Waste Trading System: managing waste with high population density and low sorting rate

Coline Metta-Versmessen*[1] and Julie Metta[2]

[1]LEDa Paris Dauphine University, Chaire Economie du Climat & EDF, Paris, France
[2]HIVA, & Cedon, Faculty of Economics and Business KU Leuven, Leuven, Belgium

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Abstract

Landfilling notoriously has environmental impacts, adversely affecting air, soil and water. It therefore represents a waste management strategy of last resort, and reducing the landfilling rate is essential to mitigating these externalities. Nevertheless, deploying this potential is difficult in the absence of citizen participation in sorting. To correct for these negative externalities and market failure, contemporary policy discussions so far mainly focus on taxation and thus largely overlook market-based solutions. In this study, we first discuss the conditions favouring the effectiveness of a C&T approach for MSW management. We identify five elements characterizing a C&T system for waste: cap definition, allocation of pollution permits, liquidity and market power, price volatility, and participant compliance; that we further investigate for the implementation of a WTS in large and populated urban areas. We subsequently applied our analysis to the specific case of Hong Kong. We determine the agents concerned, the optimal social cost of waste, the number of permits for the total period as well as its allocation method, together with the potential market design scenario with regard to the particularities of Hong Kong and its climate regulation in the broad sense.

Keywords : pollution regulation, quantity-based scheme, Hong Kong, permit allocation, market equilibrium, recycling, social cost of waste

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1 Introduction

Waste, when managed by landfilling, is a stock pollutant inducing negative externalities on the environment and society, encompassing loss of biodiversity[1], climate change,[2] health problems and social discomfort. The detrimental consequences of inefficient waste management underscore the need for more effective strategies, as highlighted by, among others, Hoornweg et al. (2013); Vaverková (2019); Wong (2022). The waste management sector has thus gained attention on the global policy stage. This recognition has, in turn, sparked a focus on the development of waste management chains by governments.

However, establishing and maintaining these chains can be a resource-intensive endeavor, often requiring substantial subsidies. Despite efforts to establish recycling infrastructure and waste-to-energy facilities, challenges lie in motivating citizens to actively participate in waste reduction, sorting and recycling programs. The limited citizen engagement in waste sorting poses a bottleneck for the effective implementation of waste management policies (Nainggolan et al., 2019). Without active participation from the public, the success of recycling initiatives may be hindered, possibly preventing the realization of policy objectives (Chung and Poon, 1994; Lo and Liu, 2018). There is a growing demand for the exploration and implementation of more effective policy instruments, potentially market-based, that encourage sustainable waste management practices while minimizing the financial burden on both the government and society (Chen and Lo, 2016; Das et al., 2019). Such instruments can help create a more economically viable and ecologically sustainable waste management landscape in the pursuit of climate policy objectives. Despite some studies showing the efficacy of Cap and Trade (C&T) over Command and control for a variety of pollutant, such as shale gas, (Milt and Armsworth, 2017), and even for regulating energy related emissions of households Shammin and Bullard (2009), existing literature and practices seem to focus on tax-based instruments and Command-and-Control approach, omitting the potential of a C&T policy for municipal solid waste (MSW).[3]

The objective of this study is therefore to examine the potential of a C&T approach to address externalities associated with MSW in densely populated urban areas. C&T is an instrument type characterized by the establishment of an emissions cap on total externalities by regulatory authorities, alongside the allocation and trading of permits among entities, fostering cost-effective reductions of externalities. We aim to explore the conditions and design parameters of Waste Trading System (WTS), with a specific focus on mitigating landfill disposal in contexts where recovering capacities mainly exist but citizen involvement in sorting is low.

We first discuss the conditions favouring the effectiveness of a C&T approach for MSW management.

[1]The United Nations reported waste as one key factor of biodiversity loss [UN.org] visited on November 30, 2022.

[2]Indeed, the waste sector is one of the highest emitters of greenhouse gas. In 2016, it was responsible for 3.2% of global emissions, right after the industry with 5.2% (Ritchie and Roser, 2020).

[3]MSW includes domestic, commercial and part of industrial waste.

We identify five elements characterizing a C&T system for waste: cap definition, allocation of pollution permits, liquidity and market power, price volatility, and participant compliance (Peng et al., 2022; Munnings et al., 2016); that we further investigate for the implementation of a WTS in large and populated urban areas. We subsequently applied our analysis to the specific case of Hong Kong. Indeed, The case of Hong Kong serves as a compelling illustration of market design for WTS, with a densely populated urban area and a low sorting rates leading to the ninth biggest landfill in the world.[4] We thus conducted a cost-benefit analysis to assess the most efficient policy tool according to an application of Weitzman's theorem to waste pollution externalities, and calculate its optimal social cost of municipal waste management.

The theoretical considerations developed in this study offer a comprehensive framework for understanding the dynamics of a WTS in large and densely populated urban area. By issuing permits for MSW landfilling, the WTS spurs waste reduction and sorting while accommodating the varying waste disposal needs of different entities. Our application to the case of Hong Kong shows that the primary challenge in managing MSW in the city stems from low citizen engagement in waste reduction and sorting. In response to this issue, we developed a Waste Trading System tailored to Hong Kong, covering various aspects such as key stakeholders, permit allocation methods, monitoring techniques, and associated penalties. Our analysis indicates that the optimal market price for one ton of MSW should surpass the existing MSW tax imposed in Hong Kong.

This paper contributes to the booming literature on MSW management by adding the C&T perspective. Economic literature generally favors tax-based approaches over Command-and-Control (CAC) tools for addressing environmental externalities (Hepburn, 2006; Requate, 2013), but the choice between them depends on cost and benefit uncertainties (Weitzman, 1974). In the context of Municipal Solid Waste (MSW) management, studies and practical implementations tend to lean towards taxation or subsidies, driven by social acceptance and efficiency considerations, especially in urban areas like Hong Kong (Cohen et al., 2017). The preference for taxation aligns with the price-versus-quantity debate, which depends on the relative slopes of cost and benefit functions, with taxation typically preferred when cost curves are steeper than damage functions. However, we demonstrate the potential of a C&T approach for MSW in the case of large and densely populated cities. The application to the case of Hong Kong, using a cost-benefits analysis, further demonstrates its potential effectiveness and design in a real-world setting, contributing to the development of innovative waste management policies that align with evolving global environmental agendas.

The paper is organized as follows. In Section 2, we clarify both the background and the motivation of our analysis. In Section 3, we outline the conditions favouring a C&T approach and characterize the Waste Trade System. In section 4, we apply that conceptual market-based waste management framework to the case of Hong Kong. Finally, we discuss the limitations of this model and provide conclusions in Section 5.

[4][World Atlas] visited on September 15, 2022.

2 Background and motivation

In this section, we provide a concise overview of the methods currently studied or applied for municipal waste management. We then review the existing the literature and examine the emerging applications of cap and trade (C&T) for the waste sector. Finally, we briefly characterize the specific features of waste management in dense and large cities, with the aim to clarify both the background and the motivation of our analysis.

2.1 Contemporary approaches in Municipal Solid Waste management

Different waste management practices and policies

Public authorities are implementing diverse strategies to reduce the disposal of MSW in landfills. they focus on two key aspects in their municipal waste regulation strategies: downstream waste treatment, aimed at reducing landfilling through tools like bans and restrictions, and upstream waste generation reduction, which relies on Extended Producer Responsibility (EPR) principles, making producers financially responsible for waste treatment costs. Defined by the OECD[5] as "an environmental policy approach in which a producer's responsibility for a product extends to the post-consumer stage of the product's life cycle," it aligns with the "polluter-pays principle". In theory, its objective is to integrate waste treatment costs into the production expenses of the waste. Within this framework, producers bear financial responsibility for their waste, while competent companies assume responsibility for its treatment (Gupt and Sahay, 2015).

Overall, international data[6] reveals that countries employing a combination of these instruments tend to be more effective in managing Municipal Solid Waste (MSW). Leading the way in MSW management are countries belonging to the Organisation for Economic Co-operation and Development (OECD), notably the European Union (EU), which has established stringent targets and instruments. Examples include Landfill Directive, which introduces standards for waste types and the authorized procedure for landfilling, or the Effort Sharing Regulation (ESR), according to which the greenhouse gases produced by landfills are regulated. These findings substantiate the conclusions of Alzamora and Barros (2020), who asserts that the most advanced waste management systems incorporate financial tools akin to the "pay as you throw" principle, fostering greater citizen engagement in MSW reduction efforts.

Insights from the literature

A vast literature has compared the merits and limitation of MBI (including tax, Cap and Trade C&T but also pricing, offsets, etc.) and CAC (Hepburn, 2006; Gómez-Baggethun and Muradian, 2015; Tang et al., 2019). MBI is often seen as more flexible and economically efficient approaches

[5] OCDE, visited on 12/09/22.

[6] See OECD (access on September 13th, 2023); EEA (2016); AgencyEEA (2017)).

to environmental regulation. Hepburn (2006) highlights that CACs are most suitable when there is certainty regarding costs and damages. However, this is seldom the case in the context of MSW management. In the context of Municipal Solid Waste (MSW) management, uncertainty can arise in estimating the environmental effects, costs, and behavioral responses associated with waste management practices and policies. It can be challenging to predict how specific waste components will interact with the environment over time. Supporting this perspective, Acuff and Kaffine (2013), Pearce and Turner (1993) and Goddard (1995) have conducted specific analyses on MSW management policies, reinforcing the inclination toward taxation or subsidies. Additionally, social acceptance play a role in the successful implementation of waste regulation, as underscored by Hong (1999) in the South Korean context and by Wan et al. (2014) for the Hong Kong case. In this regards, studies tend to indicate a preference among governments and industries MBI over CAC mechanisms in MSW management, particularly evident in the case of large and dense urban area (Wan et al., 2015).

MBI theoretically encompasses two instruments : taxation and C&T scheme. Yet, to the best of our knowledge, the latter instrument has so far little been considered in the literature. The preference for taxation over C&T can be contextualized within the theoretical debate of price versus quantity, rooted in the seminal work of Weitzman (1974), subsequently reinforced by Adar and Griffin (1976) and Fishelson (1976). They elucidate that, when uncertainties regarding cost and benefits, the choice between taxation and C&T depends on the relative slopes of the marginal cost and benefit functions. Specifically, a tax is preferable when the cost function exhibits greater steepness than the damage function, and vice versa.[7] If extensions [8] of the "Weitzman theorem" temper the previous conclusions, they mainly corroborate the general preference for price-based tools.

The literature on environmental policies (MBI and CAC) has primarily focused on carbon-related issues rather than local environmental challenges, such as waste landfilling. Thus, further research may be needed to assess the effectiveness of C&T in the specific context of waste management.

2.2 Cap and Trade, an emerging policy option for waste management?

We now review the emerging discussions on the possibility of using market-based instruments in the waste sector. There are at least four arguments in favor of re-examining the C&T system as a potential waste management tool.

First, the United Kingdom (UK) has has pioneered the application of cap and trade by an alternative approach to the Extended Producer Responsibility (EPR). Since 1997, the UK has established a

[7]As a reminder, in the optimal situation, marginal abatement cost would equal to marginal damage to give the optimal pollution level and the optimal tax level. However, a small error in the tax level would induce an increase in pollution level compare to the optimal.

[8]See Requate (2013); Tang et al. (2019) for literature reviews on the subject.

tradable recycling credit system for packaging (Walls, 2006; Mayers, 2007). This system mandates packaging producers to demonstrate that a specific volume of their production undergoes recycling by procuring Packaging Recovery Notes from recycling entities. These credits can only be issued for the actual amount of waste recycled. In their study of Packaging Recovery Notes, (Vaudey and Glachant, 2007) conclude on the relevance of using the market to manage the recycling of plastic packaging. They explain that the market establishes a financial flow enabling both the financing of recycling centers and the adaptation of plastics production to recycling needs. While this scheme bears similarities to a WTS, it exclusively pertains to packaging waste and does not encompass all municipal solid waste (MSW).

Second, climate policies also favor that reappraisal. In New Zealand, Australia and Europe, the waste management sector is now included within a broader Emission Trading System. As the ETS in New Zealand (NZ ETS) has a large coverage, waste sector has been included in it since 2013 by the first amendment of the Scheme.[9] This reflects an innovative approach to addressing waste-related emissions within the broader carbon market landscape. In the Australian context of a mainly voluntary market, waste-to-energy projects make up 14% of the projects registered for Australian Carbon Credit Units.[10] Meanwhile, the European Union (EU) has embarked on a path to assess the potential inclusion of waste incineration within the EU-ETS as of 2026.[11] While distinct from a dedicated waste trading platform, these developments underscore the evolving strategies aimed for waste management within the larger context of emissions reduction.

Third, from a theoretical standpoint, it is important to stress that the conditions for the feasibility and economic efficiency for C&T are well established. (Baumol and Oates, 1971) assert that, under the suitable conditions (see Section 3), it can correct for a negative externality such as landfilling of waste while maximizing social welfare. This theorem is complemented by Montgomery's analysis, which proves that there is an equilibrium in any market for tradable allowances, and that this equilibrium maximizes social welfare (Montgomery, 1972). He thus demonstrated the theoretical dichotomy, in a certain universe, between taxation and Cap and Trade (C&T). With the proliferation of carbon markets around the world, multiple authors examined their effectiveness. Indeed, Tietenberg (2002) recognizes that a C&T is one of the most effective mechanisms for dealing with externalities, provided it is optimally designed and free of transaction costs.

Lastly, academic studies consistently highlight the positive impact of using Cap and Trade (C&T) mechanisms to regulate stock pollutants such as waste. Peng et al. (2022) suggests that given the success of carbon markets in regulating elusive gases, implementing a waste quota market is feasible.[12] The authors propose a quantitative approach to solid construction waste management as an effective regulatory tool for Chinese cities. El Hanandeh and El-Zein (2009) use a stochastic

[9] See Climate Change Response (Moderated Emissions Trading) Amendment Act 2009.

[10] See Reputex, accessed September 13th 2023.

[11] See Directive (EU) 2023/959.

[12] The social cost of carbon encompasses health, agriculture, and biodiversity effects, while landfilling affects hygiene, soil, water pollution, neighborhood nuisance, and land use.

multi-criteria decision-making tool to assess the carbon credit potential of MSW management in Sydney, showing financial and environmental benefits. OECD also supports the implementation of such schemes for MSW regulation (OCDE, 2002; Salmons, 2002).

2.3 The unsorted waste management issues of large urban areas

Addressing waste management in large and densely populated cities is a multifaceted challenge that requires adequate policies. A distinctive feature is the intricate interplay of the following three key factors.

First and foremost, these urban centers generate a substantial volume of waste (Gutberlet, 2017; Cohen et al., 2017) which is barely sorted. This is undeniably linked to the number of residents but also to the difficulties to involve cities' residents in sorting their waste (Khan et al., 2019; Wang et al., 2019).

Second, the confluence of space scarcity and hygienic concerns exacerbates the predicament of landfilling waste in urban areas. To establish an efficient waste management in cities, Wilson et al. (2012), in their comparative study of urban solid waste management, argue that their is no unique solution adapted for every cities. Instead, each one need a tailor-made solution according to its specific strengths and challenges (Wong, 2022). If their is no "one-size-fits-all" solution, certain fundamental principals endure, such as ceasing landfilling. For instance, Lombrano (2009), in his study of solid urban waste, advocates for the end of landfilling in cities and the development of capital-intensive recovery methods, especially with regards to hygienic concerns.

Lastly, in shared building scenarios, Property Management companies (PMC) often handle waste management services. Due to their resources and ability to respond to regulations, They emerge as a suitable entity to bear obligations in a Waste Trading System (WTS). Their proximity to tenants facilitates impactful awareness campaigns, and their position higher up the chain reduces market complexity.[13] Waste sorting correlates with socio-economic factors (Hornik et al., 1995), leading to natural variations among properties. Beyond sociological factors, the urban distribution of sorting bins varies (Leeabai et al., 2019), incurring extra costs for isolated residents. This results in a spatially heterogeneous sorting rate distribution among PMCs (Ma et al., 2023).

To summarize, while C&T is widely used for greenhouse gases regulation, it has so far only been tangentially considered for the management of municipal solid waste. However, due to the specific features and challenges faced in large and densely populated cities, a well-designed WTS may be an efficient approach.

[13] Argument used by the European Commission regarding carbon market targeting in transport and buildings (ETS 2).

3 Theoretical considerations on the Waste Trading System approach and design

In this section, we reexamine the literature on Cap and Trade (C&T) with the aim to first identify the preconditions that make C&T a suitable management policy for solid waste in large and densely populated areas. As C&T is unlikely to provide a "one size fits all" policy recommendation, we then question under which circumstances and through which design parameters C&T achieves optimal efficiency..

3.1 Conditions Favouring Market Efficiency

Efficient waste management is a multifaceted challenge, and choosing the most effective approach depends on specific circumstances. To understand the conditions under which a quantity-based approach can outperformed taxation, we reexamine the advantages of Cap and Trade (C&T) approach with regards to waste management issues. There is three primary advantages listed by, among others, Tietenberg (2002); OCDE (2002); Hepburn (2006) and developed thereafter.

First, in scenarios marked by uncertainty with urgency or excessive environmental damage, conditions that prevail for the landfilling of MSW, a C&T provides public decision-makers with a level of certainty regarding pollution levels, specifically the quantities of waste sent to landfills. Such level serves to minimize the overall social cost of the policy if the slightest error has been made in the abatement cost. The idea is aligned with Weitzman theory according to which when there is uncertainty and a relatively steep marginal damage function, it would be beneficial to use a quantity-based scheme (Weitzman, 1974). In our context, the use of Weitzman's theorem appears appropriate because: (i) there are negative externalities associated with waste disposal, such as environmental pollution and health hazards; (ii) regulatory measures would likely foster proper waste sorting practices while internalizing the abatement costs; (iii) the efficacy of these regulatory measures remains uncertain and contingent on factors such as population growth and economic fluctuations.

Second, when market participants subject to regulation have divergent abatement costs, the market gains a comparative advantage over taxation. In other words, a WTS may be efficient if the agent bearing the obligation have diversified abatement costs function. This criterion is intrinsically tied to the selection of the responsible parties. It presupposes for the obliged parties: (i) the ability to engage in economic strategies, (ii) alignment with common objectives but divergent abatement cost structures, and (iii) enough agents to facilitate efficient trading while maintaining regulatory oversight. These conditions find a natural alignment in scenarios involving Property Management Companies. As explained in Sub-section 2.3, PMC, while being in sufficient numbers for the proper functioning of a market, exhibit the capacity for efficient waste management strategies coupled with distinct abatement cost profiles, rendering them suitable candidates for assuming waste permits.

Third, when a market with free permit allocation is employed, it diminishes the risk of regulated companies losing competitiveness and relocating. This final advantage does not apply to the municipal solid waste production sector, as waste generation is inherently tied to the locations where residents live and work. If the competitiveness of the region is not at risk with a Waste Trading System, what can actually happen is fraud: by the illegal deposit or export of waste. To overcome this, appropriate monitoring and a convincing contravention can be effective (see Subsection 3.2).

To summarize, to consider a Waste Trading System as a potential efficient tool for MSW management, the target region must meet two key conditions. First, the region should experience a relatively steep marginal damage from landfill waste disposal compare to a relatively flat marginal abatement cost curve. Second, The target city must have the potential to organize waste management at building level, with the presence of PMC-type players. The latter are ideal players for the role of obligated parties.

3.2 Designing the Waste Trading System

Beyond contextual conditions, the applicability of Cap and Trade (C&T) also relies on internal characteristics (Yan et al., 2020; Gao et al., 2020; Munnings et al., 2016). As explained by Tietenberg (2002), the effectiveness of a C&T system can be compromised in the presence of market imperfections: the Waste Trading System (WTS) desing merits appropriate analysis.

We focus on the characterization of a WTS to reduce landfilling of waste in large and dense urban areas. We assume that, nonetheless the existing infrastructures for both waste collection and proper recovery treatments,citizens' participation in waste sorting is low, impeding alternatives to landfill disposal.[14] Moreover, we assume the presence of waste management within buildings by Property Management Companies (PMC) with diversified abatement costs. Thus, the introduction of a WTS emerges as a viable solution to regulate the volume of waste sent to landfills: one permit represents one ton of MSW disposed in landfill. Two types of actors[15] would be mainly concerned by this regulation: 1) the government that sets the objectives, allocates the obligations and ensures compliance with the regulation; and 2) the PMC that receive the permits and implement abatement strategies.

Drawing insights from Peng et al. (2022) who explore the feasibility of implementing C&T for construction waste management, and from Munnings et al. (2016) who evaluates Emissions Trading System pilot projects in China, we identify five elements characterizing a C&T system for waste:

- **Definition of the cap**: the cap is the limit on the total waste disposal in landfills over the entire designated period. Since all landfill externalities can be attributed to either the mass

[14]This situation corresponds to a scenario characterized by high polarization, where a steeply rising marginal damage curve intersects with a nearly flat marginal abatement cost curve.

[15]Optionally, NGOs could participate in awareness and education campaigns to prevent illegal dumping (also called "fly-tipping").

or the volume of waste deposited in landfills, either of these units may be employed. Building upon the discussion in the preceding subsection, we advocate for PMC to assume this responsibility. The specific cap level for the entire duration should be defined by the equality between the marginal damage costs and the marginal abatement costs functions. The annual adjustment function can be modeled as a linear function of this global cap, because it offers simplicity, adaptability, and predictability in aligning the cap with evolving waste management needs. This approach strikes a balance between stability and flexibility, facilitating gradual and manageable changes in waste management practices to meet environmental objectives. We do not consider the possibility of banking or borrowing of permits over the period as a whole. Indeed, Weitzman (2020) underscores the dominance of a fixed quantity over time flexibility. Furthermore, given the predetermined yearly maximum capacities for these facilities, any attempt to introduce dynamics into the system would be restricted by these inherent limitations. This reinforces the argument against the inclusion of temporal evolution within the model.

- **Allocation method for the permits**: To achieve the most effective distribution of permits among participants (i.e.; bearers) in the system, the dual considerations of fairness and efficiency in permit allocation should be addressed. Auctions are consistently recommended as the preferred method due to their inherent economic efficiency (Tietenberg, 2002; OCDE, 2002). This mechanism enables the revelation of optimal abatement costs by the participating actors while generating revenue. This generated revenue can be labeled for redistribution, benefiting vulnerable households and supporting additional waste abatement strategies. Criticisms of this method primarily arise within the context of international competition, a concern that is not applicable in the current context. Alternative approaches, such as grandfathering and output-based allocation, exist as viable options. Grandfathering involves the distribution of permits between companies based on historical criteria, while output-based allocation distributes permits to companies based on their current performance (Demailly and Quirion, 2006). In situations characterized by uncertainty, Meunier et al. (2018) suggest that output-based allocation should supersede grandfathering as the preferred method.

- **Liquidity and market power**: market power might occur when a limited number of dominant waste management entities can influence permit prices, potentially hindering competition and efficiency in the system. The market should be created to assure the liquidity of the market and prevent actors to exert market power. We should consider to analyze strategies employed by the regulated entities[16] to maximize their profit within the trading framework. In this context, one should take care of market power from relatively large PMC, as highlighted by Munnings et al. (2016). Indeed, if Montgomery (1972) demonstrates that the efficiency of regulation remains unaffected by the level of the chain being regulated, this

[16]Note that the regulation would be on the producers of MSW, not on the recovering facilities, thus we would not detail strategies for recyclers.

assertion holds true solely under the condition of a perfectly competitive market. According to the Packaging Recycling Notes study by Vaudey and Glachant (2007), the allocation of allowances among firms is not neutral when certain levels of the packaging chain exert market power over others. To prevent market power, it may be advisable to put quotas ceiling on the number of permits one is allowed to have above its own obligations.

- **Volatility**: High price fluctuations and market volatility within the Waste Trading System can affect the efficacy of waste regulation. In the presence of a fixed trajectory of the cap over every periods, the regulatory mechanism is unable to respond adequately to economic shocks, resulting in a cap that is too lenient during periods of recession and overly stringent during periods of economic expansion (Kollenberg and Taschini, 2016). To address this issue, consideration may be given to a system allowing for cap revisions aimed at mitigating the effects of economic shocks over the designated period. Such shocks could stem from factors like changes in Gross Domestic Product (GDP), shifts in demographics, or unforeseen events such as the COVID-19 pandemic.[17]

- **Compliance**: Efficiency within an economic regulation framework hinges on the presence of suitable enforcement measures, encompassing both monitoring and non-compliance penalties. While various penalty structures have been explored in the literature for addressing non-compliance with regulatory obligations (Schaeffer and Sonnemans, 2000), the effectiveness of the penalty mechanism is paramount in empowering the market to instigate tangible change (Yan et al., 2020). The penalty imposed should exceed the marginal cost of waste reduction. In the event of potential linkage with another market, as elucidated by Haites et al. (2001), the penalty in one market should not fall below the abatement cost in the other. The fine should comprise two distinct components: a fixed and sufficiently substantial component and a variable component corresponding to the carry-over of unmet obligations into the subsequent compliance period. Monitoring must be established in the initial stages to ensure seamless functionality and to furnish policymakers with insights into waste production levels. This can be achieved by implementing waste weighing processes during collection, utilizing appropriate dump trucks—a methodology already employed in several regions worldwide.

These aspects should be considered and tailored to the unique characteristics of each region or location to ensure the seamless operation of the system.

[17]This system could be inspired by the Market Stability reserve (MSR), introduced in the EU Emissions Trading System (EU-ETS) and designed to adjust the cumulative cap (Quemin and Trotignon, 2019). Nevertheless, while the MSR was introduced primarily to offset the effect of excessive banking activity, the cap revision system should be designed to absorb unforeseen, long-term economic shocks.

4 Application: assessment of a Waste Trading System for Hong Kong

In this section, we assess the suitability of a Waste Trading System for municipal solid waste management in Hong Kong.

4.1 Current situation in Hong Kong: the sorting challenge

In 2020, Hong Kong generated 5446.5 kilo-tons of MSW and 71% of it is being landfilled, as depicted by Figure 1, while the rest (i.e., 29%) is either exported (supposedly for recycling) or locally recycled. However, since 2020, Hong Kong has the theoretic capacities to recover up to 45% of its yearly MSW generated. This capacity would increase to 65% in 2025, once the Waste-to-energy infrastructure will be operational. Indeed, the government has taken the leadership to cope with MSW. As it has no financial burden, the supervision of MSW is mainly driven by the lack of space and negative externalities waste management can create. Its strategy follows the internationally recognized waste management hierarchy: reduce, recycle and landfill as a last resort (Environment Bureau, 2013). For waste reduction, the government has set different targets for MSW reduction, which echo more general objectives of reducing greenhouse gas emissions, as depicted in Table 3 in the Supplementary Document A. For waste recycling, the city has funded the construction and management of small- and large-scale facilities.[18] Alas, despite lower amount of waste being discarded between 2005 and 2020, higher amounts of MSW are being landfilled. This situation is a major issue because current landfill are already saturated. According to the government, the two landfills currently in use (even extended)[19] will run out of space by 2035. Beside the drop in waste export[20] which is not the government's responsibility, the lack of waste sorting from the citizens seems to be the main barrier.

The major issue is rooted at the first step of the waste management chain: the lack of incentive for citizen to sort their waste. Currently, sorting is voluntary and done by citizens mostly in public areas through dedicated bins because there is no compulsory separation at source for households and most buildings do not even offer separate bins.[21] Indeed, the responsibility for collecting and managing MSW within buildings lies with the Property Management Companies (PMC). However, PMC seldom invest in sorting containers (Lo and Liu, 2018). To address this issue, the government initiated the Program on Source Separation of Domestic Waste in 2005, offering free waste sorting

[18] Small-scale facilities can be on-site compost or sorting container while large-scale ones can be recycling plant ore waste-to-energy plant.

[19] The HK government was constrained to invest HK\$ 7.8×10^9 (US\$$10^9$) to increase their capacity to dispose MSW.

[20] Many countries, like China in 2018, that used to receive exported waste to be recycled from Hong Kong strengthened their policies in terms of quality of the waste received (Kojima, 2020).

[21] Only 5% of the buildings in Hong Kong offer such bins. According to the Hong Kong government, only 2,605 buildings has participated (Hong Kong Waste Reduction Website, accessed on September 1, 2023.

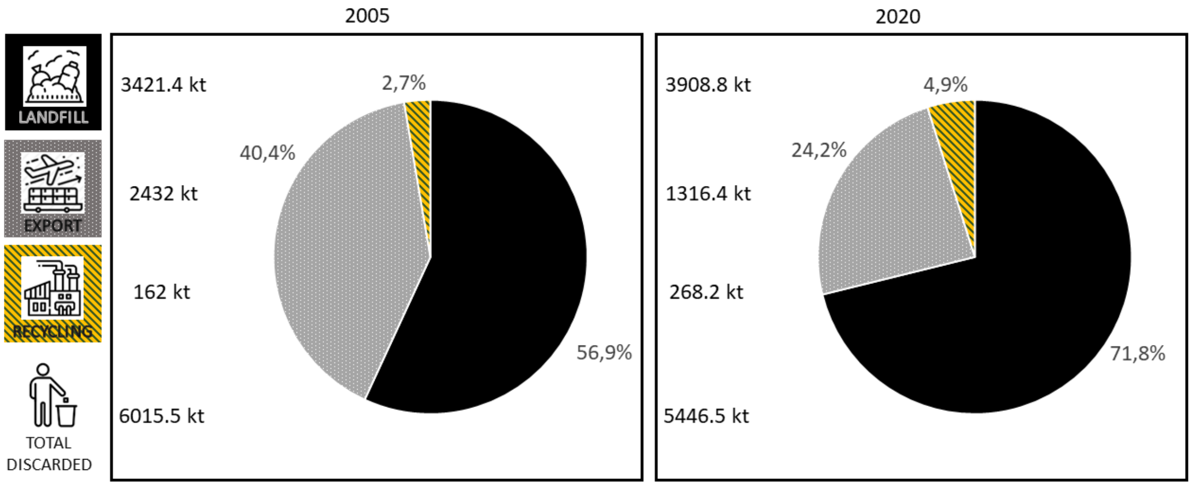

Figure 1: Hong Kong MSW shares in management strategies
Source: Data are provided by the HK government, which seems to be the main and only stakeholder that possesses data on current MSW situation Environment Bureau (2013, 2021c).

garbage containers to PMC willing to participate and providing support for waste management reevaluation. Unfortunately, the voluntary nature of this program, coupled with the limited space in Hong Kong's housing, has led to minimal adoption of sorting containers[22] within buildings (Yau, 2010). Consequently, sorting containers are predominantly situated in public spaces and encompassed for only 15% of the total MSW containers of the city in 2020,[23] posing a challenge to citizen engagement due to the effort required by residents to sort their waste (Ng, 2019). The distance to sorting containers adds an extra cost for citizens (Chung and Poon, 1994; Luyben and Bailey, 1979), which must be compared with the historically low charges for municipal solid waste disposal in Hong Kong.

For years, landfilling was provided free of charge to all stakeholders. However, the Waste Disposal Bill, enacted on August 26, 2021, introduced a consumer tax based on the quantity of MSW discarded. Under this system, MSW must be placed in designated bags, sold to citizens through conventional retail outlets. The price of these bags includes a quasi-linear tax based on the volume of waste, approximately HK\$0.11 (US\$0.014) per liter of MSW. The tax revenue is directed to the government (Environment Bureau, 2021a, 2017). The tax appears relatively low with regards to previous studies. Yeung and Chung (2018) indicate that over 60% of Hong Kong's population was willing to pay HK\$30 (US\$3.83) per month for MSW[24]. The seemingly low level of taxation raises

[22]As of 2023, only 5% of the city's buildings had participated in the program (only 2,605 buildings out of 50,000), see Hong Kong Waste Reduction Website, accessed on September 1, 2023) and (Loh, 2023).

[23]The number of sorting containers in Hong Kong public spaces has decreased from 2800 in 1998 (HK Government Website visited on October 27, 2022), to 1800 in 2020 (HK Government Website visited on October 27, 2022).

[24]According to the government (Hong Kong Waste Blueprint 2035), the per capita average rate of disposal is around 93 liters per month. With an HK\$0.11 (US\$0.014) per liter charge, citizens would pay around HK\$10 (US\$1.28) per month.

questions about its effectiveness in providing a real incentive for waste sorting and reduction. These challenges extend beyond economic factors, as the literature suggests that involving Hong Kong citizens in recycling initiatives faces numerous hurdles. They encompass issues related to hygiene (Yau, 2010), spatial inequalities (Ma et al., 2023; Yang et al., 2022), and a general lack of awareness (Wong, 2022; Wan et al., 2014; Li et al., 2023), all of which contribute to citizen reluctance to participate in waste sorting.

All of this result in a situation where, despite of a capital-intensive waste management chain, there is a low recovering rate due to low sorting rates. While the government is aware of these issues, the incentive strategies put in place do not seem up to the challenge. The urgency of the issue, the capacity of existing waste management infrastructure, and the potentiality for increasing citizen involvement collectively emphasize the suitability for a Waste Trading System.

4.2 Data and parameterization

In this sub-section, we present the data and the construction of the marginal damage and marginal abatement cost curves needed to apply Weitzman's theorem.

We construct the curves within a fixed time period. Indeed, until 2047, the region operates under a distinct framework before transitioning into a different political and administrative landscape when China will assume a more direct role. Within this 25-year period (2022-2047), the Hong Kong government should determine whether the existing MSW management capacities are sufficient to meet the needs to handle the MSW generated. We can consider a considerable shift in Hong Kong's waste management dynamics post-2047, when Hong Kong government will be taken over by China, and thus will not be further in charge of the MSW management. For any additional information considering assumptions for the construction of the curves, further details can be found in Supplementary Document B.

4.2.1 Construction of marginal damage function

To construct the Hong Kong marginal damage function associated to waste disposal in landfill, We should first analyse the externalities of waste mismanagement. They encompass the opportunity costs of landfills, the pollution costs (pollution of waters and soils) and the social costs of carbon equivalent. Thus, we express the annual damage costs of landfilling as:

$$\mathcal{D}(L_\rho(t)) = P_c(L_\rho(t)) + SCC(L_\rho(t)) + K_c(L_\rho(t)) \tag{4.1}$$

Where ρ is the share of MSW being locally recovered and recycled or exported for such operations. $(L_\rho) = (1-\rho)G$ is the amount of MSW generated G being landfilled, while $R_\rho = \rho G$ is the amount MSW generated being recovered and recycled (locally or through exports). $P_c(L_\rho(t)) = \alpha_P(L_\rho(t))^{\beta_P}$ is the cost of the pollution induced by the MSW landfilled during a t

year, $SCC(L_\rho)(t) = \alpha_{SCC}(t)(L_\rho(t))$ the social cost of carbon equivalent related to the MSW being landfilled, with , and $K_c(L_\rho(t)) = \alpha_K L_\rho(t) + f(L)$ the capital cost needed for the MSW to be landfilled. It relates to both cost for landfill use and maintenance $\alpha_K L_\rho(t)$, and the cost of building new landfills $f(L)$. All data can be found in Supplementary Document B.1. Costs associated with landfill use and maintenance, as well as the expenses incurred in building new landfills, are considered as damages. They encompass operational and upkeep expenses for existing landfill sites. They can result in environmental contamination and public health risks, impacting society wealth. Similarly, the cost of constructing new landfills, when required due to excessive landfilling, can lead to land use conflicts and financial burdens on communities. These externalities highlight the broader, long-term negative consequences of landfilling that extend beyond the immediate economic considerations of waste disposal.

$$f(L) = \begin{cases} 0 & \text{if } L < L_1 \\ K_1 & \text{if } L_1 \leqslant L < L_2 \\ \vdots & \\ K_i & \text{if } L_i \leqslant L < L_{i+1} \end{cases}$$

In this notation, $f(L)$ is a step function, L represents the amount of waste that has been landfilled, and L_i represents the threshold at which the i-th landfill is considered full. When L is less than L_1, no new landfill is needed, and the cost is zero. When L falls within the range of L_i and L_{i+1}, the cost is K_i, indicating the need for the i-th landfill. This allows for the dynamic adjustment of the threshold as new landfills are built.

The marginal damage cost function being the derivative of the damage costs of landfilling with respect to the amount of MSW landfilled $L_\rho(t)$ is given by:[25]

$$\frac{\partial \mathcal{D}(L_\rho(t))}{\partial L_\rho(t)} = \frac{\partial}{\partial L_\rho(t)} \left[P_c(L_\rho(t)) + SCC(L_\rho(t)) + K_c(L_\rho(t)) \right]$$

$$\frac{\partial \mathcal{D}(L_\rho(t))}{\partial L_\rho(t)} = \alpha_P \beta_P (L_\rho(t))^{\beta_P - 1} + \alpha_{SCC}(t) + \alpha_K + f'(L)$$

With $f'(L)$ given by:

$$f'(L) = \sum_i K_i \delta(L - L_i)$$

Where $\delta(L - L_i)$ is the Dirac delta function centered at L_i.[26]

[25] While this function may not always be a simple linear relationship, it can be approximated as linear over small intervals or steps of landfilling to simplify calculations and modeling.

[26] The derivative of a step function results in a Dirac delta function, denoted as $\delta(L - L_i)$, represents a distribution that is concentrated at a specific point L_i. It has the property that its integral over any interval

4.2.2 Construction of marginal abatement cost curve

The marginal abatement costs curve (MACC) represents the costs of the reduction of the negative externalities, therefore, the additional costs necessary by ton of waste, compared to the existing situation (Business-as-usual: BAU) to produce treated waste. We assume perfect rationality, implying that once the financial incentive in place, citizens will efficiently and effectively sort their waste and thus the facilities will be able to reach their recovery capacity of 80%.

To construct the curve, we therefore need to know the Cost-Effectiveness (CE) each of the available technological options during this period, which is the ratio between Net Present Costs NPC_i Reduction Potential (RP) of the option :

$$CE_i = \frac{NPC_i}{RP_i}. \tag{4.2}$$

The NPC_i are net present costs of the option over its lifetime duration in Hong Kong Dollars. They include the annual costs of option i $C_i(t)$, in comparison to the annual costs of the Business-as-usual (BAU) situation $C_{BAU}(t)$, updated with r is the interest rate :

$$NPC_i = \sum_t^T (C_i(t) - C_{BAU}(t)) \text{x} \frac{(1+r)^t - 1}{r(1+r)^t}. \tag{4.3}$$

The RP of landfilled waste in tons achieved by option i over its lifetime is calculated for FC_i (full capacity of the reduction option) and R_{BAU} (the actual reduction achieved by the BAU situation) :

$$RP_i = FC_i - R_{BAU}. \tag{4.4}$$

Based on the above method and using data for Hong Kong from 2000 and extrapolating the results until 2047, as presented in Table 4.2.2, we build the BAU scenario and the MACC. The assumptions made and the details of the BAU and MACC can be found in Supplementary Document B. This analysis is from the Social Planner point of view. For instance, NPCs of the options do not include capital costs as investments have already been realised and there is no need to invest in new technologies. Our main assumption is an increase in waste sorting leading to 80% capacity utilization of existing infrastructures, which is considered to be free. Indeed, they already pay a constant flat rate for operational costs, covering infrastructure costs as if they were operating at maximum capacity. In the BAU, HK reaches a total recovery rate of 63.81% (compared to barely 40% in 2020) over the period 2022-2047. Nevertheless, in the BAU scenario, there are 5.55×10^7 tons of waste that still need to be recovered in the period from 2022 until 2047, and the current BAU scenario,

containing L_i is equal to 1.

the existing landfill would only be able to absorb 10.16% of this total amount. For the additional infrastructure needs we ranked in ascending order the possible infrastructures by marginal costs of recovering one ton of MSW over the 25 years of operation and accounting for the type of MSW in Hong Kong. Following such approach, the government should firstly invest in three additional O-Parks, two E-Parks and one I-Park.

Tech.	Full capacity (10^3 ton)	Management + Capital costs (10^6 HK$)	Marginal Costs (HK$/ton)	Sources
Opark	4425.625	3350	757	LegCo website & Opark website
EcoPark	8103.157493	8819	1088	HK Gov website & Greening HK website
Ipark	26553.75	40223	1515	SCMP website & EPD notice
Ypark	531	2013	3790	EPD website & EPD notices
WEEEpark	728	3727	5123	WEEE park website

Table 1: Costs and sources for the MACC

4.3 Results

Recall that, according to Weitzman's theory, one should compare the shapes of the Marginal Damage Curve (MDC) and the Marginal Abatement Cost Curve (MACC) around their intersection point to choose the best instrument to regulate MSW disposal.

On the one hand, we observe from Figure 2 that the MDC is steep[27], which means the damages associated with increasing levels of MSW landfilling rise rapidly. On the second hand, the MACC is the relatively flat [28] due to the already deployed waste management technologies and infrastructures. Thanks to the previous investments by the government, the MACC suggests that the additional cost incurred to further reduce waste and enhance recycling efforts may not experience substantial increases.

Therefore, from our empirical results, the quantity-based approach is the most appropriate policy instrument to reduce effectively the amount of MSW being disposed in landfills. The optimal quantity of waste disposed in landfill, reported in Table 2, comes from the equalization of the marginal damage with the marginal abatement cost. At this intersection, the optimal recovering rate, ρ^*, is of 0.68. In other words, only 32% of generated waste can be disposed in landfill. To reach this recovery rate, the Honk Kong government has to built two more O-ParK. At this optimum, the social cost of municipal waste management, a'^* is of 314 HK$/ton (40.10 US$/ton). In the event that sorting costs would surpass this figure for some Property Management companies (PMC), they would likely choose the economically favorable option of acquiring more permits rather than incurring higher expenses on sorting while PMC with lower costs would increase their sorting rates.

[27]Polynomial trendline: $4E^{-10} * x^2 - 0.1186 * x + 8000000$
[28]Polynomial trendline : $1E^{-13} * x^2 - 0.000008 * x + 67.691$

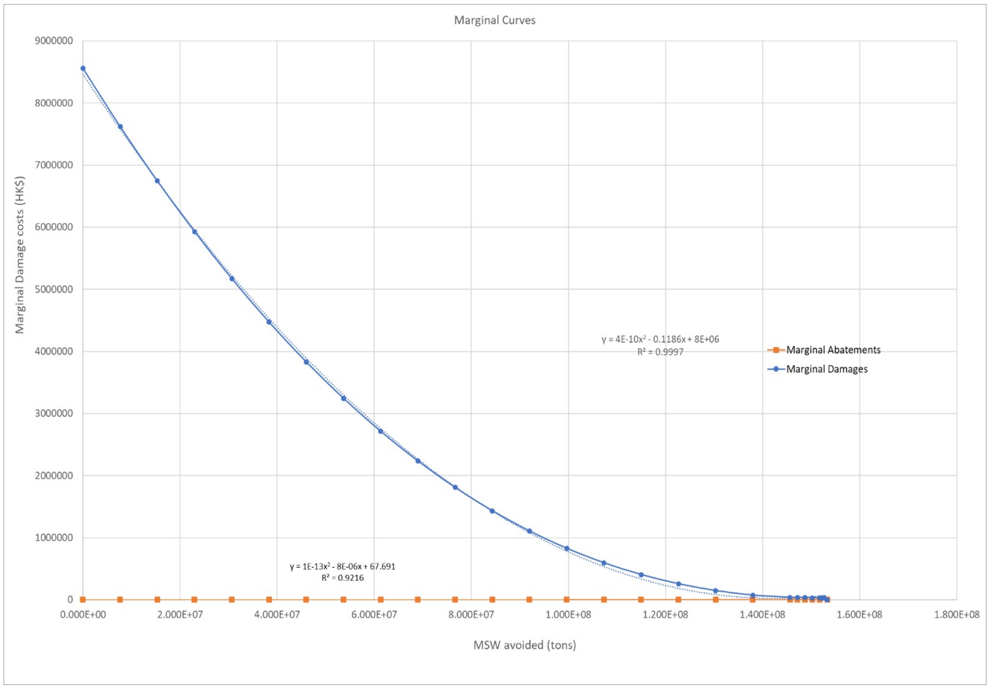

Figure 2: Hong Kong MACC and MDC intersection

Table 2: Results from empirical analysis in Hong Kong for 2022-2047

Variable	Symbol	Optimal value
MSW Generated	W	1.53E+08 tons
MSW Landfilled	L*	4.95E+07 tons
MSW Recovered	R*	1.04E+08 tons
Recovery rate	ρ*	0.68
Abatement cost*	a'*	314 HK$
Additional Facilities needed	OPark	2

To guide policymaking, it is instructive to compare these results with the actual waste charging system implemented in Hong Kong. The optimal social cost computed in our analysis is in-between the current MSW tax on garbage, set at 228.69 HK$/ton (29.20 US$/ton), and the landfill MSW gate fee , up to 365 HK$/ton[29] (46.61 US$/ton).

[29]See HK MSW Charging, accessed on September 13, 2023. These two regulations are not additive because they target either waste collected by bags or either taken directly to landfill by skips. We use this Conversion rates, accessed on September 13, 2023.

5 Discussion and Policy recommendations

5.1 Insights for the design of the Waste Trading System in Hong Kong

Building upon preceding sections, envisioning a Waste Trading System (WTS) tailored to Hong Kong's unique context is now possible. In this proposed framework, the fundamental principle mandates that each ton of waste destined for landfill disposal must correspond to the possession of a landfill permit. Property Management Companies (PMCs) bear the responsibility of adhering to the government-set limit on landfill waste.[30] Applying the methodology from Sub-Section 3.2, the following design characteristics can be outlined:

- **Definition of the cap**: The determination of the total waste cap for the specified period is derived through the intersection of the Marginal Abatement Cost Curve (MACC) and the Marginal Damage Cost (MDC) curve, as supported by empirical findings. Specifically, a quantity of $4.95x10^7$ tons of waste can be landfilled between the years 2022 and 2047. This overall cap must be distributed between each year of the period to respect the treatment capacities of the infrastructures. One way to do so may be to distribute linearly the overall capacity over the timeframe to ensure an average landfilling rate below 32% for each year.

- **Allocation method for permits**: Recognizing the inherent link between Municipal Solid Waste (MSW) production and the housing sector, relocating this activity is deemed impractical. Thus, a recommended approach involves implementing an auction-based permit allocation system, generating revenue for the waste management system. However, social acceptability is crucial for environmental policy success, prompting consideration of an output-based allocation system as a contingency measure.[31] The revenue generated could serve as a social fund to address inequalities in waste management access and capabilities within buildings.

- **Liquidity and market power**: In Hong Kong there were 1,940 PMC overseeing a total of 49,000 buildings (41,000 private and 8,000 government-owned units, 87% being residential and 13% being C&I) in 2019 (LegCo., 2021). With this number of PMC, ensuring liquidity in the market would facilitate smooth operations and the efficient allocation of resources. The large amount of PMC may induce a diversity of abatement costs that PMC may encounter in their waste management efforts. PMC overseeing a wide range of buildings, including residential and commercial properties, may face varying levels of complexity and expense in implementing waste reduction and sorting practices. However, some PMC may have the ability to exert influence over pricing and service quality, potentially hindering competition and the efficient functioning of the market. Indeed, according to a report by Frost & Sullivan

[30] PMCs manage a large majority of residents in Hong Kong. For those not covered, the creation of social associations could handle the obligation.

[31] This output-based system should align with annual and overall caps.

for the Hong Kong Government, in 2017, five companies were handling one third of the market. As mentioned in the previous Section 4.2.1, a maximum limit on the number of permits that PMC are allowed to have above their own obligations would help prevent market power.

- **Volatility**: In the context of Hong Kong's waste trade system, the adoption of a Cap Revision System may effectively address issues arising from price fluctuations and market volatility. Similar to emissions trading systems like the EU Emissions Trading System, Hong Kong's waste trading system may be affected by economic shocks and unforeseen events, potentially undermining regulatory efficacy. By employing Cap Revision System, the system could flexibly adjust the supply of waste permits to stabilize prices during economic downturns and expansions, ensuring affordable waste disposal and maintaining regulatory effectiveness. This reserve would enable Hong Kong to efficiently manage waste while responding to changing market (and economic) conditions.

- **Compliance**: As mentioned earlier, the fine should be composed of a fixed part and of the reimbursement of the missing permits. We propose, for the fixed part, a penalty of at least ten times the social cost of waste in landfill to be implemented to avoid fraud from PMC and "fly-tipping" from Hong Kong residents. In order for the penalty to be convincing, an appropriate monitoring system should be instated. As the use of cameras and citizen whistleblowing is widespread in Hong Kong, the introduction of strong monitoring should not be the most difficult point for the government.

5.2 Limitations

While this study offers insights into waste management policy, we acknowledge certain limitations of the Waste Trading System (WTS). We can begin using the case of Hong Kong as illustration.

First, a WTS being a complex system, it comes at non insignificant administrative costs (Vaudey and Glachant, 2007), especially for implementation and monitoring. This additional cost must be seen in the light of the relatively low cost of the current taxation strategy, which is already underway. Second, inadequate waste sorting habits can have negative consequences. When citizens do not engage in proper waste separation (i.e., sorting), it can lead to increased contamination in waste streams, making recycling and resource recovery policies less effective Zhang et al. (2023). This, in turn, can drive up disposal costs for waste management companies and undermine the overall efficiency of the waste trading system. Third, environmental goals related to reduce landfilling and lower greenhouse gas emissions may not be met if waste sorting rates remain insufficient. Therefore, understanding the dynamics between market efficiency and waste sorting behaviors is pivotal for designing effective waste management policies that balance economic incentives with environmental objectives.

6 Conclusions

The challenges due to landfilling of municipal solid waste (MSW) are particularly acute in large, densely populated urban areas. Because of the high cost of land and the difficulty of encouraging citizens to sort their waste, tailor-made regulations need to be devised. However, in practice as well as in the literature, the potential of Cap and Trade (C&T) has so far never been fully considered for the management of municipal solid waste.

In this study, we investigate for the very first time the feasibility and potential of implementing a C&T scheme aimed at mitigating the disposal of municipal solid waste (MSW) in landfills. The so-called "Waste Trading System" is characterized in a general case and then assessed for the specific case of the city of Hong Kong. By applying the results from Weitzman (1974), we draw a cost-benefit analysis to evaluate the pertinence of a quantity-based instrument. We analysed Hong Kong data for the twenty past years (2000-2021) and extrapolated for the upcoming twenty five years (2022-2047).

We show that low citizen involvement in waste reduction and in sorting is the main issue for MSW management in the city. In this context, we characterise a Waste Trading System for Hong Kong, from the pivotal role of Property Management Companies to the permit allocation method, including monitoring techniques and the associated penalty. We provide an estimate of the optimal social cost of municipal waste management for Hong Kong. Based on our analysis, the optimal market price for one ton of Municipal Solid Waste (MSW) would exceed the existing MSW tax levied in Hong Kong. More generally, this approach is particularly tailored to circumstances characterized by spatial constraints and the substantial volume of waste necessitating urgent and effective regulation.

For future research, further analysis would be required to gauge how the introduction of a market mechanism will affect business profitability and household welfare. Such analyses could consider potential ramifications, such as changes in rental prices resulting from increased demand for recycling permits, as well as the overall economic and environmental implications of the proposed market-based strategy.

References

K. Acuff and D. T. Kaffine. Greenhouse gas emissions, waste and recycling policy. *Journal of Environmental Economics and Management*, 65(1):74–86, Jan. 2013. ISSN 0095-0696. doi:10.1016/j.jeem.2012.05.003. URL http://www.sciencedirect.com/science/article/pii/S0095069612000551.

Z. Adar and J. M. Griffin. Uncertainty and the choice of pollution control instruments. *Journal of Environmental Economics and Management*, 3(3):178–188, Oct. 1976. ISSN 0095-0696. doi:10.1016/0095-0696(76)90017-6. URL https://www.sciencedirect.com/science/article/pii/0095069676900176.

E. E. AgencyEEA. Municipal waste management across European countries, Dec. 2017. URL https://www.eea.europa.eu/themes/waste/municipal-waste/municipal-waste-management-across-european-countries.

B. R. Alzamora and R. T. d. V. Barros. Review of municipal waste management charging methods in different countries. *Waste Management*, 115:47–55, Sept. 2020. ISSN 0956-053X. doi:10.1016/j.wasman.2020.07.020. URL https://www.sciencedirect.com/science/article/pii/S0956053X2030386X.

W. J. Baumol and W. E. Oates. The use of standards and prices for protection of the environment. *The Swedish Journal of Economics*, 73(1):42–54, 1971. ISSN 00397318. URL http://www.jstor.org/stable/3439132.

H. K. E. Bureau. Our submission to EA Panel – The need for Plan B, Mar. 2014. URL https://wastehk.org/2014/03/14/our-submission-to-ea-panel-the-need-for-plan-b/.

Y.-C. Chen and S.-L. Lo. Evaluation of greenhouse gas emissions for several municipal solid waste management strategies. *Journal of Cleaner Production*, 113:606–612, Feb. 2016. ISSN 0959-6526. doi:10.1016/j.jclepro.2015.11.058. URL https://www.sciencedirect.com/science/article/pii/S0959652615017230.

S. S. Chung and C. S. Poon. Recycling behaviour and attitude: the case of the Hong Kong people and commercial and household wastes. *International Journal of Sustainable Development & World Ecology*, 1(2):130–145, June 1994. ISSN 1350-4509, 1745-2627. doi:10.1080/13504509409469868. URL https://www.tandfonline.com/doi/full/10.1080/13504509409469868.

S. A. Cohen, H. Martinez, and A. Schroder. Waste Management Practices in New York City, Hong Kong and Beijing. In *The Sustainable City*. Columbia University Press, 2017. URL https://doi.org/10.7916/d8-zw22-ph20.

S. Das, S. H. Lee, P. Kumar, K.-H. Kim, S. S. Lee, and S. S. Bhattacharya. Solid waste management: Scope and the challenge of sustainability. *Journal of Cleaner Production*, 228:658–678, Aug. 2019. ISSN 0959-6526. doi:10.1016/j.jclepro.2019.04.323. URL https://www.sciencedirect.com/science/article/pii/S0959652619314209.

D. Demailly and P. Quirion. CO2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: Grandfathering vs. output-based allocation. *Climate Policy*, 6 (1):93–113, 2006.

EEA. *Municipal waste management across European countries*. European Environmental Agency, European Union. Reporte Copenhague, Dinamarca, 2016.

A. El Hanandeh and A. El-Zein. Strategies for the municipal waste management system to take advantage of carbon trading under competing policies: The role of energy from waste in Sydney. *Waste Management*, 29(7):2188–2194, July 2009. ISSN 0956-053X. doi:10.1016/j.wasman.2009.03.002. URL https://www.sciencedirect.com/science/article/pii/S0956053X09000816.

Environment Bureau. Hong Kong Blueprint for Sustainable Use of Resources 2013 – 2022. Technical report, Hong Kong Government, Hong Kong, SAR, 2013. URL https://sc.legco.gov.hk/sc/www.legco.gov.hk/yr12-13/chinese/panels/ea/papers/ea0527cb1-1140-1-ec.pdf.

Environment Bureau. Greenhouse Gas Emissions in Hong Kong by Sector. Technical report, Hong Kong Government, Hong Kong, SAR, 2017. URL https://www.climateready.gov.hk/files/pdf/HKGHG_Sectors_201612.pdf.

Environment Bureau. Clean Air Plan for Hong Kong 2035. Technical report, Hong Kong Government, Hong Kong, SAR, 2021a. URL https://www.enb.gov.hk/sites/default/files/pdf/Clean_Air_Plan_2035_eng.pdf.

Environment Bureau. Hong Kong's Climate Action Plan 2050. Technical report, Hong Kong Government, Hong Kong, SAR, 2021b. URL https://www.climateready.gov.hk/files/pdf/CAP2050_booklet_en.pdf.

Environment Bureau. Waste Blue Print for Hong Kong 2035. Technical report, Hong Kong Government, Hong Kong, SAR, 2021c. URL https://www.enb.gov.hk/sites/default/files/pdf/waste_blueprint_2035_eng.pdf.

H. K. E. P. D. EPD. Ecopark newsletter, 2019. URL https://www.ecopark.com.hk/newsletter/201806/en.html.

G. Fishelson. Emission control policies under uncertainty. *Journal of Environmental Economics and Management*, 3(3):189–197, Oct. 1976. ISSN 0095-0696. doi:10.1016/0095-0696(76)90018-8. URL https://www.sciencedirect.com/science/article/pii/0095069676900188.

Y. Gao, M. Li, J. Xue, and Y. Liu. Evaluation of effectiveness of China's carbon emissions trading scheme in carbon mitigation. *Energy Economics*, 90:104872, Aug. 2020. ISSN 0140-9883. doi:10.1016/j.eneco.2020.104872. URL https://www.sciencedirect.com/science/article/pii/S0140988320302127.

H. C. Goddard. The benefits and costs of alternative solid waste management policies. *Resources, Conservation and Recycling*, 13(3):183–213, June 1995. ISSN 0921-3449. doi:10.1016/0921-3449(94)00021-V. URL https://www.sciencedirect.com/science/article/pii/092134499400021V.

C. Gollier. Valorisation des investissements ultra-longs et dÉveloppement durable. *L'Actualité économique*, 92(4):667–701, 2016. ISSN 0001-771X, 1710-3991. doi:10.7202/1040502ar. URL https://www.erudit.org/fr/revues/ae/2016-v92-n4-ae03128/1040502ar/. Publisher: HEC Montréal.

Y. Gupt and S. Sahay. Review of extended producer responsibility: A case study approach. *Waste Management & Research*, 33(7):595–611, July 2015. ISSN 0734-242X. doi:10.1177/0734242X15592275. URL https://doi.org/10.1177/0734242X15592275. Publisher: SAGE Publications Ltd STM.

J. Gutberlet. Waste in the City: Challenges and Opportunities for Urban Agglomerations. In *Urban Agglomeration*. IntechOpen, Dec. 2017. ISBN 978-953-51-3898-3. doi:10.5772/intechopen.72047. URL https://www.intechopen.com/chapters/57824.

E. Gómez-Baggethun and R. Muradian. In markets we trust? Setting the boundaries of Market-Based Instruments in ecosystem services governance. *Ecological Economics*, 117:217–224, Sept. 2015. ISSN 0921-8009. doi:10.1016/j.ecolecon.2015.03.016. URL https://www.sciencedirect.com/science/article/pii/S0921800915001019.

E. Haites, F. Mullins, T. Bosteels, A. Burkhardt, D. Ellerman, D. Hone, J. Janssen, S. Kolar, R. Lewis, D. Mackay, A. Marcu, F. Missfeldt, L. Parker, S. Sadler, L. Solsbery, B. Swift, R. Thomson, and F. Trimnell. Linking Domestic and Industry Greenhouse Gas Emission Trading Systems. Technical report, EPRI, 2001.

C. Hepburn. Regulation by Prices, Quantities, or Both: A Review of Instrument Choice. *Oxford Review of*

Economic Policy, 22(2):226–247, June 2006. ISSN 0266-903X, 1460-2121. doi:10.1093/oxrep/grj014. URL https://academic.oup.com/oxrep/article-lookup/doi/10.1093/oxrep/grj014.

S. Hong. The effects of unit pricing system upon household solid waste management: The Korean experience. *Journal of environmental management*, 57(1):1–10, 1999. ISBN: 0301-4797 Publisher: Elsevier.

D. Hoornweg, P. Bhada-Tata, and C. Kennedy. Environment: Waste production must peak this century. *Nature*, 502(7473):615–617, 2013.

J. Hornik, J. Cherian, M. Madansky, and C. Narayana. Determinants of recycling behavior: A synthesis of research results. *The Journal of Socio-Economics*, 24(1):105–127, Mar. 1995. ISSN 1053-5357. doi:10.1016/1053-5357(95)90032-2. URL https://www.sciencedirect.com/science/article/pii/1053535795900322.

F. Khan, W. Ahmed, A. Najmi, and M. Younus. Managing plastic waste disposal by assessing consumers' recycling behavior: the case of a densely populated developing country. *Environmental Science and Pollution Research*, 26(32):33054–33066, Nov. 2019. ISSN 1614-7499. doi:10.1007/s11356-019-06411-4. URL https://doi.org/10.1007/s11356-019-06411-4.

M. Kojima. The impact of recyclable waste trade restrictions on producer recycling activities. *International Journal of Automation Technology*, 14(6):873–881, 2020.

S. Kollenberg and L. Taschini. Emissions trading systems with cap adjustments. *Journal of Environmental Economics and Management*, 80:20–36, Nov. 2016. ISSN 0095-0696. doi:10.1016/j.jeem.2016.09.003. URL https://www.sciencedirect.com/science/article/pii/S0095069616302601.

N. Leeabai, S. Suzuki, Q. Jiang, D. Dilixiati, and F. Takahashi. The effects of setting conditions of trash bins on waste collection performance and waste separation behaviors; distance from walking path, separated setting, and arrangements. *Waste Management*, 94:58–67, July 2019. ISSN 0956-053X. doi:10.1016/j.wasman.2019.05.039. URL https://www.sciencedirect.com/science/article/pii/S0956053X19303472.

C. H. Li, T. T. Lee, and S. S. Y. Lau. Enhancement of Municipal Solid Waste Management in Hong Kong through Innovative Solutions: A Review. *Sustainability*, 15(4):3310, Feb. 2023. ISSN 2071-1050. doi:10.3390/su15043310. URL https://www.mdpi.com/2071-1050/15/4/3310.

C. Liu, H. Dong, Y. Cao, Y. Geng, H. Li, C. Zhang, and S. Xiao. Environmental damage cost assessment from municipal solid waste treatment based on lime3 model. *Waste Management*, 125:249–256, 2021.

A. Y. Lo and S. Liu. Towards sustainable consumption: A socio-economic analysis of household waste recycling outcomes in Hong Kong. *Journal of Environmental Management*, 214:416–425, May 2018. ISSN 0301-4797. doi:10.1016/j.jenvman.2018.03.029. URL http://www.sciencedirect.com/science/article/pii/S0301479718302524.

C. Loh. Aging buildings problem needs to be addressed aggressively. *China Daily*, Feb. 2023. URL https://www.chinadailyhk.com/article/a/314422#Aging-buildings-problem-needs-to-be-addressed-aggressively.

A. Lombrano. Cost efficiency in the management of solid urban waste. *Resources, Conservation and Recycling*, 53(11):601–611, Sept. 2009. ISSN 0921-3449. doi:10.1016/j.resconrec.2009.04.017. URL https://www.sciencedirect.com/science/article/pii/S092134490900072X. Number: 11.

P. D. Luyben and J. S. Bailey. Newspaper Recycling: The Effects of Rewards and Proximity of Containers. *Environment and Behavior*, 11(4):539–557, Dec. 1979. ISSN 0013-9165. doi:10.1177/0013916579114006. URL https://doi.org/10.1177/0013916579114006. Publisher: SAGE Publications Inc.

F. C. Ma, T. L. Wong, C. N. Chan, and L. Ran. Revising the effectiveness of municipal waste management in Hong Kong. *Frontiers in Environmental Science*, 11, 2023. ISSN 2296-665X. URL https://www.frontiersin.org/articles/10.3389/fenvs.2023.1178363.

S. Manfredi, D. Tonini, T. H. Christensen, and H. Scharff. Landfilling of waste: accounting of greenhouse gases and global warming contributions. *Waste Management & Research*, 27(8):825–836, Nov. 2009. ISSN 0734-242X. doi:10.1177/0734242X09348529. URL https://doi.org/10.1177/0734242X09348529. Publisher: SAGE Publications Ltd STM.

C. K. Mayers. Strategic, Financial, and Design Implications of Extended Producer Responsibility in Europe: A Producer Case Study. *Journal of Industrial Ecology*, 11(3):113–131, 2007. ISSN 1530-9290. doi:10.1162/jiec.2007.1228. URL https://onlinelibrary.wiley.com/doi/abs/10.1162/jiec.2007.1228. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1162/jiec.2007.1228.

G. Meunier, J.-P. Montero, and J.-P. Ponssard. Output-based allocations in pollution markets with uncertainty and self-selection. *Journal of Environmental Economics and Management*, 92:832–851, Nov. 2018. ISSN 0095-0696. doi:10.1016/j.jeem.2017.10.001. URL http://www.sciencedirect.com/science/article/pii/S009506961730147X.

A. W. Milt and P. R. Armsworth. Performance of a cap and trade system for managing environmental impacts of shale gas surface infrastructure. *Ecological Economics*, 131:399–406, 2017.

W. D. Montgomery. Markets in licenses and efficient pollution control programs. *Journal of economic theory*, 5(3):395–418, 1972.

C. Munnings, R. D. Morgenstern, Z. Wang, and X. Liu. Assessing the design of three carbon trading pilot programs in China. *Energy Policy*, 96:688–699, Sept. 2016. ISSN 0301-4215. doi:10.1016/j.enpol.2016.06.015. URL https://www.sciencedirect.com/science/article/pii/S0301421516302981.

D. Nainggolan, A. B. Pedersen, S. Smed, K. H. Zemo, B. Hasler, and M. Termansen. Consumers in a circular economy: economic analysis of household waste sorting behaviour. *Ecological Economics*, 166:106402, 2019.

S. Ng. An assessment of multi-family dwelling recycling in hong kong: A managerial perspective. *Waste Management*, 89:294–302, 2019.

OCDE. *Implementing Domestic Tradeable Permits.* Edition OECD, 2002. doi:https://doi.org/https://doi.org/10.1787/9789264191983-en. URL https://www.oecd-ilibrary.org/content/publication/9789264191983-en.

D. W. Pearce and R. K. Turner. Market-based approaches to solid waste management. *Resources, Conservation and Recycling*, 8(1):63–90, Jan. 1993. ISSN 0921-3449. doi:10.1016/0921-3449(93)90020-G. URL https://www.sciencedirect.com/science/article/pii/092134499390020G.

Z. Peng, W. Lu, and C. Webster. If invisible carbon waste can be traded, why not visible construction waste? Establishing the construction waste trading 'missing market'. *Resources, Conservation and Recycling*, 187:106607, Dec. 2022. ISSN 0921-3449. doi:10.1016/j.resconrec.2022.106607. URL https://www.sciencedirect.com/science/article/pii/S0921344922004414.

S. Quemin and R. Trotignon. Intertemporal Emissions Trading and Market Design: An Application to the EU-ETS. Policy Working Paper 348, Centre for Climate Change Economics/ Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, 2019.

T. Requate. Prices versus Quantities. In J. F. Shogren, editor, *Encyclopedia of Energy, Natural Resource, and Environmental Economics*, pages 193–203. Elsevier, Waltham, Jan. 2013. ISBN 978-0-08-096452-2. doi:10.1016/B978-0-12-375067-9.00027-9. URL http://www.sciencedirect.com/science/article/pii/B9780123750679000279.

H. Ritchie and M. Roser. Co_2 and greenhouse gas emissions. *Our World in Data*, 2020. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

R. Salmons. New areas for the application of tradable permits: solid waste management. In *Implementing domestic tradable permits: recent developments and future challenges*, pages 187–226. Organisation for Economic Co-operation and Development, Paris, 2002. ISBN 978-92-64-19763-3. URL https://westminsterresearch.westminster.ac.uk/item/93y3y/new-areas-for-the-application-of-tradable-permits-solid-waste-management.

G. Schaeffer and J. Sonnemans. The Influence of Banking and Borrowing under Different Penalty Regimes in Tradable Green Certificate Markets – Results from an Experimental Economics Laboratory Experiment. *Energy & Environment*, 11(4):407–422, July 2000. ISSN 0958-305X. doi:10.1260/0958305001500211. URL https://doi.org/10.1260/0958305001500211. Publisher: SAGE Publications Ltd STM.

M. R. Shammin and C. W. Bullard. Impact of cap-and-trade policies for reducing greenhouse gas emissions on us households. *Ecological Economics*, 68(8-9):2432–2438, 2009.

B.-J. Tang, X.-Y. Wang, and Y.-M. Wei. Quantities versus prices for best social welfare in carbon reduction: A literature review. *Applied Energy*, 233-234:554–564, Jan. 2019. ISSN 0306-2619. doi:10.1016/j.apenergy.2018.10.018. URL http://www.sciencedirect.com/science/article/pii/S0306261918315642.

T. Tietenberg. The Tradable Permits Approach to Protecting the Commons: What Have We Learned? *SSRN Electronic Journal*, 2002. ISSN 1556-5068. doi:10.2139/ssrn.315500. URL http://www.ssrn.com/abstract=315500.

A. D. Vaudey and M. Glachant. Les packaging recovery notes (PRN) sont-ils économiquement efficaces ? *Environnement, Ingénierie & Développement*, N°46 - Avril-Mai-Juin 2007, Jan. 2007. ISSN 2778-844X. doi:10.4267/dechets-sciences-techniques.1617. URL https://eid.episciences.org/7956. Publisher: Episciences.org.

M. D. Vaverková. Landfill Impacts on the Environment—Review. *Geosciences*, 9(10):431, Oct. 2019. doi:10.3390/geosciences9100431. URL https://www.mdpi.com/2076-3263/9/10/431. Number: 10 Publisher: Multidisciplinary Digital Publishing Institute.

M. Walls. Extended Producer Responsibility and Product Design: Economic Theory and Selected Case Studies. *SSRN Electronic Journal*, 2006. ISSN 1556-5068. doi:10.2139/ssrn.901661. URL http://www.ssrn.com/abstract=901661.

C. Wan, G. Q. Shen, and A. Yu. The role of perceived effectiveness of policy measures in predicting recycling behaviour in Hong Kong. *Resources, Conservation and Recycling*, 83:141–151, Feb. 2014. ISSN 0921-3449. doi:10.1016/j.resconrec.2013.12.009. URL https://www.sciencedirect.com/science/article/pii/S0921344913002759.

C. Wan, G. Q. Shen, and A. Yu. Key determinants of willingness to support policy measures on recycling: A case study in Hong Kong. *Environmental Science & Policy*, 54:409–418, Dec. 2015. ISSN 1462-9011. doi:10.1016/j.envsci.2015.06.023. URL https://www.sciencedirect.com/science/article/pii/S1462901115300241.

S. Wang, J. Wang, S. Zhao, and S. Yang. Information publicity and resident's waste separation behavior: An empirical study based on the norm activation model. *Waste Management*, 87:33–42, Mar. 2019. ISSN 0956-053X. doi:10.1016/j.wasman.2019.01.038. URL https://www.sciencedirect.com/science/article/pii/S0956053X19300522.

M. L. Weitzman. Prices vs. Quantities. *The Review of Economic Studies*, 41(4):477, Oct. 1974. ISSN

00346527. doi:10.2307/2296698. URL https://academic.oup.com/restud/article-lookup/doi/10.2307/2296698.

M. L. Weitzman. Prices or Quantities Can Dominate Banking and Borrowing*. *The Scandinavian Journal of Economics*, 122(2):437–463, 2020. ISSN 1467-9442. doi:10.1111/sjoe.12351. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/sjoe.12351. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/sjoe.12351.

D. C. Wilson, L. Rodic, A. Scheinberg, C. A. Velis, and G. Alabaster. Comparative analysis of solid waste management in 20 cities. *Waste Management & Research*, 30(3):237–254, Mar. 2012. ISSN 0734-242X. doi:10.1177/0734242X12437569. URL https://doi.org/10.1177/0734242X12437569. Number: 3 Publisher: SAGE Publications Ltd STM.

M. H. Wong. Integrated sustainable waste management in densely populated cities: The case of Hong Kong. *Sustainable Horizons*, 2:100014, Mar. 2022. ISSN 2772-7378. doi:10.1016/j.horiz.2022.100014. URL https://www.sciencedirect.com/science/article/pii/S2772737822000098.

Y. Yan, X. Zhang, J. Zhang, and K. Li. Emissions trading system (ETS) implementation and its collaborative governance effects on air pollution: The China story. *Energy Policy*, 138:111282, Mar. 2020. ISSN 0301-4215. doi:10.1016/j.enpol.2020.111282. URL https://www.sciencedirect.com/science/article/pii/S0301421520300410.

J. Yang, P. Jiang, M. Zheng, J. Zhou, and X. Liu. Investigating the influencing factors of incentive-based household waste recycling using structural equation modelling. *Waste Management*, 142:120–131, Apr. 2022. ISSN 0956053X. doi:10.1016/j.wasman.2022.02.014. URL https://linkinghub.elsevier.com/retrieve/pii/S0956053X2200099X.

Y. Yau. Domestic waste recycling, collective action and economic incentive: The case in Hong Kong. *Waste Management*, 30(12):2440–2447, Dec. 2010. ISSN 0956-053X. doi:10.1016/j.wasman.2010.06.009. URL http://www.sciencedirect.com/science/article/pii/S0956053X10003247.

I. M. H. Yeung and W. Chung. Factors that affect the willingness of residents to pay for solid waste management in Hong Kong. *Environmental Science and Pollution Research*, 25(8):7504–7517, Mar. 2018. ISSN 1614-7499. doi:10.1007/s11356-017-1009-8. URL https://doi.org/10.1007/s11356-017-1009-8.

J. Zhang, Q. Qin, G. Li, C.-H. Tseng, and G. Fang. Assessing the impact of waste separation on system transition and environmental performance through a city-scale life cycle assessment. *Ecological Economics*, 211:107886, 2023. ISSN 0921-8009. doi:https://doi.org/10.1016/j.ecolecon.2023.107886. URL https://www.sciencedirect.com/science/article/pii/S0921800923001490.

Supplementary Materials

A MSW management in Hong Kong

A.1 MSW amount and target reduction in Hong Kong

The Environmental Protection Department (EPD) of Hong Kong government is responsible for municipal solid waste management, and they are in charge of the implementation of the measures and schemes to manage waste. The schemes are regulated with a guaranteed yield public service delegation contract (i.e., cost-plus). However, it cannot be directly considered a regulated natural monopoly as there are multiple companies handling the different streams of recycling, and different companies handling the landfills. Also there are different companies that are responsible for the collection of the MSW in the different regions of Hong Kong. The financing of waste management in Hong Kong is primarily through government funding. The Hong Kong government published the Waste Blueprint 2035, which outlines specific steps the territory will take to increase recycling and materials recovery, reduce waste flows into landfills, and ultimately reach a zero-landfill target (Environment Bureau, 2013).[32] In the 2022-23 budget, the government allocated US$670 million for waste management programs. In addition to this, US$130 million was set aside to establish a recycling fund (Environment Bureau, 2013). This fund is intended to assist Hong Kong companies and industries in procuring advanced equipment and technologies associated with recycling and waste management.

Tables A1 and A2 provide a summary of how different MSW streams are managed, including the amounts discarded, landfilled, exported, recycled locally, and recovered in Hong Kong respectively in 2005 and 2020. In Hong Kong, the MSW can be decomposed in nine main streams. The largest stream of MSW being discarded is paper, followed closely by food. Then by degrading order there is metal, plastic, other[33], textile, wood, yard and glass. Furthermore, and as Figure 2 shows, the recycling, landfill and export rates vary significantly from one MSW stream to the other. Certain waste streams are not exported at all, highlighting a limitation in equating waste streams and emphasizing the challenge linked to the aggregation of data in our analysis, as highlighted in Section 5.2. Notably, in the year 2020, paper, food, and plastic emerged as the largest contributors to waste being discarded and sent to landfills. On the other hand, in terms of total recovery, metals and paper stand out as the waste streams with the highest quantities and shares of materials recovered and recycled, underscoring the potential for improved measures in sorting and recycling of MSW streams.

Table A3 presents pollution reduction targets for both Hong Kong and China. Hong Kong waste reduction targets outlined in the table appear challenging to achieve in the current circumstances.

[32] ITA, 2022

[33] Other encompasses all other MSW not being listed such as tyres, WEEE, etc.

This observation underscores the pressing need for more effective and comprehensive strategies to address waste management issues in Hong Kong. As MSW is the third source of CO2 emissions and accounts for about 7% of the Hong Kong CO2 emissions (EPD, 2023), reducing emissions from MSW would contribute to the carbon reduction targets. Meeting these targets will likely require concerted efforts, and stronger commitment from various stakeholders, including government bodies, industries, and citizens.

Table 1: MSW management amount in Hong Kong in 2005

Stream	Discarded	Landfilled	Exported	Recycled locally	Recovered
Metal	1023,5	86,5	931,0	6	937
Paper	1791,7	883,7	792,0	116	908
Glass	129,4	127,4	-	2	2
Yard	13,9	13,9	-	0	-
Food	1150,1	1150,1	-	0	-
Wood	140,7	126,7	13,0	1	14
Plastic	1281,3	637,3	637,0	7	644
Textile	116,1	101,1	12,0	3	15
Other	368,9	294,9	47,0	27	74
Total	6015,5	3421,5	2432,0	162	2594

Table 2: MSW management amount in Hong Kong in 2020

Stream	Discarded	Landfilled	Exported	Recycled locally	Recovered
Metal	942,9	86,9	854,7	1,3	856
Paper	1414,7	964,7	442,1	7,9	450
Glass	81,5	66,8	3,5	11,2	14,7
Yard	83,0	81,0	-	2	2
Food	1242,8	1188,1	-	54,7	54,7
Wood	93,5	89,4	-	4,1	4,1
Plastic	945,9	843,9	7,3	94,7	102
Textile	95,6	88,3	0,2	7,1	7,3
Other	546,6	499,7	4,3	42,6	46,9
Total	5446,485	3908,785	1316,4	268,2	1584,6

A.2 Hong Kong MSW end-of-life management facilities

The high emission share of MSW in HK is due to the management style of the MSW in HK (i.e. landfills) but also to the waste composition. As depicted by Figure 1, Hong Kong's highest share of MSW is food, which accounts for more than 30% of the MSW (Environment Bureau, 2021a).

Table 3: China & Hong Kong pollution reduction targets

Area	Type of pollutant	Target	Ref. Year	Target Year	Pub. Year	Source
HK	MSW per capita reduction	-40%	2011	2022	2013	EPD 2020
HK	MSW absolute reduction	-40%	not mentioned	2035	2021	ENB 2030
HK	MSW recycling intensity increase	+55%	not mentioned	2035	2021	ENB 2030
China	MSW reuse intensity increase	+60%	2015	2025	2020	CIRCULARONLINE 2020
HK	CO2 intensity reduction	-65-70%	2005	2030	2016	ENB 2030
HK	CO2 absolute reduction	-26-36%	2005	2030	2016	ENB 2030
HK	CO2 per capita reduction	-3.3-3.8 tons	2005	2030	2016	ENB 2030
China	CO2 intensity reduction	-60-65%	2005	2030	2015	ORG 2020

Notes: Only targets which refer to MSW and CO2 are presented here. "Ref. Year" stands for the year taken as reference for the target. "Pub. Year" stands for the publication year when the target was publicly announced.

Compared to other parts of Asia, the weight of food waste per day per person in Hong Kong is 6.3, 1.6, 1.7 and 2.6 times higher than in Shanghai, Singapore, South Korea and Taiwan respectively. Those numbers are growing as the amount of MSW in Hong Kong has jumped by 80% over the past 30 years, while its population has only expanded by 34% in the same period (Environment Bureau, 2013, 2021c).

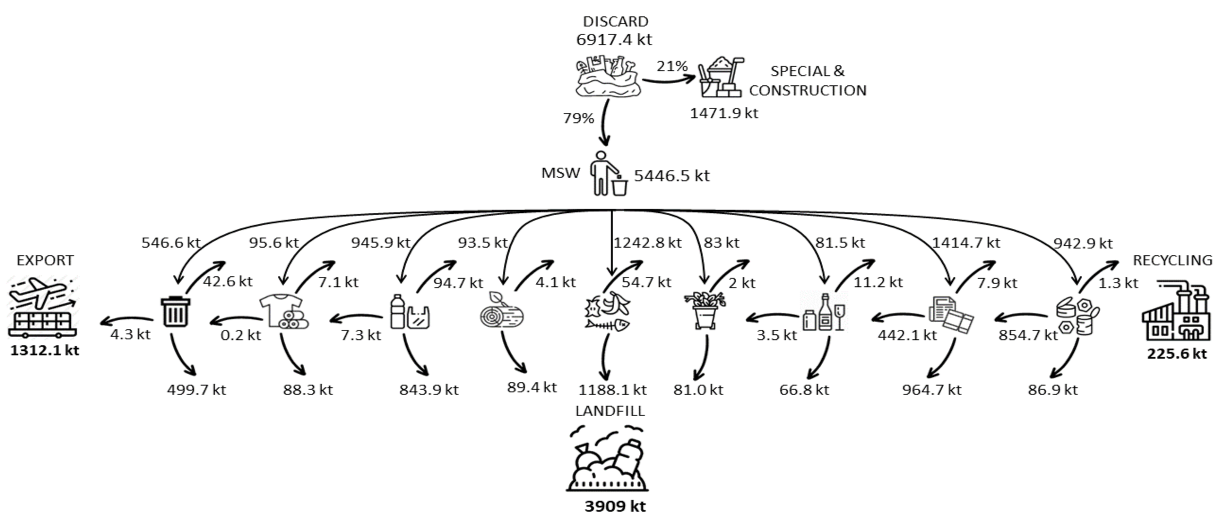

Figure 1: Hong Kong waste distribution in 2020

Source: Environment Bureau (2021c) Data are provided by the HK government, which seems to be the main and only stakeholder that possesses data on current MSW situation.

Figure 2 breaks down - in terms of management strategies - each of the main waste streams, constituting the total MSW generated in Hong Kong.

As depicted by Figure 3 Hong Kong had in 2020, two landfills where MSW is disposed. The total capacity of these landfills were limited and thus, the HK government was constrained to invest HK$ 7.8×10^9 (US$ 10^9) to increase their capacity to dispose MSW[34]. According to the government, the

[34]Further investments were made to increase the capacity of construction and other waste, but these

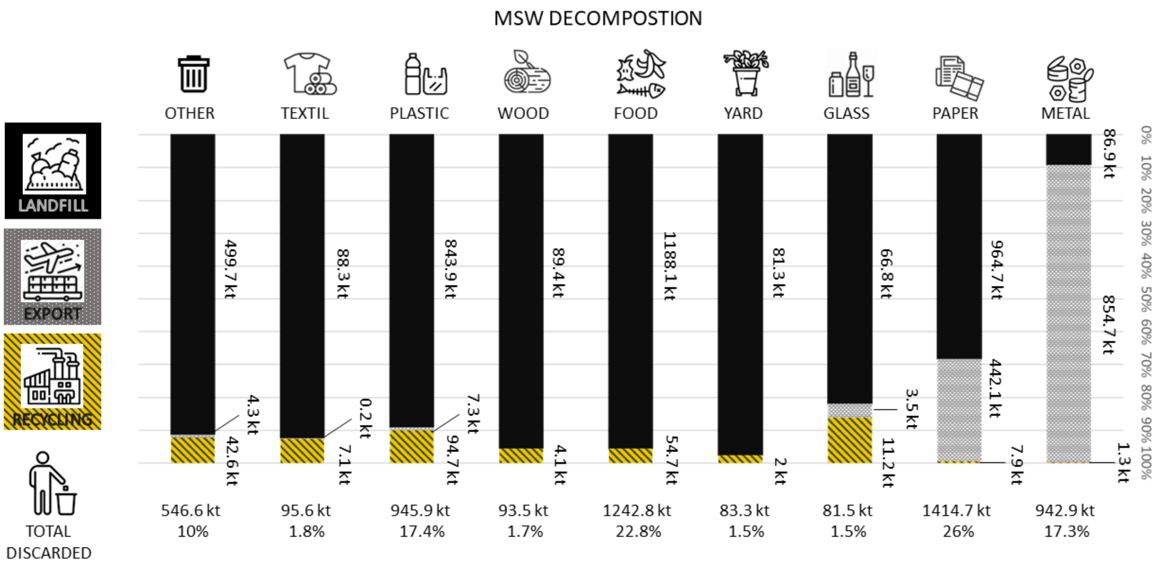

Figure 2: MSW main streams and their types of management in 2020
Source: Environment Bureau (2021c) - Data are provided by the HK government, which seems to be the main and only stakeholder that possesses data on current MSW situation.

landfills - even extended - will run out of space by 2035. Thus the Hong Kong government plans to stop disposing MSW in landfills by 2035 (Environment Bureau, 2021a,b).

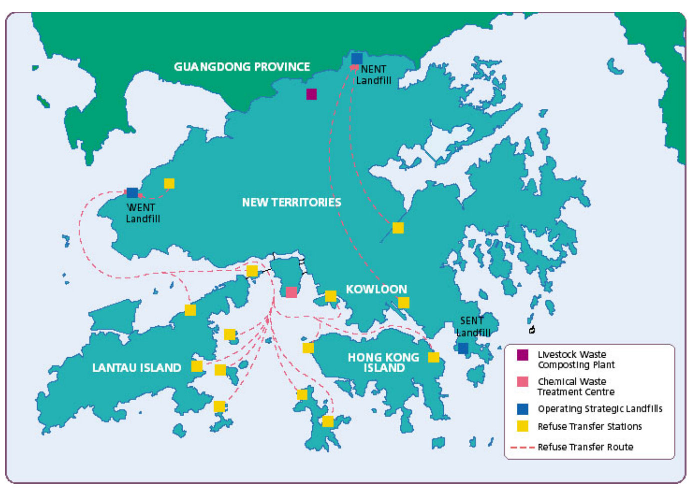

Figure 3: Hong Kong MSW management in 2018 *Source: EPD (2019)*

As shown in Figure 1, in 2020, Hong Kong exported 1312.1 kilotons of MSW to be recycled and recycled 225.6 kt of MSW. While metal has the largest share and the largest amount diverted to export, plastic is the stream with the highest amount diverted to recycle (corresponding to 11% of total amount discarded). These differences can be explained by the physical properties of each

investment are not mentioned here are there are not the focus of this study.

MSW stream (e.g. metal and paper are easy to stack and send to export compared to food waste). Furthermore, the disparities in local capacities of the recycling facilities can explain the disparate end-of-life strategies among MSW streams.

The other types of MSW recovered are textile, plastic, wood, food, yard, glass and paper. WEEE[35] and tyres are also recycled. Overall, less than 5% of the total MSW discraded is recycled locally. To increase the share of MSW being recycled locally, in 2020, the Hong Kong government invested about HK\$ 34×10^9 (US\$ 4.34×10^9) in several infrastructures for MSW recycling and recovery.

The existing main recycling facilities, illustrated in Figure 4 are: 1) the I-Park, an incineration plant with energy recovery which is able to treat up to 1095 kilotons per year of MSW; 2)the Eco-Park, an industrial center composed of several industries recycling up to 334.15 kilotons per year of several types of MSW among them: glass, plastic, fabric and metal; 3) the O-Parks, a set of three facilities recycling up to 182.5 kilotons per year of organic MSW; 4) the WEEE-park, recycling up to 30 kilotons per year of electric MSW; 5) the Y-Park, recycling up to 21.9 kilotons per year of yard MSW. However, currently (in 2020) none of the facilities were reaching its full recycling rate as promoted initially by the government. This poor performance is mainly due to the low collection rate, induced by a low citizen engagement.

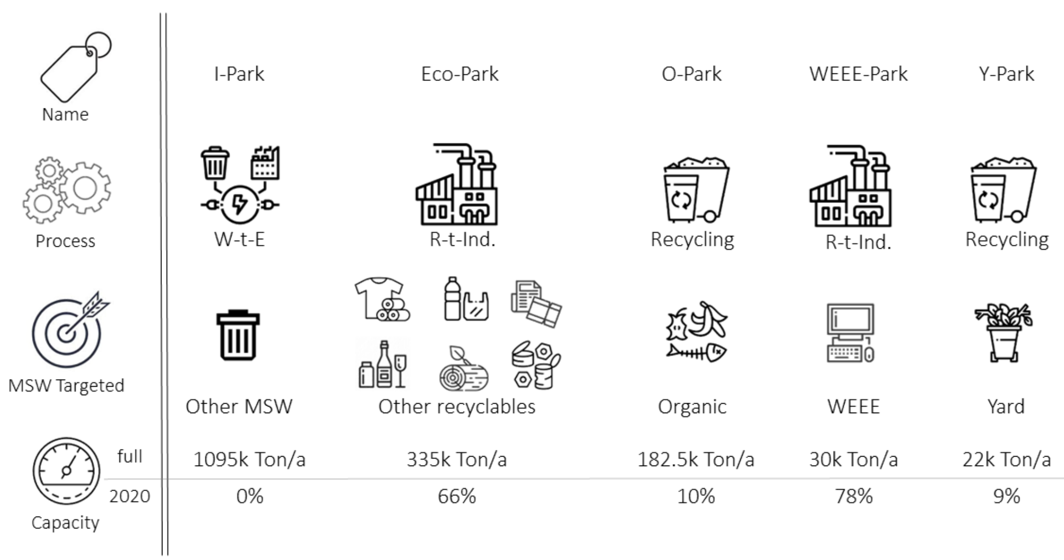

Figure 4: Hong Kong MSW recycling facilities

Source: Environment Bureau (2021c) *Note: W-t-E means waste-to-energy, the facility incinerates waste and use heat recovery to produce electricity. R-t-Ind. means Resources-to-industry, the facility turn the waste into valuable resources for other industries. By recycling, the authors mean that the waste are directly converted into a final product (here compost).*

Next to this large scale infrastructure, the Hong Kong government is also investing in smaller

[35]WEEE stands for Waste Electrical and Electronic Equipment

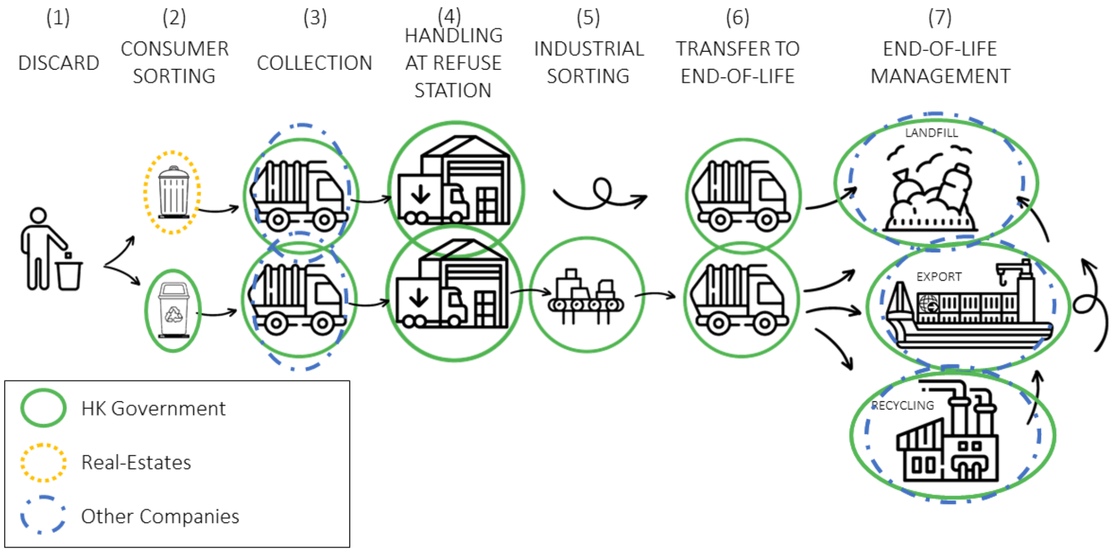

Figure 5: Hong Kong MSW management schematised

infrastructure projects for MSW management, such as the network of organic MSW treatment facilities (OWTF)(eg: Kowloon Bay Pilot Food Waste Composting Plant, Food Waste Recycling Partnership Scheme, Food Waste Recycling Projects in Housing Estates, Food Waste Reduction Program) (Bureau, 2014; EPD, 2019).

A.3 Hong Kong incentive strategies

Hong Kong Government has implemented a range of incentive strategies specifically dedicated to engage its citizens in effective waste sorting and reduction efforts. Next to the existing landfilling charging scheme (gate fee of 365 HK$/ton - 46.61 US$/ton), Hong Kong has implemented the following::

- Education Campaign: Education plays a crucial role in fostering environmental awareness and behavioral change. Hong Kong has initiated comprehensive education campaigns to inform citizens about the importance of waste reduction, recycling, and responsible waste disposal. Informative posters and materials are illustrated by Figure 6.
- Voluntary Program on Source Separation of Waste: Encouraging citizens to separate their waste at the source is a key strategy in waste management. Voluntary programs provide individuals with the opportunity to actively participate in waste sorting, contributing to increased recycling rates and reduced contamination in waste streams. An example of such event is illustrated by Figure 7.

- Tax on Garbage Bags: Implementing a tax on garbage bags, as described in Table A.3, serves as a financial incentive for citizens to generate less waste and sort their recyclables properly. The bags are compulsory for citizens. This strategy not only reduces waste but also generates revenue for waste management initiatives.

Additionally, Hong Kong has deployed innovative solutions such as return vending machines for plastic bottles, see Figure 8, and reusable container machines, see Figure 9. These technologies provide incentives in the form of refunds or discounts, further encouraging responsible waste disposal and resource conservation. Through these strategies, Hong Kong aims to actively involve its citizens in waste reduction and recycling efforts.

Figure 6: Hong Kong education campaign
Source: EPD (2019)

Figure 7: Recycling event in Hong Kong
Source: EPD (2023)

Table 4: Quantity-based MSW charging scheme pricing (HK$/L)

volume	cost/bag
3	0.3
5	0.6
10	1.1
15	1.7
20	2.2
35	3.9
50	5.5
75	8.5
100	11
240	26
660	73

Sources: Environment Bureau (2021c)

To monitor and discourage citizens from abusively discarding waste in public bins and sorting improperly, the Hong Kong government employs a surveillance system that monitors recycling bins, stations, vending machines, and uses cameras and facial recognition technology to identify and fine individuals who violate waste disposal regulations, see Figures 8 and 10. While this approach aims to enforce responsible waste management, it raises concerns about the potential negative impact on citizen engagement and encouragement. Some citizens may perceive these measures as intrusive or punitive, which could affect their active participation in sorting efforts.

Figure 8: Return vending machine in Hong Kong
Source: EPD (2023)

Figure 9: Reusable container Machine in Hong Kong
Source: EPD (2023)

Figure 10: Hong Kong sorting containers being monitored.
Photo by J. Metta in 2019

B Assumptions for BAU, MDC & MACC

Table B1 provides details and sources for the calculations related to MDC (Marginal Damage Cost) and MACC (Marginal Abatement Cost of Carbon). The sources include government websites, publications, and relevant environmental agencies.

Table B1: Details and Sources for BAU MDC and MACC Calculations

Data	Sources
Waste data	Gov
Land used & cost	EPD 1 & 2 & 3 Gov & Prop.
CO_2 emitted	EPA Manfredi et al. (2009)
Social Cost	EPA
Health cost	Liu et al. (2021)
Opark	LegCo website & Opark website
EcoPark	HK Gov website & Greening HK website
Ypark	EPD website & EPD notices
WEEEpark	WEEE park website
Export	Trading website
Ipark	SCMP website & EPD notice

To build the Business-as-usual (BAU) scenario, we take a fictive scenario for 2022 (as we do not have actual data after 2020) where:

- Demographic: The demographic expectations are based on data updated by the US government in 2022, reflecting post-COVID trends. These updated demographic figures provide a more accurate basis for future population projections in Hong Kong.
- MSW Generated /Capita: The assumption of constant municipal solid waste generation per capita, at 0.89 ton per inhabitant, is a conservative estimate. This assumption aligns with the trend since 2020, despite a decrease in the total waste amount due to a declining population. This approach reflects the current waste generation pattern in Hong Kong.
- Total MSW Generated in 25 years = $1.53 * 10^8 tons$ This estimation is based on the previously mentioned trends, and serves as a foundational data point for formulating effective waste management strategies in Hong Kong. Understanding the expected volume of waste production over this extended period provides a quantitative basis for planning and implementing sustainable waste management practices to meet the growing waste challenges in the region.

- Current capacities of Recovery facilities = $9.78 * 10^7$
- Recovery facilities efficiency rate = 0.8% Recycling facilities which started in 2020 (and thus which capital has already been invested) can recycle at 80% of the maximum capacity (as it the case for the existing and running recycling facilities). The efficiency rate of 80% for recovery facilities established since 2020 is a reasonable estimate, considering the existing recycling rates for similar waste types in Hong Kong. These new facilities are expected to perform at par with the current ones, as they target similar solid waste categories.
- Fixed time-frame from 2022-2047 - The specified time-frame from 2022 to 2047, followed by integration back into China, is a critical parameter in the waste management plan.
- Exportation: The assumption of constant exportation at consistent prices until 2020 aligns with current trends, ensuring a conservative approach to financial projections.
- There is no new landfills nor refuse stations but the current infrastructures are exploited with constant costs;
- All money flows (costs and benefits) are from the government. Exportation is done by a government company and all the maintenance and management costs are the ones beard by the Hong Kong government.
- Discount rate: 3% The chosen discount rate is based on Gollier (2016).

Table B2: Baseline data of 2020 to build the BAU

Parameter	Value
MSW_L/Pop	0.553
MSW landfilled	4,145,670
MSW Generated	5,990,000
MSW Landfilled (%)	69.2%
MSW_G/Pop	0.799
Population	7,494,578
Annual Growth Rate	-0.09
Year	2021

Sources: UN, 2022; US, 2022; EPD, 2022

Table B3: BAU Extrapolation of MSW in Hong Kong Data

Details	Unit	TOTAL	2022	2025	2030	2035	2040	2045	2047
Population	inh.	1.92×10^8	7.49×10^6	7.50×10^6	7.49×10^6	7.42×10^6	7.31×10^6	7.16×10^6	7.09×10^6
MSW Generated	ton	1.53×10^8	5.99×10^6	5.99×10^6	5.98×10^6	5.93×10^6	5.84×10^6	5.72×10^6	5.67×10^6
MSW Exported	ton	5.64×10^7	2.17×10^6	2.17×10^6	2.17×10^6	2.17×10^6	2.17×10^6	2.17×10^6	2.17×10^6
MSW Recycled (Ypark)	ton	5.52×10^5	2.12×10^4	2.12×10^4	2.12×10^4	2.12×10^4	2.12×10^4	2.12×10^4	2.12×10^4
MSW Recycled (Opark1)	ton	4.60×10^6	1.77×10^5	1.77×10^5	1.77×10^5	1.77×10^5	1.77×10^5	1.77×10^5	1.77×10^5
MSW Recycled (Opark2)	ton	2.66×10^6	0.00×10^0	1.06×10^5	1.06×10^5	1.06×10^5	1.06×10^5	1.06×10^5	1.06×10^5
MSW Recycled (WEEEpark)	ton	7.57×10^5	2.91×10^4	2.91×10^4	2.91×10^4	2.91×10^4	2.91×10^4	2.91×10^4	2.91×10^4
MSW Recycled (EcoPark)	ton	8.43×10^6	3.24×10^5	3.24×10^5	3.24×10^5	3.24×10^5	3.24×10^5	3.24×10^5	3.24×10^5
MSW Recycled (Ipark)	ton	2.44×10^7	0.00×10^0	1.06×10^6	1.06×10^6	1.06×10^6	1.06×10^6	1.06×10^6	1.06×10^6
Total Recovered Locally	ton	4.14×10^7	5.51×10^5	1.72×10^6	1.72×10^6	1.72×10^6	1.72×10^6	1.72×10^6	1.72×10^6
Total MSW Recovered	ton	9.78×10^7	2.72×10^6	3.89×10^6	3.89×10^6	3.89×10^6	3.89×10^6	3.89×10^6	3.89×10^6
Recovery Rate		6.38×10^{-1}	4.55×10^{-1}	6.49×10^{-1}	6.50×10^{-1}	6.56×10^{-1}	6.66×10^{-1}	6.80×10^{-1}	6.86×10^{-1}
Total to be Landfilled	ton	5.55×10^7	3.26×10^6	2.11×10^6	2.09×10^6	2.04×10^6	1.95×10^6	1.83×10^6	1.78×10^6
Landfill Rate		3.62×10^{-1}	5.45×10^{-1}	3.51×10^{-1}	3.50×10^{-1}	3.44×10^{-1}	3.34×10^{-1}	3.20×10^{-1}	3.14×10^{-1}
Capacity of Landfill	m^3	2.08×10^7	1.64×10^7	5.18×10^6	-8.83×10^6	-2.26×10^7	-3.59×10^7	-4.84×10^7	-5.32×10^7

B.1 Details of the Marginal Damage Costs Function

For the calculation of the Marginal Damage Cost (MDC), several assumptions have been made to provide a comprehensive assessment of the environmental and economic impact. These assumptions include:

- Land cost: We estimated a land cost reduction of 6% per year, which is considered conservative based on current trends in the housing market. According to Bloomberg[36], Hong Kong's housing market had already experienced an 8% drop in 2022, with expectations of a further 20% decline in the following year. This projection takes into account the prevailing market conditions and potential fluctuations in property values.

- Social cost of CO2 emissions : The trends in the social cost of CO2 emissions are derived from data provided by the US government. This factor accounts for the environmental implications and associated costs of carbon emissions in the region.

- Health cost: The health cost assumptions are based on the trends observed in the social cost of CO2 emissions, considering the health impacts associated with carbon emissions. This factor encompasses the health-related expenses attributed to pollution and environmental degradation.

- Capital costs for new landfills: The capital costs for establishing new landfills are modeled as a step function, reflecting the real current prices for such infrastructure development. This approach provides an accurate representation of the financial commitments required for expanding waste management facilities.

- Discount rate: A discount rate of 3%, as cited in Gollier's research, is used to evaluate the present value of future costs and benefits.

- Polynomial trendline: The specific polynomial function used is: $4E^{-10} * x^2 - 0.1186 * x + 8000000$ This polynomial trendline serves as a mathematical model to capture and project the evolving trends and dynamics related to the MDCost over additional MSW to be landfilled.

For the computation of the Social Cost of MSW landfilling, we referenced the data presented in Table B4, which provides a detailed breakdown of the Social Carbon Costs (SCC) in HKD (Real 2010) per ton of CO2 for various years. Using this data, we constructed Figure 11, which illustrates how these SCC values evolve over time. To assess the overall social cost associated with MSW landfilling, we integrated these SCC values over the corresponding levels of MSW landfilled, to compute the MDC.
In the context of assessing the pollution linked to MSW landfilling, we referred to the data provided in Table B5, which outlines the amount of MSW landfilled and the associated pollution and health

[36] bloomberg.com visited on October 15, 2022

Table B4: Social Carbon Costs (SCC) of MSW landfilling in HKD (Real 2010) per ton CO2 (HKD/ton CO2)

Year	SCC
2050	946.44
2045	877.56
2040	808.67
2035	739.78
2030	670.89
2025	602.00
2020	533.11
2015	464.22
2010	395.33
2005	326.44
2000	257.56
1995	188.67

impact measured in HK$ for different years. To gain a comprehensive perspective on the pollution generated by MSW landfilling, we generated Figure 12, which visualizes how pollution and health impact values vary over time. By integrating these figures over the corresponding quantities of MSW landfilled, we quantify the environmental costs and implications associated with these landfilling activities to compute the MDC.

Table B5: MSW Landfilled and Pollution+Health Impact in HK$ (10^6)

Year	Amount of MSW Landfilled (ton)	Pollution+Health Impact ($HK\$10^6$)
2020	3,956,094	2,897,175,429,611
2015	3,708,035	2,988,262,451,937
2010	3,326,610	2,532,792,186,459
2005	3,422,605	1,950,754,805,512
2000	3,407,275	9,961

The details of the MDC are reported in Table B6

The details of the MAC are reported in Table B7

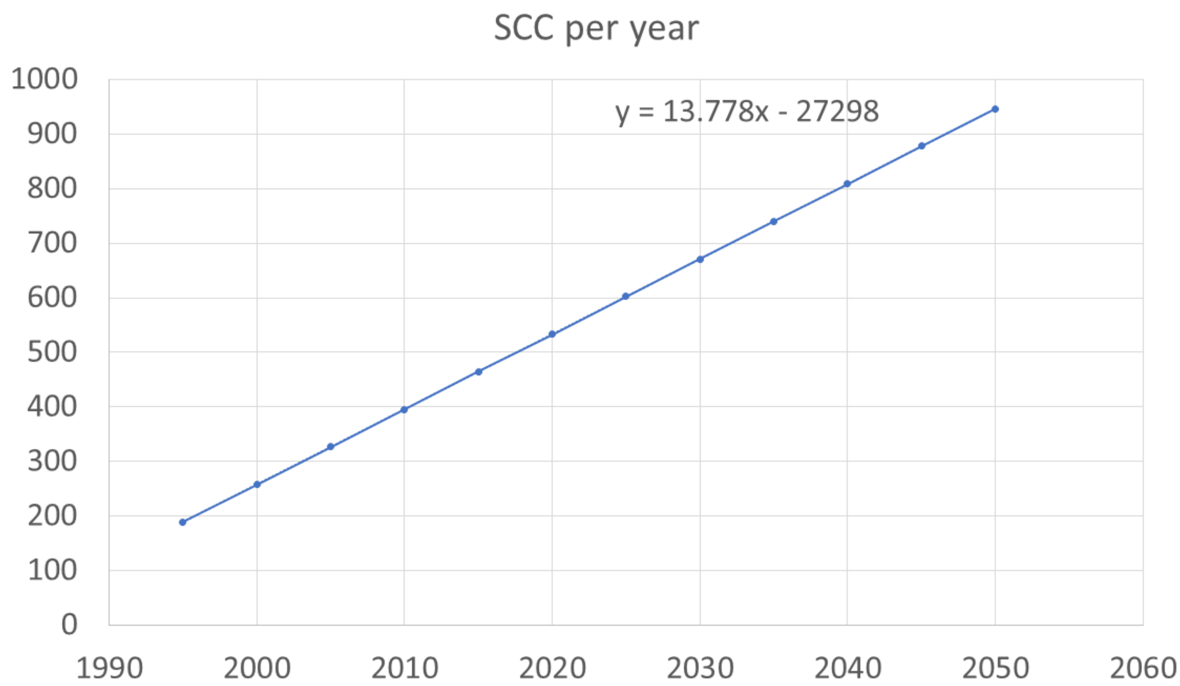

Figure 11: SCC

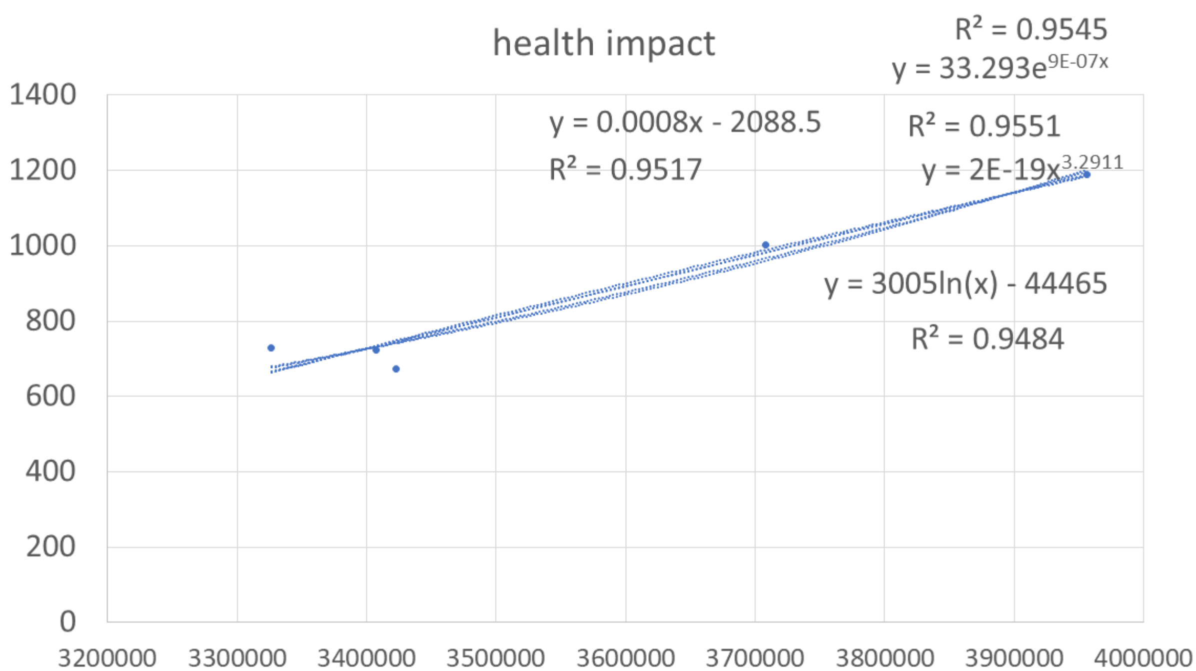

Figure 12: SCC

Table B6: Details of the MDC

ρ	L_ρ (tons)	R_ρ (tons)	New landfills needed	K_c	$\frac{dK_c}{dL}$	Damages	Marginal Damages
0	1.53×10^8	0.00×10^0	8.73	3.69×10^{12}	1.71×10^5	3.95×10^{14}	9×10^6
0.05	1.46×10^8	8.00×10^6	8.25	3.51×10^{12}	1.63×10^5	3.34×10^{14}	8×10^6
0.1	1.38×10^8	2.00×10^7	7.76	3.32×10^{12}	1.54×10^5	2.80×10^{14}	7×10^6
0.15	1.30×10^8	2.00×10^7	7.27	3.14×10^{12}	1.46×10^5	2.33×10^{14}	6×10^6
0.2	1.23×10^8	3.00×10^7	6.79	2.95×10^{12}	1.38×10^5	1.91×10^{14}	5×10^6
0.25	1.15×10^8	4.00×10^7	6.30	2.77×10^{12}	1.30×10^5	1.55×10^{14}	4×10^6
0.3	1.07×10^8	5.00×10^7	5.81	2.58×10^{12}	1.22×10^5	1.24×10^{14}	4×10^6
0.35	9.96×10^7	5.00×10^7	5.33	2.40×10^{12}	1.14×10^5	9.76×10^{13}	3×10^6
0.4	9.20×10^7	6.00×10^7	4.84	2.22×10^{12}	1.05×10^5	7.54×10^{13}	3×10^6
0.45	8.43×10^7	7.00×10^7	4.35	2.03×10^{12}	9.72×10^4	5.71×10^{13}	2×10^6
0.5	7.66×10^7	8.00×10^7	3.87	1.85×10^{12}	8.90×10^4	4.22×10^{13}	2×10^6
0.55	6.90×10^7	8.00×10^7	3.38	1.66×10^{12}	8.09×10^4	3.03×10^{13}	1×10^6
0.6	6.13×10^7	9.00×10^7	2.89	1.48×10^{12}	7.27×10^4	2.10×10^{13}	1×10^6
0.65	5.37×10^7	1.00×10^8	2.41	1.29×10^{12}	6.45×10^4	1.39×10^{13}	8×10^5
0.7	4.60×10^7	1.00×10^8	1.92	1.11×10^{12}	5.63×10^4	8.80×10^{12}	6×10^5
0.75	3.83×10^7	1.00×10^8	1.43	9.23×10^{11}	4.82×10^4	5.22×10^{12}	4×10^5
0.8	3.07×10^7	1.00×10^8	0.95	7.38×10^{11}	4.00×10^4	2.87×10^{12}	3×10^5
0.85	2.30×10^7	1.00×10^8	0.46	5.54×10^{11}	3.18×10^4	1.45×10^{12}	1×10^5
0.9	1.53×10^7	1.00×10^8	0.00	3.69×10^{11}	2.41×10^4	6.58×10^{11}	7×10^4
0.95	7.66×10^6	1.00×10^8	0.00	1.85×10^{11}	2.41×10^4	2.49×10^{11}	4×10^4
0.96	6.13×10^6	1.00×10^8	0.00	1.48×10^{11}	2.41×10^4	1.93×10^{11}	4×10^4
0.97	4.60×10^6	1.00×10^8	0.00	1.11×10^{11}	2.41×10^4	1.41×10^{11}	3×10^4
0.98	3.07×10^6	2.00×10^8	0.00	7.38×10^{10}	2.41×10^4	9.26×10^{10}	3×10^4
0.99	1.53×10^6	2.00×10^8	0.00	3.69×10^{10}	2.41×10^4	4.59×10^{10}	3×10^4
0.993	1.07×10^6	2.00×10^8	0.00	2.58×10^{10}	2.41×10^4	3.21×10^{10}	3×10^4
0.996	6.13×10^5	2.00×10^8	0.00	1.48×10^{10}	2.41×10^4	1.83×10^{10}	3×10^4
1	0.00×10^0	2.00×10^8	0.00	0.00×10^0	2.41×10^4	0.00×10^0	0×10^0

Table B7: MAC Details

ρ	L_ρ (tons)	R_ρ (tons)	Capacity needed	Marginal Ab.	Marginal Ab.	OPark	Ecopark	Ipark	Abatement costs (HK$)
0.68	4.95×10^7	1.04×10^8	5.95×10^6	1.51×10^3	1.51×10^{-3}	2	0	0	$5,846,228,894$
0	1.53×10^8	0.00×10^0	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.05	1.46×10^8	7.66×10^6	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.1	1.38×10^8	1.53×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.15	1.30×10^8	2.30×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.2	1.23×10^8	3.07×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.25	1.15×10^8	3.83×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.3	1.07×10^8	4.60×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.35	9.96×10^7	5.37×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.4	9.20×10^7	6.13×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.45	8.43×10^7	6.90×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.5	7.66×10^7	7.66×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.55	6.90×10^7	8.43×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.6	6.13×10^7	9.20×10^7	0.00×10^0	0.00×10^0	0.00×10^0	0	0	0	$2,717,498,369$
0.65	5.37×10^7	9.96×10^7		0.00×10^0	0.00×10^0				
0.65	5.37×10^7	9.96×10^7	1.82×10^6	7.57×10^2	7.57×10^{-4}	1	0	0	$4,281,863,632$
0.7	4.60×10^7	1.07×10^8	9.49×10^6	7.57×10^2	7.57×10^{-4}	3	0	0	$7,410,594,157$
0.75	3.83×10^7	1.15×10^8	1.72×10^7	7.57×10^2	7.57×10^{-4}				
0.75	3.83×10^7	1.15×10^8	1.72×10^7	1.09×10^3	1.09×10^{-3}	3	1	0	$11,528,844,083$
0.8	3.07×10^7	1.23×10^8	2.48×10^7	1.09×10^3	1.09×10^{-3}	3	2	0	$15,647,094,008$
0.85	2.30×10^7	1.30×10^8	3.25×10^7	1.09×10^3	1.09×10^{-3}	3	3	0	$19,765,343,934$
0.9	1.53×10^7	1.38×10^8	4.01×10^7	1.09×10^3	1.09×10^{-3}	3	3	0	$19,765,343,934$
0.95	7.66×10^6	1.46×10^8		1.09×10^3	1.09×10^{-3}				
0.95	7.66×10^6	1.46×10^8	4.78×10^7	1.51×10^3	1.51×10^{-3}	3	3	1	$38,548,514,201$
0.96	6.13×10^6	1.47×10^8	4.93×10^7	1.51×10^3	1.51×10^{-3}	3	3	1	$38,548,514,201$
0.97	4.60×10^6	1.49×10^8	5.09×10^7	1.51×10^3	1.51×10^{-3}	3	3	1	$38,548,514,201$
0.98	3.07×10^6	1.50×10^8	5.24×10^7	1.51×10^3	1.51×10^{-3}	3	3	1	$38,548,514,201$
0.99	1.53×10^6	1.52×10^8	5.39×10^7	1.51×10^3	1.51×10^{-3}	3	3	1	$38,548,514,201$
1	0.00×10^0	1.53×10^8	5.55×10^7	1.51×10^3	1.51×10^{-3}	3	3	1	$38,548,514,201$