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 are two Thai islands that have pursued contrasting paths in the attempt to deal with this increasing amount of waste since 2011. The purpose of this study is to determine, in general, 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 6 of the 8 impact categories analyzed and a higher capital cost. However, the materials recovery technology specified in the study produced a higher impact in 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

1.1 Basic 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 MSW incinerators on each island (Liamsanguan, Gheewala, 2008; Chaijit and Wiwattanadate, 2012). Phuket has a population of 357,711, but receives between 9 and 12 million tourists per year (National Statistics Office, 2010). Samui has 53,000 residents and receives about 1.1 million tourists a year (DEDE, 2011). 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 (Udomsri et al. 2011). 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 (Chaya, Gheewala, 2006). 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 (Liamsanguan, Gheewala, 2008). 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 (Thiengburanathum et al., 2010). 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 (Chaijit, Wiwattanadate, 2012). 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 RDF, and capture energy (Samui Muncipality, 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.

1.2 Background on Islands

See Appendix A for a description of the previous state of each island's waste management scenario, the changes that Phuket's scenario has undergone, and the new system that Samui plans to implement.

1.3 Objective

The objective of this study is to compare a mass burn incineration system (Scenario 1) and a materials recovery system that includes incineration of RDF (Scenario 2). Both scenarios are assessed based on their handling of 1 tonne of untreated municipal solid waste. 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.

1.4 Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool for calculating the net environmental impact from a product or process throughout its lifetime (from raw material acquisition through production, use and disposal). This 'cradle-to-grave' thinking considers every process involved, taking into account both direct emissions, such as emissions to the air, water and soil, and indirect emissions, such as the use of energy and materials.

ISO 14040 standards define the four steps of LCA as *Goal and Scope Definition*, which includes the functional unit, system boundaries, and assumptions; *Life Cycle Inventory (LCI)*, which compiles the energy and mass flows and the associated emissions; *Life Cycle Impact Assessment (LCIA)*, which compiles and assesses the environmental burdens by impact type; and *Life Cycle Interpretation*, which aims to evaluate the areas of possible improvement (ISO, 2000).

LCA has developed into a principle decision support tool for waste management (Khoo, 2009). It accounts for both the environmental burdens and benefits that waste management systems to more accurately compare the different systems (Cherubini et al., 2009).

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. In Scenario 2, this functional unit is separated into four treatment technologies (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, waste water 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 substitute 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.

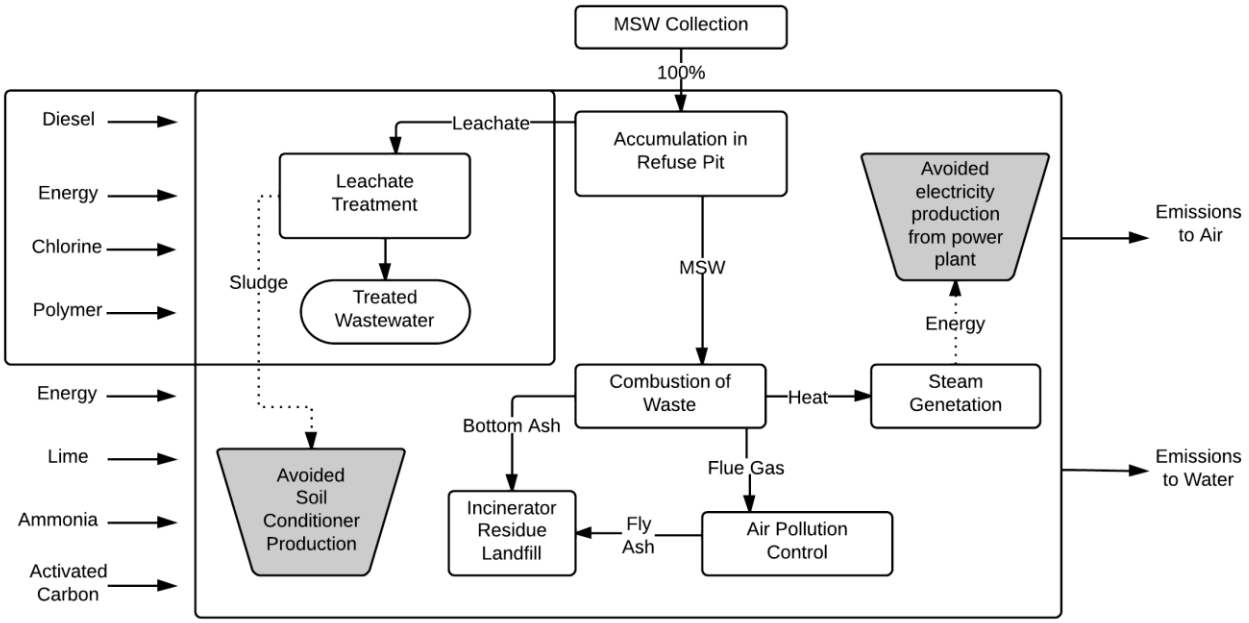

Figure 1. System diagram for Scenario 1.

For Scenario 2, see Figure 2. Due to the complicated nature of Scenario 2, each technology is separated into a separate diagrams for ease of understanding. These additional figures D.1, D.2, D.3, and D.4 are presented in Appendix B. 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.

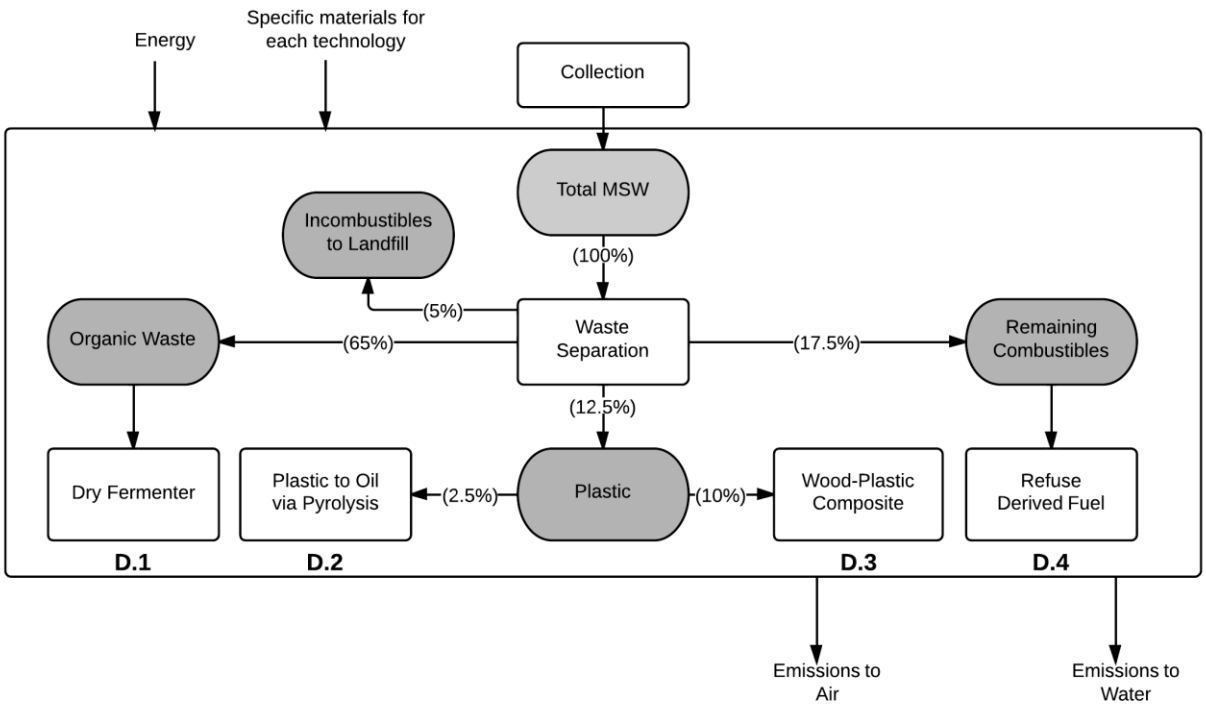

Figure 2. System diagram for Scenario 2.

2.1.2.3 Assumptions and Limitations

The following assumptions are made in order to complete this study:

Electricity used from the grid follows typical Thai grid electricity production (Itten et al., 2012). 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 using Simapro software.

All incoming waste is of the same composition, shown below in Table 1, which is characteristic of the composition of waste produced in Samui in 2003 (Sharp, and Sang-Arun, 2012). 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). 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.

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

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.

All air emission reports of NO_x and SO_x are assumed to be nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) respectively.

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 is 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 PCD, 2004). 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 an technologically advanced incinerator in Italy (Arena et al., 2003); see Appendix C.

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, 21.5% and 2.1% 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 Waste Water Treatment Plant (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 waste water and their Biological 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 waste water 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. This calculation is presented in Appendix D.

Inventory data is listed in Appendix E.

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 (Arena et al., 2003). 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 (IPCC, 2007).

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 (Moller et al., 2009). Additional non-GHG emissions are taken from another LCA study (Fruergaard and Astrup, 2011). This addition was justified based on the similarity of both the system boundaries and the total methane releases (calculated to be 9.04g m^3 of biogas and 10.70 g 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 (IPCC, 2007). All ranges present in the data are averaged, except for the amount of biogas and electricity produced, for which the lowest value was picked based on professional consultation (Komsilp Wangyao, Joint Graduate School of Energy and Environment, personal communication).

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 (Arena et al., 2003). 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 (Zhou et al., 2007). The LHVs are found to be approximately equivalent, although the two compositions slightly differ. These results are presented in Table 2.

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

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**

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 (RTI International, 2012). 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 EPA's website (EPA, 2009).

For converting plastic to WPC, a LCA completed in the US comparing a typical blend of WPC to ACQ treated lumber is used (Bolin, Smith, 2011). Since this data for the WPC product includes the impact of 50% virgin plastic in the composite, some alterations are made. The inputs and outputs for producing an equivalent amount of virgin plastic are found and subtracted from the data provided in the study. Any time a negative number resulted, it is assumed that that input or output was solely attributed to virgin plastic production and its impact is assumed to be zero. This only occurred for uranium, and crude oil, as well as emissions of carbon monoxide, VOCs and copper emissions to water.

Inventory data for the above processes are listed in Appendix E.

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. The individual Simapro materials used for each of our inventory items can be found in Appendix F.

2.3 Choice of Impact Categories

The first mandatory element of the Life Cycle Impact Assessment (LCIA) is the selection of a number of impact categories to quantify the contributions to environmental harm that each input and output in the inventory contributes. 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, consistent with ISO standards of LCA (ISO, 2000). 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 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 blindly 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. See Appendix G for more detailed data acquisition information. 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 of the third step in the ISO defined LCA methodology, the Life Cycle Impact Assessment (LCIA), are presented according to the impact categories described in Section 2.4 and separated into positive environmental burdens and credits from productions.

The characterized results are displayed in Table 3 for both Scenario 1 and Scenario 2.

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

Impact Category	Scenario 1 Contribution	Scenario 1 Credit	Scenario 2 Contribution	Scenario 2 Credit
GWP (kg CO_2 eq)	6.62E+02	8.59E+01	6.58E+02	3.15E+02
MEP (kg N eq)	6.80E-01	1.00E-02	8.37E-02	5.68E-02
AP (kg SO_2 eq)	9.39E-01	4.76E-01	2.17E+00	1.82E+00
POFP (kg NMVOC eq)	6.05E-01	1.76E-01	2.36E+00	9.45E-01
PMFP (kg PM10 eq)	2.61E-01	1.29E-01	7.77E-01	4.32E-01
FDP (kg Oil eq)	7.04E-02	5.18E-02	2.40E+01	7.23E-02
HTP (kg 1,4-DB eq)	1.62E+02	2.29E+00	4.49E+01	5.05E+00
MTP (kg 1,4-DB eq)	2.41E+00	9.93E-03	4.87E-01	6.50E-02
TTP (kg 1,4-DB eq)	1.08E-01	7.04E-03	9.77E-02	1.56E-02

The net environmental load of each scenario is displayed in Table 4 for the direct comparison of the net impacts of each impact category for each scenario.

Table 4. Net environmental load by impact category for each scenario.

Impact Category	Scenario 1 Net	Scenario 2 Net
GWP (kg CO_2 eq)	5.76E+02	3.43E+02
MEP (kg N eq)	6.70E-01	2.70E-02
AP (kg SO_2 eq)	4.62E-01	3.50E-01
POFP (kg NMVOC eq)	4.29E-01	1.41E+00
PMFP (kg PM10 eq)	1.32E-01	3.46E-01
FDP (kg Oil eq)	1.87E-02	2.39E+01
HTP (kg 1,4-DB eq)	1.60E+02	3.99E+01
MTP (kg 1,4-DB eq)	2.40E+00	4.22E-01
TTP (kg 1,4-DB eq)	1.01E-01	8.22E-02

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 higher than for Scenario 2 with a 50.7% difference. 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 (Yang et al., 2012).

The Marine Eutrophication Potential for Scenario 1 is higher than for Scenario 2 with a 184.5% difference. 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 waste water released into the surrounding marine waterway has a high eutrophication potential.

With a difference of 27.6%, 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 higher than Scenario 2, with a difference of 120%. 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. More bottom ash means more impact.

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 (Siddique, 2010).

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 1.

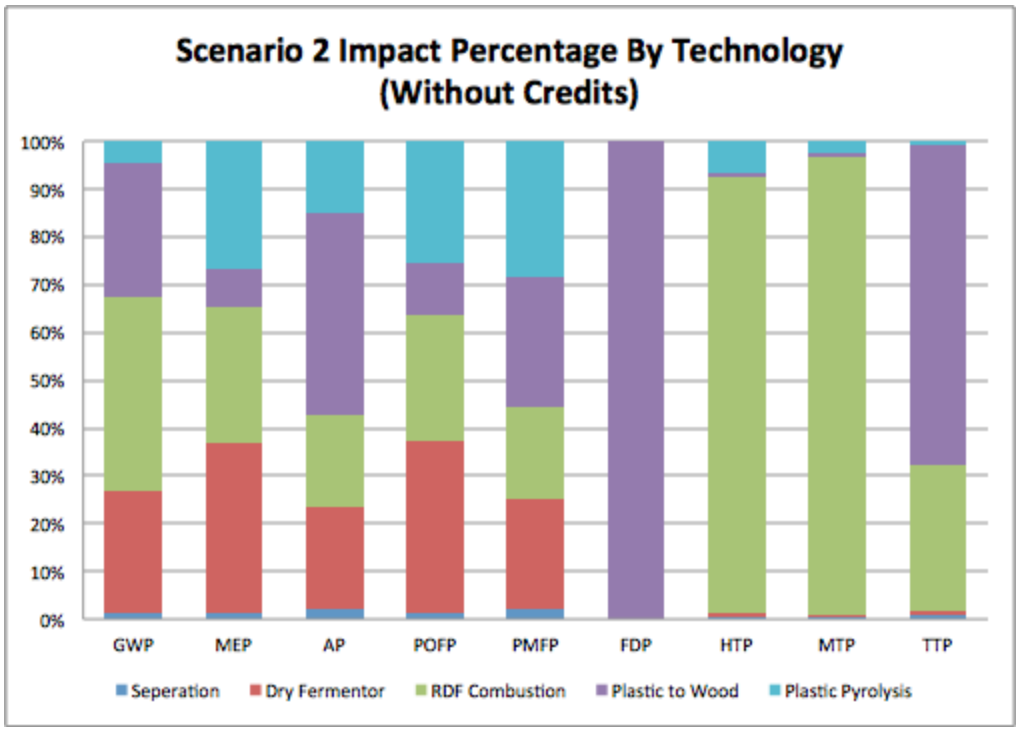

Figure 1 Percentage breakdown of impacts by technology for Scenario 2, not including credits.

Figure 1 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 higher than Scenario 1. The RDF incineration accounts for 35.75% of the POFP in Scenario 2; 93.75% 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.

For Particulate Matter Formation, Scenario 2 is also higher than Scenario 1. The plastic pyrolysis process accounts for 28.38% of the Particulate Matter Formation, 56.90% and 42.61% are attributed to the release of NO_x and PM10 air emissions in the processes, respectively.

The extreme 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. (This procedure is detailed in Section 2.1.2.2 System Boundaries). 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 (seen in detail in Appendix E) 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 (unprocessed natural gas, unprocessed coal in Appendix E) 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 99.0% 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 as the toxicity impacts were significantly higher in both scenarios than all other impact categories. 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 (Sleeswijk et al., 2008). The results are separated into two categories for comparison: ecosystem and resource effects and toxicity effects.

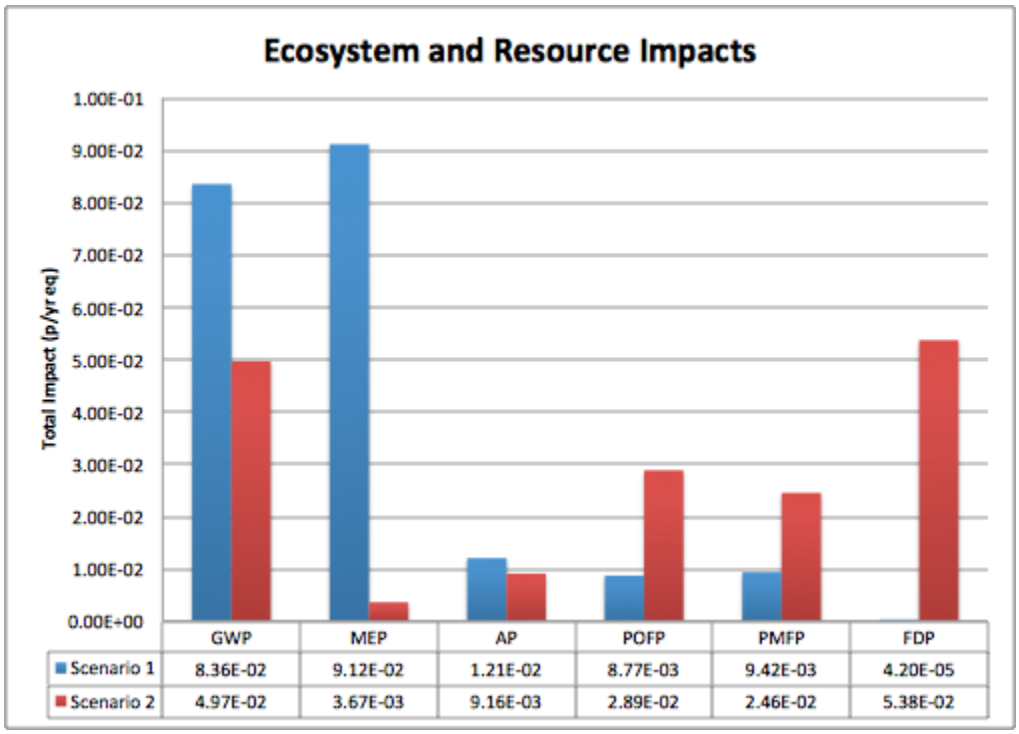

Figure 2. Ecosystem and resource impacts in person equivalents per year.

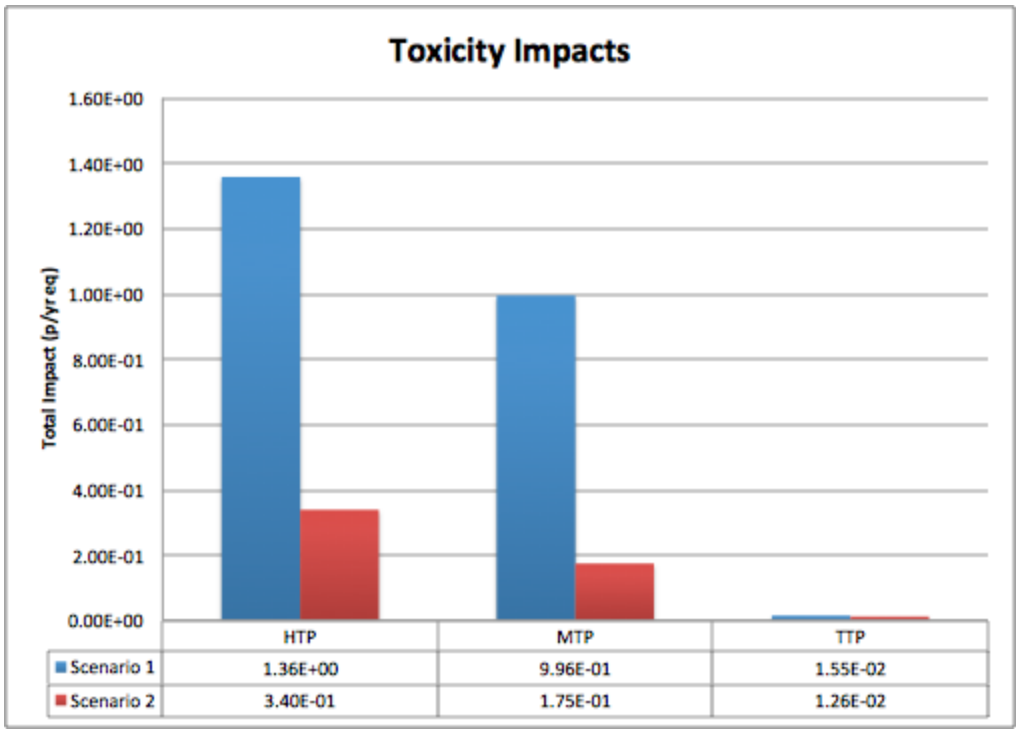

Figure 3. Toxicity impacts in person equivalents per year.

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 2 and 3 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.

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 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 (Liamsanguan and Gheewala, 2006). 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 Table 4 and Table 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.

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

The capital cost for Scenario 2 is slightly lower than for Scenario 1, with an average 24.9% difference. 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 is a 157.4% difference between the credit for Scenario 1 and Scenario 2. The net operation and maintenance costs are lower in Scenario 2 than in 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.

With an average of a 166.4% difference between Scenario 1 and Scenario 2's net cost of operation and maintenance, 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. It takes 2.2-4.2 years for Scenario 2 to pay off its capital cost, depending on capacity.

Figure 4 and Figure 5 provide a visual representation of the costs and profits of the two scenarios for illustrative purposes.

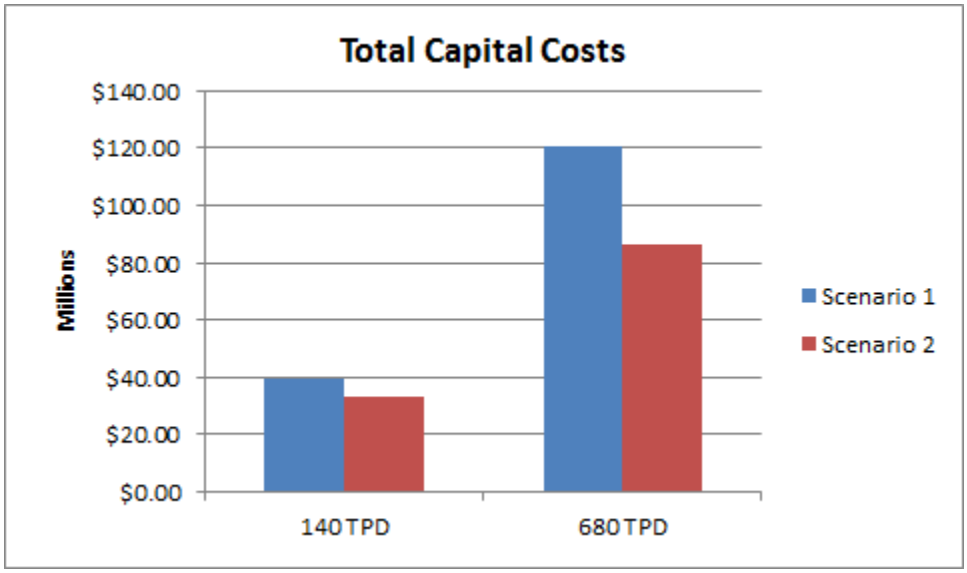

Figure 4. Total capital costs of each scenario.

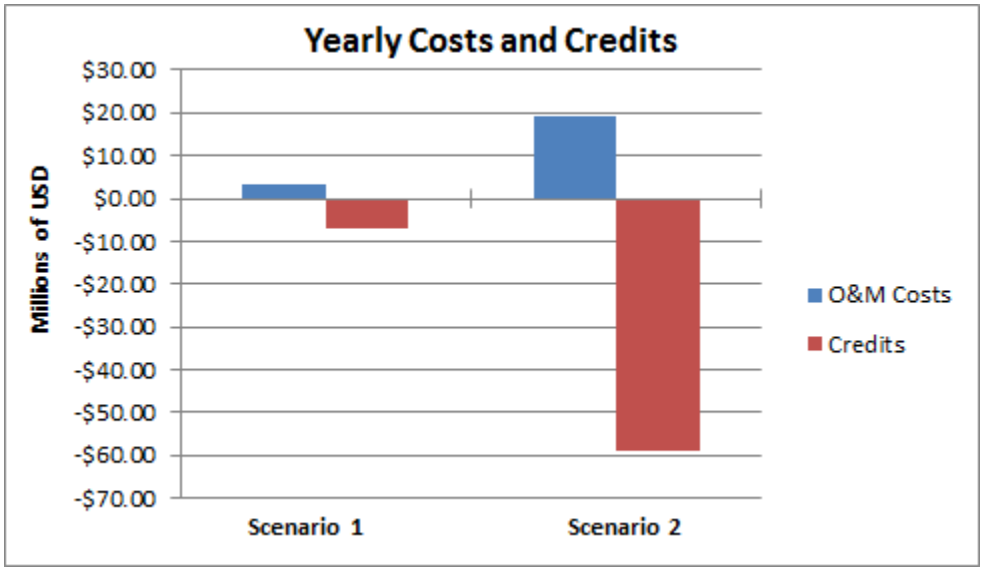

Figure 5. Total operational costs of each scenario.

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 adds an additional $34,000,000 to 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 28%. This suggests that other methods should be considered before building the incineration plant such as using an anaerobic digester in place of a WWTP.

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

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.

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 highest for Scenario 1 and the highest normalized impact in Figure 2. Proper separation of the organic waste at the mass-burn incinerator could reduce the CO2 release during combustion.
- Marine Eutrophication Potential is also highest for Scenario 1. A more effective waste water 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 deNOx 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, whether the capacity is 140 tonnes or 680 tonnes per day. If is unable to sell the co-products than Scenario 1 may be more preferable. As suggested previously the results of this study could be different if emissions data from the Phuket incinerator was provided and the cost analysis was more specific to each site.

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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6. Appendices

A. Background on Islands

Phuket

In addition to being incapable of processing the total amount of waste produced by the island, Phuket's old incinerator began malfunctioning and was shut down. A new incinerator was built to process 700 tonnes per day and generate up to 11 MW of power.

The island has no major industrial regions; therefore, tourists and locals produce essentially all of the waste on the island, which can easily be incinerated. The incinerator receives an average of 650-700 tonnes per day. This varies seasonally with the tourist population. Before arriving at the incinerator, separation takes place by the collection workers looking for recyclables that can be sold as a secondary revenue source. No other separation is carried out, with the exception of cement, furniture, or large trees.

The bottom ash and fly ash from the incinerator are sent to surrounding landfills. As there is less waste produced per day than the incinerator can manage, leftover waste in the landfill supplements the incinerator's higher capacity.

Phuket is currently experiencing an increase in total waste generation of about 7.3% per year and is projected to reach 1,000 tonnes per day by 2020.

Samui

In October 2012, Samui's incinerator was shut down due to problems including corrosion of the boiler tank, which caused the incinerator to run at half of its 140 tonne capacity. This became increasingly problematic given the increasing tourist populations and subsequent increase in total waste production. In 1995, when the incinerator was built, Samui only produced 30 tonnes of waste per day. Now, Samui's municipality brings approximately 150-200 tonnes of waste per day to the treatment facility. After the incinerator was shut down, nearly 100 tonnes of waste per day was diverted to the landfill beside the incinerator.

Subsequently, the landfill exceeded capacity, overflowing into buffer zones, resulting in plans for a new project. This new project consists of a materials recovery system with RDF incineration rather than a high capacity mass burn incinerator, as in Phuket. In this system, plastic and organic contents of the incoming waste are separated out. A portion of the plastic is pyrolyzed to create oil co-products, which can be refined and sold. The other portion of the plastic is mixed with wood fiber and extruded to create a wood-plastic composite for building supply. The organic portion is processed in a dry fermenter and then anaerobically digested to create a marketable fertilizer and biogas, which can be combusted to create electricity. The remaining portion of the waste is converted into RDF to be burned in the incinerator once it has been refurbished. Any residues or incombustible waste is landfilled.

Samui has estimated that by 2022, the waste generation rate will reach 275 tonnes per day and by 2032, 400 tonnes a day.

B. Specific Process Diagrams for Scenario 2

Figure D.1 System Diagram for Dry Anaerobic Digester

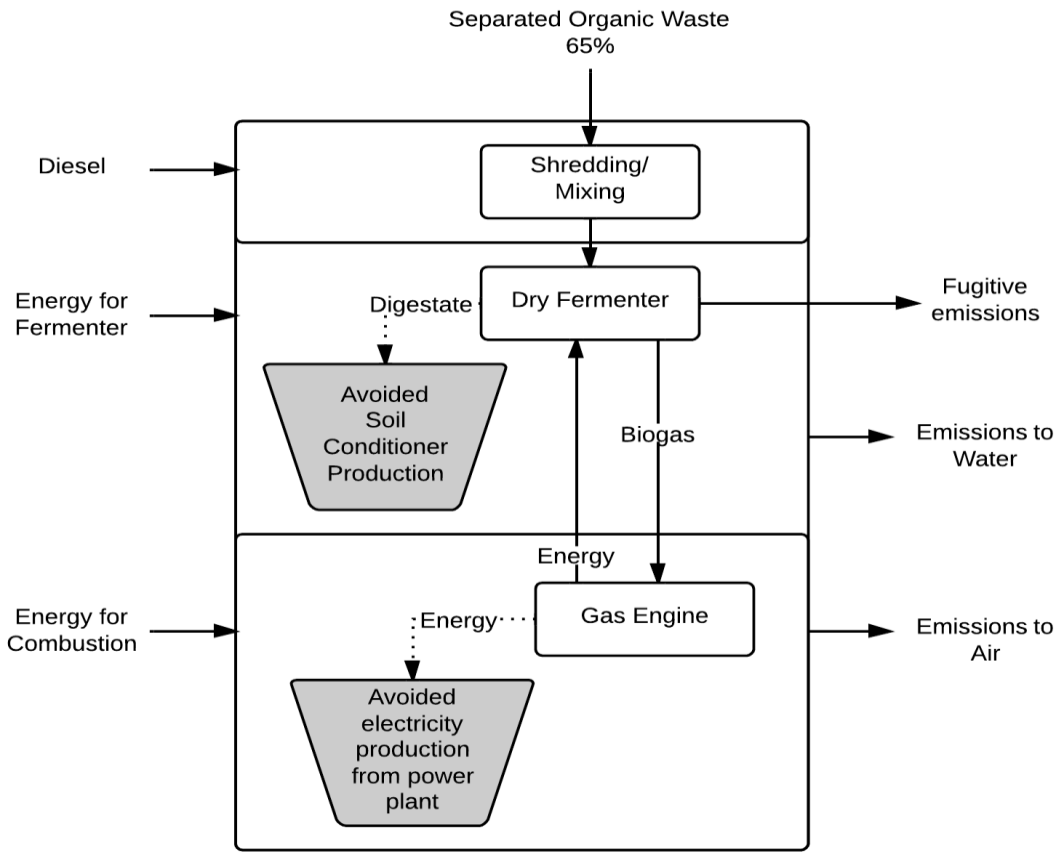


Figure D.2 System Diagram for Plastic to Oil Pyrolysis

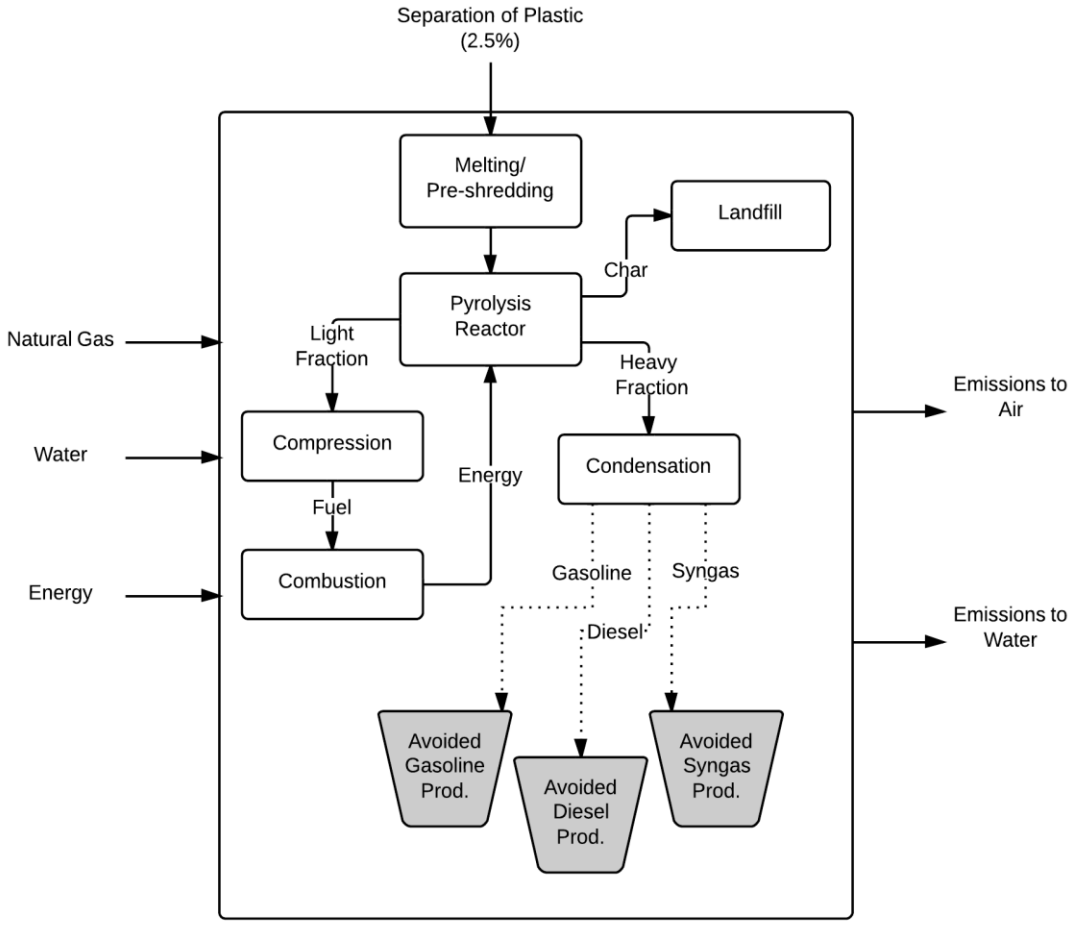


Figure D.3 System Diagram for Plastic to WPC

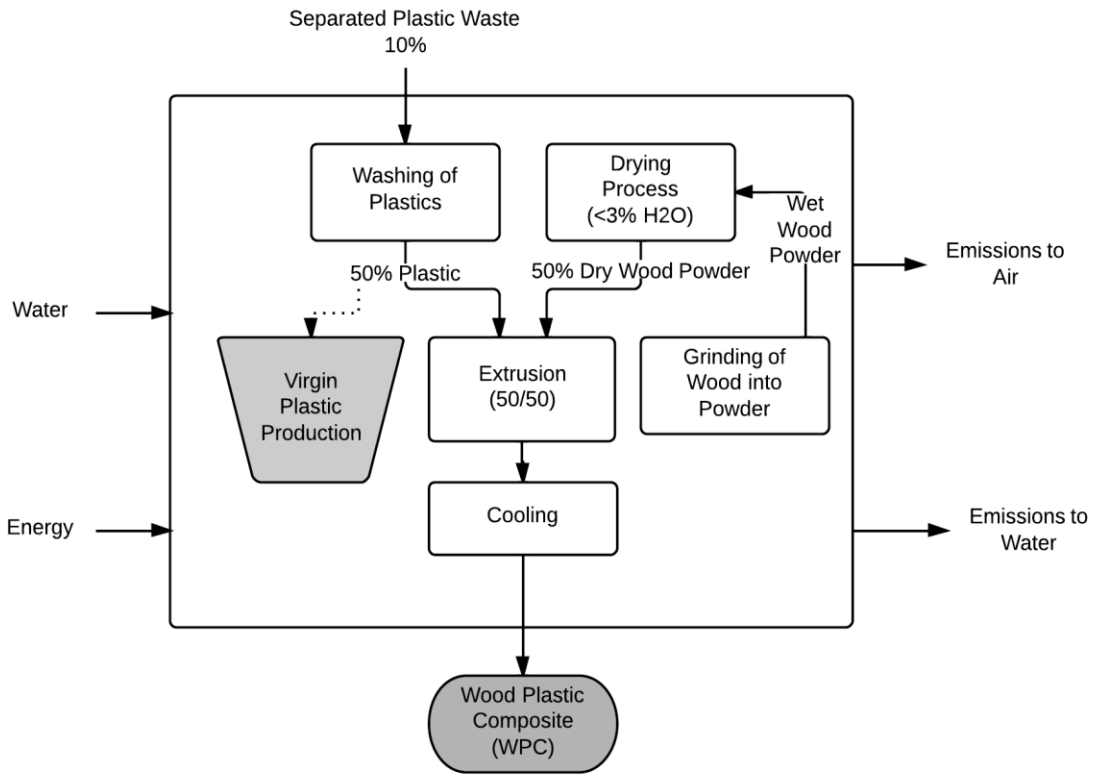
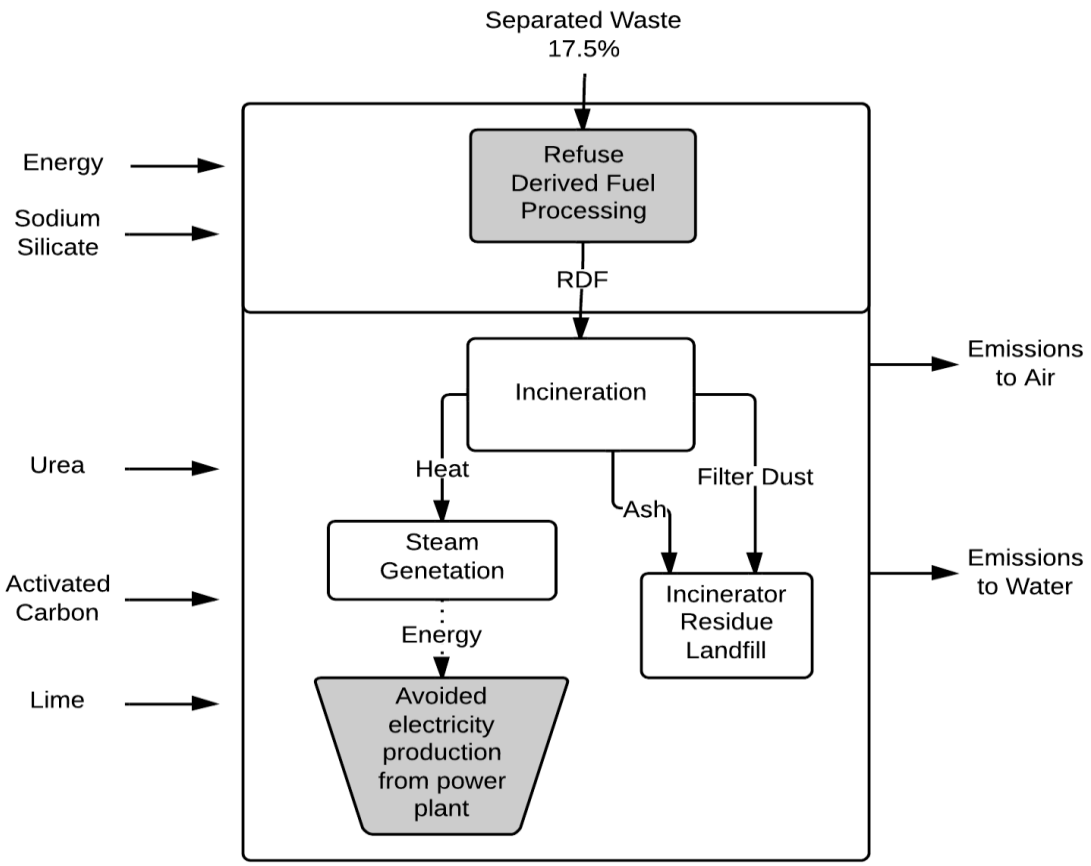


Figure D.4 System Diagram for RDF Production and Combustion



C. Comparison of Incinerator Emissions

The highlighted column is the emissions used in our study.

Table 7. Emissions from Incinerators in kg/day.

Emission	Italy	Samui	Old Phuket
CO2	9.53E+02	5.56E+02	1.80E+03
CO	9.80E-02	1.50E-01	5.98E-01
Nox	1.97E+00	3.43E-01	2.46E+00
N2	4.77E+03		
SO2	1.97E-01	2.18E-01	4.61E-01
HCl	9.80E-02	1.18E-01	1.55E-01
Hg	6.60E-04	4.35E-05	
Cd	6.60E-04		
Heavy Metals	2.00E-04		
Dioxin			

Table 8. Emissions from Incinerators compared to standards

Emission	Samui	Old Phuket	Thai National Standards	Unit
CO	20.6	63.9	115.5	mg/m3
Nox	25.2	139.8	180.0	ppm
SO2	78.6	18.8	30.0	ppm
HCl	10.9	11.2	25.0	ppm
TSP	21.3	3.4	120.0	mg/Nm3
Dioxin			0.5	ng/m3

D. Formula for Sludge calculation at Waste Water Treatment Plant

Table 17. Average efficiency of WWTP for 7 months.

Parameters	**Before treated**	**After treated**
BOD (mg/l)	269.3332679	6.201027906
COD (mg/l)	690.5604625	41.73488161
TSS (mg/l)	600.2242265	14.39648888
TDS (mg/l)	8570.111718	7078.460429
Total Flow Rate	**30.70255389**	**ML/day**

$$W_s = W_{sp} + W_{ss} \quad (1)$$

where W_s = total dry solids, kg/day

W_{sp} = raw primary solids, kg/day
= f x SS x Q

where f = fraction of suspended solids removed in primary settling = 1 - (TSS before)/(TSS after)
SS = suspended solids in unsettled wastewater, mg/L = TSS before
Q = daily wastewater flow, ML/d

W_{ss} = secondary biological solids, kg/day
= (k x BOD + 0.27SS)Q

where k = fraction of applied BOD that appears as excess biological growth in waste - activated sludge or filter humus, assuming about 30 mg/L of BOD and suspended solids remaining in the secondary effluent. For trickling - filter humus, k is assumed to be in the range 0.3 - 0.5. = 0.4 average
BOD = concentration in applied wastewater, mg/L
Q = daily wastewater flow, ML/d

Original formula available at:
http://home.engineering.iastate.edu/~leeuwen/CE%20523/Supplementary%20Notes/Sludge%20Disposal.doc

E. Inventory Data

Scenario 1

Listed below is the inventory data for all processes involved in Scenario 1. Grey cells represent credited outputs.

Table 9. Phuket incinerator inventory data. Flows are representative of 1 tonne of MSW.

Inputs	Amount per tonne of MSW	Units
Lime Slurry	1.25E+01	kg
Activated Carbon	6.33E-01	kg
Electricity	3.52E+00	MJ
Ammonia Spray	8.80E+00	kg
Municipal Solid Waste	1.00E+00	tonne
Outputs	**Amount per tonne of MSW**	**Units**
Electricity	8.85E+02	MJ
Bottom Ash	2.15E+02	kg
Fly Ash	2.50E+01	kg
Leachate	9.01E-02	tonne
CO_2	5.56E+02	kg
Hg	4.35E-05	kg
NO_x	3.43E-01	kg
CO	1.50E-01	kg
HCl	1.18E-01	kg
SO_2	5.70E-01	kg
Dioxin	3.63E-09	kg

Table 10. Waste Water Treatment Plant inventory data. Flows are representative of 1 tonne of MSW.

Inputs	Amount per tonne of MSW	Units
Incinerator Wastewater	9.01E-02	tonne
Sewage	1.77E-01	tonne
Domestic Wastewater	1.04E+02	tonne
Landfill Wastewater	1.10E+00	tonne
Chlorine	6.49E-01	kg
Polymer	2.23E-02	kg
Electricity	9.91E+01	MJ
Outputs	**Amount per tonne of MSW**	**Units**
Sludge (Fertilizer)	9.02E+01	kg
Treated Wastewater*	1.06E+02	tonne
BOD	*6.56E-01*	*kg*
COD	*4.41E+00*	*kg*
TSS	*1.52E+00*	*kg*
TDS	*7.49E+02*	*kg*
TP	*6.52E-02*	*kg*
TN	*9.77E-01*	*kg*

*The cells below Treated Wastewater are the characteristics of the water itself, rather than a further release.

Scenario 2

Listed below is the inventory data for all processes involved in Scenario 1. Grey cells represent credited outputs.

Table 11. Inventory data for separation process to organics and RDF. Flows representative of 1 tonne of MSW.

Inputs	Amount per tonne of MSW	Units
Mixed Waste	1.00E+00	tonne

Water	8.80E-02	m^3
Ferrous Wire	3.00E-01	kg
PE Film	1.60E-01	kg
Diesel	2.32E-01	kg
Electrical Energy	8.30E+01	MJ
Outputs	**Amount per tonne of MSW**	**Units**
Organic Waste to Dry Fermenter	6.50E-01	tonne
Plastic Waste to Pyrolysis	2.50E-02	tonne
Plastic Waste to WPC	1.00E-01	tonne
RDF	1.75E-01	tonne
Scrap to Landfill	5.00E-02	tonne

Table 12. Dry fermentation inventory data. Flows representative of 1 tonne of MSW.

Inputs	Amount per tonne of MSW	Units
Organic Waste	6.50E-01	tonne
Diesel Used at the AD Facility	8.65E-01	kg
Electricity Used at the AD Facility	8.19E+01	MJ
Outputs	**Amount per tonne of MSW**	**Units**
Biogenic CH_4 Loss at the Facility (Fugitive Gases)	1.00E+00	kg
N_20 Loss at the Facility (Fugitive Gases)	6.18E-01	kg
Biogas Produced	6.01E+01	kg

Electricity Produced from Biogas	4.31E+02	MJ
CO_2 From Combustion	1.31E+02	kg
Biogenic CH_4 From Combustion	5.10E-01	kg
N_2O From Combustion	7.87E-04	kg
Digestate/Fertilizer Produced	3.25E+02	kg
NMVOC	5.93E-02	kg
CO	6.50E-02	kg
NO_x from Combustion	8.36E-02	kg

Table 13. RDF combustion inventory data. Flows representative of 0.175 tonne of RDF or 1 tonne of MSW.

Inputs	Amount per tonne of MSW	Units
RDF	1.75E-01	tonne
Air (moist)	1.86E+03	kg
Process Water	2.77E-02	m^3
Ash Conditioning Water	3.01E+00	kg
Sodium Silicate (30%)	2.63E-01	kg
Activated Carbon	4.38E-01	kg
$Ca(OH_2)$ (Lime)	5.60E-01	kg
Urea	5.25E-01	kg
Outputs	**Amount per tonne of MSW**	**Units**
CO_2	2.65E+02	kg
H_2O	1.19E+02	kg
O_2	1.47E+02	kg

N_2	1.44E+03	kg
NO_x	5.84E-01	kg
SO_2	5.83E-02	kg
HCl	2.92E-02	kg
Dusts	1.45E-02	kg
TOC	7.00E-04	kg
CO	2.92E-02	kg
PCDD/F	2.98E-10	kg
Hg	1.75E-04	kg
Cd	1.75E-04	kg
Heavy Metals	5.25E-04	kg
Filter dusts	1.58E+01	kg
Bottom Ash	1.93E+01	kg
Electric Energy	7.16E+02	MJ

Table 14. Plastic to WPC inventory data. Flows representative 0.1 tonne of incoming waste plastic or 1 tonne of MSW.

Inputs	Amount per tonne of MSW	Units
Thai Electricity	2.76E+02	MJ
Waste plastic	1.00E-01	tonne
Wood fiber by-product	1.09E+02	kg
Water	1.43E-01	m3
Unprocessed coal	1.40E+01	kg
Unprocessed natural gas	1.36E+01	m3

Outputs	**Amount per tonne of MSW**	**Units**
WPC	2.00E-01	tonne
CO2-fossil	6.13E+01	kg
CO2-non-fossil	1.83E+01	kg
Ammonia	6.03E-05	kg
Hydrochloric acid	9.99E-03	kg
Hydrofluoric acid	1.39E-03	kg
Nitrogen oxides (NOx)	9.10E-02	kg
Nitrous oxide (N2O)	5.24E-04	kg
Sulfur dioxide	7.88E-01	kg
Sulfur oxides	1.11E-02	kg
Particulates (PM10)	8.30E-03	kg
Methane	2.82E+00	kg
Acrolein	2.83E-06	kg
Arsenic	4.04E-06	kg
Cadmium	7.87E-07	kg
Lead	4.16E-06	kg
Mercury	8.26E-07	kg
Copper (to soil)	3.84E-03	kg
Solid wastes-landfill	9.03E-02	kg
Solid wastes-recycled	2.02E-08	kg
Virgin Plastic	5.00E+01	kg

Table 15. Plastic to oil via pyrolysis inventory data. Flows representative of 0.025 tonne incoming plastic or 1 tonne of MSW.

Inputs	Amount per tonne of MSW	Units
Power Consumption	6.65E+00	MJ
Plastic waste	2.50E-02	tonne
Water	8.95E-04	m^3
Supplemental Fuel Use (Natural Gas)	2.49E-02	m^3
Outputs	**Amount per tonne of MSW**	**Units**
Syngas	5.82E+00	MJ
Gasoline	2.87E-01	kg
Diesel	2.14E+01	kg
Char	1.25E+00	kg
Water Loss	1.83E-04	m3
PM	9.40E-02	kg
CO_2 (Carbon)	9.14E+00	kg
Methane	5.69E+01	kg
HCl	3.75E-06	kg
Hydrocarbons	5.01E-02	kg
N_2O	2.50E-02	kg
NO_x	5.71E-01	kg
CO	1.12E-01	kg
Lead	1.26E-04	kg
VOC	1.25E-02	kg

F. Specific Simapro entries used for each inventory material

Table 16. Simapro specifics.

Type of Material	Material Name in Database	Simapro Name	System Boundaries/Assumptions
Credit	Virgin Plastic	Polyethylene, LDPE, granulate, at plant/RER S	Impacts from raw material extraction to delivery to plant. Based on European values.
Credit	Gasoline	Petrol, unleaded, at refinery/RER S	Excludes emissions from combustion, but includes WWTP, process emissions and discharges to river. Based on European averages.
Credit	Diesel	Diesel, at refinery/RER S	Excludes emissions from combustion, but includes WWTP, process emissions and discharges to river. Based on European averages.
Credit	Syngas	Synthetic gas, production mix, at plant/CH S	Impacts from the production of syngas from wood chips, 50% fluidized bed, 50% fixed bed gasification. Molar composition of gas is 22% H2, 39.9% CO, 29.3% CO2. Density is 1.15kg/Nm3, lower heating value is 5.3MJ/Nm3. Based on Swiss data.
Credit	Compost/Fertilizer	Compost, at plant/CH U	Impacts from energy demand for operating compost plant, process emissions, transports of biogenic waste. Compost water content = 50%. Based on Swiss Data.
Landfill	Disposal of incinerator residue	Disposal, average incineration residue,	Disposal to Swiss landfill in 2000 with base seal and leachate

		0% water, to residual material landfill/CH U	collection. Heavy metals contained in waste are: Ag, As, Cd, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Se, Sn, V, Zn, Al, Mg.
Landfill	Disposal of inert waste	Disposal, inert material, 0% water, to sanitary landfill/CH U	Disposal to Swiss inert material landfill in 2000 with no direct emissions (leachate). Only includes energy burdens.
Material Input	Ammonia	Ammonia, steam reforming, liquid, at plant/RER S	Inputs of NG, water and electricity, added auxiliaries, energy, transport(only of materials, not final product), land use. Outputs of wastes and emissions into air and water. Based on European average values.
Material Input	Urea	Urea, as N, at regional storehouse/RER S	Production of urea from ammonia and CO2, transport of intermediate products and transport of product to storehouse. Based on European mean values.
Material Input	Polymer	Cationic resin, at plant/CH S	Cationic resin is the typical polymer used in WWTP of sludge. Impacts from materials used for production, transport of materials to manufacturing plant, emissions and wastes from production (incomplete), energy demand. Used stoichiometry to calculate data. Based on Swiss data.
Material Input	Activated carbon	Charcoal, at plant/GLO S	Charcoal is assumed to be the same as activated carbon. Impacts from production of charcoal from forest wood,

			including emissions. Based on data from global sources, with no flue gas treatment.
Material Input	Lime	Lime, hydrated, packed, at plant/CH S	Impacts from slaking, crushing, dust abatement, transport, storing and packaging in Switzerland.
Material Input	Natural gas	Natural gas, at production/NG S	Impacts from production of oil and gas including energy use and emissions, allocated based on heating value. Based on two companies in Niger Delta, mostly onshore, partly offshore.
Material Input	PE film	Packaging film, LDPE, at plant/RER S	Impacts from extrusion of plastic film, transport from production of plastic to conversion into film. Based on data from Europe.
Material Input	Sodium silicate	Sodium silicate, hydrothermal liquor, 48% in H2O, at plant/RER S	Impacts from material and energy input, production of waste and emissions for production of sodium phosphate out of phosphoric acid. Transport estimated. Based on averages from Europe.
Material Input	Water	GEP WT01B Pipe water By PWA (m3)	Impacts from Principal Water Authority distributing pipe water.
Material Input	Ferrous wire	GEP MT06 CRS - Steel	Production of steel only, actual wire making was assumed to have neglible impact.
Thai Electricity Mix	Heavy fuel oil	Heavy fuel oil, burned in power plant/RER S	Impacts from all energy use, use of chemicals, emissions to air and water including treatment of flue gases and effluents.

			Average of Europe oil plant.
Thai Electricity Mix	Wood pellets	Heat, wood pellets, at furnace 50kW/CH S	Net efficiency of 85%. System boundary is outlet of boiler. Air emissions adjusted to reflect experience of installed heaters. Based on average technology available on market in Switzerland.
Thai Electricity Mix	Lignite	Lignite, burned in power plant/BA S	Particle removal is included, desox and denox not included. Country specific data for Bosnia.
Thai Electricity Mix	Hard coal	Hard coal, burned in power plant/CN S	Impacts from energy conversion for electricity production in China, fuel oil for startup. Particle removal is included in module, deSOx and deNOx technology is assumed not installed (only 5% of installed capacity has it).
Thai Electricity Mix	Natural gas	Natural gas, burned in power plant/JP S	Impacts from high pressure network in Japan, emissions to air and substances needed for operation, Efficiencies from burning gas in Japanese power plant. Emissions data from German power plant.

G. Cost Analysis Data Acquisition and Manipulation

Scenario 1, Phuket

Capital cost data for the incineration and landfill processes in Scenario 1was acquired from the Phuket municipality (PJT Technologies, personal communication). Thus, no manipulation of this data was required. Capital cost data for the waste water treatment process in Scenario 1 was acquired from a study that compares the costs of wastewater management systems in Cape Cod (BCWCT, 2010). Provided by this study was the capital cost of constructing a wastewater treatment plant or various capacity sizes. From these data points, a trend line was calculated, from which the capital cost of constructing a treatment plant of each considered capacity (the original Scenario 1 capacity and the capacity of the scaled down version) could be extrapolated.

Operational costs for Scenario 1 were taken from various places. Maintenance costs associated with running the incinerator, as well as the quantities of the materials used in operation per year were provided by the Phuket municipality. The cost per year of these materials was determined using the Chemical Industry News and Chemical Market Intelligence website (ICIC, 2008). The operating costs for the WWTP were also provided by the Phuket municipality. However, not all of these costs can be attributed to the incineration system. To allocate the total WWTP operating costs to the treatment of landfill leachate, the same BOD content based allocation method that was used in the LCA was utilized again (see section 2.3.1 Phuket). It is assumed that the maintenance data provided by the municipality includes costs associated with electricity, ash handling, cleaning, and general maintenance and excludes labor costs. It is also assumed that the operational costs of the landfill are negligible; these costs are thus, excluded.

Scenario 2, Samui

The main data source used for determining the costs associated with the materials recovery technologies system in Scenario 2 was the Waste Control Database of Waste Management Technologies, which includes the capital and operational costs of a general MBT plant. Included in the system are pretreatment, sorting, RDF production, dry fermentation and the production of biogas and soil improver, diversion of waste to the landfill, and SRF production (“Mechanical Biological Treatment Processes,” 2013). Since the cost allocations for these processes was not included in this study, it was impossible to determine the costs associated with SRF production for subtracting purposes (since SRF production is not within scope of Scenario 2). However, it was assumed that the diversion of some waste to SRF in the MBT system considered in this source and the increased waste diversion to RDF and other processes in this study balance out. Additionally, this study does not include the costs associated with the conversion of plastic to oil via pyrolysis or the conversion of plastic to WPC, so data for these costs were taken from other sources and summed together.

The data for the general MBT system from the Waste Management Technologies Database also provided the investment costs of the MBT system for different system capacities in terms of tonnes per annum (tpa) ("Mechanical Biological Treatment Processes," 2013). These values were used to determine a line of best fit, which was then used to extrapolate the investment cost associated with the construction of this system for the two capacities considered in this cost analysis. This source, as mentioned above, includes dry fermentation and the subsequent production of biogas and soil improver in its system boundaries. However, it does not include the burning of the biogas for energy capture, which is included within the scope of Scenario 2 in this study. As a result, capital cost data for the burner required for the combustion of the biogas produced from dry fermentation was taken from another source, a study that investigates energy production from four MSW technologies (J.D. Murphy, 2004). The aforementioned study provided the capital costs associated with burners of various capacities. The same extrapolation method as described above was used to determine the capital costs associated with the burner for the two schemes (scaled up and original) considered in Scenario 2.

Since the study that considers the general MBT system does not include the conversion of plastic to oil via pyrolysis in its system, the capital costs of the required machinery was taken from an RTI International study on emerging plastics conversion technologies, which provides actual cost data for three companies that produce syngas via pyrolysis ("Mechanical Biological Treatment Processes," 2013). The cost of building the pyrolysis system was provided for each company in dollars per TPD (RTI International, 2012). This data was thus averaged and multiplied by the appropriate TPD value for each scheme considered, the scaled up version and the original.

The general MBT system study also excludes the conversion of a portion of the plastic fraction of the incoming waste to wood plastic composite (WPC) ("Mechanical Biological Treatment Processes," 2013). Capital cost data for the technology required for this process was taken from Cincinnati Milacron's website. Cincinnati Milacron is a company that produces a "plug and play" WPC system that includes all technologies required for the processes associated with the conversion of plastic to WPC (Cincinnati Milacron, 2013). This source provided a value required for a system that can process 16.8 tonnes per day, which was used to calculate the capital cost associated with each tonne of capacity. Therefore, it was assumed that there is a linear relationship between the capacity of the system and the capital cost of producing that system. This cost per TPD value was then multiplied by the capacities for each scheme (the scaled up version and the original) to determine the capital costs of this system for each scheme in Scenario 2. However, the data provided by Cincinnati Milacron does not include the costs associated with the wood grinder. This data was taken from a woodworking machinery retail website and added to the total capital cost of the WPC system ("LHK Wood Flour Milll," 2013). A single value was provided as the cost per amount of incoming plastic per day, so this value was multiplied by the amount of incoming plastic for each scheme in Scenario 2.

Finally, the capital costs of the RDF incinerator must also be included in the total capital costs of the system in Scenario 2. It was assumed that the price of this RDF incinerator is

comparable to the cost of a standard MSW incinerator, and Database of Waste management Technologies was used to estimate the cost of an RDF incinerator of the capacities considered in scenario 2 ("Cost of Waste Treatment Technologies," 2013).

The data for the general MBT system from the Waste Management Technologies Database also provided many of the operational costs associated with Scenario 2 ("Mechanical Biological Treatment Processes," 2013). The operational cost of running the MBT system described in this source was provided per tonne of incoming waste. This number was used to estimate the operational costs associated with the technologies included in the scope of that study: pretreatment, sorting, RDF production, dry fermentation and the production of biogas and soil improver, and diversion of waste to the landfill. The study provided a range for the operational costs of this system per tonne of MSW coming in, which was used to estimate a range for the operational costs of running a system of each capacity considered in Scenario 2. However, the operational costs of the burning of the biogas produced via dry fermentation were not included in the estimation provided by the database, and data for these costs was taken from the same study used to estimate the capital costs of the burner. This source provided the operational costs of biogas combustion and energy capture for various amounts of biogas burned, so the same extrapolation method was used to estimate the operational costs of biogas combustion for the two capacities considered.

The operational costs associated with the conversion of plastic to oil via pyrolysis were taken from the same source as the capital costs. The study provided a range of costs per amount of waste coming in daily. This range was used to determine a high and low value for the operational costs of a pyrolysis system for each capacity in Scenario 2 (RTI International, 2012).

The operational costs of the WPC system were also taken from the same source as the capital costs (Cincinnati Milacron, 2013). That study includes labor costs in the presented operational costs, so the "Business in Asia" website was used to determine the cost of labor and subtracted from the costs provided by Cincinnati Milacron ("Typical Costs of Starting a Business," 2005). Again, the operational costs of a system of both capacity sizes were determined.

Finally, the operational costs of running the RDF incinerator must be included. It is assumed that these costs are included in the operational costs of running the general MBT system presented provided by the Waste Management Technologies database ("Mechanical Biological Treatment Processes," 2013).

Crediting Data

For Scenario 1a and 1b the only credits came from the sale of electricity generated at the incineration plant. The incineration plant sells the energy produced to the grid for 3.5 baht/kWh (Phuket Municipality). In Scenario 2a and 2b there are credits coming from the sale of syngas, diesel, gasoline, compost like output or soil improver, and wood plastic composite. The largest assumption in the crediting is that the products coming from Scenario 2 will be of equal or higher quality than the traditional methods of production. Wood plastic composite is sold for around $700-$1000 per tonne of WPC (Guizhou Provincial Investment Promotion Bureau 2012).

Soil improver is sold at $51 per 1000 liters (Jersey 2013). Syngas is sold at $40 per tonne, while diesel is sold at $3.85 a gallon and gasoline at $3.60 per gallon (Raman et al 2010). All of the prices were multiplied by the amount produced per year and per tonne of MSW to get the total cost credits. This number can then be subtracted from the operation and maintenance costs to get the net costs of running the system in Scenario 2.