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Process design and feasibility study for small scale MSW gasification

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Abstract

A process design study has been carried out to assess the feasibility of installing a small-scale municipal solid waste (MSW) gasifier on a university campus. The objective was to gasify all the non-recyclable MSW produced on campus and then combust the gaseous product to produce energy and electricity for the campus. Five energy generation combination scenarios were studied at two different mass gasification rates. The scenarios involved hot water (based on site demand), electricity (only, less the demand for hot water) and excess hot water for export (with electricity, with no electricity). Due to the high capital cost of generating electricity from a 10 tonnes per day MSW gasifier, the optimum rate of return on capital investment is 14.8%. On a heat basis only a return of 23.4% is achievable. However, this optimum solution is based on being able to export 60% of the hot water off campus. If an additional 10 tonnes per day MSW is imported onto campus the optimum rate of return increases to 36.1% but over 75% hot water has to be exported. Alternatively, with 400 kW of electricity generation a rate of return of 32.5% can be achieved at this higher mass throughput.

Keywords: MSW gasification; Municipal solid waste; Process design; Economic evaluation

1. Introduction

For many years strategic landfilling has been the most common method of disposal for the majority of municipal solid waste (MSW). The present study is based on research in Hong Kong, whose waste management problems are typical of many countries, possibly more, because of the shortage of land and high land prices. The population is predicted to rise from the current 6.8–9.6 million in the next twenty years with Hong Kong's integration into China. There are currently three landfill sites in operation that will be full in 10–12 years. The construction of these sites cost US$ 750 million, their annual running costs are US$ 45 million, the total landfill sites area of 270 hectares is worth US$ 1000 million as agricultural land and over US$ 3000 million as prime real estate [1]. Therefore, there are tremendous economic, social and environmental factors that justify the search for alternative solid waste management options.

The concept of separating and recycling many materials is well discussed [2–4] but from an economic viability only 25–40% of MSW seems viable over the next few years. Much this-tins, cans, bottles etc.-can and is already done at source; therefore a major problem still exists. In the late sixties and seventies there was a tremendous worldwide drive towards MSW incineration, however, lack of technical knowledge led to serious emission problems [5,6] and the disrepute of these incinerators. The development and better understanding of combustion technology throughout the eighties has led to a new generation of large-scale highly effective MSW incinerators/thermal processing units meeting highly stringent emission limit guidelines [7–9].

The current status of waste management embraces many options [10,11] and encourages many new and novel concepts. This includes the large application of recycling solid waste into cement processing [12,13].

In spite of all these potential opportunities, one of the major cost factors in solid waste management is collection and transportation [14,15], usually over significant distances, for final handling and disposal. Each load comprises relatively low materials value and also moderately low energy values.

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Therefore, if the transportation phase can be eliminated, initial collecting and sorting efforts minimized, and final disposal costs reduced; then there are significant financial savings to be recouped. However, if the transportation distances are to be reduced or eliminated then there are two restricting factors, firstly, there must be a centralized high density population and, secondly, the process application must inevitably be small or medium scale therefore, making profitability more difficult.

The present paper describes a process which could be carried out at industrial estates, large commercial centers, large holding camps, prison complexes or university campuses. This study was carried out at a relatively isolated university campus in Hong Kong having twelve thousand personnel working on site during the day and a permanent resident community of three thousand people. The total site energy/utility costs are US$ 6.9 million per year. The first phase of the waste management project was to establish a site wide network for the collection of cans, metals, glass, plastic, computer cartridges, special paper/cardboard fractions, computers and accessories, composting systems for vegetative wastes etc. The second phase, and the purpose of this study, was to undertake a theoretical study to design and carry out the economic evaluation of a small-scale gasifier for the residual solid waste to produce energy for the provision of the site utilities. The systems studied were to provide: (1) electricity only; (2) hot water only, and (3) both electricity and hot water.

2. Municipal solid waste characteristics

2.1. Physical composition of municipal solid waste (MSW)

Information and data on the physical composition of solid wastes are important in the selection and operation of equipment and facilities, in assessing the feasibility of resource and energy recovery, and in the analysis and design of landfill disposal facilities. For example, if the solid wastes generated at a commercial facility consist of only paper products, the use of special processing equipment, such as shredders and balers, may be appropriate. Separate collection may also be considered if the city or collection agency is involved in a paper-products recycling program. Physical composition is the term used to describe the individual components that make up a solid waste stream and their relative distribution, usually based on percent by weight. Typical data from EPD on the distribution of MSW in Hong Kong (2001) are presented in Table 1 [1]. The municipal solid waste is mainly divided into two types-domestic waste and commercial & industrial waste. From Table 1, putrescibles, paper and plastics are the major components constituting about 76% of the municipal solid waste, representing about 33.1, 26.7 and 16.6%, respectively. Other minor components included textiles (3.2%), metals (3.0%), glass (3.1%), bulky waste (3.5%), and wood/rattan (4.3%) and the average moisture content for municipal solid waste is 28%. It will be necessary to determine more accurately typical physical compositions of MSW at HKUST in the future, if the feasibility study of the MSW gasification process at HKUST is to be continued.

2.2. Chemical properties of municipal solid waste (MSW)

Information on the chemical composition of the components that constitute MSW is important in evaluating alternative processing and recovery options. The feasibility of combustion depends on the chemical composition of the municipal solid waste. Determining the elemental composition of MSW by ultimate analysis is a key factor for the detailed design of the MSW gasification plant and helps confirm the accuracy of material and energy balances of the MSW gasification process. The ultimate analysis of a MSW component typically involves the determination of the percent of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S) and ash. Because of the concerns over the emission of chlorinated compounds during combustion, the determination of halogens is often included in an ultimate analy-

Table 1
Physical composition of MSW in Hong Kong (2001)

Physical component	Quantity (tpd) and percentage by weight		
	Domestic waste (a)	Commercial & industrial waste (b)	Municipal solid waste (c) = (a) + (b)
Bulky waste[a]	223 (3%)	106 (5.9%)	329 (3.5%)
Glass	260 (3.4%)	28 (1.6%)	288 (3.1%)
Metals	232 (3.1%)	52 (2.0%)	284 (3.0%)
Paper	2003 (26.6%)	490 (27.3%)	2493 (26.7%)
Plastics	1210 (16.0%)	334 (18.6%)	1544 (16.6%)
Putrescibles	2792 (37.0%)	299 (16.7%)	3091 (33.1%)
Textiles	224 (3.0%)	73 (4.0%)	297 (3.2%)
Wood/rattan	152 (2.0%)	247 (13.7%)	399 (4.3%)
Others[b]	444 (5.9%)	166 (9.3%)	610 (6.5%)
Total	7540 (100%)	1795 (100%)	9334 (100%)

[a] Bulky waste-big furniture, household machine (e.g., refrigerator, air condition and washing machine), it is assumed to include 50% wood and 50% metal.
[b] Others-ash, pottery, dirt (e.g., office/house, sweepings).

Table 2
Typical data on the ultimate analysis of the combustible materials

Type of waste	Percent by weight (dry basis)					
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Bulky waste[a]	27.0	3.3	23.4	0.2	0.1	46.0
Glass	0.5	0.1	0.4	<0.1	0	98.9
Metals	4.5	0.6	4.3	<0.1	0	90.5
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Plastics	60.0	7.2	22.8	0	0	10.0
Putrescibles	48.0	6.4	37.6	2.6	0.4	5.0
Textiles	55.0	6.6	31.2	4.5	0.2	2.5
Wood/rattan	49.5	6.0	42.7	0.2	0.1	1.5
Others[b]	26.3	3.0	2.0	0.5	0.2	68.0
MSW (average)	43.9	5.6	32.1	1.1	0.3	17.1

Note: The estimated composition of MSW is based on the data in Tables 1 and 2.

[a] Bulky waste-big furniture, household machine (e.g., refrigerator, air condition and washing machine), it is assumed to include 50% wood and 50% metal.

[b] Others-ash, pottery, dirt (e.g., office/house, sweepings).

Table 3
Energy content of MSW in Hong Kong (2001)

Physical component	100 kg MSW		
	MSW (kg)	Energy, Btu/lb[a]	Total energy[b], Btu
Bulky waste	3.5	4,150	31,955
Glass	3.1	60	409
Metals	3.0	300	1,980
Paper	26.7	7,200	422,928
Plastics	16.6	14,000	511,280
Putrescibles	33.1	2,000	145,640
Textiles	3.2	7,500	52,800
Wood/Rattan	4.3	8,000	75,680
Others	6.5	3,000	42,900
Total	100		1,285,572
Heat value of MSW (Btu/lb) =			5843.5
Heat value of MSW (kJ/kg) =			13592.0

Note: 1 Btu/lb × 2.326 = 1 kJ/kg.

[a] Adapted in part from Tchobanoglous et al. (1993) [4].

[b] As discarded basis.

sis. The results of the ultimate analysis are used to characterize the chemical composition of the organic matter in MSW. Representative data on the ultimate analysis for the typical MSW components given in Table 1 are presented in Table 2 [4]. The average chemical composition of municipal solid waste is estimated and is shown in Table 2. The major elements are carbon (43.9%), oxygen (32.1%) and ash (17.1%) accounting for around 93% of MSW in Hong Kong. Other elements include hydrogen (5.6%), nitrogen (1.1%) and sulfur (0.3%). In the calculation of the material and energy balances of the MSW gasification process, the difference, 0.8% of chlorine is assumed to be present and has been used to simulate the formation of the chlorinated compounds during gasification. The specific chemical compositions of MSW at HKUST can be determined by elemental analysis and will be determined in future if the feasibility study of the MSW gasification process at HKUST is to proceed.

2.3. Energy content of municipal solid waste (MSW)

After estimating the elemental composition of the MSW, the energy content of the MSW can be determined. Typical data for the energy content for the components of MSW are reported in Table 3. Based on 100 kg of MSW and using the physical components in Table 1, the total energy content of the MSW using the data given in Table 3 is estimated and is also shown in Table 3 where the energy content values are on an as discarded basis. The energy content value of MSW in Hong Kong is 5843.5 Btu/lb that compares well with the typical value of 5000 Btu/lb [4]. The specific energy content of MSW at HKUST can be determined by using a laboratory bomb calorimeter based on the elemental compositions of MSW (found by the elemental analyzer).

3. Process design and description

3.1. Process description

This municipal solid waste (MSW) gasification plant is designed to gasify 10 tonnes of MSW per day since HKUST generates about 10.7 tonnes of municipal solid waste daily. A fixed bed shaft type gasifier operating at atmospheric pressure is used to gasify the MSW. Before feeding the MSW into the gasifier, a simple system for processing MSW into refuse derived fuels suitable for the gasifier is needed. This system will consist of grinding, mixing and compacting of MSW to produce bales (fuel blocks). The MSW bales are automatically batch-fed into the gasification and combustion zone at the bottom of the primary chamber via load chamber at the top of the gasifier. The MSW bales are exposed to primary air from the underneath, a partial combustion of MSW take place at substoichiometric conditions generating a burned-out ash in the bottom zone of the gasifier. The gasification rate is controlled by the injection of primary air through nozzles at the bottom of the gasifier and the temperature of the bottom zone of the gasifier is kept at 800–900 °C in order to ensure the bottom ash remains as solid and does not melt.

The generated hot gas from the primary chamber is then fed to the secondary combustion chamber mixing with a secondary air for final combustion. Additional fuel may be supplied in this unit again to maintain a high combustion temperature (900–1100 °C) with a residence time of not less than 2.5 s to reduce the formation of NO_x. The outlet temperature of the secondary combustion chamber is high so that harmful materials are destroyed. Following the secondary combustion chamber the flue gas is led into a cyclone for complete combustion. The particles (greater than 20 micron) are separated out, collected and discharged at the bottom of the cyclone.

The hot flue gas coming out from the cyclone is then treated with NH_3 for NO_x reduction in a selective non-catalytic reactor (SNCR). After taking away NO_x and dust,

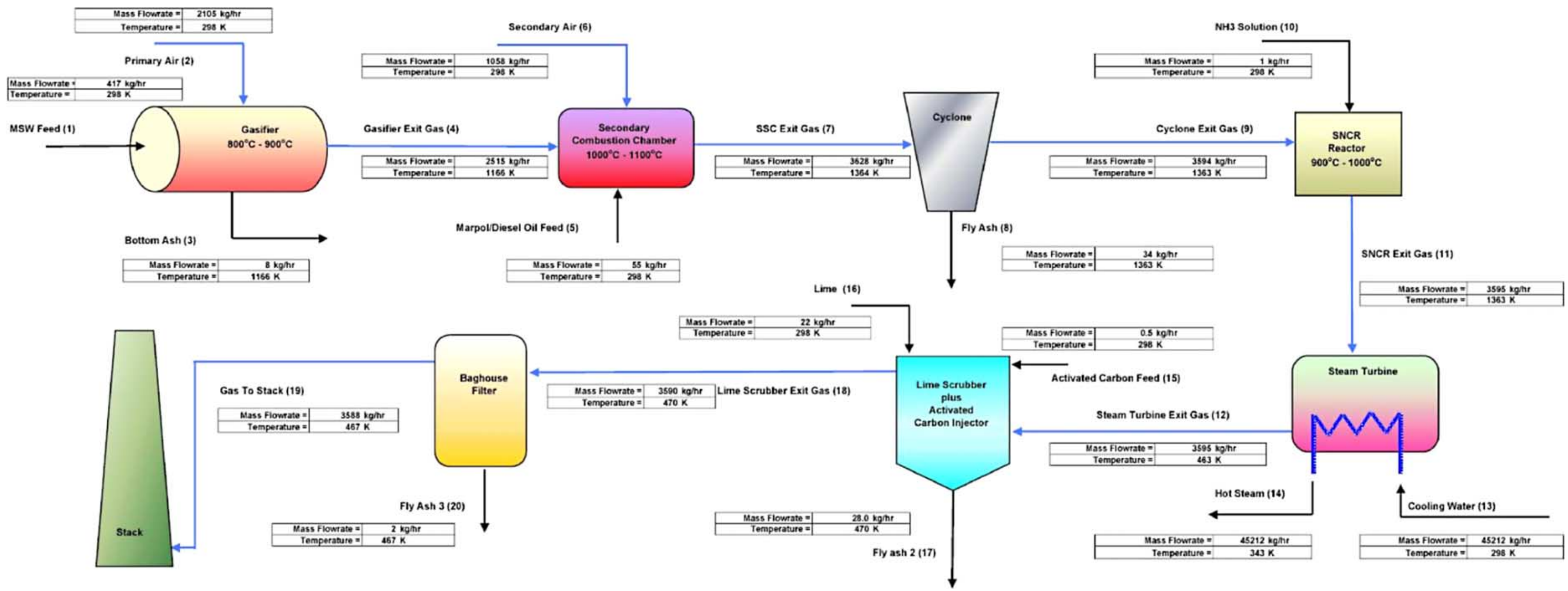

Fig. 1. Process flow diagram of MSW gasification system.

the flue gas at around 950 °C flows to a steam boiler for energy recovery; and electricity is generated by a steam turbine. Then, a heat exchanger is used to produce hot water from the remaining heat. The steam turbine and heat exchanger system are designed to cool down the flue gas to around 200 °C. The driving force of the gas flow through the gasifier and the energy recovery system is a slight suction-pressure created by the flue gas fan.

Flue gas coming out from the heat exchanger will then enter a lime scrubber unit for HCl and SO_x removal. At the same time, activated carbon is fed with lime in order to remove trace heavy metals, HF, organic chemicals at around 180 °C in the scrubber. The tail gas is then sent to the stack after removing fly ash and fine particles using a bag-house filter system. A continuous-emission-monitoring unit is installed at the end of the pipe to ensure that the quality of the gas emission does not exceed the government set limits. The process flow diagram is shown in Fig. 1.

3.2. Scenarios of the MSW gasification process

Five scenarios have been studied for the MSW gasification process to examine its economic feasibility. The main differences between each scenario are the energy recovery systems and the daily gasification flowrate of the MSW. The scenarios are listed as follows:

1. The energy recovery systems of the MSW gasification plant include both an electricity generation system and a hot water production system and 10 tonnes per day of MSW will be gasified. The hot water will be supplied to the existing domestic hot water system and will also be used in the rest of the student or staff hostels (new domestic hot water system).
2. The energy recovery systems of the MSW gasification plant include both the electricity generation system and the hot water production system and 10 tonnes per day of MSW will be gasified. The hot water will be supplied to the existing domestic hot water system only.
3. Only electricity generation is involved in the energy recovery system and 10 tonnes per day of MSW will be gasified.
4. Only hot water is produced in the energy recovery system and 10 tonnes per day of MSW will be gasified. The hot water is utilized in both existing and new domestic hot water systems.
5. Only hot water is produced in the energy recovery system and 10 tonnes per day of MSW will be gasified. The hot water is utilized in existing domestic hot water systems only.

3.3. Process simulation

A material and energy balance simulation program of the MSW gasification process has been developed to carry out the costing and economic evaluation of the MSW gasification system. Microsoft Excel has been chosen as the software to simulate the whole MSW gasification process in order to find out all the information required in the economic evaluation such as the gasification rate of MSW, the sizing parameter of each operating units, temperature of the process, heat energy (MSW) in the rotary kiln system, etc. The basic principle for both material and energy is based on the law of conservation of mass and energy in a continuous steady-state process. The general mass balance equation is:

$$\text{Input} + \text{Generation} = \text{Output} + \text{Consumption} + \text{Accumulation}$$

4. Results and discussion

4.1. Economic evaluation and feasibility

The aim of this study is to present information regarding the economic feasibility for the installation of a power generating MSW gasifier at HKUST. The technical feasibility and the process routes have been established and outlined in the previous section. For the purpose of this economic study, the mass balance information at different scenarios presented in Section 3 has been used. This economic evaluation is based on the gasification of 10 tonnes MSW per day, the rate of production of 85 °C hot water is 15 m^3 per hour and 225 kW electricity will be generated by the MSW gasification process (scenario (1)).

The following steps were undertaken to establish the economical viability of the MSW gasifier plant proposed in this project. The complete cost estimation of the plant is included into two main parts–total capital investment and production cost. A detailed breakdown of each part is given in the following sections.

4.2. Total capital investment

Before a plant can be put into operation, a large sum of money must be supplied to purchase and install the necessary machinery and equipment. Land and service facilities must be obtained, and the plant must be erected complete with all piping, controls, and services. In addition, it is necessary to have money available for the payment of expenses involved in the plant operation. The capital needed to supply the necessary manufacturing and plant facilities is called the fixed capital investment and includes direct and indirect costs, while that necessary for the operation of the plant is termed the working capital. The sum of the fixed capital investment and the working capital is known as the total capital investment.

4.3. Costing for the major plant items

Most cost information was provided and obtained by Allied Process International Company, Matches Company and reference books [16,17]. The expected error into the factored costing estimation is ±20–30%. The total cost of the major plant equipment items is US$ 972,047. We have assumed an additional factor of 15% for carrier delivery of those equipment items to HKUST; hence the total delivered equipment cost is US$ 1,117,854. The equipment items are for a process with a processing rate of 10 tonnes MSW per day, the generation of hot water and electricity production. The range of process options considered in this limited project is presented in Section 3 and will be discussed in the following sections.

A "Lang" factor method is used to calculate the rest of the capital investment based on the total purchase equipment cost. This technique, proposed originally by Lang [15], is used quite frequently to an accuracy of ±20–30%. This approach recognizes that the cost of a process plant is obtained by multiplying the basic equipment cost by some factor to approximate the total capital investment. The rest of the capital investment is divided into direct costs and indirect costs of the project fixed capital cost.

4.4. Direct costs

Besides the equipment cost, many other factors should be considered in the estimation of the capital investment such as installation, piping and site development in order to complete the process plant. The direct-cost items that are incurred in the construction of a plant, in addition to the cost of the equipment items are: (1) purchased-equipment erection, installation; (2) piping, including insulation and painting; (3) electrical equipment and materials, power and lighting; (4) instrumentation and controls; (5) process buildings and structures; (6) yard improvements (site development); (7) service facilities (utilities), provision of plant for steam, water, air, firefighting services and (8) land.

The total direct plant cost of the MSW gasification process is US$ 3,235,224. A continuous-emission-monitoring (CEM) unit is installed at the end of the pipe to ensure the quality of the gas emission does not exceed the government set limits in the MSW gasification plant. The cost of CEM including installation is US$ 160,256; hence, the revised total direct plant cost of the MSW gasification process is US$ 3,395,480.

4.5. Indirect costs

In addition to the direct cost of the purchase and installation of equipment, the capital cost of a project will include the indirect cost the process plant. The indirect-cost items [16] that are incurred in the construction of a plant are: (1) engineering and supervision; (2) construction expense; (3) contractor's fee, and (4) contingency. The total direct plant cost of the MSW gasification process is US$ 1,368,754. Hence, the fixed-capital investment of the MSW gasification plant is US$ 4,924,491, which is equal to the sum of the direct plant cost and indirect plant cost.

4.6. Working capital

The working capital for an industrial plant consists of the total amount of money invested in raw materials and supplies carried in stock, finished products in stock and semi-finished products in the process of being manufactured, accounts receivable, cash kept on hand for monthly payment of operating expenses, such as salaries, wages, and raw-material purchases, accounts payable and taxes payable. The ratio of working capital to total capital investment varies with different companies, but most chemical plants use an initial working capital amounting to 5–20% of the total capital investment. This percentage may increase to as much as 30% or more for companies producing products of seasonal demand because of the large inventories. In this project, the working capital is assumed to be 10% of the total capital investment since the MSW gasification plant is a single process with little finished storage (ash). The working capital of this MSW gasification plant is US$ 541,390. The total cost for the environmental impact assessment and the HAZOP studies is estimated to be around 2% of the total capital investment, which will be US$ 108,278.

4.7. Summary

By adding the direct plant cost, indirect plant cost, working capital and the costs of EIA and HAZOP, the total investment required can be estimated. The total capital investment for this project is US$ 5,413,902. The cost summary of the total capital investment of the MSW gasification process is shown in Table 4.

4.8. Production costs

The determination of the necessary capital investment is only one part of a complete cost and evaluation estimate. Another equally important part is the estimation of the cost of operating the plant. The total production cost is generally divided into the categories of manufacturing costs and general expenses. All expenses directly connected with the manufacturing operation or the physical equipment of a process plant itself are included in the manufacturing costs. The manufacturing costs are divided into two main groups as follows: (1) fixed operating costs and (2) variable operating costs. The general expenses are involved in any company's operations.

Table 4
Summary of the total capital investment of the MSW gasification plant

	Percent	US$
Delivered-equipment cost	23.6	1,278,111
Direct cost (including equipment cost)	62.7	3,395,480
Indirect cost	25.3	1,368,754
Working capital	10.0	541,390
EIA and HAZOP	2.0	108,278
Total capital investment	100.0	5,413,902

Table 5
Summary of the fixed operating cost items and its factors

Fixed operating costs items	Values used in the gasification project	US$/year
1. Maintenance	4% of fixed capital investment	190,569
2. Operating labour	Three shift workers (HK$ 20,000 per month)	92,308
3. Laboratory costs	20% of operating labour	18,462
4. Supervision	20% of operating labour	18,462
5. Plant overheads	25% of operating labour	23,077
6. Capital charges	Not applicable	0
7. Insurance	1.25% of fixed capital investment	59,553
8. Local taxes	Not applicable	0
9. Royalties	Not applicable	0
Total fixed operating cost per year =		402, 430

The total production costs are calculated on an annual basis in this project.

4.9. Fixed operating costs

Fixed operating cost are expenses which are practically constant from year to year and do not vary widely with changes in production rate. These are the bills that have to be paid whatever the quantity of "product" produced. The items of the fixed operating costs are: (1) maintenance; (2) operating labour; (3) laboratory cost; (4) supervision; (5) plant overheads; (6) capital charges; (7) insurance; (8) local taxes and (9) royalties. The capital charges represent interest on a capital loan, which is often recovered using a depreciation technique. We have not considered this but when considering the return on investment this fact should be considered. The typical value of capital charges is 15% of the fixed capital. Moreover, no selling products are produced in this process; local taxes and royalties will be zero. The fixed operating cost items and its factors using in this project are presented in Table 5, the total fixed operating cost is US$ 402,430 per year.

4.10. Variable operating costs

Variable operating costs include expenses directly associated with the manufacturing operation and they are dependent on the amount of product produced. The variable operating cost items are: (1) raw materials; (2) utilities; (3) miscellaneous operating materials and (4) shipping and packaging.

The plant will be operated for 330 days of the year with the rest of time for maintenance and 10 tonnes per day of MSW will be gasified in this MSW gasification plant. Table 6 shows the raw material required and the corresponding estimated prices per year for the MSW gasification process. The prices given are delivered prices. The amount of different utilities required per annum and the current cost of utilities for the MSW gasification process are shown in Table 7. We have assumed 5% of water in the close-loop boiler system will be lost during the gasification process (from blowdown and purging) and the quantity of water usage is 1900 m^3 per year. Another utility required in the gasification is electricity in which the electricity is mainly used to drive all the motors in the plant and the consumption is estimated at 80 kW. The cost of miscellaneous materials is taken as 5% of the maintenance cost and the cost is US$ 9,528 per year. The cost of shipping and packaging is negligible in this process. The total variable operating costs are summarised in Table 8. The annual total manufacturing cost, the sum of fixed and variable operating cost, is US$ 482,421.

Table 6
Estimated prices of raw materials

Raw material	Quantity (per annum)	Price US$/unit	Cost (US$/year)
Municipal solid waste	3,300 tonnes	0	0
Lime Ca(OH)2	39,600 kg	0.11/kg	4,356
Ammonia anhydrous	3,960 kg	0.20/kg	792
Activated carbon	2,250 kg	1.5/kg	3,375
Total =			8,523

Table 7
Estimated costs of utilities in the MSW gasification process

Utility	Quantity (per annum)	Price US$/unit	Cost (US$/year)
Electricity	633,600 kWh	0.095/kWh	60,192
Water	1,900 m^3	0.92/m^3	1,748
Total =			61,940

Table 8
Summary of the variable operating cost items

Variable operating costs items	US$/year
Raw materials	8,523
Utilities	61,940
Miscellaneous materials	9,528
Shipping and packaging	0
Total	79,991

4.11. General expenses

Besides, the fixed and variable manufacturing costs, other general expenses are involved in any company's operations. These general expenses are administrative expenses, distribution and marketing expenses, research and development expenses and gross-earnings expense. The general expenses of the MSW gasification plant, 15% of operation labour, are US$ 13,846 per year.

4.12. Summary

By adding the fixed operating cost, variable operating cost and general expenses, the total production cost required can be estimated. The annual total production cost for this MSW gasification project is US$ 496,268. The cost summary of the total capital investment of the MSW gasification process is

Table 9
Summary of the total production cost of the MSW gasification plant

	Percent	US$/year
Fixed operating cost	81.09	402,430
Variable operating cost	16.12	79,991
General expense	2.79	13,846
Total production cost	100.00	496,268

shown in Table 9. More than 80% of total production cost is due to the fixed operating costs, particularly maintenance and operating labour.

4.13. Revenues for the gasification process

The revenues of the MSW gasification process options mainly come from the generation of electricity and the production of hot water by utilizing the waste heat energy from the flue gas. The electricity can be supplied to the academic building and the hot water can be used for domestic usage on campus such as in the student halls, main buildings and also for dehumidification purposes in the academic building. Each of the ten scenarios for MSW gasification mentioned in Section 3 will produce different revenues due to differences in the designs of each of the energy recovery systems. The revenues of scenario (1) of MSW gasification process are shown below:

Scenario (1): The MSW gasification process is designed to gasify 10 tonnes per day of MSW and the energy recovery system includes both the electricity generation system and the hot water production system (ACMV system, both existing and excess hot water domestic systems).

For an electricity generation system, typically, 1 kg municipal solid waste can produce 0.4–0.6 kWh of electricity by the combustion process [18]. Therefore, 10 tonnes per day of MSW can generate approximately 5000 kWh per day (208 kW) and the annual electricity generation is 1,650,000 kWh, if the plant is assumed to operate 330 days per year. According to the calculated material and energy balances in the MSW gasifier simulation program, if the electricity generation efficiency of the steam turbine is 13% [19], and the energy content (wet basis) of the MSW at HKUST is 13,592 kJ/kg (see Section 2), then the MSW gasification plant will generate 4837 kWh (202 kW) electricity per day and the annual electricity generation will be 1,596,389 kWh. Thus the results from two different estimation methods are very close and comparable. According to the electricity bills from China Light Power (CLP) Company (Hong Kong), the charge of electricity is 74 HK cents per kWh unit. Hence, the potential revenue from the electricity generation system is HK$ 1,181,328 (US$ 151,452) per year.

The rest of the waste heat energy from the flue gas, 4466 MJ/h, is used to produce hot water for the domestic circuit and the ACMV system. In 2001, the total energy consumption of the ACMV system was 4,669,863 MJ and 13.7% of flue gas energy can be utilized to provide all the energy required in the ACMV system to save HK$ 1,537,854 (US$ 197,161) annually. The remaining heat energy is used to provide 65 °C hot water in the usage of domestic system. The volume of 65 °C hot water produced by the MSW gasification plant after generating electricity and supplying heat energy to the ACMV system is 152,286.4 m^3. The hot water usage in 2001 for the domestic system is 56,647 m^3 and it costs HK$ 2,705,123; the price of hot water produced by the town gas boiler in the domestic system is HK$ 47.75 per cubic meter. Around 37.2% of hot water produced from the MSW gasification plant can be fully supplied to the existing hot water system and the revenue, saving HK$ 2,705,123 (US$ 583,779) annually. If the rest of hot water (62.7%) can be supplied and used in the other staff or student towers/hostels, the potential revenue of the new domestic hot water system is HK$ 4,553,479 (US$ 583,779) per year. The revenues of the MSW gasification plant in different energy recovery systems are shown in Table 10 and the annual total revenue of the MSW gasification process in scenario (1) is HK$ 9,978,173 (US$ 1,279,253).

Table 10
Revenues for different energy recovery systems in scenario (1)

Energy recovery system	Revenue (US$/year)
Electricity generation system	151,529
ACMV hot water system	197,161
Existing domestic hot water system	346,784
New domestic hot water system	583,779
Total	1,279,253

Other scenarios: For the other MSW gasification scenarios (see Section 3), due to the different designs of the energy recovery systems and different plant capacities, the revenues and the quantities of energy recovered are different. Table 11 summarizes the energy recovery options used in each of the ten scenarios including a comparison of the revenues and energy outputs. For scenario (2), without utilizing the excess amounts of hot water, the annual total revenues of the MSW gasification plant (10 tonnes per day) including electricity generation, ACMV and domestic hot water systems are US$ 695,424. If the MSW gasification plant only generates electricity from 10 tonnes MSW per day, scenario (3), the total revenues will be US$ 151,452 per year. On the other hand, if the MSW gasification only produces hot water utilizing in the existing hot water system at HKUST (ACMV and domestic systems), scenario (5), and the total revenues are US$ 543,972 per year.

Increasing the gasification capacity of MSW from 10 to 20 tonnes per day in all five scenarios, it will generate five more scenarios (scenarios (6)–(10), as shown in Table 11), the MSW plant will generate twice the amount of electricity (403 kW) and will provide US$ 303,113 per year in revenue (scenario (8)). The revenues of both existing domestic and ACMV hot water systems are fixed for all scenarios involving hot water production systems (except scenarios (3) and (8)) and they are US$ 346,811 and US$ 197,161 per year, respectively. If the excess amounts of hot water can be used in a new

Table 11
Revenues for different scenarios of the MSW gasification plant

Scenario (MSW capacity)	Revenue (US$/year) (quantity)				
	Electricity	ACMV hot water	Existing domestic hot water	Excess domestic hot water	Annual total revenue
1 (10 tpd)	$151,529 (202 kW)	$197,161	$346,784 (7.15 m^3/h)	$583,779 (12.04 m^3/h)	$1,279,253
2 (10 tpd)	$151,452 (202 kW)	$197,161	$346,811 (7.15 m^3/h)	–	$695,424
3 (10 tpd)	$151,452 (202 kW)	–	–	–	$151,452
4 (10 tpd)	–	$197,161	$346,811 (7.15 m^3/h)	$904,742 (18.66 m^3/h)	$1,448,686
5 (10 tpd)	–	$197,161	$346,811 (7.15 m^3/h)	–	$543,972
6 (20 tpd)	$303,113 (403 kW)	$197,161	$346,784 (7.15 m^3/h)	$1,693,589 (34.93 m^3/h)	$3,193,058
7 (20 tpd)	$303,113 (403 kW)	$197,161	$346,811 (7.15 m^3/h)	–	$847,057
8 (20 tpd)	$303,113 (403 kW)	–	–	–	$303,113
9 (20 tpd)	–	$197,161	$346,811 (7.15 m^3/h)	$2,346,234 (48.39 m^3/h)	$2,890,179
10 (20 tpd)	–	$197,161	$346,811 (7.15 m^3/h)	–	$543,972

domestic hot water system, this has the potential to generate significant additional revenues in scenario (1) (US$ 583,779), scenario (4) (US$ 904,742), scenario (6) (US$ 1,693,589) and scenario (9) (US$ 2,346,234) per year. However, it may not be possible to utilize all the hot water (48.39 m^3/h) that can be generated by the new domestic hot water system in the rest of the hostels/towers at HKUST and produce this additional annual revenue of US$ 2,346,234 since the demand of hot water by the students and staff in the hostels may not be so large.

On the other hand, increasing the gasification capacity of MSW from 10 to 20 tonnes per day in scenarios (6)–(10) will also increase the variable operating cost of the process since additional 10 tonnes MSW are to be brought in from the outlying regions. The cost of MSW transport is HK$ 30–HK$ 110 per tonne in Hong Kong at different districts and the average MSW transport cost is around HK$ 55 [20]. Therefore, the cost of MSW transport in scenarios (6)–(10) is US$ 23,269 per year.

4.14. Economic evaluation

The total income minus the total production cost gives the annual profit made by the MSW gasification operation, ignoring tax. The annual profits of the different scenarios of the MSW gasification process are presented in Table 11. By comparing the annual profit with the total capital investment, the rate of return of different processes can be calculated and the rate of return of each scenario is also shown in Table 12. The annual profit and the rate of return for the MSW gasification plant in scenario (1) are US$ 782,985 per year and 14.79%, respectively. Scenarios (3), (8) and (10) are not profitable.

4.15. Rate of return for different scenarios

From Table 12, the order of these rates of return is scenario (9) (36.08%) > scenario (6) (32.54%) > scenario (4) (23.38%) > scenario (1) (14.79%) > scenario (2) (3.76%) > scenario (7) (2.25%) > scenario (5) (2.43%). Furthermore, the reciprocal of these percentage rates of returns give us the simple "payback" times for the project. Since the annual profits of scenarios (3), (8) and (10) are negative (these only include electricity generation in the energy recovery system), then these scenarios of the MSW gasification process do not provide any economic return on the total capital investment (i.e. no rate of return value). The higher values of rate of returns in scenarios (9), (6), (4) and (1) are based on utilizing of the large amounts of hot water (surplus to requirements) produced from the MSW gasification process in the hostels/towers at HKUST. However, the amount of hot water produced from the MSW gasification process is greater than the current usage of hot water in HKUST. Therefore, the usage of this excess amount of hot water in the domestic system is potential revenue

Table 12
Annual profit and rate of return (ROR) for different scenarios of the MSW gasification plant

Scenario (MSW capacity)	(US$/year)				
	Total capital investment	Total production cost	Total revenue	Annual profit	Rate of return (ROR)
1 (10 tpd)	$5,293,593	$496,268	$1,279,253	$782,985	14.79%
2 (10 tpd)	$5,293,593	$496,268	$695,424	$199,156	3.76%
3 (10 tpd)	$5,217,230	$477,474	$151,452	−$326,022	–
4 (10 tpd)	$4,317,347	$439,111	$1,448,686	$1,009,575	23.38%
5 (10 tpd)	$4,317,347	$439,111	$543,972	$104,861	2.43%
6 (20 tpd)	$7,747,046	$672,385	$3,193,058	$2,520,673	32.54%
7 (20 tpd)	$7,747,046	$672,385	$847,057	$174,672	2.25%
8 (20 tpd)	$7,614,661	$650,843	$303,113	−$347,730	–
9 (20 tpd)	$6,356,624	$596,661	$2,890,179	$2,293,518	36.08%
10 (20 tpd)	$6,356,624	$596,661	$543,972	−$52,689	–

and necessary for a reasonable ROI (>20%). If the excess hot water cannot be utilized, the rate return of the MSW gasification process is fairly low such as represented by scenarios (2), (5) and (7). A significant conclusion is that there is only a small amount of electricity produced from the gasification scheme.

4.16. Sensitivity analysis

Two parameters have been studied in the sensitivity analysis of the MSW gasification plant. They are (1) gasification capacity of MSW and (2) cost of the major equipment items.

4.16.1. Gasification capacity factors

Increasing the gasification capacity of MSW from 10 to 20 tonnes per day, the MSW plant will generate twice the amount of electricity (from 202 to 403 kW) and will provide double the annual electricity revenue (from US$ 151,529 to US$ 303,113 per year). Since the revenues of both existing domestic and ACMV hot water systems are fixed, the change of gasification capacity of MSW will affect the revenue of the excess hot water only and in this case the revenue of the excess hot water increases 2.5 times.

The total capital investment (TCI) for the 20 tonnes per day MSW gasification plant is only increased by 50% of the TCI for the 10 tonnes per day MSW gasification plant. The rates of return of MSW gasification process using 20 tonnes MSW per day in scenarios (6) and (9) (32.54 and 36.08%, respectively) are higher than using 10 tonnes MSW per day in scenarios (1) and (4) (see Table 12). The drawback for gasifying 20 tonnes MSW per day at HKUST is that the average rate of MSW generation at HKUST is 10.7 tonnes per day only; the demand of MSW in the gasification plant is much higher than the generation of MSW at HKUST. Therefore, 10 tonnes MSW per day more at HKUST from the outlying region need to be collected. The annual operating cost of 10 tonnes MSW transport is US$ 23,269 and it will increase about 4% of the total annual operating cost of the MSW gasification plant. The cost of MSW transport in Hong Kong is a minor factor in the process economics since it only reduces 0.3% of ROR values in the scenarios (6)–(10).

4.16.2. Cost of major equipment items

The total capital investment is calculated by multiplying the total purchased equipment by an appropriate factor, which accounts for all direct and indirect capital cost. Around 50% of the total production cost is based on the maintenance and insurance and the total cost of these two items amounts to 5.25% of the total capital investment. Therefore, the cost of the equipment items is another main factor to control the rates of return in the different scenarios of the MSW gasification process. The costs of the MSW gasifier (US$ 502,000), MSW feed handling system (US$ 132,000) and steam turbine (US$ 94,000) are the major equipment items constituting about 75% of total equipment cost, representing about 51.6, 13.6 and 9.7%, respectively. The equipment costs of these three items are provided from European and American companies. In general, the price of the equipment items bought and constructed from Chinese contract companies are much cheaper than the European and the American companies and the potential cost savings of the equipment items can save more than 50%. Therefore, if the costs of the MSW gasifier, MSW feed handling system are steam turbine can be halved, the total investment of the MSW gasification plant in the scenario (1) will drop down from US$ 5,293,593 to US$ 3,380,640 (36% reduced) and the annual total production cost will reduce from US$ 402,437 to US$ 496,268 per year (19% reduced). As a result, the rate of return (ROR) of the MSW gasification plant at HKUST in scenario (1) will increase from 14.8 to 25.9%.

4.16.3. Gate fee for waste disposal

In Hong Kong, it seems likely that the Hong Kong government will pay a gate fee for MSW in the future. The gate fee for waste disposal is usually the key element in waste disposal/treatment plant economics. In 2002, 7.7 million tonnes were landfilled in 2002 so the total capital and operating cost spent since the commissioning of the landfills was up to HK$ 9 billion [20]; it costs HK$ 125 per tonne to build and operate landfills. If the MSW gate fee is assumed to be the cost of building and operation of MSW landfills, this MSW gasification process can have a capacity of 10 or 20 tonnes per day, which would induce an additional income of US$ 52,885 or US$ 105,769, respectively, to the project. Hence, the ROR of scenario (1) will increase from 14.79 to 15.79% while the ROR of scenario (6) will increase from 32.54 to 33.90%.

5. Conclusion

A design and economic feasibility study has been carried out to investigate the option of designing, building and operating a municipal solid waste (MSW) gasifier at the HKUST campus. Two design capacities have been investigated, namely, 10 tonnes per day MSW consumption (the current MSW generated at HKUST) and 20 tonnes per day MSW consumption. A process scheme has been designed and a process flow diagram has been developed. Based on this schematic and other process alternatives the energy (heat) from the gasifier can be used to produce electricity and hot water. From these two energy production options at two MSW utilization rates, it is possible to analyse ten process scenarios. Each scenario analysis is based on the total capital investment, production costs, energy savings, simple rate of return.

Two of the scenarios (6) and (9) have very attractive rates of return, namely, 32.5 and 36.1%, respectively. However, there are two disadvantages, an additional 10 tonnes per day MSW has to be brought into HKUST, and secondly, there is a surplus of hot water-about 70% excess above HKUST requirements for hot water (halls and main building) and air conditioning requirements. The best option from the 10 tonnes per day MSW plant is scenario (4) which still produces 72% excess hot water. Therefore, based on the current method of costing the plant, there is no economically attractive option (>20% ROR) to fulfill current hot water demands or involving electricity production.

Besides the economic benefit of this MSW gasification process, there is the clear environmental benefit here, which is the reduction of need for landfilling. This prolongs the life of our existing landfills, which in turn reduces the need to find new sites for landfilling purposes. Moreover, the other factor that is now important is the reduction in net CO_2 emissions that result from use of waste containing biomass (e.g. MSW) rather than fossil fuels to provide electricity or hot water. This environmental benefit is now recognized through different economic instruments in many countries.

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