Systems & Control Transactions

Original Research Article
Peer Reviewed Conference Proceeding
ESCAPE 36 - European Symposium on Computer Aided Process Engineering
Sheffield, UK. 21-24 June 2026

PSE PRESS

Optimising Waste-to-Energy Power Generation in Trinidad and Tobago

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ABSTRACT

Trinidad and Tobago emits 11.3 metric tonnes of $CO_{2\text{-eq}}$ per capita per year, making it one of the highest per capita per year greenhouse gas (GHG) emitters globally. An estimated 87% of these emissions are linked to the industrial sector, including power generation. This study aims to reduce the national environmental impact of the power generation and waste disposal sectors, with the goal of reducing the country's reliance on natural gas and promoting sustainable power generation via waste-to-energy (WTE) pathways. This work seeks to implement a mixed-integer linear programming (MILP) framework, along with techno-economic analysis (TEA) and life-cycle assessment (LCA) to determine potential sustainable objectives with respect to T&T's power system. The study implements supply chain optimisation considering single objective optimisation (SOO) with life-cycle (LC) endpoint externalities included. The key constraint of the system was the production of sufficient electricity to sustain the national power grid. A WTE model was proposed in which incineration, gasification and anaerobic digestion (AD) were implemented to supplement the country's natural gas based power generation system. When considering LC endpoint externalities, inclusion of WTE along with improved natural gas power generation efficiency resulted in a maximum reduction of 31% in total annualised life-cycle cost (TALC) and 38% in total annualised GHG emissions (TAGE). Thus, indicating the potential of WTE as a key factor in achieving sustainable development goals in SIDS. This work provides a roadmap for the implementation of sustainable power generation practices for policymakers.

Keywords: mixed-integer linear programming, supply chain optimisation, life-cycle assessment, techno-economic analysis, sustainable power generation, waste-to-energy

INTRODUCTION

The Caribbean comprises of 13 island nations- most of which are classed as developing states. Across the Caribbean archipelago, energy is an expensive necessity as most of the region is heavily reliant on fossil fuels in meeting its energy needs. The deployment of clean affordable energy (SDG-7) is integral in combatting the effects of climate change and promoting climate action (SDG-13). A holistic approach is required to aid in this transition, considering all aspects of a robust and sustainable energy system supporting the development of sustainable communities (SDG-11). This transition, however, remains a challenging task as both economic and environmental constraints need to be optimised to guarantee SDGs are met across the wider global population.

Waste-to-energy (WTE) technology provides a potential solution to problems related to fossil fuel power generation in Trinidad and Tobago (T&T). At present, like most developing nations and small island developing states (SIDS), waste disposal in T&T is not considered to be sustainable due to an over-reliance on landfilling and open dumping. This over-reliance on landfilling has resulted in overcrowded landfill sites and is also a source of significant greenhouse gas (GHG) emissions along with other environmental impacts such as toxic gases, toxins in soils and waterways.

Thus, the introduction of WTE technology can provide a potential solution to two problems evident in T&T and other developing nations. WTE technology can lower both environmental impacts of fossil fuel power generation and disposal of municipal solid waste (MSW).

By utilising a supply chain optimisation framework, guidance on achieving clean and affordable energy through whole systems thinking can be fostered and implemented locally and within the Caribbean region, and among SIDS globally. Hence our work aims to utilise mixed-integer linear programming (MILP) to minimise total annualised costs (TALC) via the use of single objective optimisation (SOO). Environmental indicators are considered in this study via the use of life-cycle externality costs related to endpoint indicator categories. One of the key novelties of the presented work is our MILP framework is tailored to resource availability, local infrastructure, energy system capabilities and waste disposal systems within the Caribbean. This is of critical importance as previous works in this field generally focus on larger and more developed nations.

METHODOLOGY

The model represented in this study focuses on SOO, with monetised impacts for endpoint indicators aligned to human health (HH), eco-system quality (EQ) and resource depletion (RD) being considered in addition to total annualised costs for both power generation and waste disposal. The general superstructure used in this model, which highlights the inputs and outputs of the system along with the technologies utilised, is shown in Figure 1. The scenarios represented in this study generally focus on altering the objective function between minimisation of TALC, minimisation of total annualised GHG emissions (TAGE) and maximisation of power generated from WTE sources.

The model involves the use of binary variables to represent each power plant and WTE technology, thus allowing the model the opportunity to select which power plants and WTE technology can be used. Each plant was constrained to a minimum capacity factor of 0.3. Key variables included the energy required by each plant for both peak and normal times (assumed to be 12 hours each), along with natural gas utilised. The system was constrained to meet the national electricity demand of 8.87 TWh, with a daily peak load of 1350 MW. There are four major classifications of waste considered in the model: organic, paper, plastic and textiles.

Scenario Description

Scenario 1

The Business-as-usual (BAU) case combines the present cases for both power generation and waste disposal in T&T. The model minimises TALC for the present power generation case (two single-cycle (SC) natural gas power plants and two combined cycle (CC) natural gas power plants). There is a total power capacity of 1950MW, 990MW and 960MW for SC and CC, respectively.

The waste collection system involves the movement of MSW from fourteen municipalities to any of three landfill sites. This case only considers landfilling as that is the only major waste disposal platform in the country at present.

Scenario 2

Scenario 2 is split into three subsections (Scenario 2A, 2B and 2C). The general layout and constraints of the model remain constant across all subsections, but the objective function differs. Scenario 2A minimises TALC, Scenario 2B minimises TAGE and Scenario 2C maximises the power generation attributed to WTE technology.

This Scenario considers an upgraded SC plant, resulting in an increased total of 1725MW CC grid power available. The power generated per $\text{tonne}_{\text{MSW}}$ for each WTE technology is defined in Table 1, and these values are utilised in Scenarios 2 and 3. Additionally, incineration, gasification and anaerobic digestion (AD) are implemented in this case. Scenario 2 also considers the recycling of all rigid plastics.

Scenario 3

Scenario 3 follows a similar formulation to Scenario 2; however, the system is constrained to ensure all organic waste is directed to AD. Scenario 3 considers a total of 1725 MW of CC grid (same as Scenario 2). TALC is minimised in this scenario as was done in Scenario 2A.

Table 1: Power generation for each WTE technology ($\text{MWh/tonne}_{\text{MSW}}$) (values used for both Scenario 2 and 3).

Waste Type	Incineration	Gasification	AD
Plastic	1.87	0.96	-
Paper	1.69	1.07	-
Textile	1.87	1.27	-
Organic	2.00	1.04	0.08

Model Formulation

Environmental Assessment

A life cycle assessment (LCA) was carried out to primarily examine environmental impacts related to endpoint indicators of human health (HH), ecosystem quality (EQ) and resource depletion (RD). However, GHG is also calculated via the midpoint impact category for global warming potential (GWP). This was done in alignment with T&T's policy focus on decarbonisation. A cradle-to-power generation gate approach was followed using the

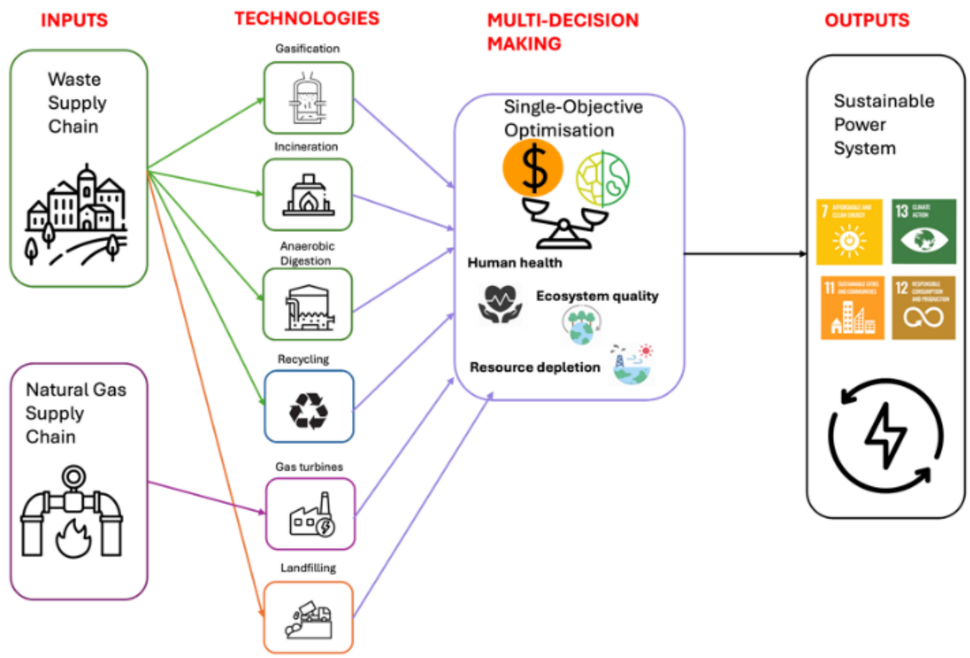

Figure 1. Superstructure highlighting waste disposal and power generation pathways and relevant SDGs impacted.

ISO 14040:2006 methodology [1]. When examining the life cycle impact assessment (LCIA), the ReCiPe 2016 Hierarchist (H) (endpoint) method within SimaPRo software was utilised.

The LCI steps compiled the inputs and outputs for each waste fraction (organic, plastic, paper, textiles) for incineration, gasification, recycling, AD and landfilling. Background inventories were derived from the EcoInvent v3.7.1 database using the Attributional Partly Optimised System (APOS) model. Foreground inventories for gasification were derived from Aspen Plus process models, which provide mass and energy balances for gasification. Inputs to the gasification models include MSW, process water and electricity for operations. This model includes emissions related to transport of MSW to waste technology sites, derived from EcoInvent v3.7.1. Total Annualised GHG Emissions (TAGE) is calculated by:

$$TAGE = \sum(F_{i,k} \cdot e_{F,i,k}) + \sum(W_{i,k} \cdot e_{W,i,k}) + \sum(\omega_{i,k} \cdot e_{\omega,i,k}) + \sum(T_{i,k} \cdot e_{T,i,k}) \quad (1)$$

$F_{i,k}$, $W_{i,k}$ and $\omega_{i,k}$ represent the feedstock, waste and residual flows in the system, with i representing inputs into the system, and k, the waste disposal technologies. The inputs, waste and residual system for transportation is denoted by $T_{i,k}$.The environmental impact of each input, output and residual flow is represented by $e_{F,i,k}$, $e_{W,i,k}$, $e_{\omega,i,k}$ and $e_{T,i,k}$, respectively.

Economic Assessment

The economic assessment is based on the Total Annualised Life-Cycle Cost (TALC), computed by estimating CAPEX and OPEX expenditure based on literature sources. This is inclusive of landfilling, sorting[2], incineration (with energy recovery) [3], gasification[4], plastic recycling [5], anaerobic digestion[6, 7], alongside natural gas power generation[8, 9]. Incineration, AD and recycling costs are estimated based on MSW throughput of the plant (in tonnes), but gasification is estimated based on the cost to run a 10 MW plant. The total costs for power generation via natural gas, waste disposal and transport, and WTE are combined with the externalities attributed to the environmental endpoint impact categories (HH, EQ, RD).

TAC_{Elec} is given by the following equation, accounting for each plant, *j*, and its relevant CAPEX and OPEX, along with the cost, C, of inputs, *i*, into the process:

$$TAC_{Elec} = CAPEX_j + OPEX_j + C_i \quad (2)$$

TAC_{WD} is given by the following equation, accounting for each waste technology, *k*, and its relevant CAPEX and OPEX, along with the cost, C, of inputs, *i*, into the process and the cost of transport in the system ($C_{Transport}$):

$$TAC_{WD} = CAPEX_k + OPEX_k + C_i + C_{Transport} \quad (3)$$

Monetised values for endpoint impact categories, *IC*, are calculated based on each waste fraction, *s*, at each WTE tech, *k*, and for the inputs and production attributed to natural gas power production. The variable $v_{s,k}$ represented the total waste of each type (organic, paper, plastic and textiles) treated by each given technology (incineration, recycling, gasification and AD). $Y_{i,j}$ defines the amount of power produced by each natural gas power

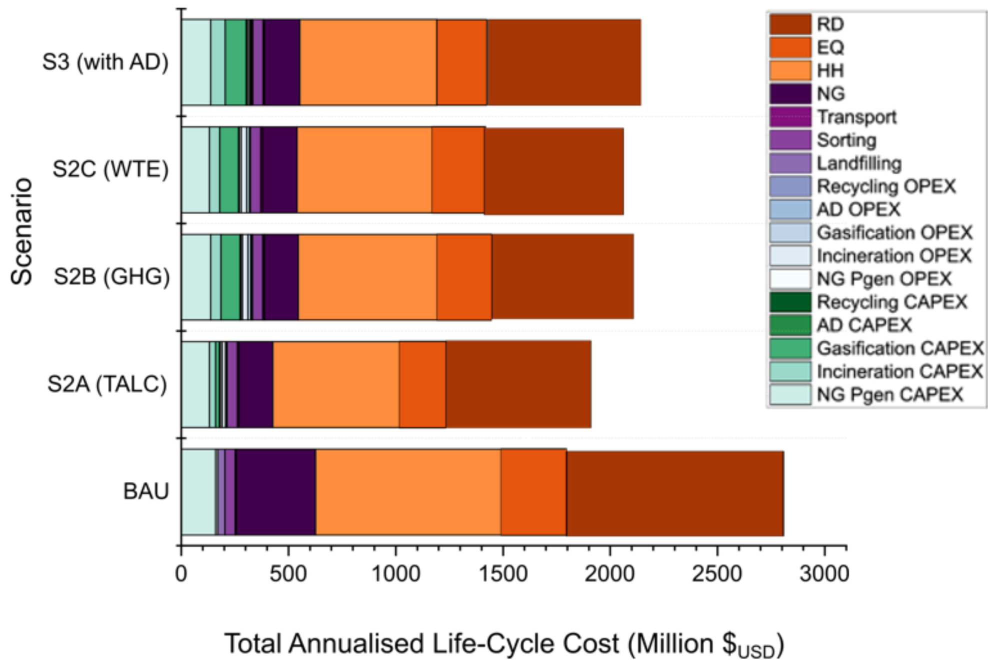

Figure 2. Total Annualised Life-Cycle Costs (TALC) for each Scenario, highlighting effects of varied objective funcitons on overall costs, inclusive of life-cycle externality costs.

plant. Endpoint indicators are related to the three categories, HH, EQ and RD, with $EP_{s,k}$ representing the impact for each waste disposal technology (including WTE) for every characterised waste fraction and $EP_{i,j}$ denoting the impact for natural gas combustion for both SC and CC plants. This is then multiplied by the monetisation factors for each category, Mon $_{IC}$, and the following equation is given:

$$LC_{IC} = \left[\sum_{s,k}(EP_{s,k} \cdot \upsilon_{s,k}) + \sum_{j}(EP_{i,j} \cdot Y_{i,j})\right].Mon_{IC} \qquad (4)$$

The summation of TAC for both waste disposal and WTE technology (TAC_{WD}), natural gas power generation (TAC_{Elec}) and monetised life-cycle costs, LC_{IC}, is given in Equation 4:

$$TALC = TAC_{WD} + TAC_{Elec} + LC_{IC} \qquad (5)$$

Constraints

The following equations, 6, 7 and 8, ensure the HH, EQ and RD values cannot surpass the BAU levels. This ensures no burden shifting occurs to artificially decrease TALC, by trading off performance in one endpoint indicator for another.

$$HH_{Scenario} \leq HH_{BAU} \qquad (6)$$

$$EQ_{Scenario} \leq EQ_{BAU} \qquad (7)$$

$$RD_{Scenario} \leq RD_{BAU} \qquad (8)$$

Objective Function

The SOO model minimises TALC (Equation 2) for Scenario 2A, minimises TAGE for Scenario 2B (Equation 1) and maximises WTE for Scenario 2C.

Model Environment

The MILP model was simulated using the General Algebraic Modeling System (GAMS) version 34.3 on an Intel Core i7, 8th Gen. Processor (16 GB RAM).

RESULTS

The model primarily examined Total Annualised Life-cycle Costs (TALC), which combined overall costs related to the system and life-cycle externality costs related to HH, EQ and RD. Figure 2 highlights the TALC values across 3 scenarios. Scenario 1 represented the BAU case, whilst Scenario 2 highlighted an upgraded efficiency in natural gas power generation combined with WTE in the form of gasification, incineration and AD. Scenario 3 constrained all organic waste to be dispatched to AD. Scenarios 2 and 3 also included recycling of rigid plastics as part of the waste disposal system.

The TALC for the BAU case was found to be $2.74 billion, which included 31.3% for HH, 11% for EQ and 36.7% for RD indicators, respectively. Production of power from natural gas plants accounted for approximately 19% of the TALC and waste disposal via landfilling (including transport) accounted for the remainder.

In comparison to the BAU case, the optimised

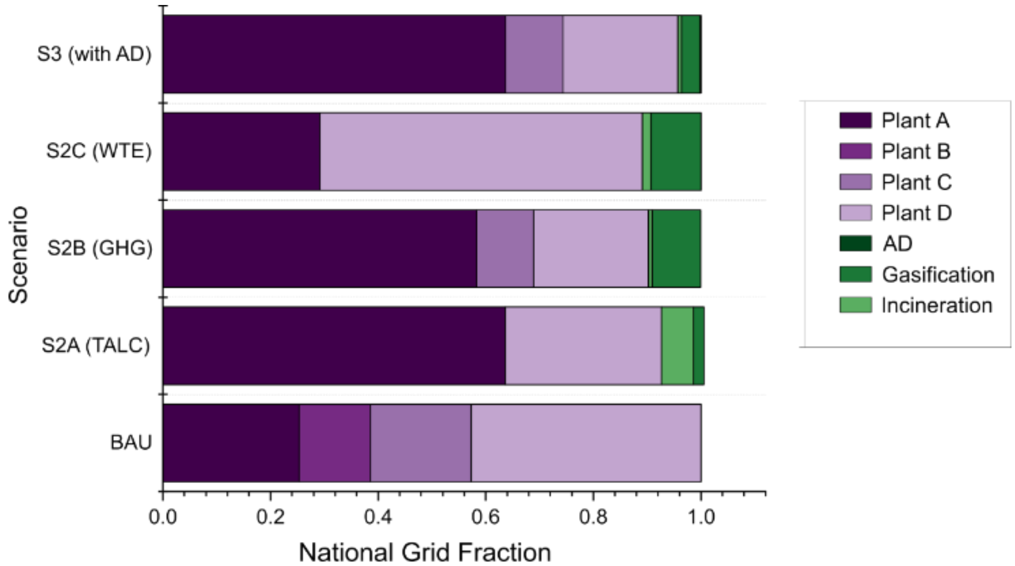

Figure 3. Power grid breakdown for each scenario exhibiting fossil-fuel and WTE sources.

(minimised TALC) values for Scenario 2A highlighted a reduction of 31.1% ($1.93 billion TALC). Externality costs attributed to HH, EQ and RD reduced by 31.6%, 29.9% and 33% compared the BAU values, respectively. Costs related to power generation accounted for approximately 16% of the TALC, with recycling, sorting, incineration and gasification representing the remaining 6% of TALC. The WTE from incineration and gasification represents 7.4% of the national grid presently. Due to the increase in power to supply the grid from WTE, only Plant A (765MW – CC) and Plant D (720MW – CC) were required and accounted for 8.2 TWh a year.

When the TAGE of the system was minimised for Scenario 2B, it was noted that TALC increased by 10% to $2.10 billion. This trade-off can be attributed to a 9.4% increase for the HH indicator and an 18.7% increase for EQ whilst there was subsequent decrease in RD of 2.5%, from Scenario 2A to 2B. The model reduced TAGE by increasing the proportion of waste allocated to gasification, thus avoiding potential TAGE emissions by increasing the WTE value to 9.7% of the national grid. Since GHG is prioritised, gasification is preferred to incineration. Production of electricity from gasification results in a reduced GHG emission value for each characterised waste fraction type (organic, paper, plastic and textiles). This increased use of gasification enhanced WTE output to the national grid as it yields approximately double the electricity per $tonne_{MSW}$ compared to incineration.

Scenario 2C explores the maximisation of WTE as the objective function of the model. This gives a TALC of $2.07 billion and a WTE accounting for 10.9% of the national grid. When compared to Scenario 2A, there is a 6.5% increase for the HH indicator and a 16% increase for EQ. There was a subsequent 3.14% decrease in RD. Across Scenarios 2A, 2B and 2C, it can be noted that as WTE increases RD decreases, which can be attributed to the reduced fossil fuel requirement to supply the national grid.

Scenario 3, which constrains all organic waste to be sent to AD, presents a TALC of $2.15 billion which represents a 10% increase when compared to Scenario 2A. The HH indicator only improves upon Scenario 2B and is the worst performing optimised scenario in terms of RD, recording a 5.5% increase compared to Scenario 2B. The increased HH and RD indicators can be attributed to the reduced WTE value of 4.3%. The outcome reflects the reduced power generation potential of AD in comparison to incineration and gasification. The use of AD and thus reduced gasification capacity in this scenario results in a reduction in EQ of (5.5 – 7.5) %. Despite being the worst performing of the optimised scenario with respect to TALC, the introduction of AD still exhibits a 22.4% reduction in comparison to the present BAU case and proves an improvement in terms of EQ when compared to scenarios 2B and 2C. This indicates that AD can be included as a potential WTE option in T&T, alongside gasification and incineration.

Minimisation of TAGE results in 38% GHG_{LC} reduction compared to the BAU case, with a reduction from 6.26 million tonne-$CO_{2\text{-eq}}$ to 3.86 million tonne-$CO_{2\text{-eq}}$. The model achieves this by significantly increasing the waste sent to gasification, from 94, 000 tonnes (S2A – min. TALC) to 426, 000 tonnes and reducing incineration, from 445, 000 tonnes to 47, 000 tonnes. This trade-off is due to gasification's higher electricity production potential compared to incineration. Natural gas power generation is reduced by 2.5% with 3 combined-cycle power plants online, Plant A, Plant B and Plant C, and sharing the national grid load 58%, 11% and 21% respectively (Figure 3). Power produced from WTE sources accounts for 9.7% of the national grid. Overall, natural gas power generation accounts for 92% of the GHG emissions in the scenario, with incineration and gasification making up 7.5% and transport resulting in a negligible value.

The TAGE for this Scenario 2A (min. TALC) was found to be 4.05 million tonne-$CO2_{eq}$, signifying a reduction of approximately 35% compared to the BAU case and a 5% increase compared to Scenario 2B (min. TAGE). WTE sources account for approximately 9.8% of TAGE, with gasification making up 8.3% and incineration 1.5% of TAGE. Plant A, Plant D, incineration and gasification make up over 99% of TAGE for optimised cases.

CONCLUSIONS

We present the use of MILP framework tailored to Trinidad and Tobago to promote the sustainable energy transition within SIDS. This work demonstrates the potential of WTE as a cleaner power generation source within the Caribbean. Additionally, upgraded efficiency within the country's natural gas power generation sector can play a significant role in reducing environmental emissions.

The integration of waste-to-energy (WTE) in the form of gasification, incineration and anaerobic digestion (AD) proves to have a beneficial effect in terms of total annualised life-cycle costs (TALC) with reductions of 22 – 31 % for optimised scenarios, when compared to BAU. Similar effects are observed for total annualised GHG emissions (TAGE), with decreases in the range of 34 – 38 % in comparison to the BAU scenario. The scenarios are optimised using SOO, accounting for environmental emissions related to endpoint indicators which are monetised. Drastic reductions were recorded for all optimal scenarios due to the diminished use of natural gas to provide power. This reduction is attributed to increased resource efficiency from the SC to CC upgrade, coupled with 4 – 11 % of the grid being supplied by WTE.

These results validate the use of supply chain optimisation to guide decision making with respect to SDGs for the Caribbean and SIDS globally.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following companies for their assistance with regards to data acquisition for this work: Power Generation Company of Trinidad and Tobago (Powergen), Trinidad Generation Unlimited (TGU) and Solid Waste Management Company Limited of Trinidad and Tobago (SWMCOL).

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