Landfill-to-Biorefinery Transitions in Municipal Waste Systems: A System Dynamics Approach

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Abstract

Municipal solid waste (MSW) systems face increasing pressure from growing waste generation, limited landfill capacity, and methane (CH_4) emissions associated with organic waste decomposition. These challenges are particularly relevant in rapidly urbanizing regions where landfill disposal remains the dominant waste management strategy. This study develops a System Dynamics (SD) model to explore potential transitions from landfill-based waste management toward integrated waste-to-energy (WtE) biorefinery systems. The model is parameterized using Bogotá, Colombia, as a case study and represents the interactions between waste generation, landfill accumulation, waste separation behavior, and alternative energy conversion pathways.

A scenario-based analysis evaluates four configurations: (1) a baseline landfill system, (2) source separation with anaerobic digestion and electricity generation, (3) RDF gasification with methanol production, and (4) RDF gasification with sustainable aviation fuel (SAF) production. Results show that under baseline conditions landfill capacity is reached within the next decade. Implementing source separation policies significantly reduces landfill inflows and methane emissions while enabling multiple resource recovery pathways.

A key insight from the model is that upstream waste separation policies determine the availability of refuse-derived fuel (RDF), which becomes the main structural constraint governing electricity and fuel production across WtE pathways. These findings highlight how policy-driven changes in waste sorting behavior can enable the transition from landfill-dominated disposal systems toward integrated waste-to-energy biorefineries.

Keywords: Municipal Solid Waste (MSW), Waste-to-Energy (WtE), Landfill methane emissions, Refuse-Derived Fuel (RDF), Sustainable Aviation Fuel (SAF), Methanol production

1. Introduction

Municipal solid waste (MSW) management has become an increasingly critical challenge for rapidly urbanizing societies. Global MSW generation has increased significantly over the past decades, reaching approximately two billion tonnes annually and projected to reach about 3.5 billion tonnes by 2050 if current trends continue (Chen et al., 2020). At present, landfilling remains the dominant disposal method worldwide, with more than 60% of MSW ultimately disposed of in landfills or dumpsites (Osazee, 2021). The continued reliance on landfill-based waste management systems creates environmental and operational challenges, including increasing pressure on landfill capacity and the release of greenhouse gases associated with organic waste decomposition (Sharma & Jain, 2020). One of the most significant environmental impacts associated with landfill disposal is CH_4 emission. When organic waste decomposes under anaerobic conditions within landfill environments, methane is produced and released into the atmosphere, contributing substantially to global greenhouse gas emissions (Gupta et al., 2022). Recent measurement-based studies indicate that landfill emissions represent a significant fraction of anthropogenic methane sources and may even be underestimated in national greenhouse gas inventories. Because methane has a much higher short-term warming potential than carbon dioxide (CO_2), reducing emissions from waste management systems has become a key priority for climate mitigation strategies (Manheim et al., 2024).

WtE technologies have emerged as an important pathway for addressing these challenges by diverting waste from landfill disposal while recovering energy from residual waste streams (Yadav et al., 2024). Several technological pathways are currently used for energy recovery from MSW, including incineration, anaerobic digestion (AD), landfill gas recovery, and thermochemical conversion processes such as pyrolysis and gasification. These technologies allow waste streams to be converted into electricity, heat, or liquid fuels while simultaneously reducing landfill volumes and mitigating methane emissions (Joshi, 2021; Masud et al., 2024). Despite their potential benefits, transitioning from traditional landfill systems toward integrated WtE infrastructures involves complex interactions among technological adoption, economic incentives, waste generation patterns, and policy interventions (Rezania et al., 2023). Waste flows, infrastructure investment, energy markets, and regulatory frameworks interact through multiple feedback mechanisms that influence the long-term performance of waste management systems. Understanding these interactions requires analytical approaches capable of representing nonlinear dynamics and feedback processes within socio-technical systems (Berenjkar et al., 2021).

SD modeling provides a useful framework for analyzing such complex systems. To effectively navigate these complexities, applying SD modeling can provide valuable insights into the feedback loops and emergent behaviors inherent in waste management systems (Babalola, 2019; Pinha & Sagawa, 2020; Scholl & Richardson, 2003). SD models have been widely applied to evaluate municipal solid waste management policies, simulate alternative treatment pathways, and explore how changes in waste classification, recycling, and treatment technologies influence system behavior over time. By representing feedback loops, delays, and stock–flow relationships, SD modeling allows researchers to evaluate the long-term implications of policy decisions and infrastructure investments in waste management systems (Ibarra Vega & Bautista-Rodriguez, 2024). The application of SD modeling in waste management can help identify optimal strategies for reducing greenhouse gas emissions while maximizing resource recovery and sustainability in urban environments.

Methane emissions from MSW systems represent a critical climate challenge, particularly in regions where landfill disposal remains the dominant waste management practice. In Colombia, the waste sector accounts for more than 20% of national CH_4 emissions, highlighting substantial mitigation potential through improved waste management strategies (Clean Air Task Force, 2024). At the same time, increasing waste generation is placing pressure on landfill capacity worldwide, with global municipal waste exceeding two billion tonnes annually and many regions facing limited disposal space (Beyond an Age of Waste Turning Rubbish into a Resource, 2024; World Bank Group, 2022). These dual pressures create the need for systemic transitions toward alternative waste management pathways such as WtE systems.

In this context, this study develops a SD modeling framework to analyze the transition from conventional landfill-based waste management systems to integrated WtE biorefineries capable of producing renewable energy carriers such as methane, methanol, and SAF. Using a scenario-based approach, the model evaluates how behavioral changes in waste separation and the deployment of alternative waste conversion technologies can influence landfill utilization, CH_4 emissions, and energy production pathways in municipal waste systems.

2. Literature Review

SD has been widely applied to analyze complex sustainability transitions, particularly in energy systems, waste management, and circular economy frameworks. Previous studies have demonstrated the ability of SD models to capture feedback relationships between waste generation, policy interventions, and environmental outcomes.

One of the earliest applications of SD to waste management was developed by Mashavekhi, (1993), who constructed an SD model to analyze urban waste management transitions. His work demonstrated how policy decisions influence the development of waste treatment infrastructure and long-term environmental outcomes in urban systems.

Later studies expanded the application of SD modeling to explore waste management planning and technology adoption. Sudhir et al., (1997) modeled the dynamics of urban waste management systems and highlighted the role of technology adoption in improving waste treatment efficiency and reducing environmental impacts. More recent research has applied SD to analyze global waste dynamics and sustainability transitions. Kapmeier & Gonçalves, (2018) used SD to explore global waste accumulation dynamics and identify structural causes of increasing waste generation. Their work highlights how delays in recycling capacity expansion and consumption patterns can reinforce waste growth trajectories.

Other studies have incorporated broader sustainability and circular economic perspectives. For example, Ghanbari, (2022) applied SD to evaluate construction waste management systems, illustrating how feedback loops among regulatory frameworks, economic incentives, and waste flows shape system performance. Research focusing on emerging economies have also examined how policy incentives and technological adoption influence WtE deployment. Warlina & Listyarini, (2022) demonstrated that government policy and infrastructure investments are key drivers for scaling sustainable waste management systems.

More recent studies continue to emphasize the importance of integrated modeling approaches for waste management transitions. (Berenjkar et al., 2021) highlighted the importance of system based approaches for evaluating waste management strategies, emphasizing that feedback driven models are essential for understanding the complex interactions between waste flows, technological adoption, and environmental outcomes.

Similarly, Ibarra Vega & Bautista-Rodriguez, (2024) applied SD to evaluate MSW management policies and demonstrate how SD models can support long-term planning by capturing interactions among waste generation, treatment infrastructure, and environmental impacts.

However, despite these advances, relatively few studies have examined the transition from landfill-based waste management toward integrated biorefinery systems producing renewable fuels such as methane, methanol, or SAF. Furthermore, existing research often focuses on electricity generation from waste rather than multi-product bioenergy pathways. This gap highlights the need for integrated modeling frameworks capable of exploring multiple waste-to-fuel pathways and their environmental implications. This study addresses this gap by developing a SD model that captures the transition from landfill disposal to waste-based biorefineries producing methane, methanol, and SAF.

3. Methods

3.1 Modeling Approach and Assumptions

This study develops a SD model to explore alternative pathways for transforming MSW management systems from landfill-based disposal toward integrated Waste-to-Energy (WtE) biorefinery systems. The model represents the dynamics of waste generation, waste separation practices, landfill accumulation, organic waste treatment, and energy recovery technologies. The model was implemented in Stella Architect, which allows representation of the system through stocks, flows feedback loops, and nonlinear relationships governing waste management dynamics (isee systems inc, 2025).

The modeling approach focuses on evaluating transitions from landfill-based systems to WtE pathways using a "what-if" scenario framework. This approach allows the analysis of how changes in waste separation behavior and technology deployment influence new source of energy production or liquids biofuel production over time.

The model is parameterized using Bogotá, Colombia, as the reference case study. Bogotá represents one of the largest urban waste systems in Colombia and faces increasing challenges related to landfill capacity, CH_4 emissions, and waste management infrastructure. The city relies primarily on the Doña Juana landfill for MSW disposal, which receives most of the waste generated in the metropolitan area. Figure 1 illustrates the Conceptual framework of the waste-to-energy SD model.

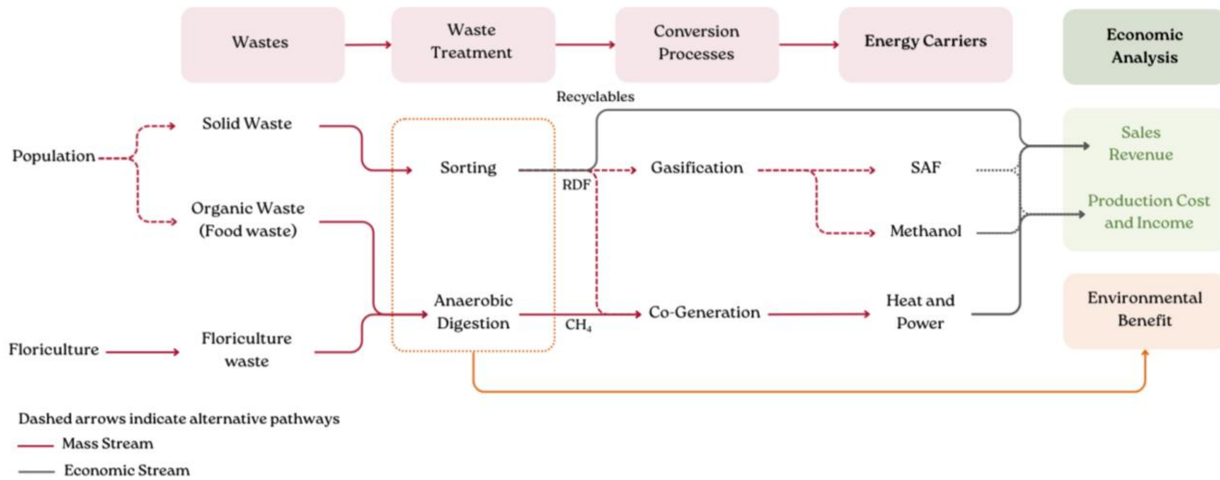


Figure 1 Conceptual framework of the waste-to-energy System Dynamics model.

A key assumption in the model is the implementation of public education and awareness programs aimed at improving waste separation at the source. Under baseline conditions, most waste is disposed of without separation, reflecting the current behavior observed in many landfill-dependent waste management systems. Education campaigns are assumed to increase the fraction of households separating organic waste from recyclable and residual solid waste. This behavioral shift modifies the composition of waste streams arriving at the landfill and enables the implementation of different waste treatment pathways.

Separated organic waste is directed toward an AD stage located within the landfill complex. In addition to MSW, the model incorporates floricultural residues generated in the surrounding region as an additional feedstock for the digestion process. The AD process produces biogas rich in CH_4, which is assumed to be used in combined heat and power (CHP) systems to generate electricity exported to the regional power grid.

Non-organic solid waste streams undergo material sorting and recovery processes, where recyclable materials such as plastics, metals, and glass are separated and sold in secondary material markets. The remaining non-recyclable fraction is processed into Refuse-Derived Fuel (RDF), which can be used as a feedstock for alternative energy conversion pathways. RDF can be gasified to produce syngas, which can subsequently be upgraded to produce liquid fuels such as methanol or SAF.

3.2 What-If Scenario Design

The SD model evaluates several what-if scenarios representing alternatives waste management strategies and technology pathways. Table 1 summarizes the assumptions and key considerations associated with each scenario.

Table 1 Scenario description and assumptions for the what-if SD model.

Scenario	Description	Key Consideration
Scenario 1 Base landfill System	This scenario represents the current situation in which most MSW is disposed in landfills without prior separation at the source. This scenario serves as the reference case for comparison with alternative policy and technology interventions.	• Organic and inorganic waste are mixed • Limited material recovery occurs • Methane emissions result primarily from uncontrolled landfill decomposition • Energy recovery from waste remains minimal
Scenario 2 Source separation	In this scenario, public education campaigns increase the rate of waste separation at the source: organic waste from solid waste; allowing organic waste to be diverted toward biological treatment processes. The residual solid waste is directed to a sorting stage, where recyclable material are recovered. The remaining non-recyclable fractions is converted into RDF after the material recovery stage. The RDF is then used as a fuel in combustion based energy recovery systems, producing electricity that is exported to the grid.	Total electricity generation results from the combination of: • Electricity produced from AD (biogas based CHP) • Electricity generated from RDF combustion
Scenario 3 RDF Gasification and Syngas conversion to Methanol	In this scenario, instead of direct combustion, RDF can also be processed through a gasification process. RDF is converted into syngas, a mixture composed of carbon monoxide and hydrogen. The syngas can then be used as an intermediate feedstock to produce liquid fuels as Methanol.	• RDF is converted to syngas through gasification • Syngas is upgraded to methanol through catalytic synthesis
Scenario 4 RDF Gasification and Syngas conversion to Sustainable Aviation Fuel (SAF)	In this pathway, syngas produced from RDF gasification are further through catalytic upgrading processes to produce SAF. This scenario explores the potential role of MSW as feedstock providers for advanced biofuel production pathways supporting aviation decarbonization.	• RDF gasification produces syngas • Syngas is upgraded to SAF through fuel synthesis pathways

3.3 Dynamic Hypothesis

Figure 2 presents the main feedback structure and process pathways represented in the model. The dynamic hypothesis proposes that methane emissions and landfill pressure in MSW systems are primarily driven by the continuous inflow of waste into landfill facilities under baseline disposal conditions. As population increases, municipal solid waste generation also increases, leading to larger waste flows toward the landfill. When source separation is limited, most organic and inorganic fractions are disposed of together, increasing landfill accumulation and methane emissions associated with anaerobic decomposition.

The main endogenous feedback represented in the model is the balancing loop B1 (Landfill Capacity Constraint). In this loop, an increase in the flow of waste to landfill raises the amount of waste in landfill, which progressively reduces the remaining landfill capacity. As available capacity declines, the landfill becomes increasingly constrained, creating a balancing effect on the continued growth of waste disposal to landfill. This loop captures the physical limitation of landfill-based waste management systems and represents the main structural pressure motivating the transition toward alternative waste treatment pathways.

Beyond B1, the model includes a set of causal pathways that represent policy interventions and technology allocation choices rather than additional closed feedback loops. In particular, educational programs increase waste separation at the source, which diverts organic waste toward AD and non-organic residuals toward sorting, recycling, and RDF production. Organic waste directed to AD, together with floriculture residues, produces methane that can be used for cogeneration and electricity production. At the same time, RDF can be allocated either to combustion for electricity generation or to gasification for syngas production, which can subsequently be upgraded into methanol or sustainable aviation fuel SAF.

The dynamic hypothesis therefore suggests that the transition from landfill-dominated disposal to WtE and waste-to-fuel pathways is not driven by multiple internal feedback loops, but rather by the interaction between the landfill capacity constraint (B1) and policy-driven changes in waste flow allocation. Under this structure, upstream waste separation becomes the key enabling mechanism for reducing landfill dependence, lowering methane emissions, and increasing the recovery of energy and fuel products from municipal waste streams.

3.4 Techno-Economic Analysis and Environmental Considerations

Although the focus of the study is SD modeling, techno-economic analysis (TEA) is used to parameterize technology costs. The TEA framework follows the methodology described by Peters et al., (2003) for process economic evaluation. In addition, publicly available techno-economic datasets developed by Brandt & Wolcott, (2021) for the ASCENT program are used to represent conversion pathways for advanced aviation fuels. These cost and performance parameters are integrated into the SD model to simulate the economic feasibility of alternative WtE pathways. Net Present Value (NPV) calculations are performed using the built-in financial functions available in Stella Architect, allowing the economic performance of different WtE pathways to be evaluated dynamically withing the simulation environment.

Environmental impacts such as CO_2 emissions or water related effects are not explicitly quantified in the model. Nevertheless, the system structure captures the potential environmental benefits associated with waste diversion and energy recovery, including reduced landfill CH_4 and improve resource recovery.

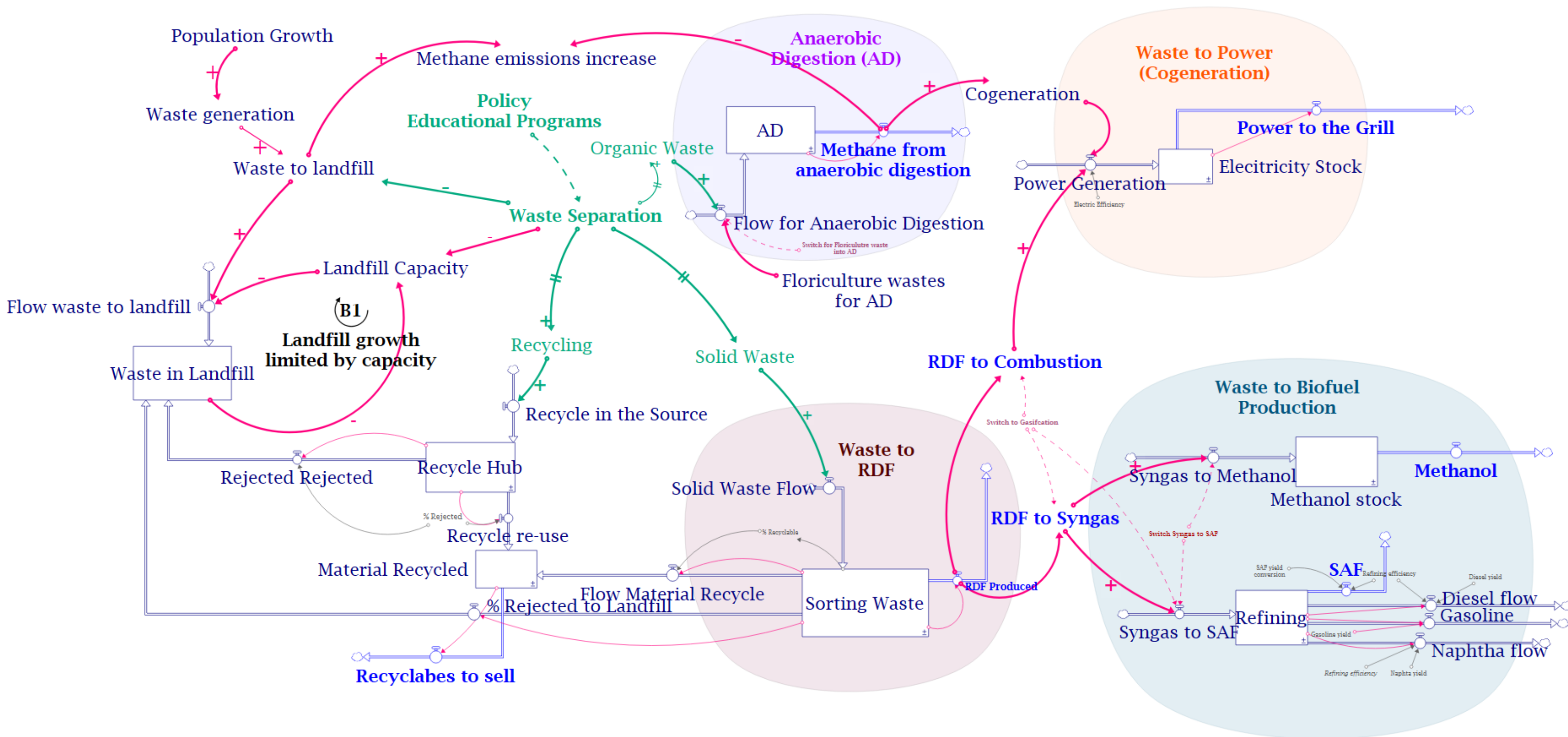


Figure 2. Main feedback structure and process pathways of the waste-to-energy System Dynamics model. The balancing loop B1 represents the landfill capacity constraint, while the remaining links describe policy-driven waste diversion and technology allocation pathways.

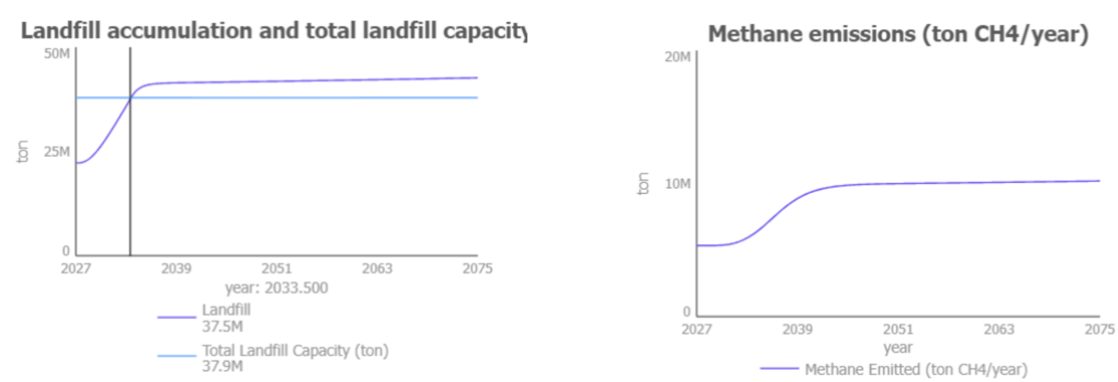
4. Results and Discussion

4.1 Scenario 1- Base landfill System

Scenario 1 represents the baseline condition in which no waste separation policies or education programs are implemented. Under this scenario, most MSW is transported directly to the landfill without prior sorting, resulting in mixed disposal of organic and inorganic waste streams.

The landfill stock is initialized with an existing accumulated waste mass, representing current operating conditions rather than the creation of a new landfill. As shown in Figure 3a, landfill accumulation increases rapidly and reaches the total landfill capacity of approximately 37.9 million tons around 2033. This behavior reflects the structural constraint represented by the balancing loop B1 (Landfill Capacity Constraint), where continued waste inflows progressively reduce the remaining available capacity. The results suggest that, under a landfill-only management strategy, the facility would reach its operational limit within the next few years, consistent with current projections for the Doña Juana landfill (Lozano. J., et al 2024).

Methane emissions increase more gradually due to the delayed response associated with anaerobic decomposition processes. Because methane generation is modeled using a third-order delay, emissions rise as waste accumulates and stabilize once landfill growth approaches its capacity limit. This indicates that methane emissions are driven by both the existing landfill mass at the start of the simulation and the continued disposal of waste over time.

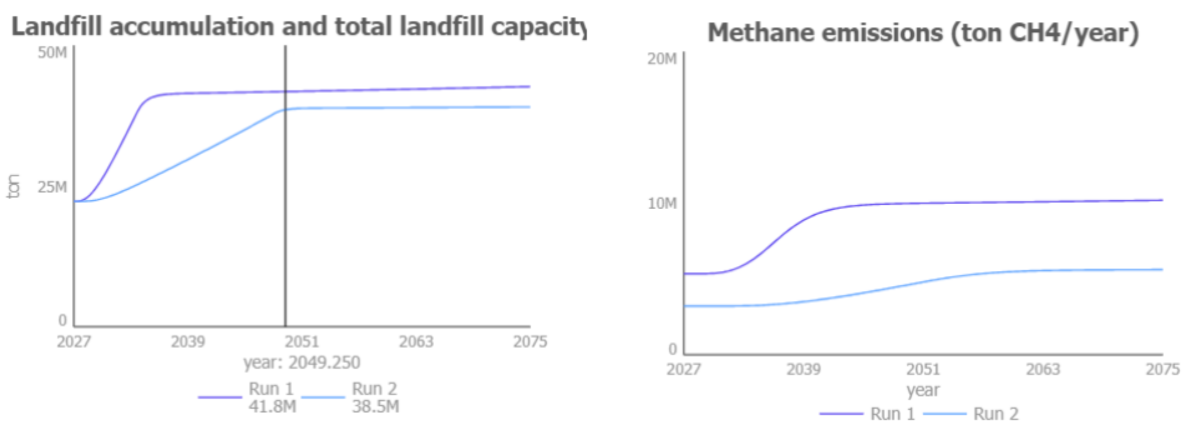


a. b.

Figure 3 a) Landfill accumulation and total land capacity b) methane emissions under the baseline landfill scenario.

4.2 Scenario 2- Source separation

Scenario 2 represents the implementation of public education programs aimed at promoting waste separation at the source. Figure 4 compares the baseline landfill Scenario 1 (Run 1) with the Scenario 2 (Run 2). As a result, the amount of waste sent to the landfill decreases substantially, although some residual waste still reaches the landfill due to sorting rejects and waste that is not separated at the source. This reduction in landfill inflows delays the approach to landfill capacity and lowers the long-term accumulation of waste. A similar effect is observed for methane emissions. Because less organic waste is disposed of in the landfill under Run 2, methane emissions are significantly reduced compared with the baseline scenario. However, methane emissions do not fall to zero because some biodegradable material still reaches the landfill through rejected fractions and unseparated waste. Overall, the results show that source separation policies can both reduce pressure on landfill capacity and mitigate methane emissions by diverting organic waste toward controlled treatment pathways.

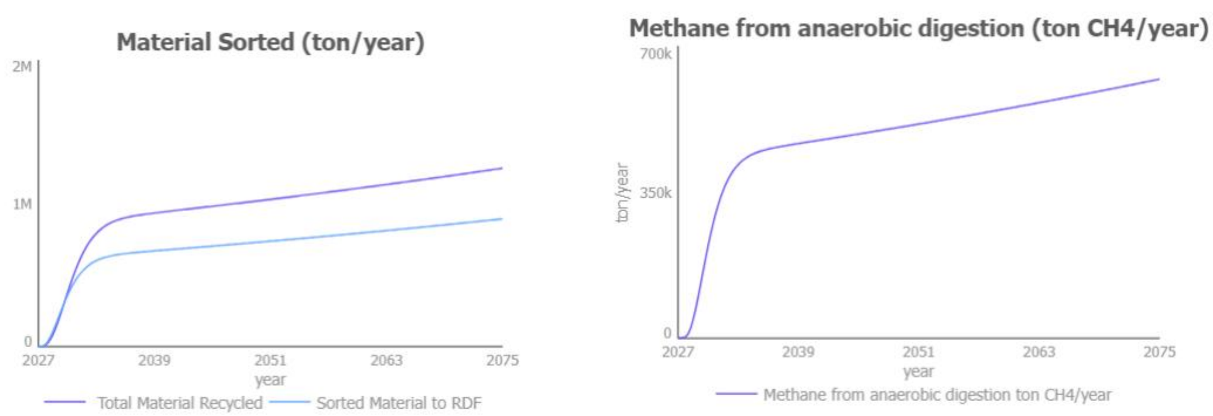


a. b.

Figure 4. a) Comparison of landfill waste reception and b) methane emissions under baseline and source separation scenarios. Run 1 refers to Scenario 1 and Run 2 refers to Scenario 2

Under the source separation scenario, the implementation of education programs enables households to separate organic waste from recyclable and residual solid waste prior to collection. As shown in Figure 5, this separation allows the recovery of significant quantities of recyclable materials while also generating residual sorted material that can be processed into

RDF. Both material recovery and RDF production increase steadily over time as waste generation grows and sorting capacity improves. At the same time, the organic fraction diverted from the landfill is directed toward the AD subsystem, where it is combined with floriculture residues to produce methane. The results indicate that methane production from AD also increases over time, reaching approximately 650,000 tons of CH_4 per year by the end of the simulation period. From a system perspective, these results highlight how source separation policies enable multiple resource recovery pathways within the waste management system, including material recycling, RDF production for energy conversion, and controlled methane generation through anaerobic digestion. This diversification of waste treatment pathways reduces reliance on landfill disposal while supporting the transition toward waste-based energy and fuel production systems.



a. b.

Figure 5 a) Material recovery, RDF production, and b) methane generation from anaerobic digestion under the source separation scenario.

Figure 6 shows the electricity generated from the combined WtE pathways in the system, including methane produced through anaerobic digestion and energy recovered from the combustion of RDF. The results indicate a rapid increase in electricity generation during the early years of the simulation as source separation policies enable the diversion of organic waste to AD and residual waste to RDF production. After this initial transition, electricity generation increases more gradually as waste flows stabilize over time. Assuming an electrical conversion efficiency of 25%, the system reaches approximately 550 MWh of electricity per year by the end of the simulation period. These results illustrate how integrating anaerobic digestion and RDF combustion can contribute to energy recovery from municipal waste streams within a WtE framework.

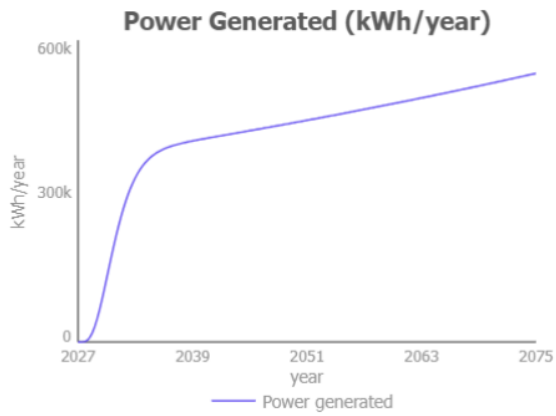
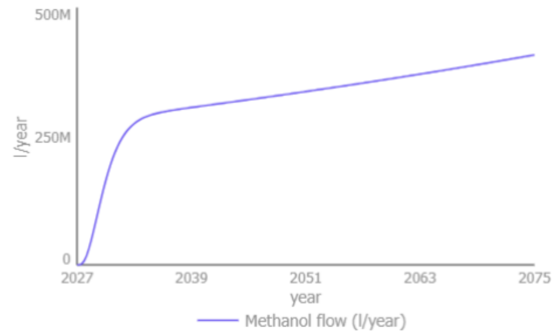


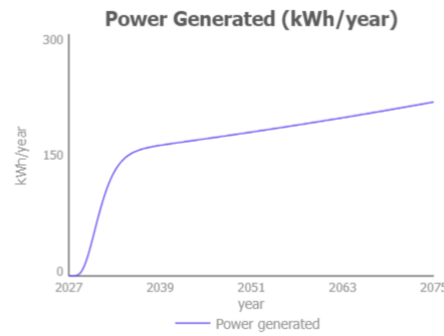
Figure 6. Annual electricity generation from AD and RDF combustion.

4.3 Scenario 3 - RDF Gasification and Syngas conversion to Methanol

In this scenario, the residual fraction of sorted waste is processed through gasification to produce synthesis gas (syngas), which is subsequently converted into methanol through catalytic synthesis processes. The conversion efficiency from RDF to syngas is assumed to be 67% (Santos et al., 2023), while the conversion from syngas to methanol is modeled using a yield of 684 L of methanol per ton of syngas (NREL, 1998). As shown in Figure 7a, methanol production increases rapidly during the early years of the simulation as RDF availability grows due to improved waste sorting and separation processes. After this initial phase, methanol production continues to increase gradually as the system approaches steady operational conditions and waste flows stabilize. Although balancing effects associated with sorting capacity and waste diversion begin to influence system behavior over time, the continued increase in methanol production is primarily driven by population growth, which leads to higher municipal solid waste generation and consequently greater RDF availability for gasification. In this sense, the technology does not offset the effects of population growth but rather scales with it by converting an expanding residual waste stream into liquid fuels. Similar dynamics have been observed in waste-to-fuel systems where fuel production potential increases proportionally with waste generation as urban populations expand (IEA Bioenergy, 2018). These results indicate that RDF gasification and syngas upgrading can provide an additional valorization pathway for residual waste streams within municipal waste management systems.



a.



b.

Figure 7 a) Annual methanol production from RDF-Gasification-Methanol production b) Power produced when just the CH_4 from the AD is used for cogeneration.

Figure 7b shows the electricity generated when RDF is diverted to gasification instead of being used for cogeneration. In this scenario, electricity is produced only from methane generated through the anaerobic digestion of source-separated organic waste and floriculture residues. The results indicate a rapid increase in electricity generation during the early years of the simulation, followed by a slower growth as waste flows stabilize. Compared with scenarios where RDF is also used for electricity production, total power generation remains lower, highlighting the trade-off between using RDF for electricity generation and redirecting it toward liquid fuel production pathways.

4.4 RDF Gasification and Syngas conversion to SAF

Figure 8 shows the projected production of SAF when RDF is converted through gasification and subsequent fuel upgrading processes. SAF production increases almost linearly over time, indicating that the availability of RDF feedstock grows at a relatively constant rate within the system. In the model structure, RDF generation is primarily driven by steady increases in waste generation and stable waste separation rates, which produce a proportional growth in sorted residual material. Because the conversion yields from RDF to syngas and from syngas to SAF remain constant in the model, SAF production scales proportionally with feedstock availability. This linear trend suggests that, under stable operational conditions, SAF output is largely constrained by the availability of RDF rather than by technological limitations within the conversion process.

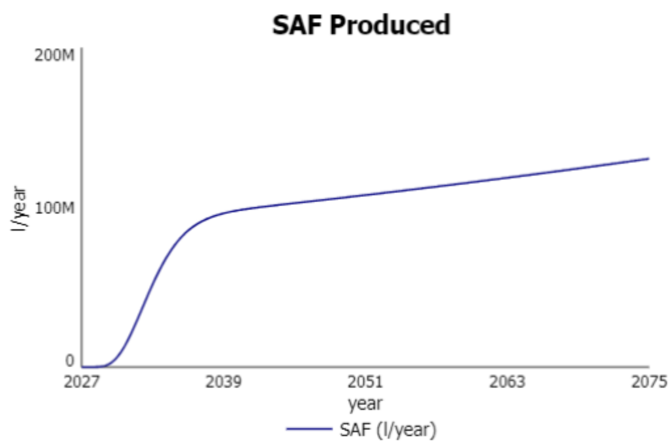


Figure 8 Projected Sustainable Aviation Fuel (SAF) production from RDF gasification pathway (L/year).

A comparison of the three RDF utilization pathways, electricity generation, methanol production, and SAF synthesis, highlights how different technology allocations influence the distribution of energy outputs within the waste-to-energy system. When RDF is used for combustion-based cogeneration, the system prioritizes electricity production, allowing immediate energy recovery from residual waste streams. In contrast, directing RDF toward gasification enables the production of liquid fuels such as methanol or SAF through syngas upgrading processes. While these fuel pathways reduce electricity generation from RDF combustion, they create additional value by converting residual waste into transportable energy carriers suitable for chemical and aviation fuel markets. From a system perspective, the results demonstrate that the choice of conversion pathway primarily determines the form of energy produced rather than the total resource recovery potential of the waste stream. A key insight from the model is that the availability of RDF generated through waste separation and sorting becomes the main structural constraint governing electricity and fuel production, highlighting the importance of upstream waste management policies in enabling waste-to-energy biorefinery systems.

Figure 9 presents the Net Present Value (NPV) results for the economic performance of the evaluated WtE pathways. The negative NPV observed during the first years reflects the construction and commissioning period required for the sorting facility and digestion infrastructure. Once the system becomes operational, revenues from electricity generation and recovered materials gradually offset the initial investments, resulting in positive economic returns over time. Scenarios 3 and 4 represent thermochemical biorefinery pathways in which RDF is converted into methanol or SAF, respectively. The techno-economic parameters for these pathways were obtained from publicly available datasets developed for the ASCENT program and implemented through Excel-based techno-economic models representing the different conversion technologies (Brandt et al., 2021). Similar to Scenario 2, both thermochemical pathways show negative NPV values during the early years due to the capital expenditures associated with gasification and fuel upgrading facilities. As production increases, revenues from methanol and SAF sales progressively improve economic performance. A temporary dip observed around mid-simulation reflects a transitional period in which investment and operational costs associated with scaling the conversion pathways temporarily affect the cumulative NPV before revenues from fuel production dominate. Over the long term, both thermochemical pathways achieve higher economic returns than the electricity-based pathway, with the methanol scenario reaching slightly higher NPV values than the SAF scenario.

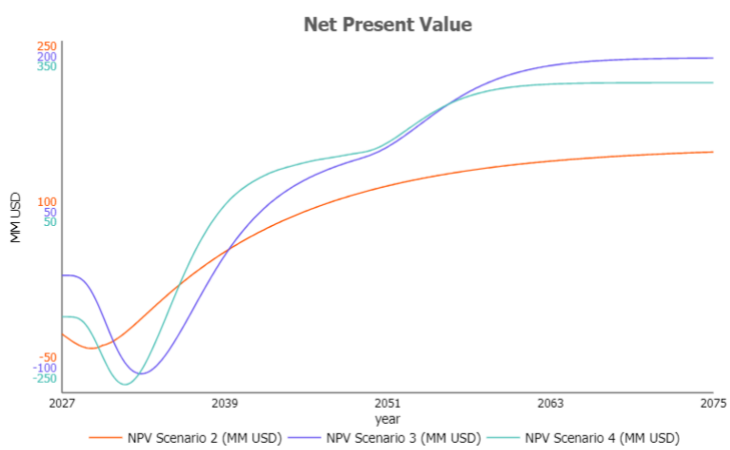


Figure 9 Net Present Value comparison of the scenarios evaluated

5. Conclusions

This study developed a SD model to explore potential transitions from landfill-based municipal waste management toward integrated WtE biorefinery systems. Using Bogotá, Colombia, as a case study, the model examined how waste separation policies and alternative energy conversion technologies influence landfill utilization, CH_4 emissions, and energy production pathways over time.

Results from the baseline scenario indicate that continued reliance on landfill disposal leads to rapid accumulation of waste and significant methane emissions, with landfill capacity projected to be reached within the next decade. These results highlight the structural limitations of landfill-dependent waste management systems.

The implementation of source separation policies significantly alters system behavior by diverting organic waste toward AD and residual waste toward recycling and RDF production. This transition reduces landfill inflows and methane emissions while enabling additional resource recovery pathways, including material recycling and electricity generation.

Thermochemical conversion pathways further expand the valorization potential of residual waste streams. Gasification of RDF enables the production of liquid fuels such as methanol and sustainable aviation fuel, creating alternative energy products while reducing reliance on landfill disposal. Economic analysis indicates that these pathways can achieve positive long-term net present value despite initial capital investment requirements.

Overall, the results demonstrate that upstream waste separation policies combined with WtE technologies can support the transition from landfill-dominated systems toward integrated waste-based energy and fuel production pathways. The findings highlight the importance of combining behavioral interventions, infrastructure development, and technology deployment to enable more sustainable urban waste management systems.

Acknowledgment

This research was funded by the US Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project ASCENT 93 through FAA Award Number 13C-AJFE-WaSU/MIT/UH under the supervision of Prem Lobo. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA.

Conference attendance supported by the Andy Ford Memorial Travel Fund.

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Appendix A

Table A1 Bogota parameters taking into account in the simulation.

Parameter	Value	Reference
Population rate birth (1/year)	0.018	(Macrotrends, 2024)
Population death rate (1/year)	0.01	(Macrotrends, 2024)
Waste generation rate (ton/hab*year)	0.31	(CONSORCIO NCU - UAESP, 2018)