuation should be conducted as far as possible to monetise the effects. Unmonetised factors should be treated as recommended for all interventions (HM Treasury, 2022).

4. Results and discussions

4.1. GHG emissions

During July 2021 to June 2022, the Sanya WTE Project emitted 486,774 tCO₂e of GHG. The major source of GHG emissions from the Sanya WTE Project was emissions from waste combustion, which contributed 99% of the project emissions. Most of the GHG emissions from waste combustion originated from the plastic waste portion. Plastic waste made up more than one-fifth of the total waste quantity received by the Sanya WTE Project. Among the different types of waste in MSW, plastic waste has the highest total carbon content and fossil carbon content, which is 75% by dry weight. Around 88% of the GHG emissions from waste combustion, equivalent to 427,890 tCO₂e of GHG, originated from the combustion of plastic waste.

The Sanya WTE Project avoided 221,398 tonnes of GHG through electricity generation from waste combustion and the avoidance of landfill gas emissions, resulting in remaining GHG emissions of 265,376 tonnes of GHG in the Study Period.

The breakdowns of GHG emissions and offset are summarised in Table 1.

Table 1. GHG emissions and offsets of the Sanya WTE Project.

GHG emissions / Offsets	Sources	Emissions (tonnes CO ₂ e)
GHG Emissions	Combustion of fossil content of waste	483,777
	Purchased electricity consumption	94
	Fossil fuel consumption	2,904
	Total emissions	486,774
GHG Offsets	Avoided methane from SWDS	51,854
	Grid electricity displacement by WTE electricity generation	169,544
	Total offsets	221,398
Remaining GHG Emissions		265,376
GHG Emission Intensity (kgCO ₂ e/kWh of electricity supplied to grid)		1.51
Remaining GHG Intensity (kgCO ₂ e/kWh of electricity supplied to grid)		0.82

4.2. Prevention of plastic waste leakage into the marine environment

The estimation was based on the monitoring data of the Sanya WTE Project and the waste composition analysis conducted during July 2021 to June 2022. MSW composition, water content and plastic waste composition were derived from the waste composition analysis results by averaging the values obtained from the 16 samples during the period (UNFCCC, 2017b; UNFCCC, 2021).

4.2.1. Quantity of plastic waste

The quantity of MSW that would have been disposed of at SWDS without the Sanya WTE Project was 907,630 tonnes in the Study Period. To differentiate the portion of plastic waste in the MSW, waste composition analysis was conducted. Based on the average percentage of plastic waste of 25.48% found in the MSW generated from Sanya City, the quantity of plastic waste in the Study Period was 232,196 tonnes.

4.2.2. Types of plastic waste prone to leakage into the marine environment

Plastic waste composition analysis was conducted on the Sanya WTE to further reveal the relative abundance of different types of plastic in the MSW. Sixteen types of plastic and their relative abundance in the MSW samples are presented in Table A2 in Appendix A. Nine types of plastic waste are commonly found in the marine environment (UNEP, 2016), and thus in this study are considered to be prone to leakage into the marine environment.

The quantity of plastic waste that could have been leaked into the marine environment is 188,280 tonnes in the Study Period.

4.2.3. Quantity of plastic waste leaked into the marine environment

The MSW generated in Sanya is 100% collected for treatment; thus, there is no observable waste littered or illegally dumped. Considering that the design capacity of the Sanya MSW Sanitary Landfill has been exhausted, the Baseline Scenario in this study assumes the disposal of fresh MSW in an open dump without proper management. The portion of mismanaged plastic waste that would enter the marine environment was estimated to be 15% to 40%. Thus, the quantity of plastic waste that would have been leaked into the marine environment in the Baseline Scenario ranged from 28,242 - 75,312 tonnes in the Study Period.

4.2.4. Microplastic pollution from landfill leachate

The amount of microplastics entering into the environment from landfill leachate was estimated based on the approach described in Section 3.3.6. The amount of landfill leachate generated in the Baseline Scenario was estimated to be 217,831 m³ in the Study Period. The quantity and weight of microplastics entering the marine environment in the Baseline Scenario were $(5.13 \pm 0.37) \times 10^{10}$ plastic particles and 2.48 ± 0.17 kg respectively in the Study Period.

4.2.5. Total avoided marine plastic waste

This study revealed that the Sanya WTE Project is a successful solution to proper waste management in the city, resulting in a reduction of 28,242 - 75,312 tonnes of marine plastic debris in the Study Period. The Project also avoided $(5.13 \pm 0.37) \times 10^{10}$ plastic particles, or 2.48 ± 0.17 kg of microplastics entering the ocean from landfill leachate. Although the weight of microplastic reduction was relatively insignificant compared to the marine plastic debris of larger sizes, it is noteworthy that the large quantity of marine plastic particles could lead to serious impacts for marine organisms and subsequently affect human health along the food chain. Such achievement contributes to the reduction of marine pollution, which is one of the targets of the SDG 14. This also echoes with the call for action to tackle marine plastic pollution by various international organisations and national agencies, such as the EU, USEPA, and WBCSD.

4.3. Natural capital-based sustainability assessment findings

To evaluate the avoided impacts of plastic pollution on marine natural capital, the goods and benefits provided by the ecosystem services affected by the Sanya WTE Project were identified. This study covered the three main sections of ecosystem services (including provisioning, regulation

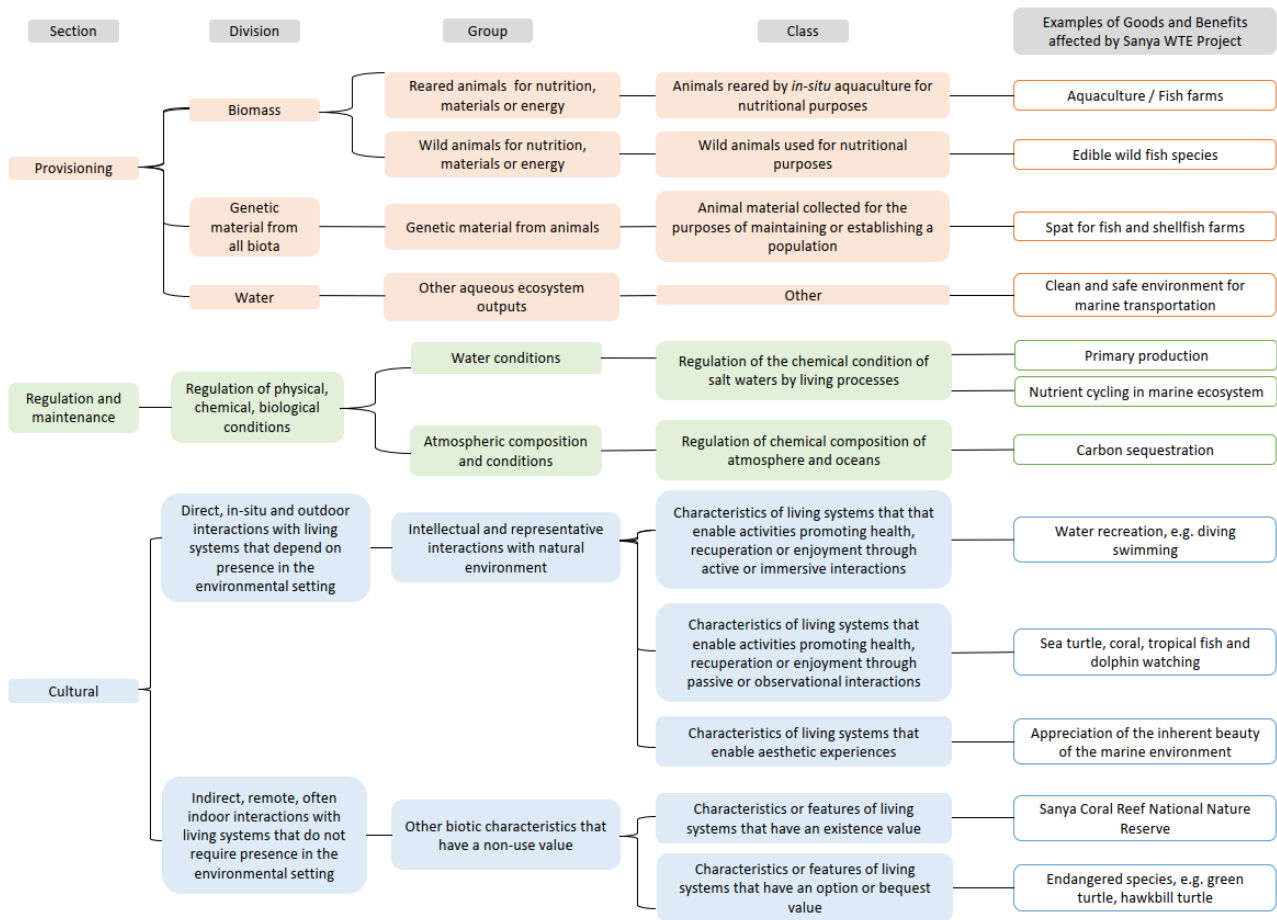


Figure 3. Summary of ecosystem goods and benefits covered in this study.

and maintenance, and cultural services) (EEA, 2022; Haines-Young and Potschin, 2018) and evaluated 12 types of goods and benefits (Figure 3).

Through the prevention of plastic waste leakage into the marine environment, the Sanya WTE Project contributed to maintaining the populations and diversity of edible aquatic species, which benefits the local fishery industry. The prevention of marine plastic pollution could reduce the potential adverse impacts on plankton communities, thus maintaining the regulating services, such as primary production, nutrient cycling and carbon sequestration, provided by the marine environment. The Sanya WTE Project also contributed to the conservation of biodiversity, including numerous coral, marine turtle, fish and marine mammal species, which provides cultural services that enhance human health and enjoyment. Table 2 summarises the effects of the Sanya WTE Project on the ecosystem goods and benefits provided by the marine environment.

The Sanya WTE Project also led to intangible environmental and social benefits, which brought intangible benefits of enhanced ecosystem health, human

health, capacity for climate change mitigation, as well as maintenance of existence, option and bequest value. These ecosystem services do not have direct market values and such unmonetised benefits were considered as qualitative recommendations in the natural capital-based sustainability assessment.

The avoided marine plastic pollution and the GHG emissions caused by the Sanya WTE Project, as well as their environmental consequences, were evaluated. The tangible environmental and social impacts were converted into economic costs and benefits through valuation. The net benefits from fisheries production, tourism, marine accident, waste clean-up and GHG emissions were CNY41.90 million - 464.45 million/year (Table 3).

The findings reveal that the Sanya WTE Project has generated CNY41.90 million - 464.45 million of benefits and other net intangible benefits every year. The results illustrate that the Sanya WTE Project is favourable to sustainable development and waste management in Sanya.

Table 2. Summary of the Sanya WTE Project’s effects on ecosystem goods and benefits.

Sections of ecosystem services	Ecosystem goods and benefits affected by the Sanya WTE Project	Descriptions	Effects of Sanya WTE Project
Provisioning services	Spat for fish and shellfish farms	Stocking of fry and spat are used for establishing a new population or replenishing the stock in fish and shellfish farms to reduce the cost of production.	The prevention of marine plastic pollution by the Sanya WTE Project could contribute to the conservation of a healthy marine environment, which supports the biodiversity and natural populations of different aquatic species.
	Fisheries	The fishery industry involves the obtainment of fish, through fish farming and fish catching, for the purpose of human consumption.	The prevention of marine plastic pollution contributes to the maintenance of the population of edible fish species, thus maintaining both the quality of the catch and the productivity of the fishery industry.
Regulation and maintenance services	Primary productivity	The marine phototrophic community contributes approximately 50% of global primary productivity and major biogeochemical and climatic cycles, and forms the base of the marine food web and food chain.	Reducing plastic pollution in marine waters could avoid the disruption of the normal photosynthetic function of marine phototrophic organism communities, which contributes to the maintenance of primary productivity and the overall health of the marine ecosystem.
	Nutrient cycling	The zooplankton and phytoplankton communities in the marine environment play an important role in nutrient cycling and regulating the oxygen content in the marine water.	If zooplankton replace some of their natural food with microplastics, disruption of the ecological system, such as increased algal blooms, and disruptions of the nutrient levels and oxygen content of the ocean water would be caused. The prevention of marine plastic pollution could contribute to maintaining the nutrient cycling and oxygen content in the marine environment.
	Carbon sequestration	The ocean is the largest active carbon sink on the planet. Carbon cycling occurs in the marine environment through the marine biological pump and microbial carbon pump regulated by phytoplankton and zooplankton activities.	Marine microplastics could affect the photosynthesis and growth of phytoplankton. Marine plastic reduction could reduce the negative impacts on phytoplankton and zooplankton, thus maintaining the carbon sequestration function of the marine environment.
Cultural services	Direct and <i>in-situ</i> interactions	The marine environment enables water recreational activities, such as swimming, diving and observation interactions, for enhancing human health and enjoyment.	Marine plastic reduction achieved by the Sanya WTE Project could reduce the adverse impacts on the following marine species, thus maintaining the cultural services provided by the biodiversity.
	Indirect and remote interactions	Indirect interactions allow people to realise the existence, option and bequest value of the living system. This could include things in nature that people think should be conserved and would like our future generation to enjoy.	<p>Corals</p> <p>Thirty-seven species of hermatypic corals, and three species of soft corals were recorded at three stations (Dongdao, Luhuitou, Dadonghai) in Sanya, which include <i>Pocillopora damicornis</i>, <i>Montipora informis</i>, <i>Pavona decussata</i>, <i>Porites</i> sp., <i>Galaxea fascicularis</i>, <i>Favia speciosa</i>, <i>Lobophyllia hemprichii</i>, <i>Turbinaria peltate</i>, <i>Hydnophora contignatio</i>, <i>Pseudosiderastrea tayamai</i>, <i>Sinularia</i> sp., <i>Briareum</i> sp. (Sun et al., 2018).</p> <p>Marine turtles</p> <p>Five species of marine turtle were found in Sanya and South Sea, the green turtle (<i>Chelonia mydas</i>), hawksbill turtle (<i>Eretmochelys imbricata</i>), loggerhead turtle (<i>Caretta caretta</i>), olive ridley turtle (<i>Lepidochelys olivacea</i>), and leatherback turtle (<i>Dermochelys coriacea</i>) (Chan et al., 2007).</p> <p>Fish</p> <p>A total of 243 species of fishes were captured by three kinds of nets in four cruises, including many edible species of high economic value such as <i>Clupanodon punctatus</i>, <i>Anchoviella</i> sp., <i>Saurida unduquamis</i>, <i>Trachinocephalus myops</i>, <i>Gerres filamentosus</i>, <i>Sparus berola</i>, <i>Epinephelus</i> sp., <i>Upeneus subvittatus</i>, <i>Trichiurus hau-mela</i> and <i>Inegocia guttatus</i>.</p> <p>Marine mammals</p> <p>In 2014, Indo-Pacific humpback dolphins (<i>Sousa chinensis</i>) were recorded for the first time in the waters southwest of Hainan Island.</p>

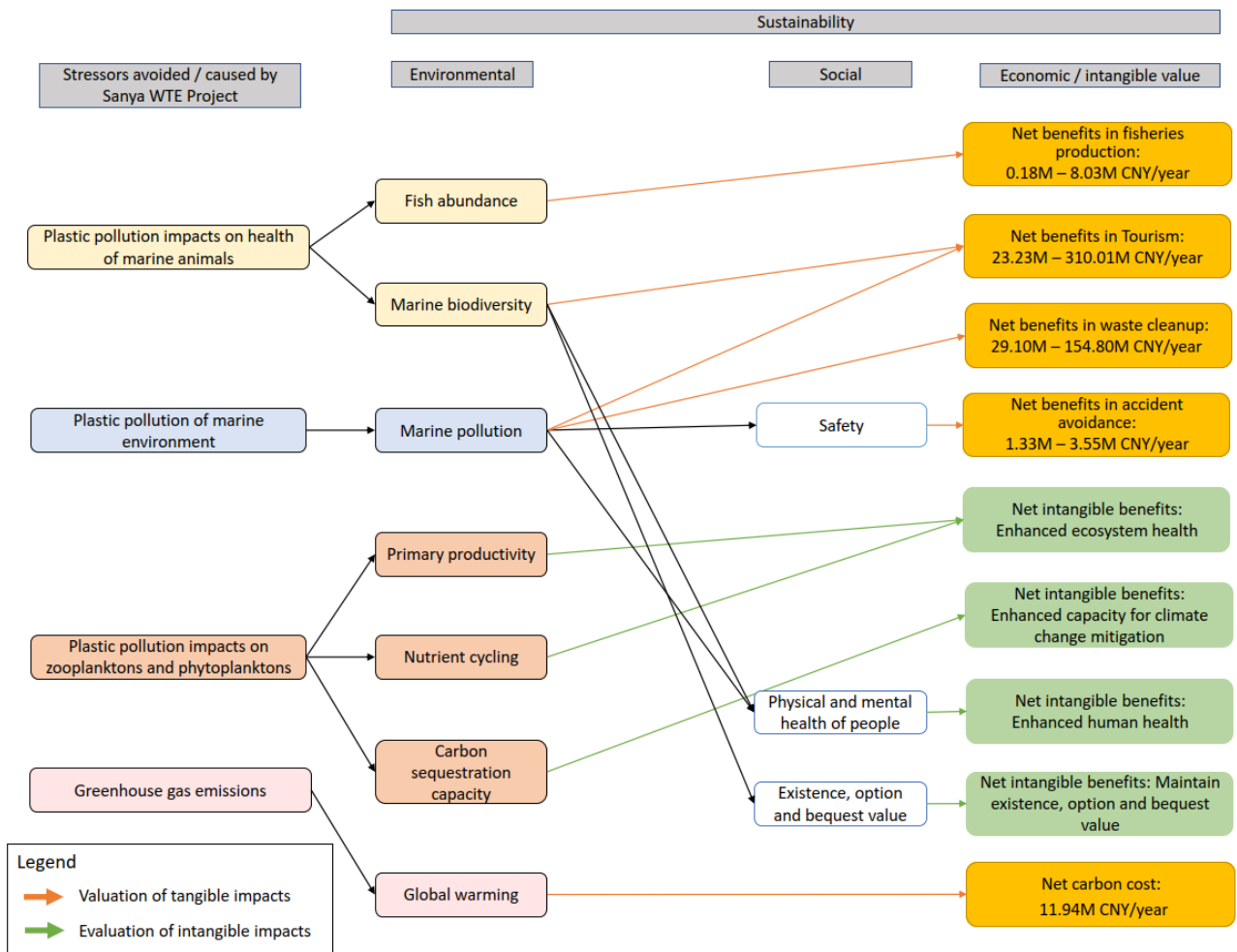


Figure 4. Summary of natural capital-based sustainability assessment of the Sanya WTE project.

Table 3. Summary of economic benefits from the Sanya WTE Project.

	Economic benefits (CNY Million/year)
Fisheries production	0.18 - 8.03
Tourism	23.23 - 310.01
Marine accident	1.33 - 3.55
Waste clean-up	29.10 - 154.80
GHG emissions	(-11.94)
Net benefits	41.90 - 464.45

5. Conclusions

This study developed an NCSA framework to holistically evaluate the environmental, economic and social impacts associated with the GHG emissions and marine plastic pollution prevented by WTE projects. The quantification of marine plastic reduction was based on multiple factors, including waste composition, relative

abundance of different types of plastic, waste collection rate and the waste management approach. The microplastics from landfill leachate were also evaluated based on the local weather conditions, leachate generation rate and concentrations of microplastics in the leachate samples of another sanitary landfill with similar loading capacity as the Sanya Landfill. GHG emissions were evaluated based on the CDM ACM0022 Methodology. Local data of Sanya city, Hainan Province, were collected and used in the calculation to reflect the actual conditions of waste management of the city.

The NCSA framework was demonstrated in the case study of the Sanya WTE Project. The Sanya WTE Project successfully prevented 28,242 - 75,312 tonnes of marine plastic debris from entering the marine environment from landfill leachate in the Study Period. A quantity of $(5.13 \pm 0.37) \times 10^{10}$ plastic particles, or 2.48 ± 0.17 kg of microplastics, were prevented from entering the marine environment from landfill leachate due to the presence of the Sanya WTE Project. In the same period, the project emitted 265,376 tonnes of GHG. Twelve ecosystem goods and benefits in three sections of the CICES classification

system were studied. The tangible impacts were monetised through valuation and the intangible impacts were evaluated qualitatively. The findings revealed that the Sanya WTE Project has brought a net benefit of CNY41.90 million - 464.45 million and other intangible benefits through the prevention of marine plastic pollution in the Study Period. The results illustrate that the Sanya WTE Project is favourable to sustainable development and waste management in Sanya.

The application of the NCSA framework for the sustainability evaluation of WTE projects has been demonstrated through the Sanya case study. NCSA is a first-of-its-kind sustainability evaluation framework for quantifying the GHG and marine plastic pollution impacts of WTE projects in terms of their environmental, social and economic consequences. The NCSA framework is widely applicable for evaluating WTE projects worldwide. The outcomes provide a comprehensive basis to guide decisions towards sustainability in the waste management sector.

A limitation of this study is that the favourability of the WTE approach compared to other waste management alternatives has not yet been evaluated. From a waste management decision supporting perspective, comparative life-cycle assessment could be conducted to compare the environmental performance of WTE projects with other waste management approaches. By inclusion of different environmental impacts in addition to marine debris and GHG emissions, the environmental performance of the waste management approaches could be evaluated more comprehensively. By showing the overall environmental performance of different waste management alternatives, the outcomes of comparative life-cycle assessments demonstrate scientific-based evidence in support of the implementation of waste management strategies to investors, government agencies and the general public.

Appendices

Appendix A

The waste samples were weighed to obtain sample weight (M). The waste in the samples was sorted into the following categories (Table A1).

Table A1. Waste categories.

	Waste Categories	Descriptions
1	Food	Remaining portion of animal-based and plant-based foods
2	Paper	Waste paper and paper products
3	Plastics	Waste plastic materials and products
4	Rubber	Waste rubber and leather
5	Textiles	Waste fabrics (including polyester), cotton, etc.
6	Vegetative waste	Waste wood, bamboo, trimmings
7	Ash and dust	Furnace ash, grey sand, dust, etc.
8	Ceramic waste	Waste bricks, clay tile, ceramics, rocks, cement, etc.

9	Glass	Waste glass and glass products
10	Metals	Waste metals and metal products (excluding button batteries)
11	Others	Waste batteries, paints, pesticides, etc.
12	Miscellaneous waste	Diameter < 10 mm, not included in the above categories

Waste of different categories was weighed to obtain the wet-based weights of the waste categories (M_i). The waste composition (wet-based) (C_i) is calculated as:

$$C_i = \frac{M_i}{M} \times 100. \quad (A1)$$

Different categories of waste were dried by heat drying for 4 to 8 hours and weighed for the dry-based weights (M'_i). The moisture content of a waste category ($C_{i(W)}$) and that of the waste sample ($C_{(W)}$) were calculated as:

$$C_{i(W)} = \frac{M_i - M'_i}{M_i} \times 100, \quad (A2)$$

$$C_{(W)} = \sum_{i=1}^n C_{i(W)} \times \frac{C_i}{100}. \quad (A3)$$

The waste composition (dry-based) (C'_i) is calculated as:

$$C'_i = C_i \times \frac{100 - C_{(W)}}{100 - C_{i(W)}}. \quad (A4)$$

The plastic waste in the MSW was further separated according to the types of plastic. Sixteen types of plastic and their relative abundance in the waste samples were analysed. The results of the plastic waste composition analysis are presented in Table A2.

Table A2. Relative abundance of plastic types in MSW.

Plastic types	Relative abundance	Found in the marine environment
Polyvinyl Chloride (PVC)	16.01%	Yes
High-density polyethylene (HDPE)	14.86%	Yes
Low-density polyethylene (LDPE)	11.26%	Yes
Polypropylene (PP)	16.07%	Yes
Polystyrene (PS)	8.14%	Yes
Acrylonitrile Butadiene Styrene (ABS)	8.81%	-
Polymethyl methacrylate (PMMA / Acrylic)	4.77%	Yes
Cellulose acetate (CA)	1.30%	Yes
Nitrocellulose (NC)	3.03%	-
Poly tetra fluoroethylene (PTFE / Teflon)	0.16%	-
Polyamide (Nylon)	4.45%	Yes

Polyethylene terephthalate (PET)	3.54%	Yes
Polycarbonate (PC)	2.08%	-
Polyoxymethylene (POM)	0.18%	-
Phenolic plastics	0.94%	-
Urea-formaldehyde (UF)	4.38%	-

Appendix B: Variables in equations

Equation (1)

- BE_y = Baseline emissions in year y (tCO₂e)
 $BE_{CH_4,y}$ = Baseline emissions of methane from the SWDS in year y (tCO₂e)
 $BE_{EC,y}$ = Baseline emissions associated with electricity generation in year y (tCO₂)

Equation (2)

- $BE_{CH_4,SWDS,y}$ = Baseline methane emissions occurring in year y generated from waste disposal at a SWDS during a time period ending in year y (tCO₂e/yr)
 ϕ_y = Model correction factor to account for model uncertainties for year y
 f_y = Fraction of methane captured at the SWDS and flared, combusted or used in another manner that prevents the emissions of methane to the atmosphere in year y
 GWP_{CH_4} = Global Warming Potential of methane
 OX = Oxidation factor (reflecting the amount of methane from SWDS that is oxidized in the soil or other material covering the waste)
 F = Fraction of methane in the SWDS gas (volume fraction)
 $DOC_{f,y}$ = Fraction of degradable organic carbon (DOC) that decomposes under the specific conditions occurring in the SWDS for year y (weight fraction)
 MCF_y = Methane correction factor for year y
 $W_{j,x}$ = Amount of solid waste type j disposed or prevented from disposal in the SWDS in the year x (t)
 DOC_j = Fraction of degradable organic carbon in the waste type j (weight fraction)
 k_j = Decay rate for the waste type DOC_f (1 / yr)
 y = Year of the crediting period for which methane emissions are calculated (y is a consecutive period of 12 months)
 x = Years in the time period in which waste is disposed at the SWDS, extending from the first year in the time period ($x = 1$) to year y ($x = y$)

Equation (3)

- $BE_{EC,y}$ = Baseline emissions from generation of electricity in year y (tCO₂ / yr)

- $EC_{BL,y}$ = Net amount of electricity generated by the project and exported to the grid in year y (MWh/yr)
 $EF_{EF,y}$ = Emission factor for electricity generation for grid consumption in year y (tCO₂/MWh)
 TDL_y = Average technical transmission and distribution losses for providing electricity to grid in year y

Equation (4)

- $PE_{INC,y}$ = Project emissions from incineration in year y (tCO₂e)
 $PE_{COM,INC,y}$ = Project emissions from combustion of fossil content of waste associated with incineration in year y (tCO₂)
 $PE_{EC,INC,y}$ = Project emissions from purchased electricity consumption associated with incineration year y (tCO₂e)
 $PE_{FC,INC,y}$ = Project emissions from fossil fuel consumption associated with incineration in year y (tCO₂e)
 $PE_{ww,INC,y}$ = Project emissions from the wastewater treatment associated with incineration in year y (tCH₄)

Equation (5)

- $PE_{COM,INC,y}$ = Project emissions from combustion within the project boundary associated with incinerators in year y (tCO₂e)
 $PE_{COM,CO_2,INC,y}$ = Project emissions of CO₂ from combustion within the project boundary associated with incinerators in year y (tCO₂)
 $PE_{COM,CH_4,N_2O,INC,y}$ = Project emissions of CH₄ and N₂O from combustion within the project boundary associated with incinerators in year y (tCO₂)

Equation (6)

- $EF_{COM,INC,y}$ = Combustion efficiency of incinerators in year y (fraction)
 $Q_{j,INC,y}$ = Quantity of MSW type j fed into incinerators the in year y (t)
 $FCC_{j,y}$ = Fraction of total carbon content in waste type j in year y (tC/t)
 $FFC_{j,y}$ = Fraction of fossil carbon in total carbon content of waste type j in year y (weight fraction)

Equation (7)

- $Q_{waste,INC,y}$ = Quantity of MSW fed into incinerators in year y

- $EF_{N_2O, INC}$ = Emission factor for N_2O associated with waste incineration ($tN_2O/twaste$)
- $EF_{CH_4, INC}$ = Emission factor for CH_4 associated with waste incineration ($tCH_4/twaste$)
- GWP_{N_2O} = Global Warming Potential of nitrous oxide (tCO_2e/tN_2O)
- GWP_{NCH_4} = Global Warming Potential of methane (tCO_2e/tCH_4)

Equation (8)

- $PE_{EC,y}$ = Project emissions from purchased electricity consumption in year y (tCO_2/yr)
- $EC_{PJ,y}$ = Quantity of electricity that would be consumed by the project from electricity grid in year y (MWh/yr)
- $EF_{EF,y}$ = Emission factor for electricity generation for grid consumption in year y (tCO_2/MWh)
- TDL_y = Average technical transmission and distribution losses for providing electricity to grid in year y

Equation (9)

- $PE_{FC,y}$ = CO_2 emissions from fossil fuel combustion in incineration during the year y (tCO_2/yr)
- $FC_{i,y}$ = Quantity of fuel type i combusted in incineration during the year y (mass or volume unit/yr)
- $COEF_{i,y}$ = CO_2 emission coefficient of fuel type i in year y ($tCO_2/mass$ or volume unit)
- i = Fuel types combusted in incineration during the year y

Equation (10)

- Q_{MPD} = Amount of plastic waste that will leak into the marine environment as marine plastic debris (tonne)
- Q_{WTE} = Quantity of MSW that would have been disposed of at SWDS without the WTE project (tonne)
- f_p = Percentage of plastic waste in MSW that is prone to leakage into the marine environment (%)
- f_{mw} = Fraction of mismanaged waste (%)
- p_{marine} = Percentage of mismanaged plastic waste that would enter the marine environment (%)

Equation (11)

- f_{im} = Fraction of inadequately managed waste (%)
- f_{id} = Fraction of littered or illegally dumped waste (%)

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Notes on contributors



Dr Chor-man Lam has a Ph.D. in Environmental Engineering and is an AECOM Project Environmental Consultant. Her research focuses on sustainability evaluation of waste and wastewater treatment strategies and technologies. She is experienced in life-cycle assessment, eco-efficiency analysis,

data envelopment analysis and agent-based modelling. In AECOM, she is responsible for greenhouse gas accounting, decarbonisation roadmap studies, circular economy studies and ESG reporting.



Mr Anthony Man-yin Keung is an Executive Director of AECOM with over 15 years of experience in waste management and services including waste planning, feasibility study, engineering design, due diligence, international development, climate change, and ESG.

Anthony's technical expertise includes waste-to-energy, anaerobic digestion, bio-treatment processes, waste transfer & disposal and recycling. On the other hand, Anthony leads corporate ESG advisory services at AECOM in Hong Kong. He has been serving as clients' key contact and the services delivered under his leadership include corporate sustainability/ESG reporting, greenhouse gas (GHG) inventory development, and dedicated support to clients in sustainability accolades application (e.g. Dow Jones Sustainability Index, CDP, GRESB, etc.).

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