CHAPTER 8
EVALUATION OF THREE-DIMENSIONAL SUSTAINABILITY OF EXISTING AND INTENDED MSW MANAGEMENT SYSTEMS IN SRI LANKA

8.1 General Background of MSW Management in Sri Lanka

The services related to solid waste management are far from satisfactory in the most developing Asian countries due to several factors including institutional weaknesses, lack of social responsibility and environmental accountability, inadequate financial resources, lack of technical competency, improper choice of technology and public apathy towards solid waste management (Visvanathan et al., 2004). As a developing Asian country, Sri Lanka is also facing a critical situation vis-à-vis MSW management.

Similar to the situation of most developing countries, local authorities in Sri Lanka have failed to deliver the required level of waste management services (Al-Khatib et al., 2010; Vidanaarachchi et al., 2006; Wel and Post, 2007). In fact, at present, only part of the waste generated is collected by local authorities due to shortage of efficient vehicles and skilled labour. In fact, the highest waste collection coverage has been recorded from the Galle Municipal Council which is 59% (Vidanaarachchi et al., 2006). The remaining waste is being illegally dumped on road sides, forest areas, river banks and low lying marshes reducing thereby significantly the aesthetic value of the environment. For the collection process, house-to house solid-waste collection is being performed by most of the municipal councils. In addition, community collection and curbside collection are also being practiced in some municipal councils (Asian Productivity Organization, 2007). Even though some local authorities have shown interest in using small scale composting and biogas production technologies, these treatment options have not been much successful (Alwis, 2002; Basnayake and Ekanayake, 2005). At present, uncontrolled open dumping is the main disposal method in Sri Lanka leading to many environmental as well as health problems (Gunawardana et al., 2009). Waste dumping creates breeding grounds for various pathogens, mosquitoes and other harmful organisms contributing to spreading of diseases (Wel and Post, 2007; Gunawardana et al., 2009). Furthermore, poor waste management systems coupled with tropical climatic conditions result in increasing environmental pollution at local, regional and global levels.

However, local communities as well as decision makers are not well aware of the severity of the impacts of open dumping in terms of environmental degradation, economic loss and social burdens or the benefits of replacing existing poor MSW management with appropriate technologies. Therefore, quantification of such impacts using appropriate indicators will be helpful as a baseline for developing appropriate policies and strategies on sustainable MSW management.

8.2 Existing Situation of MSW Management System in Sri Lanka

MSW in Sri Lanka is characterized by a high organic matter fraction, moderate plastic and paper content and low metal and glass content (Gunawardana et al., 2009). Generally, it is also characterized by high moisture content in the range of 60-80 % on a wet basis (Menikpura et al., 2007; Vidanaarachchi et al., 2006). After collection and transportation, about 85% of the total MSW generated is being open dumped (Visvanathan et al., 2004). For instance, Vidanaarachchi et al. (2006) studied solid waste management at 22 disposal sites; 21 were open dumps and 1 was producing compost commercially with the residual being open dumped. Similarly, other places are also practicing open dumping as the main disposal method and those are located in environmentally sensitive areas such as wetlands, marshes, beaches and places adjacent to water bodies or close to residential houses or public institutions (Gunawardana et al., 2009). Thus, a detailed evaluation and quantification of the burdens resulting from current MSW management on the environment, economy and society would be an important first step to develop more sustainable MSW management systems in Sri Lanka.

In order to evaluate the existing situation of MSW management in Sri Lanka, the Kandy municipal council was selected as representative case-study for the country. The composition of MSW in Kandy municipality is quite similar to that of the average composition in Sri Lanka (Menikpura et al., 2007; Database of Municipal Solid Waste in Sri Lanka, 2005). In addition, collection, transportation and final disposal practices are quite similar all over Sri Lanka. Moreover, as a deep dumpsite, Gohagoda dumpsite in Kandy can be taken to represent most of the dumpsites found in major cities of Sri Lanka including Bloemandhal dumpsite in Colombo and Karadiyana dumpsite in Moratuwa due to continuous dumping of waste even after maximum capacity has been reached.

Kandy is the second largest city of Sri Lanka. It is situated in the Central province with 110,000 persons living within the Municipality limit. According to the climatic situation, this area belongs to up country wet zone receiving an annual rainfall over 2500 mm without pronounced dry periods. At present 110 tonnes of Municipal Solid Waste (MSW) per day are collected and dumped at the Gohagoda dumpsite, 3 km away from Kandy city center (Kandy Municipality, 2009). Figure 8.1 shows the situation of MSW management in Kandy. As one of the main commercial and developed cities, waste generation has been increasing rapidly within the Kandy Municipality. For instance, MSW generation in the year 2006-2007 was 100 tonnes/day (Menikpura et al., 2008). This figure has risen to 110 tonnes /day in the year 2009-2010. The biodegradable fraction represents the largest share of the waste and is an important contributor to methane emissions under tropical climatic conditions. As a deep unmanaged solid waste disposal site with anaerobic conditions, Gohagoda is characterized by a high methane emission potential (Menikpura et al., 2008).

There is hardly any published information on assessment of open dumping in environmental and socio-economic perspective inorder to undertand the severity. Therefore, in this study, a detailed assessment was performed to understand the severity of open dumping in terms of environmental degradation, economic loss and social burdens in a tangible way within a common LCA framework.

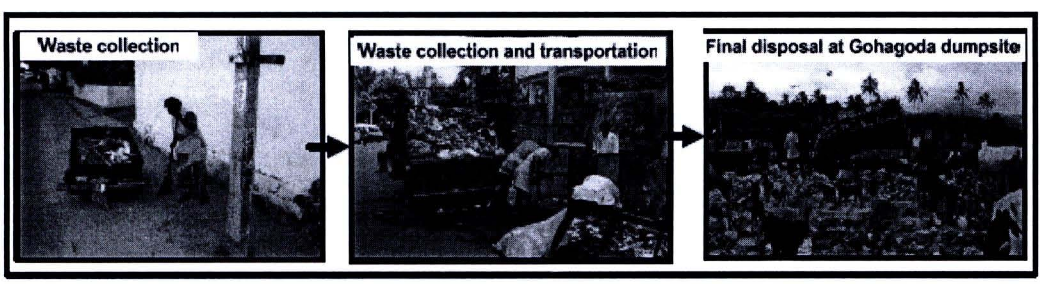

Figure 8.1: Situation of the existing MSW management system in Kandy – Sri lanka

8.3 Sustainability Assessment of the Existing MSW Management System

8.3.1Defining the LCA framework for sustainability assessment

For the evaluation of the existing situation of MSW management systems in Sri Lanka, the LCA framework was defined to include the major lifecycle phases including: raw material extraction and production of energy carriers, MSW collection and transportation, and final disposal. The functional unit was defined as one tonne of MSW management under the existing situation. The LCA framework for sustainability assessment of the existing MSW management method is shown in Figure 8.2.

8.3.2 Inventory Analysis of the Existing MSW Management System

Inventory data was collected in relation to environmental, economic and social aspects of open dumping. All the sources that were used to obtain the input and output data such as raw material, energy, environmental emissions as well as information related to economic and social aspects have been summarized in Appendix D (Table D1).

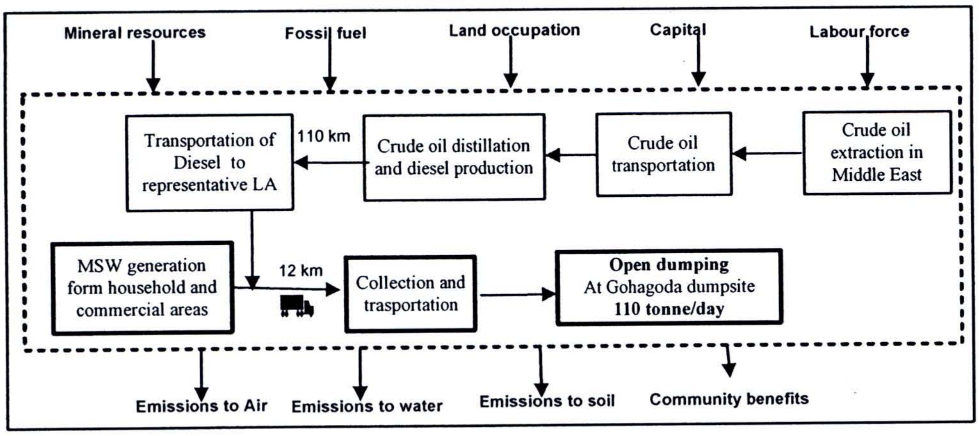

Figure 8.2: LCA framework for sustainability assessment of the existing MSW management system

Waste characteristics, material inputs and emissions from existing MSW management system in Sri Lanka

Severity of environmental degradation from open dumping is dependent on the physical and chemical composition of MSW. Physical and chemical characteristics of MSW in Kandy municipality are shown in Table 8.1.

Based on the physical and chemical characteristics of MSW, the potential environmental emissions were calculated from final disposal and it is presented in the inventory results in Appendix D (Table D2). The types and amount of energy sources needed for fuel production and transportation, and emissions released from crude oil extraction, crude oil transportation, crude oil refining, and diesel transportation are also shown in Appendix D (Table D2).

Table 8.1: Physical composition (Menikpura et al., 2007) and chemical composition of MSW in Sri Lanka (Menikpura et al., 2009; Tchobanoglous et al., 1993)

Component	MSW composition (%)	Moisture content %	Chemical composition (dry basis)						
			C%	H %	O %	N %	S %	Ash	Chemical formulae
Food waste	59.20	65.00	49.12	5.35	31.43	2.17	0.33	11.59	$C_6H_{7.8}O_{2.88}N_{0.23}S_{0.02}$
Garden waste	18.20	40.00	44.11	4.44	28.11	2.52	0.22	20.60	$C_6H_{7.2}O_{2.87}N_{0.29}S_{0.01}$
Wood	6.00	40.00	43.85	4.30	30.57	0.14	0.07	21.06	$C_6H_{7.1}O_{3.14}N_{0.02}$
Plastics	5.40	0.00	60.00	7.20	22.80	0.00	0.00	10.00	$C_6H_{8.6}O_{1.7}$
Paper	2.30	3.00	47.99	4.56	33.45	0.23	0.15	13.62	$C_6H_{6.8}O_{3.13}N_{0.02}S_{0.01}$
Cardboard	3.20	0.00	45.03	4.17	31.49	0.21	0.14	18.96	$C_6H_{6.66}O_{3.14}N_{0.02}S_{0.01}$
Rubber	0.80	0.00	78.00	10.00	0.00	2.00	0.00	10.00	$C_6H_{9.2}N_{0.13}$
Textile	0.50	0.00	55.00	6.60	31.20	4.60	0.15	2.50	$C_6H_{8.6}O_{2.6}N_{0.43}S_{0.01}$
Leather	0.40	0.00	60.00	8.00	11.60	10.00	0.40	10.00	$C_6H_{9.6}O_{0.87}N_{0.86}S_{0.02}$
Other	4.00								
Total	100.00								

8.4 Results and Discussion

Similar to the other cases, the environmental performance of the existing MSW management system was assessed by using the most relevant midpoint indicators. Detailed explanations about the LCA and quantification of midpoint environmental indicators has been described and analyzed in Appendix D2.

In this part of the research, the basic idea is to quantify the ultimate damage/effects from open dumping by using the developed endpoint composite indicators in order to understand the severity of damage and its subsequent effects on three-dimensional aspects of sustainability.

8.4.1 Environmental sustainability assessment of the existing MSW management system

-Quantification of "damage to ecosystems"

To quantify the "damage to ecosystems" the methodology described in Chapter 4 is used. Presently practiced open dumping can cause a significant damage to ecosystems due to acidifying and eutrophing substances emissions during the waste degradation process and occupation of bio-productive land area as a disposal site for a considerable period of time. In addition, indirect land occupation for fossil fuel mining is also responsible for additional damage to ecosystem.

Gohagoda dumpsite is situated in a marginal crop land thus the PDF of marginal crop land occupation is taken into consideration; the literature reported value being 1.19. The value may reach to 0.47 after a considerable restoration period (Goedkoop et al., 2008). It was assumed that at least another 50 years will be needed to grow some coniferous plant species in the dumpsite area. As reported, PDF of occupied fossil fuel mining land would be 1.19.

To convert the direct land occupation of open dump to the global bio productive area, equivalency factor and yield factor of marginal crop land are needed. The equivalency factor of marginal crop land is 1.8 global ha/ha (Wackernagel et al., 2005) and the yield factor of marginal crop land was taken as 2 relative to the yield of world average marginal crop lands. Actually there are no any reported statistics of the value of yield factors for the cropping systems in Sri Lanka. Therefore, it was assumed that yield factor of the marginal crop land in Thailand and Sri Lanka is the same since both countries have the similar tropical climatic situation. As shown in Table 8.2, considering all these factors damage to ecosystem was estimated from the presently practiced open dump.

Table 8.2: Damage to ecosystem from presently practiced open dumping

Stages of damage occurrence	**Quntified damage to ecosystem ($PDF.m^2_{global}.yr$) per tonne of MSW**
Damage to ecosystem from acidifying and euthophying substances	252.26
Damage to ecosystem due to direct land occupation for dumping	44.98
Damage to ecosystem by mining of fossil fuel	68.54
Total damage to ecosystem	**365.78**

As shown in Table 8.2, 69% of damage to ecosystem would occur due to emissions of acidifying and eutrophying substances. According to the composition, the highest fraction of MSW consists of food waste and therefore a significant amount of NH_3, H_2S and NO_3^- compounds can be generated during the waste degradation process. These compounds have created acidification/eutrophication potential and that make the highest ultimate damage to ecosystem. In addition, direct land occupation for the disposal of waste (0.16 m^2 is occupied per tonne of waste) has contributed in 12% of damage to ecosystem. The remaining 19% damage occurs as a result of indirect land occupation for mining of fossil fuel that is utilized for the transportation of waste. All in all, open dumping as practiced at present is responsible for damage to ecosystem and requires therefore remedial measures.

-Quantification of "damage to abiotic resources"

Similar to other case studies, damage to abiotic resources caused by the fossil fuel extraction process was quantified. Sri Lanka is practicing the most common and simplest MSW management method, thus the fossil fuel consumption is quite low in comparison to the situation in Thailand. As discussed before, 1.5 L of diesel is consumed per tonne of waste transported. It would increase damage to abiotic resources expressed in terms of marginal cost increase (MCI) to society, to $0.45/tonne of MSW. Unlike improved technologies, open dumping contributes to increased environmental impacts. In order to reach a more sustainable system, the selection of appropriate technologies is a pre-requisite.

8.4.2 Economic sustainability assessment of the existing MSW management system

-Life cycle cost analysis

A financial analysis using LCC, should include capital, operation and maintenance and environmental costs related to open dumping. Land cost is the major capital cost for existing MSW management system in Sri Lanka. Gohogoda dump site in Kandy spreads over 27 acres and this land has been used for open dumping for more than 40 years. This land is situated very close to the Kandy main city and has a substantial value as compared to the general prices of land in Sri Lanka. Based on the land prices trend in Sri Lanka, the initial cost of land (40 years ago) was 160,000 SLR per acre. According to this reference value, the present value of this land would be 5,336,800 SLR per acre with an average inflation rate and a prevailing interest rate of 9% and 10% respectively (CIA, 2008). Thus, considering the total capacity of waste disposed during the last 40 years (it has reached the maximum capacity of disposal), calculated capital cost for land utilization is 110 SLR per tonne of waste disposed.

At present, high operation and maintenance costs are the major expenses for local authorities. About 70 to 80% of the budget allocated to MSW management is spent for collection and transportation especially to cover labour and fuel cost, and a much lesser amount to cover final disposal costs (Visvanathan et al., 2004). In total 1,218 SLR (110 SLR= US$ 1) are spent per tonne of waste for collection and transportation of one tonne of waste out of which 10% is spent to cover fuel cost and 90 % to cover labour cost, as shown in Figure 8.3. In addition, for each tonne of waste, another 121 SLR is allocated for vehicles purchase and maintenance. In total, 1,339 SLR per tonne of waste are spent as operation and maintenance costs.

Even though local authorities are not really concerned with environmental costs yet, it is important to calculate those externalities since this amount of money will be borne by the community as health costs. Thus, environmental costs per functional unit were calculated based on the Swedish EPS model (Steen, 2000). WTP values were derived, based on income elasticity of WTP for Sri Lanka (CIA, 2008) and the estimated default values for WTP for emissions and resources consumption is presented in Appendix A (Table A 11). Based on WTP, the estimated cost per tonne of waste disposed associated to the entire life cycle environmental emissions including fossil fuel depletion (as shown in Figure 8.3) is 1,790 SLR. After adding all the other cost factors (capital costs, and operation and maintenance costs), the estimated gross LCC is 3,238 SLR (29.4 $US) per tonne of waste for the present MSW management system. About 3% of this LCC is related to capital cost, 41% to operation and maintenance costs and the remaining 55% to environmental cost. A detailed cost breakdown is shown in Figure 8.3. Also Figure 8.3 clearly shows the significant contribution of environmental cost to the total cost associated with open dumping of MSW.

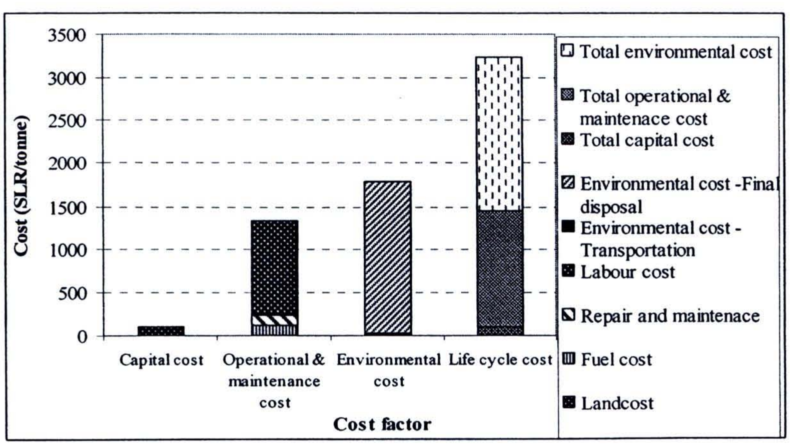

Figure 8.3: LCC analysis for the existing MSW management system in Sri Lanka

The analysis results clearly indicates that the existing MSW management system lacks sustainability, considering that local authority needs at least 1,450 SLR to cover the capital cost and operational and maintenance costs for each tonne of waste disposed at Gohagoda dumpsite. Thus, appropriate MSW management technologies are needed in Sri Lanka, not only to solve the exiting waste management problem but also to generate earnings from the management of MSW.

8.4.3 Social sustainability assessment of the existing MSW management system

-Quantification of "damage to human health"

As discussed in the last chapters, health hazards are prevalent in every step of the handling, treatment and disposal of MSW, directly or indirectly. Especially, open dumping/ non engineered landfilling can cause severe harm to human health due to the emissions of toxic gases to the atmosphere and pollution of surface and ground water with leachate. Health problems may be the result from direct exposure to pollutants (chronic and acute health effects) and/or global warming related impacts such as heat stress, starvation, lack of nutritional food, flooding accidents, malaria, etc. The Swedish EPS model was used to correlate environmental pollution and impacts on human health including mortality, severe morbidity and morbidity effects (Steen, 2000). Based on the inventory analysis of the existing MSW management system (Appendix D- Table D2), one tonne of waste open dumped in Kandy results in 1.88E-03 DALYs as a result of all pollutants that are emitted to the environment (see Figure 8.4). Of this, 69 % damage to human health arises due to the effects of global warming especially from the emissions of methane (29 kg/tonne). The remaining 46% of damage occurs due to direct and indirect exposure to human toxicity compounds, as shown in Figure 8.4.

Further more, it was noticed that final disposal contributes 99% of the total DALYs (especially due to methane emission); the remaining 1% being from collection and transportation. Those results indicate the important contribution of open dumping on human health. Thus, open dumping practices should be discouraged and solutions for the existing poor MSW management method identified.

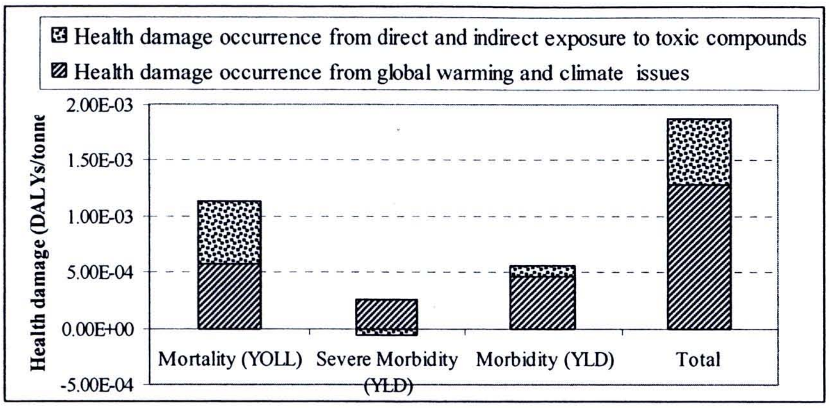

Figure 8.4: Damage to human health caused by open dumping of one tonne of MSW

-Quantification of "Income based community well-being"

Unfortunately, the existing MSW management system hardly facilitates the uplifting of the community well-being. Unlike in Thailand, there are no formal systems available for the selling and buying of recyclables in Sri Lanka. In fact, waste pickers are collecting some valuable recyclable items at the dumpsite which are sold to the informal sector for a very low price. Information related to the amount and type of collected recyclables, and their selling prices has not been recorded anywhere. Therefore, it is really difficult to assess the effects of these on the community well-being.

The existing system only contributes to improvement of the community well-being from the employment opportunities created for the poor people working as waste collectors. Although the present system has created considerable job opportunities, it is inefficient and most of the labour power is consumed only for street sweeping and the MSW collection process. The majority of the workers involved with MSW management activities are untrained, unskilled and inefficient, resulting in inefficient MSW management.

At present, there are 302 employees working on the existing MSW management system in Kandy municipality. Therefore, the labour power consumption intensity for the existing MSW management is 2.74 labour days per tonne of waste. Thus wages based income generation potential is 1,098 SLR/tonne. This money is not a significant amount when one considers the cost of living in Sri Lanka. This amount would be sufficient to cover 15-20% of the monthly living cost of a person in a middle class family.

8.5 Development of Sanitary Landfill with LFG Recovery System as a Sustainable Solution to the Present Problem

Even though local authorities and decision makers have realized that open dumping has impacts on environment and human health, there is still no clear understanding about the severity of those impacts. However, as similar to other developing Asian counties, in Sri Lanka also there is a trend for development of sanitary landfills with gas collection system to replace open dumps. The promotion of landfill gas recovery projects is an important preliminary step towards sustainable development. To this end, the replacement of open dumping by sanitary landfilling with gas collection for electricity production was assessed. Basic key assumptions for the assessment included:

-Existing vehicles have to be replaced with compactor trucks to provide an efficient service. Average transportation distance from the collection points to landfill would be 15 km and that fuel consumption for transportation would be 1.87 L/tonne of waste

-HDPE liner is to be used at the bottom and on the side walls of the landfill,

- Gas collection and flaring systems will be incorporated to collect methane and to flare the excess methane.

- Leachate will be treated to comply with local environmental standards,

-Only 75% of generated landfill gas can be collected using available technologies (EPA, 2009; Wanichpongpan and Gheewala, 2007)

- 15% of uncollected methane is oxidized in the landfill cover and electricity efficiency of internal combustion engine is 35% (Baratieri et al., 2009; EPA, 2009).

-Four sets of 100 kWh IC engine would be incorporated to produce electricity

-Produced electricity will be sold to the national grid at the rate of 12.11 SRL/kWh (Ceylon electricity board, 2007)

-Skilled and efficient labours power will be used for the operation process so that 0.5 labour days would be sufficient to collect one tonne of waste

With all those assumption, an analysis was done for the proposed sanitary landfill with LFG recovery system. The major benefit from the sanitary landfill with LFG recovery system is the possibility of electricity production from collected LFG and avoidance of methane emissions to the atmosphere. The estimated electricity production from LFG would amount to 138 kWh per tonne of waste so that this amount of electricity production from conventional methods in Sri Lanka can be avoided. Thus, electricity production from

LFG was credited for the quantification of all the midpoint and endpoint composite indicators. The life cycle inventory for sanitary landfill with LFG recovery is presented in Appendix D (Table D4). Similar to other case studies, environmental performance of sanitary landfill with LFG recovery system was evaluated by using midpoint impacts indicators since this information would be useful at the decision making stage. Thus, quantified gross and net midpoint indicators for the intended sanitary landfill with LFG recovery are shown Appendix D (Table D5).

For sustainability assessment, the developed endpoint composite indicators were used to quantify the ultimate damage/effects from the upgraded landfill with LFG recovery syste. The quantified gross and net endpoint indicators have been summarized in Table 8.3. Initiation of LFG recovery system would significantly contribute to improving environmental and social sustainability as noticed with the net negative impacts obtained for endpoint environmental and social indicators, (Table 8.3).

In order to understand the severity of open dumping, and the benefits of an upgraded system with LFG recovery, the results of the sanitary landfill with LFG recovery system were compared with the existing system. The evaluation results (Figure 8.5) clearly show that the initiation of such LFG recovery project can significantly contribute to mitigate the existing environmental, economic and social problems. Mainly, electricity production from landfill gas enables to provide a significant benefit from the avoided damage to abiotic resources that would have otherwise occurred from corresponding amount of conventional electricity production.

Table 8.3: Quantified endpoint impacts from sanitary landfill with LFG recovery

End point composite indicators	**Unit**	**Gross impact**	**Credited impact**	**Net impact**
Damage to ecosystem	$PDF.m^2_{global}.yr$ /tonne	3.72E+02	5.92E+02	-2.21E+02
Damage to abiotic resources	MCI ($/tonne)	9.12E-01	5.80E+00	-4.88E+00
Life Cycle Cost	SLR/tonne	3.87E+03	2.76E+03	1.11E+03
Damage to human health	DALYs/tonne	7.58E-04	9.06E-04	-1.48E-04
Income based community well-being	SLR/tonne	1.32E+03	1.75E+02	1.49E+03

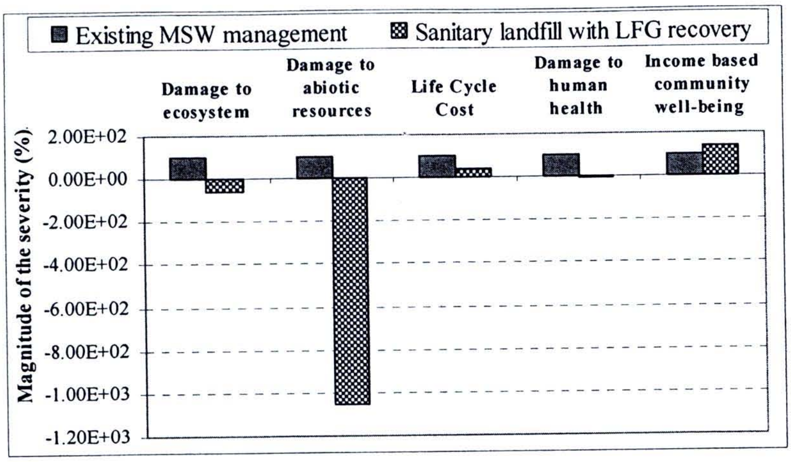

Figure 8.5: Severity of endpoint impacts of sanitary landfill with LFG recovery relative to open dumping

As shown in Figure 8.5, sanitary landfill with a gas recovery system would contribute to reducing damage to ecosystem by 160%, damage to abiotic resources by 1158%, life cycle cost by 66% and damage to human health by 108%. In addition, as a result of creating more employment opportunities for skilled labours, after initiation of sanitary landfill with LFG recovery, the wages based income would increase considerably in comparison to the existing system. Thus, the analysis results indicate that the income based community well-being improvement is 36% higher than that of the existing system.

The overall analysis shows that the implementation of a sanitary landfill with LFG recovery system would bring benefits as an intermediate solution to the existing MSW management system leading to improved sustainability. However, as in several other Asian countries, an important issue in Sri Lanka is the lack of available land for landfilling. In addition, as society becomes more advanced, simple expedient solutions may no longer be sufficient to solve the ever-growing issues of waste disposal. Thus moving towards the development of integrated MSW management systems would be an important step in the future to prolong the sustainability of MSW management in Sri Lanka.

8.6 Development of an Integrated MSW Management System as a Sustainable Solution in Kandy Municipality- Sri Lanka

In Chapter 7, analysis results in Thailand clearly showed the benefits of developing appropriate integrated system to improve the three-dimensional sustainability. Similarly, development of an appropriate integrated system would be the most sustainable solution to overcome the existing MSW management problems in Sri Lanka. Therefore, an integrated system was proposed to the Kandy Municipality by incorporating the most appropriate waste treatment technologies based on the waste composition, characteristics and country specific situations. Considering the characteristic of waste, it was noticed that plastic and paper are the only recyclables available in the mix MSW stream. In Sri Lanka, valuable waste items like metal aluminum and glass are reused for some other purposes so that such recyclables do not come out as waste. It was assumed that only 50% of available recyclables in mix waste stream can be recovered at the sorting facility for the recycling processes. Mass balance analysis was performed to estimate the amount of waste that can be treated using different technologies (Appendix D, Table D6).

There is no ongoing point source separation program in Sri Lanka. Therefore, collected mix MSW should be sorted out at a sorting facility in order to recover the useful materials and to separate the waste fraction that can be treated using different technologies. AD, recycling, incineration and landfilling technologies can be incorporated as the most compatible technologies in Sri Lanka to develop the intended integrated system. According to the characteristic and the composition of waste, 5% of waste recycling, 58% of waste AD, 33% of waste incineration and the remaining 4% of waste landfilling can be achieved through an efficient sorting process. For the sustainability assessment, the LCA framework was designed to take into account all the life cycle phases and life cycle inputs/outputs as detailed in Appendix D (Figure D1).

As of now, there is hardly any appropriate waste management technologies implemented in Sri Lanka. Therefore, it was not possible to find the country specific actual data related to those improved methods. Hence, assumptions were made based on experiences from actual case-studies in Thailand. The detailed explanations about the technologies and the inventory analysis results of the intended integrated system are presented in Appendix D4. Life cycle inventory analysis results were used to quantify the midpoint and endpoint composite indicators. Potential material and energy recovery from improved technologies were credited to quntify resulting the net impacts. Sustainability assessment results by using the midpoint indicators are summarized in Appendix D4 (Table D12). Furthermore, endpoint damage assessment was made to estimate the ultimate damages/effects of the developed integrated system on three-dimensional sustainability. The quantified ultimate environmental, economic and social effects/damages are shown in Table 8.4.

Table 8.4: Quantified ultimate damages/effects from selected appropriate technologies and the intended integrated system

Technology	Amount of waste	% of mass	Damage to ecosystem PDF.gm^2.yr/ tonne	Damage to abiotic resources MCI \$/tonne	Life cycle cost SLR/tonne	Damage to human health DALYs/tonne	Income based community well being SLR/tonne
Recycling	54.5	5.5	-2.38E+04	-1.68E+02	-5.28E+04	-5.47E-04	2.67E+03
Anaerobic digestion	580.5	58.1	-1.86E+03	-5.20E+00	3.08E+03	-9.00E-05	1.98E+03
Incineration	325.0	32.5	1.14E+02	-5.37E+00	2.74E+03	5.71E-04	1.42E+03
Landfilling	40.0	4.0	1.81E+02	6.26E-01	2.77E+03	2.55E-05	1.42E+03
Total impact from intended integrated system	**1000**	**100**	**-2.33E+03**	**-1.39E+01**	**-8.93E+01**	**1.04E-04**	**1.81E+03**

The results obtained reveal that the intended integrated system may drive the entire system towards improved ecosystem and abiotic resources protection since it has resulted in net negative impacts for both aspects in terms of ultimate damage. Also, the system would be economically feasible, since it has shown the possibility of earning significant amount of revenues from the selling of electricity (from landfill gas) and materials recovered from the waste stream. It is notably observed that the recycling of plastics would contribute substantially to the earnings of adequate revenues and drive the entire system towards financial feasibility level.

In relation to the social effects (Table 8.4), despite the potential reduction of damage to human health from both recycling and AD, the overall system still shows positive damage to human health particularly because of toxic pollutant emissions from the incineration process.

In contrast, the intended system would benefit the community, by creating trained and skilled employment opportunities, thus it would help uplifting the living standards of the community. For instance, the wages based income generation is 1,810 SLR/tonne of waste management. As noticed in Chapter 5, the largest income generation to the community would come from the selling of point source separated recyclables. However, effective community awareness approaches are needed to initiate such recycling programs in Sri

Lanka, thus local authorities must play a significant role in this regards until the system is well established. In order to understand the real effects of the intended integrated system in terms of sustainability, the severity of the impacts were compared in relation to the existing situation or sanitary landfill with the gas recovery system (Figure 8.6).

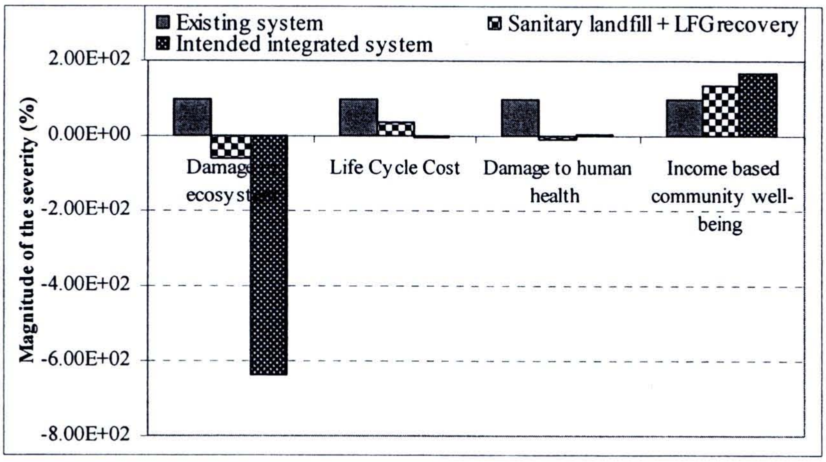

Figure 8.6: Severity of the impacts of intended integrated system relative to open dumping.

It should be noted that, the composite endpoint indicator "damage to abiotic resources" shows substantial contribution on the potential saving of abiotic resources as compared to the existing situation, as a result of useful materials and energy recovery from the waste. For instance, there is a possibility of reduction of damage to abiotic resources by 31 times as compared to the existing system. Other endpoint impacts are also reduced significantly such as damage to ecosystem by 738%, life cycle cost by 103% and damage to human health by 94.5%.

As far as community benefits are concerned, the intended integrated system would contribute to improve the community well-being, by 65% as compared to the existing system.

8.7 Sustainability Improvements of Intended Integrated systems – a Sensitivity Analysis for Future Scenarios

In this thesis, it has been proven that recycling as the most sensitive waste treatment technology for improving three-dimensional sustainability. According to the composition of waste in Kandy, total recyclable materials in the mix waste stream are amounted to 10%.

For the integrated system designed, it was assumed that only 50% of recyclables can be recovered from the mix waste stream. However, with an appropriate awareness program, the recovery rate of recyclables can be increased and simultaneously the percentage of waste incineration can be reduced. Therefore, a sensitivity analysis was performed to predict the sustainability of the future scenarios with increasing recycling rates. As shown in Figure 8.7, the level of sustainability improvement of future scenarios was compared with respect to the designed integrated system for Kandy (5% of waste recycling).

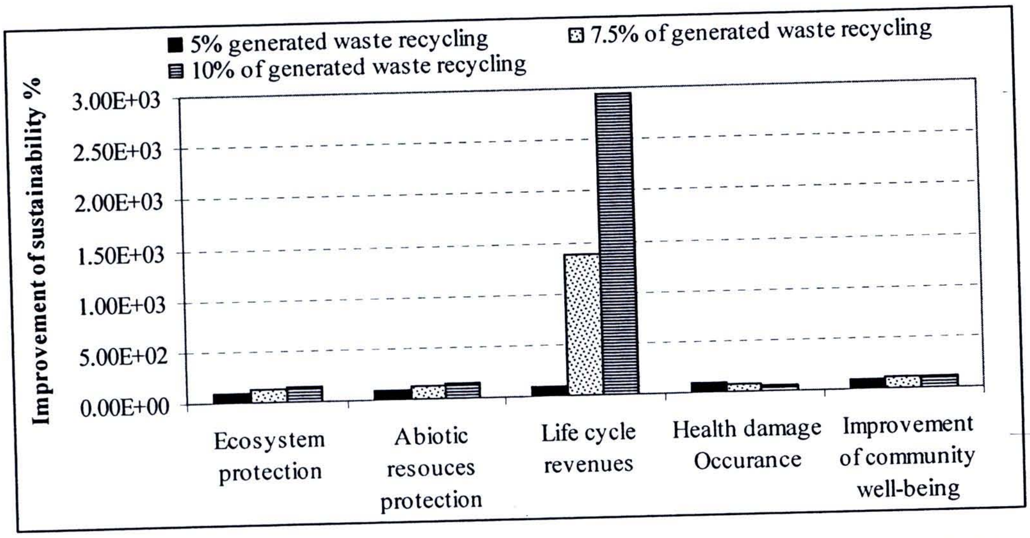

Figure 8.7: Future perspectives of sustainability improvement of the intended integrated system by improving the waste recycling rate in Kandy

For instance, if Kandy Municipality can recycle 7.5% of generated waste, instead of the planned rate of 5%, the intended integrated MSW management system would have the potential for further improvement of 21% of ecosystem protection, 24% of abiotic resource protection, 1230% of revenue earning, 22% of health damage avoidance and 1% of improvement of community well-being (see Figure 8.7). Moreover, Figure 8.7 also shows the further sustainability improvement potential by increasing the waste recycling up to 10% of generated waste. Overall sustainability of the waste management system in Kandy is highly sensitive to the recycling rate, especially for earning substantial amount revenues from the intended integrated systems. The sensitivity analysis results revealed the three-dimensional sustainability improvement potential of intended integrated systems in Sri Lanka via an efficient and effective recycling program.

8.8 Conclusion

At present, Sri Lanka is practicing open dumping as the main waste treatment method and it has created severe environmental, economic and social damages. As an initial step towards sustainability, sanitary landfill with LFG recovery system was evaluated to understand the severity of the impacts from the existing system. Open dumping was found to be substantially worse in all three environmental, economic and social perspectives than a comparative system of sanitary landfill with gas recovery. Furthermore, an appropriate integrated system was proposed and evaluated with regards to the three-dimensional aspects of sustainability. From the recovery of a substantial amount of materials and energy, the system shows improved sustainability. In fact, the results obtained indicate that the damage avoidance potential from materials and energy recovery processes is much higher than the gross damage occurrence potential from the entire MSW management activities within the integtrated system. The sustainability results obtained for the proposed waste management systems would be useful for policy making and strategic planning to develop and implement appropriate MSW management systems in the future in Sri Lanka.