Comparative Life Cycle Assessment of Tropical Island Municipal Solid Waste Strategies

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Abstract: An increase in tourism, and subsequently of waste production on Thai islands, has required some islands to reevaluate their traditional incineration-based waste management schemes in the past ten years. Koh Phuket and Koh Samui in the southern part of Thailand are two Thai islands that have pursued contrasting paths in the attempt to deal with this increasing amount of waste since 2011. This study attempts to evaluate which overall strategy is both more environmentally suitable and financially feasible. These islands serve as a guide for the comparison of two waste management scenarios: mass incineration versus the use of materials recovery technology with separation, dry anaerobic digestion of organic waste, plastic pyrolysis, wood plastic composite (WPC) production, and refuse-derived fuel (RDF) production with incineration and energy capture. A life cycle assessment and a basic cost analysis are utilized to determine the best path for future waste management planning on tropical islands. It was found that mass-burn incineration yielded higher environmental impacts in six of the eight impact categories analyzed and a higher capital cost. However, the materials recovery technology specified in the study produced a higher impact on photochemical oxidant formation, and particulate matter formation, as well as higher operation and maintenance costs. Despite these costs, the sale of usable co-products in this scenario creates a higher profit, making this scenario more recommendable.

1. Introduction

Increased tourism on Thai islands has led to challenges associated with waste management, particularly on Phuket and Samui, both of which use incineration technology. In the past ten years, total waste production surpassed the capacity of the municipal solid waste (MSW) incinerators on each island [1-2]. Phuket has a resident population of around 350,000 but receives between 9 and 12 million tourists per year [3]. Samui has 53,000 residents and receives about 1.1 million tourists a year [4]. On both islands, tourists are responsible for a majority of the waste generation, leaving the residents and their municipality to deal with the problem. Additionally, incineration faces public opposition and scrutiny for its perceived environmental and health impacts [5]. Phuket and Samui have pursued different paths in the attempt to mitigate these common problems.

Previous relevant studies, such as a comparative LCA of Phuket's old 250 tonne/day capacity incinerator versus an anaerobic digestion scheme, concluded that mass-burn incineration produces a higher overall impact as a waste-to-energy system [6]. Furthermore, an evaluation of Phuket's waste management options concluded that an integrated system of waste separation and utilization is the most sustainable option for the island [1]. Despite these recommendations, Phuket built a new incinerator with energy recovery and increased capacity and efficiency (PJT Technologies, personal communication). Recent studies on Samui, such as value-chain optimization cost analysis study of several waste management scenarios, concluded that integrating effective recycling with incineration is the most cost effective method for Samui [7]. Another study modeled the development of an integrated waste management scheme for Samui and suggests RDF production and incineration, as well as biogas capture from the organic portion of the waste [2]. Following these recommendations, Samui plans to implement materials recovery technologies to work in conjunction with their current incinerator, which will undergo renovations to increase efficiency, burn refuse-derived fuel (RDF), and capture energy (Samui Municipality, personal communication).

Using previous studies on the feasibility of different waste management technologies and the plans outlined by the two islands, this study aims to determine which waste management option minimizes environmental impact while remaining cost-effective for Thai islands. Phuket and Samui are used as cases to examine two general paths for dealing with municipal solid waste: a mass incineration system with energy capture versus a materials recovery system with separation, dry anaerobic digestion of organic waste, plastic pyrolysis, wood plastic composite (WPC) production, and refuse-derived fuel (RDF) production with incineration and energy capture. The recommendations and conclusions of this study may be used for planning future waste management strategies on tropical islands. A comparative LCA of these two scenarios is conducted to determine the most environmentally friendly scenario, while a basic cost analysis is used to consider the financial feasibility of both scenarios.

The objective of this study is to compare a mass burn incineration system and a materials recovery system that includes incineration of RDF The geographical framework for this comparison includes the Thai tourist islands of Phuket and Samui, which are both experiencing increasing waste production rates and possess limited space for landfilling (Phuket Municipality, personal communication; Samui Municipality, personal communication). By evaluating the environmental impact of mass burn incineration with energy recovery and a materials recovery system with separation, dry anaerobic digestion of organic waste, plastic pyrolysis, wood plastic composite (WPC) production, and refuse-derived fuel (RDF) production with incineration and energy capture, this study will both determine the solid waste management system that is more environmentally suitable and serve as a guide for future island waste management planning. Through a basic cost analysis, the study will also determine if the more environmentally suitable system is financially feasible.

2. Methodology

2.1 LCA Goal and Scope

2.1.1 Goal

The goal of the comparative LCA is to determine whether mass-burn incineration or a materials recovery system with RDF incineration is the more suitable waste management strategy from a life cycle environmental impact perspective for tropical islands. The functional unit for both scenarios is 1 tonne of municipal solid waste at the gate of each facility. In Scenario 1, this is mass-burned in an incinerator (Figure 1). In Scenario 2, this functional unit is separated into four treatment technologies – D.1, D.2, D.3 and D.4 (see Figure 2 for breakdown of separation).

2.1.2 Scope

2.1.2.1 System Boundaries

This study is a gate to grave analysis of waste management that begins at refuse delivery and continues to the end of life phase of each process - a usable product or disposal in a landfill - excluding the transport of any final products to their subsequent destinations.

For Scenario 1, see Figure 1. Most processes at the incineration facility, wastewater treatment plant (WWTP), and landfill compound are included. All residues from incineration are sent to an incinerator residue landfill, and other scrap is sent to an inert materials landfill. All transportation, including waste to the incineration facility, leachate from the incinerator to the WWTP, and bottom and fly ash from the incinerator to the landfill, is excluded. The transportation of waste to the incineration facility is assumed to be the same regardless of which scenario is utilized; since there is no relevant upstream separation difference between the two scenarios, so it is excluded as well. The transportation of the leachate and the ashes to their treatments are excluded because both facilities are located within 0.5 km of the incinerator and the associated impact is deemed negligible.

Scenario 1 is expanded to credit two different co-products. The first product is electricity production from MSW incineration through steam turbine technology. This electricity is assumed to replace an equal amount of Thai electricity generation. The second product is the sludge produced at the WWTP, used to create compost. Production of an equal amount of typical biogenic compost is included in the system boundary and credited.

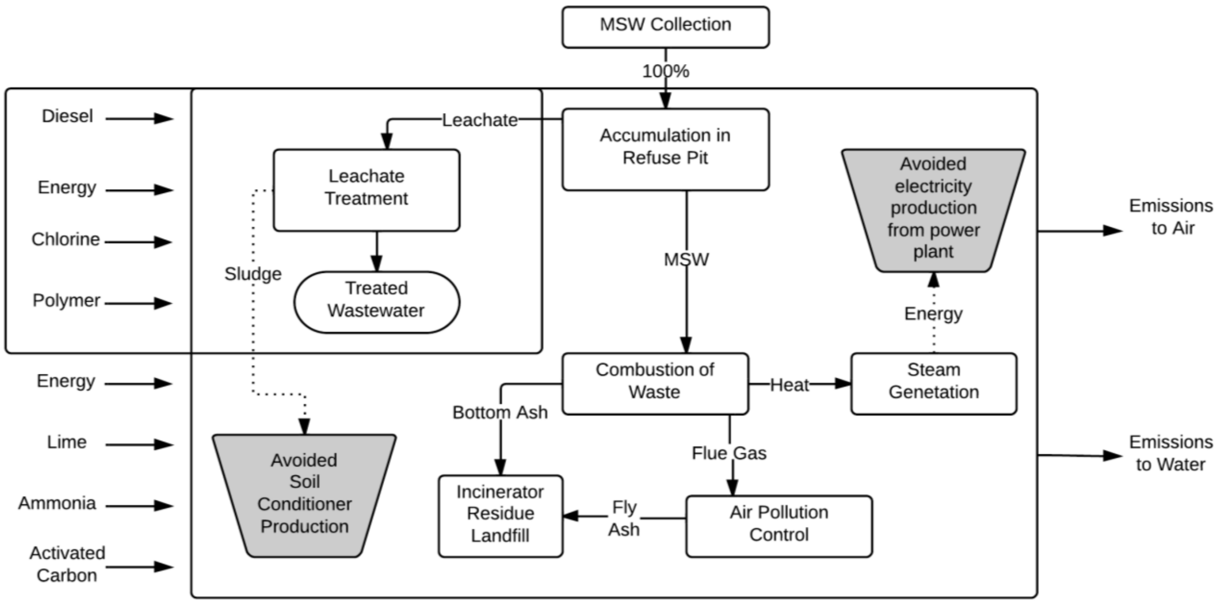

Figure 1. System diagram for Scenario 1.

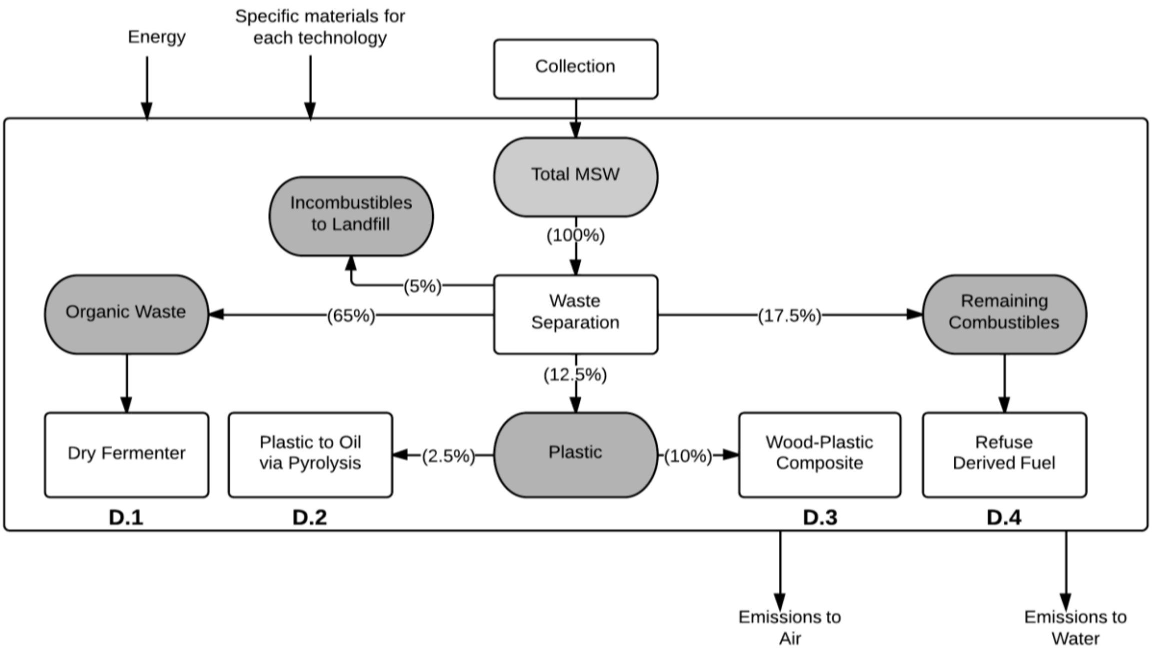

Figure 2. System diagram for Scenario 2.

Scenario 2 is illustrated in Figure 2. The system boundary includes all processes at the proposed Samui facility, including mechanical separation of the MSW, dry anaerobic digestion of the organic waste portion, the pyrolysis of plastic, the conversion of plastic to WPC, and the production and incineration of RDF. All residues from RDF incineration, as well as char from plastic pyrolysis are sent to an incinerator residue landfill. Scraps from separation and the WPC production are sent to an inert materials landfill. The transportation of the products to their next destinations and onsite transportation are excluded.

Scenario 2 is expanded to credit for several usable co-products. The dry anaerobic digester converts organic waste to biogas, which is combusted in a gas turbine for energy capture. The solid digestate is used as a compost substitute. The production of an equal amount of Thai electricity and biogenic compost is included in the system boundary for crediting. Plastic pyrolysis produces syngas, diesel, and gasoline; the production of an equivalent amount of each is included in the system boundary for crediting. Syngas substitutes wood-chip pyrolysis syngas because both gases have comparable amounts of CO and H_2. This scenario also includes the production of wood plastic composite from 100% waste plastic. The impacts of this production were compared to that of a product containing 50% virgin plastic and 50% waste plastic, so the additional production of the 50% virgin plastic is included in the system boundaries for crediting. The mixed composition of waste going to the RDF production and incineration systems includes energy capture, so an equal amount of Thai electricity production is included.

2.1.2.2 Assumptions and Limitations

The following assumptions are for this study:

Electricity used from the grid follows typical Thai grid electricity production [8]. The breakdown is 69% natural gas, 12% lignite, 9% hard coal, 5% hydro, 3% renewables and 1% fuel oil. The renewables section is 90% wood power, and assumed to be produced by wood chips. The hydropower is assumed to have no impact. The impacts from each power plant used to produce electricity were taken from the Ecoinvent database.

All incoming waste is of the same composition, shown below in Table 1, which is characteristic of the composition of waste produced in Samui [9]. Phuket's waste composition is also listed for comparison.

It is assumed that for both scenarios, glass and metal is removed by informal waste separators upstream due to financial incentives, a common practice in Thailand (Sharp and Sang-Arun, 2012 [9]). The actual amount removed is difficult to quantify or model, but it was assumed to be 100% for the sake of this study. The characteristics of the waste before and after the assumption of 100% removal of glass and metal for sale are also detailed in Table 1. The impacts from this waste picking and recycling are assumed to be out of the scope of this study, which begins at the gate of the treatment facility.

All outgoing ash or burnt residue from the incinerator in Scenario 1 and, from Scenario 2, the RDF incinerator and the plastic pyrolysis chamber, end up in an incinerator residue landfill. It is assumed that the impacts are dependent only on the total mass of ash disposed.

All separated scrap or output of non-ash residue is disposed of in an inert materials landfill. Again, it is assumed that the impacts are dependent only on the total mass of non-ash residue disposed.

This study is geographically limited to tropical islands that are popular tourist destinations and is applicable for a period of up to 10 years.

2.2 Life Cycle Inventory Analysis

2.2.1 Phuket

Input data (including electricity, lime, carbon, and ammonia spray) per tonne of MSW were provided by the Phuket municipality, who also provided data concerning the electricity, leachate, bottom ash, and fly ash produced (PJT Technologies, personal communication). Unfortunately, emissions data from the Phuket incinerator could not be acquired. As a result, emissions data from Samui's old incinerator are used, which had similar flue gas treatment methods, and burned a similar composition of waste (Samui Municipality, personal communication). As Phuket's incinerator is much newer and more effectively managed than Samui's, it is not ideal to use Samui's emission data. However, through direct interviews with Phuket incinerator officials, it was clear the incinerator emissions consistently remain below Thai emissions standards for municipal solid waste incinerators (standards taken from [10]). The majority of Samui's emissions did not exceed national standards. The SO_x emissions exceeded and were brought down to national standards. The Samui emissions data did not include dioxins, a known emission of the Phuket incinerator; the standard value for this emission was assumed. For justification purposes, the emissions registered at Samui were compared with both Phuket's old mass burn incinerator and a technologically advanced incinerator in Italy [11].

The electricity use and waste input at the incinerator are calculated from monthly Phuket data from March-January 2012, averaged per day. The bottom ash and fly ash outputs were estimated from average percentages of Phuket total waste, 22% and 2% respectively, and are assumed to be placed in residue specific landfills near the incinerator. The leachate from the waste pit at the incinerator is followed to the Phuket WWTP to allocate the appropriate treatment burdens from the incinerator.

All of the WWTP data was gathered from interviews at the Phuket study site. The inputs of the different types of wastewater and their Biochemical Oxygen Demand (BOD) are averaged per month over a seven month period from October 2012 to May 2013 (Phuket Municipality, personal communication). The totaled impacts from the WWTP were allocated to the incinerator wastewater based on the BOD-modified flow factor, obtained by multiplying each average flow rate by the BOD content of each wastewater stream. The amount of sludge that was produced was not provided, so it is estimated using a manual on Sludge Processing and Disposal from Iowa State University.

Table 1. Waste composition of Phuket and Samui pre and post recycling of glass and metals.

Waste Category	Composition Phuket Pre Recycling (%)	Composition Phuket Post Recycling (%)	Composition Samui Pre Recycling (%)	Composition Samui Post recycling (%)
Food	65.60	68.70	58.83	66.80
Paper	6.56	6.90	8.07	9.20
Plastic	19.3	20.20	13.61	15.50
Glass	4.09	0.00	10.04	0
Metals	0.35	0.00	1.93	0
Rubber/leather	0.03	0.00	N/A	N/A
Cloth	0.64	0.70	2.29	2.60
Wood/Leaf	N/A	N/A	0.76	0.90
Others	3.41	3.50	4.47	5.10

2.2.2 Samui

Due to the recent nature of Samui's plans and the subsequent lack of primary data, secondary source literature was used for the emissions data for Scenario 2. Samui's waste characteristics and the information concerning the allocation of waste to each technology provided are used as guidelines in the choice of technologies.

For separation, the data is selected from an Italian LCA involving a flail mill for bag breaking and initial size reduction, a trommel screen for separating out the RDF fraction, and a ballistic separator for removing the organic fraction [11]. The original study is adapted slightly to fit the separation needs according to Samui's plan for their materials recovery, with further manual plastic separation (without any additional electricity use). The impacts of diesel use are modeled using a diesel production system process from Ecoinvent and then using the emissions factors to account for combustion [12].

For dry anaerobic digestion, inputs and outputs are taken from a greenhouse gas inventory of a large-scale advanced digester in Europe that includes the combustion of the biogas produced in a lean-burn gas engine [13]. Additional non-GHG emissions are taken from another LCA study [14]. This addition was justified based on the similarity of both the system boundaries and the total methane releases (calculated to be 9.04 m^3 of biogas and 10.70 m^3 of biogas per tonne of organic waste inputted, respectively) of each study. The impacts of diesel use at the dry anaerobic digester are modeled using a diesel production system process from Ecoinvent and then using the emissions factors to account for combustion [12].

In order to obtain emissions from the incineration of RDF, literature data from an RDF incinerator in Italy is used with the assumption that the emissions are a reasonable estimation considering Samui has not yet begun RDF incineration [11]. The RDF incinerator at Samui does not possess electricity generation technology; however, future plans include upgrades for inclusion. The emissions at an RDF incinerator change based on composition and lower heating value (LHV) of waste. The composition of RDF at Samui is constructed from their incoming waste characteristics and compared to the composition used in the Italian study. The LHV is then approximated for both by multiplying known heating values from components of waste with their percentages in each RDF product and totaled [15]. The LHVs are found to be approximately equivalent, although the two compositions differ slightly. These results are presented in Table 2.

For plastic pyrolysis, the inputs and outputs were obtained from a final project report on the environmental analysis of several emerging technologies of plastic conversion [16]. The materials use, energy consumption and emissions data were taken from ranges of four companies and four literature studies. However, the specific amounts of products produced from plastic to oil pyrolysis were selected from one specific company. This company included outputs that could be credited, but did not have a complete emissions inventory. For natural gas use as supplemental fuel, the same procedure as the one for diesel is carried out, but the emissions factors for NO_x and SO_x release are taken from the US EPA [17].

For converting plastic to WPC, a LCA completed in the US comparing a typical blend of WPC to ACQ treated lumber is used [18]. Since this data for the WPC product includes the impact of 50% virgin plastic in the composite, some adjustments are accordingly made. The inputs and outputs for producing an equivalent amount of virgin plastic are found and subtracted from the data provided in the study.

2.2.3 Inventory Databases

For the indirect inputs (products, fuels, etc.) Simapro 7.1 software was used to generate impacts for each product based on their own individual life cycles up until the point they entered our system boundary. The ReCiPe 1.08 impact assessment method was used to characterize the impacts.

2.3 Choice of Impact Categories

The ReCiPe impact assessment method was used to determine the impact potentials for the following categories: Global Warming Potential (GWP) in kg of CO_2 eq, Marine Eutrophication Potential (MEP) in kg of N eq, Terrestrial Acidification Potential (AP) in kg of SO_2 eq, Photochemical Oxidant Formation Potential (POFP) in kg NMVOC eq, Particulate Matter Formation Potential (PMFP) in kg PM10 eq, Fossil Fuel Depletion (FD) in kg oil eq, Human Toxicity Potential (HTP), Marine Toxicity Potential (MTP), and Terrestrial Toxicity Potential (TTP), the latter three being all in 1,4-DB eq. Midpoint indicators at the hierarchist level are used for characterization and normalization to reduce the subjectivity and assumptions necessary when using endpoint indicators. The Hierarchist cultural and timeframe perspective seeks consensus between Individualistic and Egalitarian perspectives, and considers damage over 100 years. The indicators in ReCiPe are calculated on the basis of a consistent environmental cause-effect chain, except for resources.

2.4 Cost Analysis Methods

2.4.1 Introduction

A basic cost analysis is included in this study to establish the economic feasibility of both original scenarios: 1) mass incineration and 2) the use of materials recovery technologies with RDF incineration. Since the capacity of each technology and thus, the amount of waste processed, affects both the capital and operating costs of that scenario, a basic financial analysis of each scenario cannot be directly compared. To compare the scenarios, the capacity of each are scaled either up or down to match the capacity of the other, resulting in four total schemes: a scaled down version of the original Scenario 1 (140t), the original Scenario 1 (680t), the original Scenario 2 (140t), and the scaled up version of Scenario 2 (680t). This allows for the direct comparison of the total costs of each capacity size, 140 tonnes per day and 680 tonnes per day. Both scale alterations were completed to determine which scenario is more financially feasible at each capacity. For cost crediting, the revenue from the sale of electricity from Scenario 1 and all of the products from Scenario 2 are calculated and analyzed.

It should be noted that the included cost analysis is very basic and that variability associated with all inputs (construction costs, taxes, current prices, new technologies, etc.) limits its overall applicability. Additionally, while the flexibility of the materials

Table 2. Comparison of Samui RDF heating values with those of Arena et al., 2003 [11].

Waste Category	Heating Values (MJ/kg)	RDF composition of Samui (%)	RDF composition of Arena et al., 2003 (%)
Food	15.1	10.3	N/A
Paper	14.65	52.6	50.6
Plastic	27.5	17.1	23.5
Cloth	19.04	14.9	9.0
Wood/leaf	16.32	5.1	12.3
	Total Heating Values	**17.64**	**17.74**

recovery system certainly adds to its general appeal, this flexibility also limits the applicability of a cost analysis. The predicted cost of this highly variable system cannot be applied directly to any materials recovery technologies system, given the multitude of possible technology combinations and waste allocations.

2.4.2 Data Acquisition and Assumptions

Data for capital and operating costs for both scenarios are taken from various sources that analyze different waste management schemes around the world. Therefore, a major assumption associated with this general cost analysis is that the various costs of these technologies and their required materials in other countries are similar to costs in Thailand. Basic conversion rates of 1 USD to 30 Thai Baht to 0.76 Euro are used. The cost of the transport of materials required for all processes in both scenarios (lime, carbon, ammonia, etc.) is excluded. It was verified with the Phuket municipality that the cost of transporting the chlorine and polymer is 1 Baht per tonne of waste. The total cost per year this contributes comes out to be less than 1% of the total cost of the system in Scenario 1. While this only includes the transport of these two materials, the total additional materials that must be transported in either scenario is small; therefore, the cost is of such transportation is assumed to be negligible. It is also assumed that the credited products are similar in nature and cost.

3. Results and Discussion

3.1 LCIA Results and Discussion

The purpose of the life cycle assessment is to compare two pathways for dealing with unsorted municipal solid waste: mass-burn incineration with energy recovery (Scenario 1) and a materials recovery technology with separation, dry anaerobic digestion of organic waste, plastic pyrolysis, wood plastic composite (WPC) production, and refuse-derived fuel (RDF) production with incineration and energy capture (Scenario 2). Scenario 1 represents a single, large scale technology that is simpler to build and manage, while Scenario 2 represents a more complex conversion of waste to higher value products. The results are presented according to the impact categories described in Section 2.4 and separated into positive environmental burdens and credits from production. The characterized results are displayed in Table 3 for both Scenario 1 and Scenario 2.

The results are first analyzed by directly comparing the impacts for each category from each scenario separately. The credits for Scenario 2 are greater in each impact category due to the fact that the waste in this scenario is converted into a greater number of usable co-products, including electricity, fertilizer, syngas, diesel, gasoline, and WPC. This, coupled with the overall lower observed general process impacts, accounts for the lower net impact in the impact categories described below.

The Global Warming Potential for Scenario 1 is over 70% higher than for Scenario 2. The multiple conversion technologies in Scenario 2 provide more opportunities to offset GHG emissions, especially those associated with electricity. Additionally, the comparatively high organic content in the waste coupled with the low efficiency of incineration of MSW results in higher GWP in Scenario 1 than Scenario 2. For example, reducing the organic content of the waste by pre-separation, the strategy employed in Scenario 2, reduces greenhouse gas emissions by lowering the moisture content and increasing the lower heating value of the MSW burned [19].

The Marine Eutrophication Potential for Scenario 1 is almost 150% higher than for Scenario 2. The predominant source of these impacts is the WWTP. Although the Phuket plant has a high (90-97%) overall efficiency, the efficiency of the removal of eutrophication causing substances (ex. total nitrogen) is rather low, at 60%. Thus, the treated wastewater released into the surrounding marine waterway has a high eutrophication potential.

With a difference of 30%, Scenario 1 has a higher Terrestrial Acidification Potential than Scenario 2. The main cause is likely the SO_2 released in the incinerator flue gas. This result is subject to some uncertainty, however, since the emissions from the current Phuket incinerator were unavailable and the SO_2 emissions were taken from the Thai national standard on emissions. Since the Phuket municipality and the company managing the incinerator are contracted to be under standard for every emission, the actual SO_2 emissions are likely lower.

For Human Toxicity Potential, Scenario 1 is four times that of Scenario 2. This large difference is predominantly due to the disposal of bottom ash and fly ash into incinerator residue landfills. Since the bottom ash from incineration in both Scenario 1 and Scenario 2 were assumed to be deposited in the same type of incinerator residue landfill, the only difference in impact is the amount of ash deposited. RDF incineration involves a selective feedstock, consisting almost entirely of combustible material, while many components of MSW come out partially burned or in larger diameters. Thus, mass-burn incineration results in a greater percentage of bottom ash residue than does RDF incineration leading to a higher impact.

Table 3. Contributions and credits by impact category of each scenario.

Impact Category	Scenario 1			Scenario 2		
	Emissions	Credits	Net	Emissions	Credits	Net
GWP (kg CO_2 eq)	6.62E+02	8.59E+01	5.76E+02	6.58E+02	3.15E+02	3.43E+02
MEP (kg N eq)	6.80E-01	1.00E-02	6.70E-01	8.37E-02	5.68E-02	2.70E-02
AP (kg SO_2 eq)	9.39E-01	4.76E-01	4.62E-01	2.17E+00	1.82E+00	3.50E-01
POFP (kg NMVOC eq)	6.05E-01	1.76E-01	4.29E-01	2.36E+00	9.45E-01	1.41E+00
PMFP (kg PM10 eq)	2.61E-01	1.29E-01	1.32E-01	7.77E-01	4.32E-01	3.46E-01
FDP (kg Oil eq)	7.04E-02	5.18E-02	1.87E-02	2.40E+01	7.23E-02	2.39E+01
HTP (kg 1,4-DB eq)	1.62E+02	2.29E+00	1.60E+02	4.49E+01	5.05E+00	3.99E+01
MTP (kg 1,4-DB eq)	2.41E+00	9.93E-03	2.40E+00	4.87E-01	6.50E-02	4.22E-01
TTP (kg 1,4-DB eq)	1.08E-01	7.04E-03	1.01E-01	9.77E-02	1.56E-02	8.22E-02

The higher impacts in Marine Ecotoxicity and Terrestrial Ecotoxicity for Scenario 1 can be explained by the same logic, since many of the substances associated with toxicity in bottom ash and fly ash are toxic across the different environments. The level of toxicity among all three categories (Human, Marine, Terrestrial) could be reduced if something more constructive was done with the fly ash or bottom ash instead of direct disposal to landfill. Some possible uses outlined by studies include cement production, concrete, road pavement, and ceramics. Cement in particular can contain up to 10% MSW incinerator ash without any serious effects to its characteristics [20].

Since Scenario 2 includes multiple technologies, each technology's contribution to the overall impact is presented as a percentage of Scenario 2's total for each impact category (without credits included) in Figure 3.

Figure 3 demonstrates that certain technologies contribute more to some impacts than others. This highlights hotspots in Scenario 2 and could point to specific areas for improvements.

The Photochemical Oxidant Formation Potential of Scenario 2 is more than thrice that of Scenario 1. The RDF incineration accounts for over one-third of the POFP in Scenario 2, most of which is attributed to the release of NO_x at the process. Treatment of the gases before release, especially a de-NO_x system similar to the ones employed at the MSW incinerator in Scenario 1 and RDF incinerator in Scenario 2, could help curb these emissions and consequent impacts.

For Particulate Matter Formation, Scenario 2 is also almost thrice that of Scenario 1. The plastic pyrolysis process accounts for almost one-third of the Particulate Matter Formation, NO_x and PM10 air emissions in the processes contributing about 60% and 40%, respectively.

The comparatively very high Fossil Fuel Depletion associated with Scenario 2 can be attributed to a limitation in the available data. Access to an actual LCA of wood plastic composite from 100% recycled waste was unavailable, so data was modified from a LCA of a 50% waste plastic, 50% virgin plastic study. It was assumed that the data table provided by the study must have quantified all the impacts as final emissions, and that the impacts of the individual input entries were already accounted for in these emissions. Characterizing the inputs of the study as only emissions meant that fossil fuel depletion would not be accounted for. To adjust for this, each input of fossil fuels (was characterized for its Fossil Fuel Depletion Potential alone. This likely resulted in an overestimation of the fossil fuel depletion potential of the plastic to WPC process, which would account for the fact that it alone accounts for 99% of the total impact for Scenario 2. This study will no longer include Fossil Fuel Depletion in the conclusion due to these uncertainties.

Despite being lower than Scenario 1, RDF incineration at Scenario 2 is responsible for most of the impacts associated with both human and marine toxicity. This is an important area to improve the toxicity impacts. Some sort of treatment process for the flue gas that could reduce emissions associated with RDF incineration could help mitigate this technology's contributions to toxicity impacts.

To compare the results of each impact category for each scenario, the impacts were normalized into person per year equivalents according to ReCiPe's normalization method for the world population and impact potential [21]. The results are separated into two categories for comparison: ecosystem and resource effects (Figure 4) and toxicity effects (Figure 5).

The normalization of the data allows for a comparison across all impact categories, instead of an individual comparison of each impact category for each scenario. Figures 4 and 5 confirm the results discussed above. The impacts for Scenario 1 are higher for 6 of the 8 impact categories compared to Scenario 2. The figures show that the four most significant impacts with least uncertainty are GWP, MEP, HTP and MTP. Steps to mitigate these impacts should be taken first, and are outlined in the paragraphs in the characterization step of the LCIA. FDP is also among the highest impacts once normalized, but its results have been found to be inconclusive due to insufficient data and excluded from the analysis.

There is no simple answer to which scenario produces fewer total environmental burdens. For six of the nine impact categories, emissions associated with Scenario 1 are higher than Scenario 2. However, for particulate matter, photochemical oxidant formation, and fossil resource depletion, Scenario 2 has the higher impact. Assigning a weight to each impact category

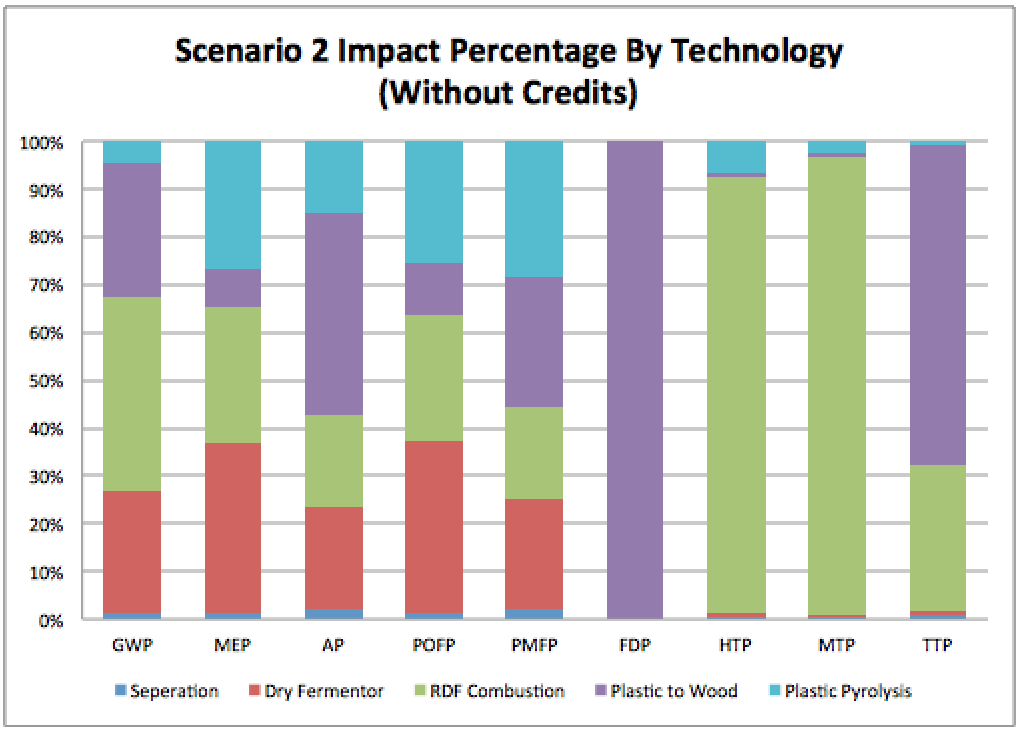

Figure 3. Percentage breakdown of impacts by technology for Scenario 2, not including credits.

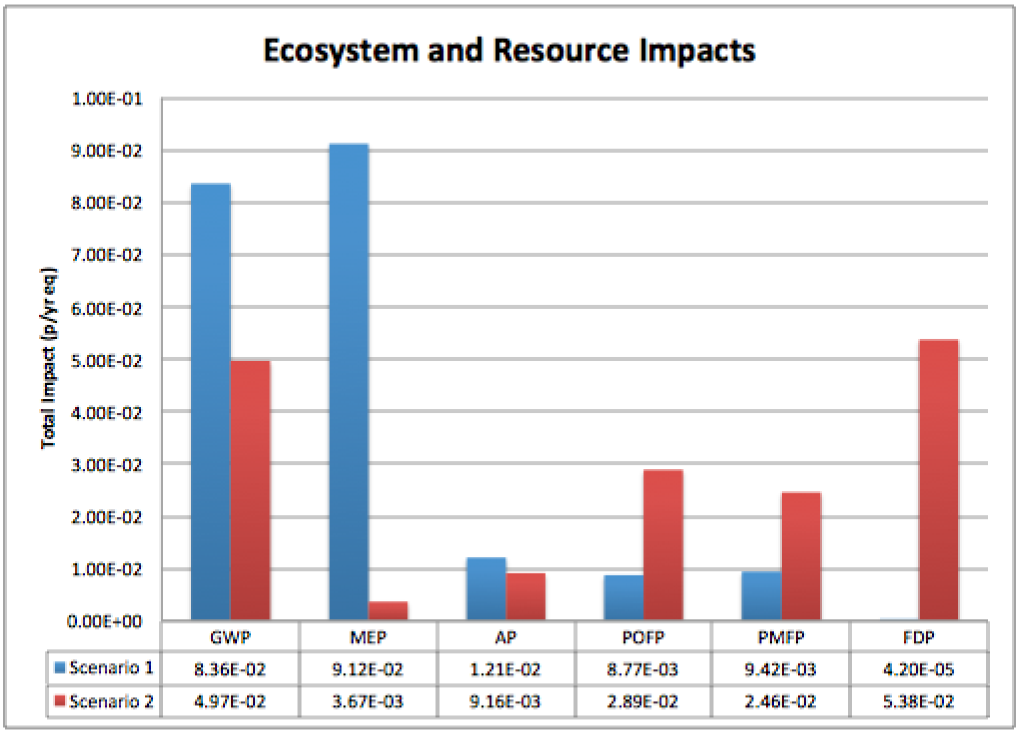

Figure 4. Ecosystem and resource impacts in person equivalents per year.

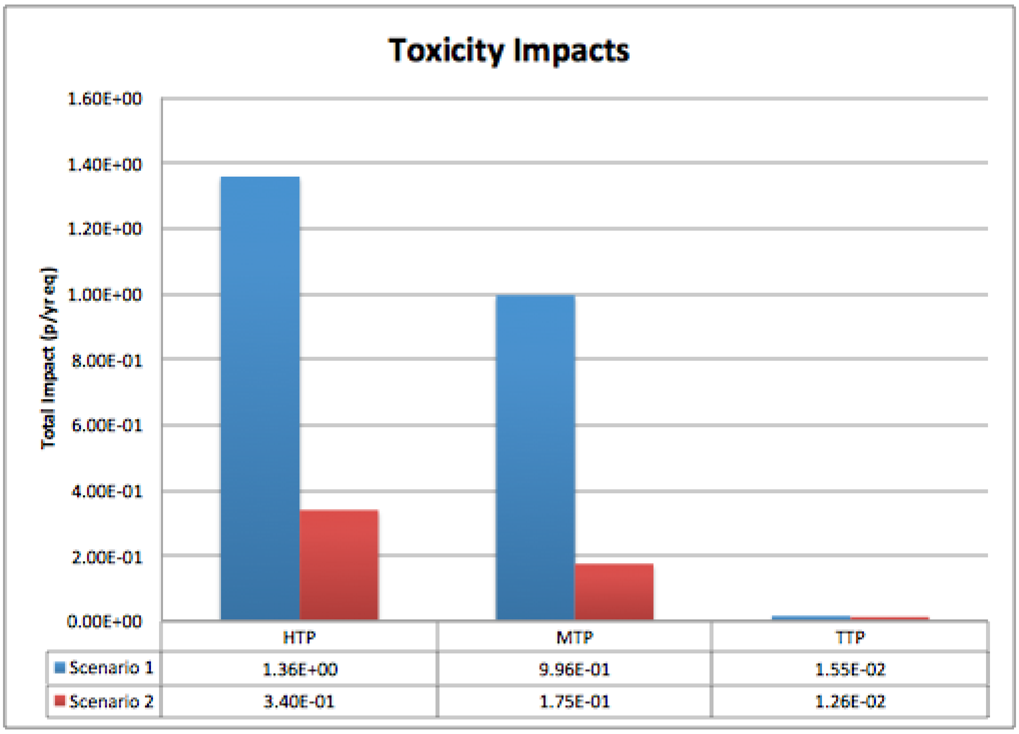

Figure 5. Toxicity impacts in person equivalents per year.

could allow for a single unit for comparison between the two scenarios, however the factors for performing weighting are relatively subjective. In order to properly give weight to the different impact categories, they have to be assigned into a hierarchy of importance. There is no consensus on this method, and many researchers feel that this assignment of hierarchy is outside the scope of LCA, since there are few empirical scientific procedures for performing this step [1]. Instead, the results of this study are more applicable to other sites than those studied by providing a general overview of the strengths and weaknesses of either scenario.

3.2 Cost Analysis Results and Discussion

Shown below in Tables 4 and 5 are the total costs per year and per ton of waste, respectively. They include the capital cost, operation and maintenance, credit benefits, and net profits.

The capital cost for Scenario 1 is about 20% higher than for Scenario 2. However, the operation and maintenance cost per tonne of MSW is higher for Scenario 2. Scenario 2 provides more opportunities to sell high value products, thus there yield an order of magnitude higher credits than Scenario 1.

In both scenarios, the larger the capacity, the lower the capital cost per tonne of MSW. The credits per tonne of MSW are not dependent on the scenario capacity.

Overall, Scenario 2 is shown to be more profitable than Scenario 1. Additionally, it takes 33.6-53.4 years for Scenario 1 to pay off its capital cost, depending on capacity. However, it takes only 2.2-4.2 years for Scenario 2 to pay off its capital cost, depending on capacity.

Figures 6 and 7 provide a visual representation of the costs and profits of the two scenarios for illustrative purposes.

Overall Scenario 1 requires more financial capital to construct; however, the upkeep and management is easier with relatively low operation and maintenance costs. Scenario 2 is less costly to construct but is more complicated to run and costs more to operate and maintain. However, when revenue from the sale of byproducts from each system is included in the financial analysis, Scenario 2 is much more profitable per annum and per ton of waste dealt with than the full incineration scheme of Scenario 1. This is only true under the assumptions that the maximum amount of coproducts will be made and that there will be a consistent market for the selling of these coproducts. They may not always be in demand whereas the electricity produced by Scenario 1 will be. In fact depending on the market, Scenario 2 may result in excess coproducts. If this is the case then the credits that this scenario currently receives for its sales will dramatically decrease and Scenario 1 may become more favorable.

Another area worth considering is the WWTP included in Scenario 1's cost assessment. This plant requires an additional $34,000,000 towards the capital building costs. There must be some sort of leachate treatment present, but it is not known to what extent the incineration company actually pays for the WWTP. If this capital cost was excluded from Scenario 1 it would lower the costs by almost a third. This suggests that other methods should be considered before building the incineration plant such as using an anaerobic digester in place of a WWTP.

Initially Scenario 1 may cost more to construct; however, due to the stable market for electricity it will turn a more reliable profit. Scenario 2 has the opportunity for much higher profits but the markets it deals in are more unstable, such as the sales of WPC and compost. The data shown is assuming readily available buyers, when in actuality there may not always be a market, especially during recessions. If the system will be managed effectively and consistently produce high quality coproducts, Scenario 2 may be the better option due to the higher available revenue. Otherwise, Scenario 1 should turn a consistent profit with inexpensive management.

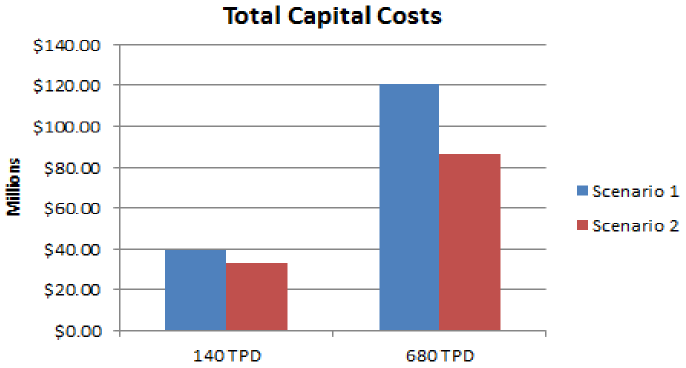

Figure 6. Total capital costs of each scenario.

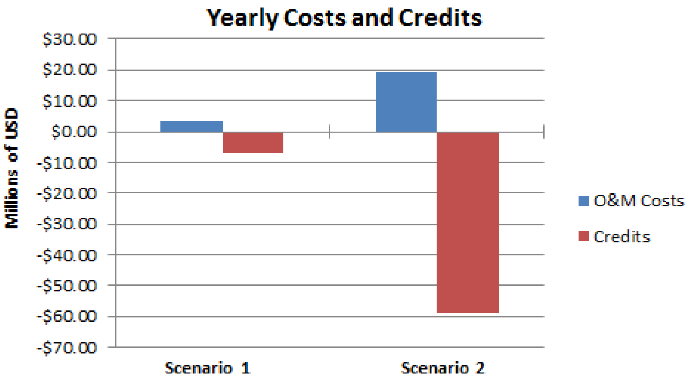

Figure 7. Total operational costs of each scenario.

Table 4. Total costs per year.

Total Capital Cost ($):	**Scenario 1**	**Scenario 2**
140 TPD	$39,465,074.08	$33, 419,470.00
680 TPD	$120,666,333.00	$86,342,181.25
Total Operation and Maintenance Costs Per Year ($)	**Scenario 1**	**Scenario 2**
140 TPD	$707,042.89	$4,179,999.60
680 TPD	$3,434,208.30	$19,381,795.20
Total Yearly Credit ($):	**Scenario 1**	**Scenario 2**
140 TPD	-$1,445,501.16	-$12,133,645.36
680 TPD	-$7,021,005.62	-$58,934,848.88
Net Operation and Maintenance Costs Per Year ($):	**Scenario 1**	**Scenario 2**
140 TPD	-$738,458.27	-$7,953,645.76
680 TPD	-$3,586,797.31	-$39,553,053.68

Table 5. Total costs per ton of waste.

Capital Cost per Tonne per Annum:	**Scenario 1**	**Scenario 2**
140 TPD	$783.04	$663.08
680 TPD	$492.92	$352.70
Total Operation and Maintenance Costs Per Tonne MSW:	**Scenario 1**	**Scenario 2**
140 TPD	$14.03	$82.94
680 TPD	$14.03	$79.17
Credits Per Tonne MSW:	**Scenario 1**	**Scenario 2**
140 TPD	$28.68	$240.75
680 TPD	$28.68	$240.75
Net Operation and Maintenance Per Tonne MSW:	**Scenario 1**	**Scenario 2**
140 TPD	-$14.65	-$149.45
680 TPD	-$14.65	-$153.21

Table 6. Capital cost breakdown by process for Scenario 1.

Capital Costs Scenario 1:	**Incinerator**	**WWTP (Allocated by BOD)**	**Landfill**
680 TPD	$86,333,333	$34,000,000	$333,000
140 TPD	$28,000,000	$11,396,515	$68,559

4. Conclusions

This study considered a comparative LCA of two waste management scenarios on Phuket and Samui. The results are inconclusive as to which scenario produces fewer environmental burdens since six of the eight impact categories are higher for Scenario 1 than Scenario 2. The judgment on which scenario is better is left up the decision maker and their valuation of certain impact categories.

Several hotspots identified are:

● Global Warming Potential is higher for Scenario 1 and the highest normalized. Proper separation of the organic waste at the mass-burn incinerator could reduce the CO_2 release during combustion.

● Marine Eutrophication Potential is also higher for Scenario 1. A more effective wastewater treatment plant that could remove more of the total nitrogen from the waste water stream before releasing it into the marine environment could curb this. The cost analysis also suggests leachate treatment by WWTP could be substituted with an anaerobic digester for less cost, and possibly less eutrophication potential.

● Human Toxicity and Marine Toxicity are high for Scenario 1. These effects could be mitigated by using the fly ash and bottom ash in concrete production. This would also increase the credit profit of Scenario 1.

● Photochemical-oxidant Formation and Particulate Matter Formation are higher for Scenario 2. The impacts could be curbed by employment of more effective NOx reduction systems at the combustion of RDF and dry anaerobic digester biogas.

The cost analysis suggests that Scenario 2 is preferable to Scenario 1 due to the high value of the co-products it creates, regardless of whether the capacity is 140 tonnes or 680 tonnes per day. If is unable to sell the co-products then Scenario 1 may be more preferable.

Conclusions could be drawn in order to determine the optimal waste management treatment for a tropical island. However, it is suggested that the LCIA results be weighted based on the policy makers hierarchy of importance. This study may be used as a model for comparing other waste technologies, but the results will vary based on the waste composition and technology used.

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