REFERENCES

Al-Khatib, I.A., Monou, M., Salam, F.A., Zahra, A., Shaheen, H.Q. and Kassinos, D. (2010). Solid waste characterization, quantification and management practices in developing countries. A case study: Nablus district – Palestine. *Journal of Environmental Management*, **91**, pp. 1131–1138.

Al-Salem, S.M., Lettieri, P and Baeyens, J. (2009). Recycling and recovery routes of plastic solid waste (PSW): A review. *Waste Management*, **29**, pp. 2625–2643.

Alvarez, J.M., Macè, S. and Llabrès, P. (2000). Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresource Technology*, **74**, pp. 3-16.

Alwis, A.D. (2002). Biogas – a review of Sri Lanka's performance with a renewable energy technology. *Energy for Sustainable Development* **6**, 1, pp. 30-37.

Asian Productivity Organization, (2007). Solid waste management issues challengers in Asia. Sri Lanka, pp 246-273, ISBN: 92-833-7058-9.

Athanassiou, M. and Zabaniotou, A. (2008). Techno-economic assessment of recycling practices of municipal solid wastes in Cyprus. *Journal of Cleaner Production*, **16**, 1474- 1483.

Aye, L. and Widjaya, E.R. (2006). Environmental and economic analyses of waste disposal options for traditional markets in Indonesia. *Waste Management*, **26**, pp. 1180–1191.

Banar, M., Cokaygil, Z. and Ozkan, A. (2008). Life cycle assessment of solid waste mana gement options. *Waste Management*, **29**, 1, pp. 54-62.

Baratieri, M., Baggio, P., Bosio, B., Grigiante, M. and Longo, G.A. (2009). The use of biomass syngas in IC engines and CCGT plants: A comparative analysis. *Applied Thermal Engineering*, **29**, pp. 3309–3318.

Basnayake, B.F.A. and Ekanayake, K.M. (2005). Evaluation of different Municipal Solid Waste landfill pretreatment (Composting) systems in Sri Lanka. Presented at Tenth International Waste Management and Landfill Symposium – Sardinia 3-7 October 2005 at Santa Margherita di Pula (Cagliari) Sardinia – Italy.

Begic, F. and Afgan, N. H. (2007). Sustainability assessment tool for the decision making in selection of energy system-Bosnian case. *Energy*, **32**, pp. 1979–1985.

Bogner, J. and Matthews, E. (2003). Global methane emissions from landfills: New methodology and annual estimates 1980–1996. Global biogeochemical cycles, **17**, 2, pp. 1065.

Böhringer, C. and Jochem, P.E.P. (2007). Measuring the immeasurable - A survey of sustainability indices. *Ecological Economics*, **63**, pp. 1-8.

Borghi, A.D., Gallo, M. and Borghi, M.D. (2009). A survey of life cycle approaches in waste management. *International Journal of Life Cycle Assessment*, **14**, 7, pp. 597-610.

Bove, R. and Lunghi, P. (2006). Electric power generation from landfill gas using traditional and innovative technologies, *Energy Conversion and Management*, **47**, pp. 1391–1401.

Buttol, P., Masoni, P., Bonoli, A., Goldoni, S., Belladonna, V. and Cavazzuti, C. (2007). LCA of integrated MSW management systems: Case study of the Bologna District. *Waste Management*, **27**, pp. 1059–1070.

Cadena, E., Colón, J., Sánchez, A., Font, X., and Artola, A. (2009). A methodology to determine gaseous emissions in a composting plant. *Waste Management*, **29**, 11, pp. 2799-2807.

CALCAS (2011). Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability. Available in http://www.calcasproject.net. Accessed 25 January 2011.

Central Bank (2008). Central Bank Annual Report Sri Lanka. Central Bank of Sri Lanka,Janadhipathi Mawatha, Colombo 01. Available in http://www.cbsl.gov.lk/pics_n_docs/10_publication/_docs/efr/annual_report/ar2008e/2.1.ar08_key_econ_indi_e.pdf. Accessed 25 January 2010.

Chakraborty, N., Mukherjee, I., Santra, A.K., Chowdhury, S., Chakraborty. S., Bhattacharya, S., Mitra, A.P and Sharma, C. (2008). Measurement of CO_2, CO, SO_2, and NO emissions from coal-based thermal power plants in India. *Atmospheric Environment*, **42**, pp. 1073–1082.

Chattopadhyay, S., Dutta, A. and Ray, S. (2009). Municipal solid waste management in Kolkata, India – A review . *Waste Management*, **29**, pp. 1449–1458.

Chaya, W. and Gheewala, S. H, (2007). Life cycle assessment of MSW-to-energy scheme s Thailand. *Journal of Cleaner Production*, **15**, pp. 1463-1468.

Chen, Y.K., Chen, C.Y. and Hsieh, T.F. (2009). Establishment and applied research on environmental sustainability assessment indicators in Taiwan. *Environment Monitoring Assessment*, **155**, 407-417.

Chiemchaisri, C., Ayuwat, K. and Putthamilinprateep, P. (2007a). Feasibility of landfill gas utilization for power generation: A case study in Thailand. *Proceedings of the International Conference on Sustainable Solid Waste Management*, 5 - 7 September 2007, Chennai, India. pp.370-376.

Chiemchaisri, C., Juanga, J.P and Visvanathan, C., (2007b). Municipal solid waste management in Thailand and disposal emission inventory. *Environmental Monitoring and Assessment*, **135**:13–20.

CIA (2008). The world fact book. The US Central Intelligence Agency, Available at https://www.cia.gov/library/publications/the-world-factbook/geos/sw.html. Accessed 25 March 2010.

Classen, M., Althaus, H.J., Blaser, S., Tuchschmin, M., Jungbluth, N., Doka, G., Faist Emmenegger, M. and Scharnhorst, W. (2009). Life cycle inventories of metals. Final report eco-invent data V2.1, No 10. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf.

Cleary, J. (2009). Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. *Environment International*, **35**, 8, pp. 1256-1266.

Cloquell-Ballester V.A., Cloquell-Ballester V.A., Monterde-Dı´az R. and Santamarina-Siurana, M. (2006). Indicators validation for the improvement of environmental and social impact quantitative assessment. *Environmental Impact Assessment Review*, **26**, pp. 79-105.

COGEN Asia (2010). LFG to power. Available in http://www.rcogenasia.com/msw-to-power/landfill-gas-to-power/. Accessed 12 January 2011.

Craighill, A.L and Powell, J.C. (1996). Life cycle assessment and economic evaluation of recycling; A case study. *Resources, Conservation and Recycling*, **17**, pp. 75-96.

CSWS (Council for Solid Waste Solutions), (1990). "Resource and Environmental Profile Analysis of Polyethylene and Unbleached Paper Grocery Sacks." CSWS (800-243-5790), Washington, DC.

Cyclone Petroleum Cooperation (2009). Petroleum cooperation, Colombo, Sri Lanka. (Personal communication).

Ceylon electricity board (2007). Annual report, Available in http://www.ceb.lk/Publications/Annual%20Report/Annual%20Report%202007.pdf Accessed 20 May 2010.

Database of Municipal Solid Waste in Sri Lanka. (2005). Ministry of environmental and natural resources, Pollution control division. Battaramulla, Sri Lanka.

Dave Tractors (Pvt) Ltd (2009). Dave Tractors (Pvt) Ltd, Yakkala, Sri Lanka. (Personal communication).

DEDE (Department of Alternative Energy Development and Efficiency) (2008). Annual report, Ministry of Energy, Thailand .

Den Boer, J., den Boer, E. and Jager, J. (2007). LCA-IWM: A decision support tool for sustainability assessment of waste management systems. *Waste Management*, **27**, pp. 1032–1045.

Dubanowitz, A.J. (2000). Design of a Materials Recovery Facility (MRF) For Processing the Recyclable Materials of New York City's Municipal Solid Waste. Department of Earth and Environmental Engineering Fu Foundation School of Engineering and Applied Science, Columbia University, USA.

EAA (European Aluminium Association) (2008). Environmental profile report for the European aluminium industry. Available in http://www.eaa.net/upl/4/en/doc/EAA_Environmental_profile_report_May08.pdf. Accessed 15 October 2010.

EGAT (Electricity Generation Authority Thailand) (2008). Annual report, Power for Thai happiness. Available in http://pr.egat.co.th/AnnualReport/annual2008/annual08_eng/Annual2008EN_ALL.pdf. Accessed 25 January 2010.

El Hanandeh, A. and El-Zein, A. (2010). Life-cycle assessment of municipal solid waste management alternatives with consideration of uncertainty: SIWMS development and application. *Waste Management*, **30**, pp. 902–911.

EPA (2009). U.S. Environmental Protection Agency, "Project Technology Options." LFG Energy Project Development Handbook.

EPA (2006). Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990 – 2020. U.S. EPA report, 1200 Pennsylvania Avenue, NW, Washington, DC 20460.

Eriksson,O., Reich, M.C., Frostell, B., BjÖrklund, A., Assefa, G., Sundqvist, J.O., Granath, J., Baky, A. and Thyselius, L.(2005). Municipal solid waste management from a systems perspective. *Journal of Cleaner Production*, **13**, pp. 241–252.

Finnveden, G. (1999). Methodological aspects of life cycle assessment of integrated solid waste management systems. *Resources, Conservation and Recycling*, **26**, pp. 173-187.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J, Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, **91**, pp. 1-21.

Giusti, L. (2009). A review of waste management practices and their impact on human health. *Waste Management*, **29**, pp. 2227–2239.

Gluch P. and Baumann, H. (2004). The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. *Build Environment*, **39**, pp. 571–80.

Goedecke, M. Therdthianwong, S. and Gheewala, S.H. (2007). Life cycle cost analysis of alternative vehicles and fuels in Thailand. *Energy Policy*, **35**, pp. 3236–3246.

Goedkoop, M.J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. and Van Zelm, R. (2009). ReCiPe-2008 - A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. First edition Report I: Characterization,. Available in http://www.lciarecipe.net Accessed 25 May 2010.

Governo, D.J., Das, K.C..and Thompson, S.A. (2010). Modeling the Design of Windrow Composting Operations to Maximize the Bottom Line. Biological and Agricultural Engineering Department, The University of Georgia, Athens, Georgia.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A.D., van Oers, L., Sleeswijk, A.W., Suh, S. and Udo de Haes, H.A. (2001). Life Cycle Assessment—An Operational Guide to the ISO Standards. Ministry of Housing, Spatial Planning and the Environment (VROM), and Centre of Environmental Science, Leiden University (CML): The Netherlands.

Guinée, J.B. and Heijungs, R. (1995). A proposal for the definition of resource equivalency factors for use in product life-cycle assessment. *Environmental Toxicology and Chemistry*, **14**, pp. 917–25.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall T. and Rydberg, T. (2011). Life cycle assessment: past, present, and future. *Environmental Science Technology*, **45**, pp. 90-96.

Gunawardana, E.G.W., Basnayake, B.F.A., Shimada, S. and Iwata, T. (2009). Influence of biological pre-treatment of municipal solid waste on landfill behaviour in Sri Lanka. *Waste Management & Research*, **27**, 5, pp. 456-462.

Hák, T., Moldan, B., Dahl, A.L, (eds.). (2007). Sustainability indicators: A scientific assessment. Washington, Covelo, London: Island Press. SCOPE, 67, ISBN 978-1-59726-131.

Hanafiah, M.M., Huijbregts, M.A.J. and Hendriks, A.J. (2010). The Influence of Nutrients and Non-CO_2 Greenhouse Gas Emissions on the Ecological Footprint of Products. *Sustainability*, **2**, pp. 963-979.

Hazra, T. and Goel, S. (2009). Solid waste management in Kolkata, India: Practices and challenges. *Waste Management*, **29**, pp. 470–478.

Heavy equipment Thailand (2009). Available in http://www.heavyequipmentthailand.com/product_view.php?product_id=2105 Accessed 13 April 2010.

Heredia, J.S.B. (1996). Methods of project evaluation. Integrated development and economics of energy projects, Asian Institute of Technology, Thailand. pp. 53-76.

Hischier, R. and St. Gallen, E.M.P.A (2007). Ecoinvent. Life cycle inventories of packaging and graphical papers. Eco-invent report no.11, Swiss Centre for Life Cycle Inventories, Dübendorf.

Huijbregts, M.A.J., Hellweg, S., Frischknecht, R., Hungerbühler, K. and Hendriks, A.J. (2008). Ecological footprint accounting in the life cycle assessment of products. *Ecological economics*, **64**, pp. 798 – 807.

Hunkeler, D. (2006). Societal LCA Methodology and Case Study. *International Journal of Life Cycle Assessment*, **11**, 6, pp. 371– 382.

IAI-International Aluminium Institute (2007). Life cycle assessment of aluminium: Inventory data for the primary aluminium industry. Available in http://www.world-aluminium.org/About+Aluminium/Story+of. Accessed 20 August 2010.

Indian oil cooperation limited (2010). The energy of India, pipeline distribution. Available in http://www.iocl.com/Services/Pipeline.aspx. Accessed 10 February 2010.

IPCC (2006). Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.). Published: IGES, Japan.

IPCC (2007). Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds) Cambridge University Press, Cambridge, United Kingdom and New York, USA.

James, P. (1994). Business Environmental Performance Measurement. *Business Strategy and the Environment*, **3**, 2, pp. 59-67.

Jha, A.K., Sharma, C., Singh, N., Ramesh, R., Purvaja, R.. and Gupta, P.K. (2008). Greenhouse gas emissions from municipal solid waste management in Indian mega-cities: A case study of Chennai landfill sites. *Chemosphere*, **71**, pp. 750–758.

Jørgensen, A., Bocq, A.L ., Nazarkina, L. and Hauschild, M. (2008). Methodologies for Social Life Cycle Assessment. *International Journal of Life Cycle Assessment*, **13**, 2, pp. 96 – 103.

KMC (Kalkota Metropolitan Cooperation) (2010). Methane to market, Assessment report of Dhapa disposal site Kolkata, India, SCS engineers, Available in http://www.globalmethane.org/Data/1128_Dhapa.Assessment.Report.4-27-10.pdf Accessed 10 January 2010.

Kandy Municipal Council (2009). Kandy Municipal Council, Central Province, Sri Lanka. (Personal communication).

Kannan, R., Leong, K.C., Osman, R., Ho, H.K. and Tso, C.P. (2005). Gas fired combined cycle plant in Singapore: energy use, GWP and cost - a life cycle approach, *Energy Conversion and Management*, **46**, pp. 2145–2157.

Kathiravale, S. and Yunus, M.N. (2008). Waste to wealth. *Asian Europe Journal*, **6**, pp. 359–371.

Kondyli, J. (2010). Measurement and evaluation of sustainable development- A composite indicator for the islands of the North Aegean region, Greece. *Environmental Impact Assessment Review*, **30**, pp. 347–356.

Lemieux, P.M., Lutes, C.C. and Santoianni, D.A. (2004). Emissions of organic air toxics from open burning: a comprehensive review. *Progress in Energy and Combustion Science*, **30**, pp. 1-32.

Liamsanguan, C. and Gheewala, S.H. (2008a). LCA: A decision support tool for environmental assessment of MSW management systems. *Journal of Environmental Management*, **87**, pp. 132–138.

Liamsanguan, C. and Gheewala, S.H. (2008b). The holistic impact of integrated solid waste management on greenhouse gas emissions in Phuket. *Journal of Cleaner Production*, **16**, pp. 1865-1871.

Liamsanguan, C. (2005). Life cycle assessment of Integrated Solid Waste Management in Phuket. PhD Thesis. The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok, Thailand. ISBN 974-185-336-1.

LiJing, G., BoRong, L., DaoJin, G. and YingXin, Z. (2008). An endpoint damage oriented model for life cycle environmental impact assessment of buildings in China. *Chinese Science Bulleting*, **53**, 23, pp. 3762-3769.

LIPASTO (2009). LIPASTO traffic emissions, VTT Technical Research Centre of Finland, Finland. Available at http://www.lipasto.vtt.fi/yksikkopaastot/tavaraliikennee/vesiliikennee/tavara_vesie.htm. Accessed on 10 November 2008.

Lou, X.F. and Nair, J. (2009). The impact of landfilling and composting on greenhouse gas emissions – A review. *Bioresource Technology*, **100**, pp. 3792–3798.

Lunda, H., Hvelplunda,F. and Nunthavorakarnb, S. (2003). Feasibility of a 1400 MW coal-fired power-plant in Thailand, *Applied Energy*, **76**, pp. 55–64.

Lutz J., Lekov, A., Chan, P., Whitehead, C.D., Meyers, S. and McMahon, J. (2006). Life-cycle cost analysis of energy efficiency design options for residential furnaces and boilers. *Energy*, **31**, pp. 311–29.

McCool, S.F. and Stankey, G.H. (2004). Indicators of Sustainability: Challenges and Opportunities at the Interface of Science and Policy. *Environmental Management*, **33,** 3, pp. 294–305.

McDougall, F.R., White, P.R., Franke, M and Hindle, P. (2001). Integrated Solid Waste Management: A Life Cycle Inventory, 2nd edition, Blackwell Science.

Meadows, D. (1998). Indicators and Information Systems for Sustainable Development—A Report to the Balaton Group. The Sustainability Institute. Hartland, USA. Available in http:// www.sustainabilityinstitute.org/resources.html#SIpapers. Accessed on 12 August 2008

Menikpua, S.N.M., Basnayake, B.F.A., Pathirana, K.P.M.N. and Senevirathne, S.A.D.S., (2008). Prediction of present pollution levels in Gohagoda dumpsite and remediation measures: Sri Lanka. Conference proceedings- APLAS international solid waste management symposium, 22-25 October 2008, Sapporo, Japan.

Menikpura, S.N.M. and Basnayake, B.F.A. (2009). New applications of 'Hess Law' and comparisons with models for determining calorific values of Municipal Solid Wastes (MSW) in Sri Lankan context. *Renewable Energy*, **34**, pp. 1587–1594.

Menikpura, S.N.M., Basnayake, B.F.A., Boyagoda, P.B. and Kularathne, I.W., (2007). Application of waste to energy concept based on experimental and model predictions of calorific values for enhancing the environment of Kandy city. *Tropical Agricultural Research* ,**19**, pp. 389-400.

Ministry of Labour and Employment (2010). Annual report, Ministry of labour and employment, Government of India, http://www.labour.nic.in/annrep/annrep0910/english/Annual%20Report%202009-10%20English.pdf. Accessed on 2 January 2011.

Ministry of power (2009). Annual report 2008-2009. Ministry of power, government of India.

Ministry of power (2009). CO_2 baseline database. Central electricity Authority, Government of India. http://www.powermin.nic.in/JSP_SERVLETS/internal.jsp. Accessed on 18 January 2011.

Ngoc , U.N. and Schnitzer, H. (2009). Sustainable solutions for solid waste management in Southeast Asian countries. *Waste Management*, **29**, pp. 1982–1995.

Nguyen, T.L.T. and Gheewala, S.H. (2008). Fuel ethanol from cane molasses in Thailand: Environmental and cost performance. *Energy Policy*, **36**, pp. 1589–1599.

Nielsen, P.H. and Hauschild, M. (1998). Product specific emissions from municipal solid waste landfills. Part I. Landfill model. *International Journal of Life Cycle Assessment*, **3**, pp. 158–168.

Nithikul, J., Karthikeyan, O.P. and Visvanathan, C. (2010). Reject management from a Mechanical Biological Treatment plant in Bangkok, Thailand. *Resources Conservation Recycling*, **55**, 4, pp. 417-422.

Nonthaburi Municipality (2009). Sustainable Environmental Management in Nonthaburi, Thailand. . Nonthaburi Municipality. Bangkrasor, Thailand11000.

Nonthaburi Municipality (2010). Personal communication. Nonthaburi Municipality. Bangkrasor, Thailand11000.

Norbu, T., Visvanathan, C. and Basnayake, B. (2005). Pretreatment of municipal solid waste prior to landflling. *Waste Management*, **25**, pp. 997–1003.

Nunn, J., Cottrell, A., Urfer, A., Wibberley. L., and Scaife, P. (2003). Life cycle assessment of the Queensland electricity grid. QCAT Technology Transfer Centre, Technology court, Pullenvale Qld 4069, Australia. Available in http://www.ccsd.biz/publications/files/TA/TA%2026%20Qld%20elec%20grid%20 YEJ2001Final.pdf. Accessed on 12 November 2010.

OECD (2008). Handbook on Constructing Composite Indicators: Methodology and User Guide – ISBN 978-92-64-04345-9; Available in www.oecd.org/publishing/corrigenda. Accessed on 5 November 2009.

Oers, L., Koning, A. and Jeroen, G. (2002). Abiotic resource depletion in LCA. Leiden: Road and Hydraulic Engineering Institute.

Ojha, K. (2010). Status of MSW management system in northern India-an Overview. *Environment, Development and Sustainability*, **13**, 1, pp. 203-215.

Omer, A.M. (2008). Energy, environment and sustainable development. *Renewable Sustainable Energy Review*, **12**, pp. 2265-2300.

Ortiz, O., Castells, F. and Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, **23**, pp. 28–39.

OEA-Organization of Europen Aluminium (2010). Aluminium Recycling in Europe. Available in http://www.world-aluminium.org/cache/fl0000217.pdf. Accessed on 10 December 2010.

Pappu, A., Saxena, M. and Asolekar, S.R. (2007). Solid wastes generation in India and their recycling potential in building materials. *Building and Environment*, **42**, pp. 2311–2320.

Patyk, A. (1996). Balance of Energy Consumption and Emissions of Fertilizer Production and Supply. Reprints from the International Conference of Life Cycle Assessment in Agriculture, Food and Non-Food Agro-Industry and Forestry: Achievements and Prospects, Brussels, Belgium, 4-5 April 1996.

PCD (2009a). Vehicle Emission Data, Pollution control department, Thailand. Available http://infofile.pcd.go.th/air/DIESEL2_Emissions%20Data.pdf?CFID=2232333&CFTOKEN=76854121. Accessed on 10 January 2010.

.PCD (2009b). State of Municipal Solid Waste. The Pollution Control Department, Thailand. Available in http://infofile.pcd.go.th/mgt/Municipal_191153.pdf?CFID=2232333&CFTOKEN=76854121. Accessed on 3 January 2010.

Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E.W., Jolliet, O., Rydberg, T. and Rebitzer, G. (2004). Life cycle assessment (Part 2): Current impact assessment practice. *Environmental International,* **30,** pp.721–739.

Phuket Municipality (2010). Personal communication with managerial team of Phuket incineration plant. Phuket City Hall, Narison Road, Phuket 83000, Thailand.

Pöschl, M., Ward, S. and Owende, P. (2010). Evaluation of energy efficiency of various biogas production and utilization pathways. *Applied Energy*, **87**, 11, pp. 3305-3321.

PRé Consultants (2001). The Eco-indicator 99 - a damage oriented method for life cycle assessment. Methodology report, The Netherlands; 2001. Available in http://www.pre.nl/. Accessed on 20 November 2009.

Pré Consultants (2007a). ETH-ESU 96 System processes, SimaPro 7.1 Manual. Amersfoort, Netherlands.

Pré Consultants (2007b). BUWAL 250, SimaPro 7.1 Manual. Amersfoort, Netherlands.

Pre Feasibility report (2009). Rehabilitation of Gohagoda dumpsite and development of an integrated solid waste management system for Kandy municipal council. Solid Waste Management Research Unit, University of Peradeniya. Sri Lanka.

Ramos, T.B. (2009). Development of regional sustainability indicators and the role of academia in this process: the Portuguese practice. *Journal of Cleaner Production*, **17**, 1101–1115

Rand, T., Haukohl, J. and Marxen, U. (2000). MSW incineration, Decision maker's guide. The International Bank for Reconstruction and Development , The World bank, 1818 H Street, N.W. Washington, D.C. 20433, U.S.A.

Rapport, D.J. (2000). Ecological footprints and ecosystem health: complementary approaches to a sustainable future. *Ecological Economics*, **32**, pp. 367-370.

Rayong Municipality (2010). Personal communication. Rayong Municipality. Thailand.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Scmidt, W.P., Suh, S., Weidema, B.P. and Pennington, D.W. (2004). Life Cycle Assessment. Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, **30**, pp. 701-720.

Reich, M.C. (2005). Economic assessment of municipal waste management systems - case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). *Journal of Cleaner Production*, **13**, pp. 253–263.

Saxena, R.C., Adhikari, D.K. and Goyal, H.B. (2009). Biomass-based energy fuel through biochemical routes: A review. *Renewable and Sustainable Energy Reviews*, **13**, 1, pp. 167-178.

Schaefer, F., Luksch, U., Steinbach, N., Cabeça, J. and Hanauer, J. (2006). Ecological Footprint and Biocapacity. Office for Official Publications of the European Communities, ISBN 92-79-02943-6.

Schaltegger, S. (ed.) (1996), 'Life cycle assessment (LCA)', Basel, Boston, Berlin: Birkhäuser. Available in http://www.ivm.vu.nl/en/Images/AT9_tcm53-161581.pdf. Accessed on 20 November 2010.

Schroeder, P.R., Aziz, N.M., Lloyd, C.M. and Zappi, P.A. (1994). "The Hydrologic Evaluation of Landfill Performance (HELP) Model: User's Guide for Version 3," EPA/600/R-94/168a, September 1994, U.S. Environmental Protection Agency Office of Research and Development, Washington, DC.

Scipioni, A., Maíz, A., Mason, M. and Manzardo, A. (2009). The Dashboard of Sustainability to measure the local urban sustainable development: The case study of Padua Municipality. *Ecological Indicators*, **9**, pp. 364-380.

Scotti, M., Bondavalli, C. and Bodini, A. (2009). Ecological Footprint as a tool for local sustainability: The municipality of Piacenza (Italy) as a case study. *Environmental Impact Assessment Review*, **29**, pp. 39–50.

Shaha, S.D., Johnson, K.C., Miller, J.W. and Cocker, D.R. (2006). Emission rates of regulated pollutants from on-road heavy-duty diesel vehicles. *Atmospheric Environment*, **40**, pp. 147–153.

Sharholy, M., Ahmad, K., Mahmood, G. and Trivedi, R.C. (2008). Municipal solid waste management in Indian cities – A review. *Waste Management*, **28**, pp. 459–467.

Shekdar, A.V. (2008). Sustainable solid waste management: An integrated approach for Asian countries, *Waste Management*, **29**, 4, pp.1438-1448.

Shrestha, S.O.B. and Narayanan, G. (2008). Landfill gas with hydrogen addition – A fuel for SI engines. *Fuel*, **87**, pp. 3616–3626.

Singh, R.K., Murty, H.R., Gupta, S.K. and Dikshite, A.K. (2009). An overview of sustainability assessment methodologies. *Ecological Indicators*, **9**, pp. 189-212.

SNG Mercantile Pvt. Ltd (2007). Outline Strategy for Solid Waste Management. Study of Solid Waste Management Disposal and Public Private Partnership Options, Kolkata, India.

Somerford, P. and Katzenellenbogen, J. (2004). Western Australian Burden of Disease Study: Disability-Adjusted Life Years: Technical overview. Department of Health, Perth, Western Australia.

Steen, B. A. (2000). Systematic approach to environmental priority strategies in product development (EPS) Version 2000—Models and data of the default method, CPM report 1999, Chalmers University of Technology, Environmental Systems Analysis;2000.

Svoboda, S. (1995). Note on Life Cycle Analysis. National Pollution Prevention Center for Higher Education. University of Michigan, Dana Building, 430 East University, Ann Arbor MI 48109-1115.

Syed, A., Melanie, J., Thorpe, S. and Penney, K. (2010), Australian energy projections to 2029-30, ABARE research report 10.02, prepared for the Department of Resources, Energy and Tourism, Canberra. Available in http://www.abare.gov.au/publications_html/energy/energy_10/energy_proj.pdf. Accessed on 10 November 2010.

Tchobanoglous, G., Theisen, H. and Vigil, S.A. (1993). Integrated solid waste management: engineering principles and management issues, McGraw Hill International editions, Civil Engineering series. Singapore: McGraw Hill Inc; pp. 81.

Troschinetz, A.M and Mihelcic, J.R. (2009). Sustainable recycling of municipal solid waste in developing countries. *Waste Management*, **29**, pp. 915–923.

UN (2001). Indicators of sustainable development: guidelines and methodologies, Available in : www.un.org/esa/sustdev/publications/indisd-mg2001.pdf. Accessed on 8 April 2009.

UNEP (2001). United Nation's Environmental Programme, Regional Resource Centre for Asia and Pacific. "Sri Lanka: State of the Environment". Available:

http://www.rrcap.unep.org/reports/soe/srilanka_waste.pdf. Accessed on 10 November 2008

UNFCCC (2010). Biopower project at Charoensuk Starch Co. Ltd, Thailand. Project design document form (CDM_SSC_PDD) - version 03. Available in http://cdm.unfccc.int/UserManagement/FileStorage/6MLX8ABGCHFPR0NW9UQVE4YZ2I5J7D. Accessed on 18 January 2011

UNFCCC/CCNUCC (2008). Methodological tool -"Combined tool to identify the baseline scenario and demonstrate additionally". CDM – Executive Board. Available at http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-02-v2.2.pdf. Accessed on 17 November 2010.

Utne, I.B. (2009). Life cycle cost (LCC) as a tool for improving sustainability in the Norwegian fishing fleet. *Journal of Cleaner Production*, **17**, pp. 335–344.

Vanarruk, P. (2009). Anaerobic Digester of Rayong Municipality. Development of Environment and Energy Foundation, Thailand.

Vidanaarachchi, C.K., Yuen, S.T.S., and Pilapitiya, S. (2006). "Municipal solid waste management in the Southern Province of Sri Lanka: Problems, issues and challenges. *Waste management*, **26**, pp. 920–930.

Visvanathan, C., Trankler, J., Joseph, K., Chiemchaisri, C., Basnayake, B. F. A. and Gongming, Z. (2004). Municipal solid waste management in Asia. Asian Regional Research Program on Environmental Technology (ARRPET). Asian Institute of Technology publications. ISBN: 974-417-258-1.

Wackernagel, M., Monfreda, C., Moran, D., Wermer, P., Goldfinger, S., Deumling, D. and Murray, M. (2005). National Footprint and Biocapacity Accounts 2005: the Underlying Calculation Method. Global Footprint Network, Oakland.

Walker, L., Charles, W. and Ruwisch, R.C. (2009). Comparison of static, in-vessel composting of MSW with thermophilic anaerobic digestion and combinations of the two processes. *Bioresource Technology*, **100**, pp. 3799–3807.

Wangyao, K., Towprayoon, S., Chiemchaisri, C. and Shabbir H. Gheewala, S.H. (2009). Application of the IPCC Waste Model to solid waste disposal sites in tropical countries: case study of Thailand. *Environmental Monitoring and Assessment*, **164**, 1-4, pp. 249-261.

Wanichpongpan, W. and Gheewala, S.H. (2007). Life cycle assessment as a decision support tool for landfill gas-to energy projects. *Journal of Cleaner Production*, **15**, pp. 1819-1826.

Warhurst, A. (2002). Sustainability Indicators and Sustainability Performance Management. Report to the Project: Mining, Minerals and Sustainable Development (MMSD). International Institute for Environment and Development (IIED). Warwick, England.

Wel, A. and Post, V. (2007). Solid Waste Management in Sri Lanka: Policy & Strategy. WASTE project report. Nieuwehaven 201, 2801 CW Gouda, The Netherlands.

Wenzel, H., Hauschild, M. and Alting, L. (1997). Environmental Assessment of products. Volume 1- Methodology, Tools and Case studies in Product Development, First edition, Chapman & Hall, London.

WHO (2007). Population health and waste management: scientific data and policy options. Report of a WHO Workshop, Rome, Italy, 29–30 March 2007.

Wilson, J., Tyedmers, P., Pelot, R., (2007). Contrasting and comparing sustainable development indicator metrics. Ecological Indicators 7, 299–314.

Wolters, T. and Danse, M. (2004). Towards sustainability indicators for product chains. environmental management accounting: Informational and Institutional Developments, Springer Netherlands, ISBN: 978-0-306-48022-5 9: pp 231-247.

World Bank Group (1999). The International Bank for Reconstruction and Development.. What a Waste: Solid Waste Management in Asia. Prepared by Hoornweg, D., Available from: http://siteresources.worldbank.org/INTEAPREGTOPURBDEV/Resources/whatawaste.pdf. Accessed on 10 November 2008.

Zou, S.C., Lee, S.C., Chan, C.Y., Ho, K.F., Wang, X.M., Chan, L.Y. and Zhang, Z..X. (2003). Characterization of ambient volatile organic compounds at a landfill site in Guangzhou, South China. *Chemosphere*, **51**, pp. 1015–1022.

APPENDIX A

A1: Background information related to sustainability assessment of recycling

Various data sources had to be utilized for sustainability assessment of the existing MSW management system in Nonthaburi. Characteristics of the recyclables were really useful for the assessment process. The average composition of collected recyclables in Nonthaburi is shown in Table A1.

Table A1: Average composition of generated recyclables in Nonthaburi (composition is shown for 243.2 kg of recyclables since that is the amount of recyclables available per finctional unit)

Paper		Plastics		Glass		Metal	
Type of recyclables	Amount (kg)	Type of recyclables	Amount (kg)	Type of recyclables	Amount (kg)	Type of recyclables	Amount (kg)
Office paper	2.75	Plastic bag (PP)	2.07	Glass clear color	6.74	Aluminum	64.68
Newsprint	14.22	PET	0.35	Amber	10.69	Steel	97.02
Laminated paper(magazine)	21.91	PVC	0.53	Green	0.35		
Craft paper	13.31	PS	0.16				
milk carton	3.56	Foam(EPS)	0.31				
		HDPE	3.95				
		LDPE	0.62				
total recyclables received to recycling plant (243.2 kg) /tonne of MSW generated	55.76	subtotal	8.00	Sub total	17.78	Subtotal	161.71

It should be noticed that, impurities are removed at the sorting facility especially for separate recyclable papers. After removing the impurities, total recyclable papers amounts to 54.4 kg. Impurities of other recyclables are considered as negligible. Based on this composition, the LCA study was done for the recycling processes of different fractions of waste.

Paper recycling in Nonthaburi

There are two different methods of paper recycling such as with de-inking (for newsprint, magazine and office paper) and without deinking (for Kraft paper). 'Recycling potential or suitability' of paper with and without de-inking processes are 85.2% and 98.7% respectively (Hischier and St. Gallen, 2007). Eco-invent database is used for collecting basic information on thermal energy, electricity consumption and material requirement for a unit process of recycling. Then those input data was adjusted to suit, the Thailand situation inorder to improvise a data set which represents the local situation. For instance, the recommended type of fuel sources for primary energy production for paper industry, fuel sources used in grid electricity production and efficiencies of furnace and power plant etc was taken into consideration to adjust the eco-invent data to the local situation. In fact, as reported by DEDE (2008), Thailand paper industry used 96.2% of thermal energy from imported coal and coal products and remaining 3.8% from fuel oil and diesel. The relative electricity requirement for recycling, energy sources and emission from grid electricity production are also taken into account in the inventory analysis. For the inventory analysis, all the steps of recycling such as transportation of waste paper (emissions from vehicle were calculated for transportation distance of 130 km- PCD, 2009a), pulping of waste paper, paper production, internal waste water treatment, etc. (Hischier and St. Gallen, 2007) were considered. Significant amount of paper can be produced from the process of waste paper recycling. So the production of same amount of paper from virgin materials can be avoided and the paper recycling process can be credited in LCA perspective. Inevitably, paper production process form virgin material was considered within the system boundary. Direct and indirect effects of the paper recycling process on avoidance of virgin production process chain and in the avoidance of presently practicing landfilling is shown in Figure A1 .

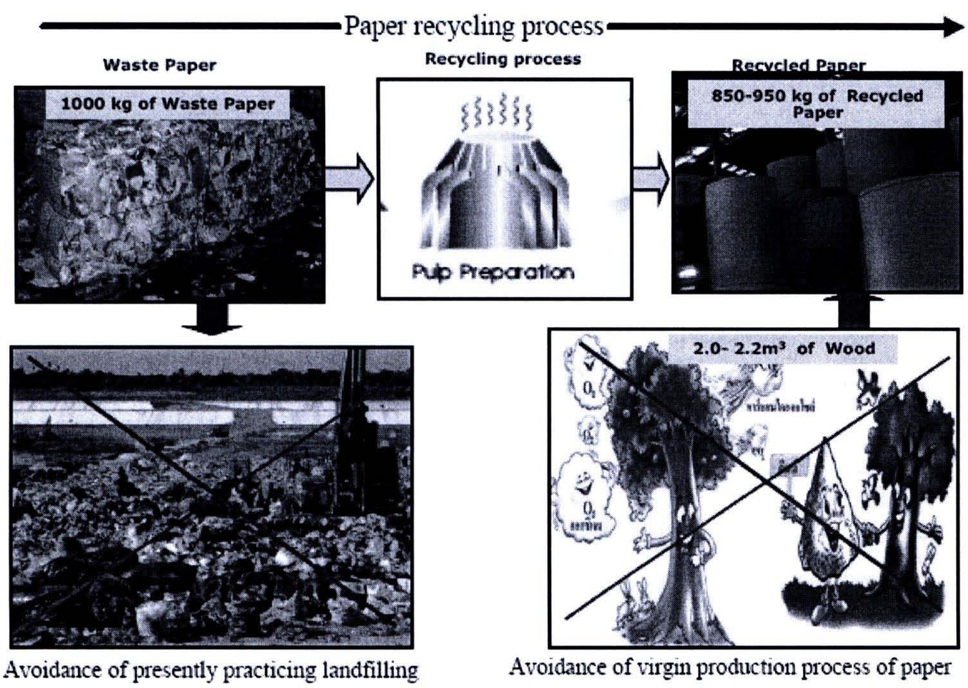


Figure A1: Direct and indirect effects of paper recycling process

Virgin production process of paper

In the pulp and paper industry, either entire pieces of wood with bark or thin woodchips are mainly used as the main raw materials. The Ecoinvent database was used to collect data on virgin paper production that has been developed in Scandinavian countries (Hischier and St. Gallen, 2007). When it is applied to the Thailand situation, in order to reduce the uncertainties, the distance involved in the transportation of wood, energy production for heating and electricity production data which are required for unit processes was adjusted to the Thailand situation (DEDE, 2008; EGAT, 2008). Most of the information related to the financial assessment, employment opportunities and social benefits from waste paper recycling was collected from the biggest paper recycling plant in Thailand.

Table A2: Inputs and outputs for recycling of paper (Note: 54.4 kg of paper recycling can be replaced 48.56 kg of virgin paper)

Life cycle inputs/outputs s	Unit	Waste paper recycling (54.4kg)	Production from virgin materials (48.56kg)					**Net resource consumption and emissions**
			Newsprint (13.88 kg)	Magazine (21.38 kg)	Office paper(2.69 kg)	Kraft paper(16.45 kg)	Virgin production of 48.56 kg of paper	
Inputs								
Hard Wood	m3				3.88E-03	0.00E+00	3.88E-03	-3.88E-03
Soft wood	m3		1.07E-02	2.71E-02	3.12E-03	6.90E-02	1.10E-01	-1.10E-01
Wood chips	m3		2.12E-03	1.88E-03	1.90E-04		4.18E-03	-4.18E-03
Sulphate pulp	kg		2.08E-01	3.61E+00	8.01E-02		3.90E+00	-3.90E+00
waste paper mixed	kg	5.44E+01	8.94E+00	1.12E+00			1.01E+01	4.43E+01
Kaolin	kg	3.21E+00	1.99E-01	4.01E+00	2.72E-01		4.48E+00	-1.27E+00
Aluminium sulphate powder	kg	5.14E-01	3.19E-02	6.01E-02		2.71E-01	3.63E-01	1.51E-01
Energy								
Electricity, at grid	kWh	2.62E+01	1.90E+01	2.75E+01	8.43E-01	1.54E+01	6.27E+01	-3.65E+01
Hard coal	kg	1.87E+01	1.36E+00	1.88E+00	1.43E-01	1.70E+00	5.09E+00	1.37E+01
Soft coal	kg	5.17E+00	5.11E+00	5.43E+00	1.67E-01	3.04E+00	1.37E+01	-8.58E+00
Heavy fuel oil	kg	8.41E-01	2.67E-01	3.88E-01	8.96E-02	8.34E-01	1.58E+00	-7.37E-01
Natural gas	m3	4.63E+00	3.30E+00	4.77E+00	1.46E-01	2.66E+00	1.09E+01	-6.24E+00
Outputs								
Amount of paper produced	kg	4.86E+01	1.18E+01	1.82E+01	2.29E+00	1.62E+01	4.86E+01	0.00E+00
CO_2 fossil	kg	6.99E+01	1.51E+01	2.16E+01	1.13E+00	1.57E+01	5.36E+01	1.64E+01
NH_3	kg	2.61E-05	1.06E-05	1.55E-05	4.38E-06	3.97E-05	7.02E-05	-4.40E-05
CO	kg	9.23E-02	2.24E-02	3.23E-02	4.79E-03	4.82E-02	1.08E-01	-1.53E-02
CH_4	kg	1.08E-02	2.78E-03	4.03E-03	6.96E-04	6.79E-03	1.43E-02	-3.55E-03
NMVOCs	kg	1.09E-02	4.15E-03	6.09E-03	1.70E-03	1.54E-02	2.74E-02	-1.64E-02

N_2O	kg	4.81E-04	1.99E-06	2.93E-06	8.26E-07	7.49E-06	1.32E-05	4.68E-04
NO_x	kg	1.80E-01	4.80E-02	6.90E-02	4.93E-03	6.08E-02	1.83E-01	-2.90E-03
SO_x	kg	7.05E-02	4.67E-02	6.74E-02	2.32E-03	3.96E-02	1.56E-01	-8.56E-02
PM >10mm	kg	4.73E-02	1.39E-02	1.99E-02	1.30E-03	1.66E-02	5.17E-02	-4.37E-03
Nitrogen	kg	7.27E-03	5.91E-04	7.28E-04	3.43E-04	3.25E-03	4.91E-03	2.36E-03
Phophorus	kg	2.61E-04	1.18E-04	1.15E-04	2.29E-05	3.25E-04	5.81E-04	-3.19E-04

Plastics recycling in Nonthaburi

At present, 8 kg of plastics is being recycled from every tonne of waste generated in Nonthaburi Municipality. At the sorting plant in Nonthaburi, plastic is separated based on the type and color, and then crushed, washed, dried, and packed. Then, these baled plastics are sent to the recycling facility in Samut Prakarn province (transportation distance is 36 km).

In order to perform the inventory analysis for plastic recycling, basic data was collected from SimaPro and Eco invent databases. Electricity is the major input resource for plastic recycling process. In fact, according to the database information (Pré Consultants, 2007b) and data obtained from recycling facilities, 3.8kWh of electricity is needed for 1 kg of plastic recycling. According to the inventory analysis, it was noticed that environmental emissions and resource consumption of recycling is mainly due to electricity requirement for recycling.

According to the SimaPro and Eco-invent databases guideline, recyclability of plastic is 90% that means 1 kg of waste plastic has the potential of producing 0.9 kg of recycled plastic granules (Hischier and St. Gallen, 2007; Pré Consultants, 2007b). Thus, plastic manufacturing process from virgin materials was studied in order to estimate the potential credited impacts from recovery materials of recycling process. The schematic diagram on effects of plastic recycling process on avoidance of virgin production process chain and avoidance of presently practicing landfilling is shown in Figure A2.

Plastic production from virgin materials

90% of the plastics used today are synthesized using fossil resources. The most important raw material for the polymer production is naphtha which is one of the fractions resulting from the refining of crude oil. In addition, plastics are also produced using natural gas as a raw material (Al-Salem et al., 2009).

Inventory analysis was done having considered all the inputs and outputs of recycling of plastics and the virgin plastic production for the entire life cycle. Processes of mechanical plastic recycling such as cutting/shredding, contaminant separation, milling, washing and drying, agglutination, extrusion, quenching and granulation of waste plastics were considered (Hischier and St. Gallen, 2007). In addition, transportation of waste plastics, electricity production, diesel production etc was considered within the system boundary. For virgin production, resource consumption and emissions from virgin production is highly significant. Compared to that, emissions from transportation of resources (mainly crude oil from Middle East to Thailand) (LIPASTO, 2009) are negligible. Detailed inventory analysis of recycling and virgin production of plastics is shown in Table A3.

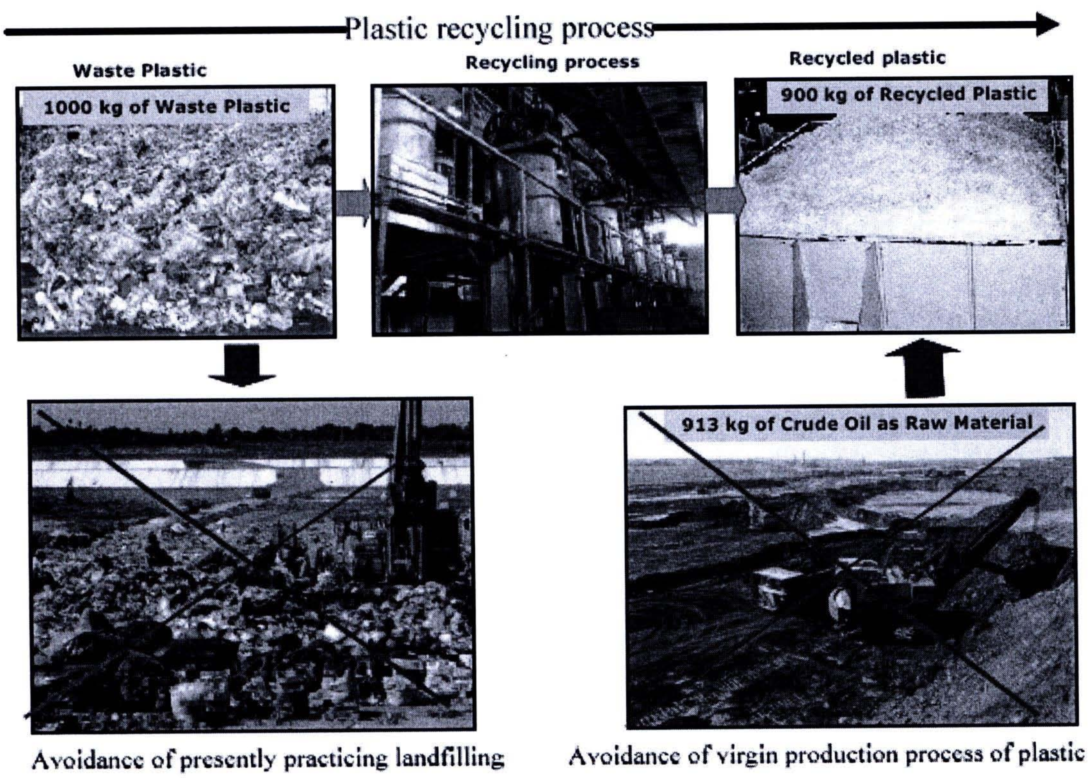


Figure A2: Direct and indirect effects of plastic recycling

A 3: Inputs and outputs of recycling of plastic (Note: recycling of 8kg of waste plastic can be used to replace 7.2 kg of virgin plastic)

Life cycle inputs/outputs	Unit	Inputs and outputs of recycling (8.00 kg of plastics)	Inputs and outputs of virgin production (7.2 kg)	Net emissions and resource consumption
Oil, crude, in ground	kg	6.95E-02	6.59E+00	-6.52E+00
Gas, natural, in ground	m^3	5.24E+00	5.00E+00	2.40E-01
Coal, hard, unspecified, in ground	kg	3.40E-04	8.22E-01	-8.21E-01
Coal, brown, in ground	kg	5.96E+00	1.21E-01	5.84E+00
Aluminium, 24% in bauxite	kg		1.21E-03	-1.21E-03
Iron, 46% in ore, 25% in crude ore, in ground	kg	7.80E-05	2.10E-02	-2.09E-02
Total amount of plastic for recycling	**kg**	**7.20E+00**	**7.20E+00**	**0.00E+00**
Emissions				
PM	kg	1.65E-02	5.34E-03	1.12E-02
CO	kg	1.48E-02	6.05E-02	-4.57E-02
CO_2	kg	1.71E+01	1.26E+01	4.50E+00
SO_2	kg	7.24E-02	3.35E-02	3.89E-02
NOx	kg	5.41E-02	3.21E-02	2.20E-02
HCl	kg	3.73E-08	4.40E-04	-4.40E-04
NMVOC	kg	1.18E-03	2.91E-02	-2.79E-02
CH_4	kg	1.37E-04	1.00E-01	-1.00E-01
Emissions to water				
COD	kg		3.64E-02	-3.64E-02
BOD_5	kg		4.15E-03	-4.15E-03
NO_3^-	kg		2.56E-04	-2.56E-04
NH_4^+	kg		8.31E-05	-8.31E-05

Aluminium Recycling in Nonthaburi

It is a well known fact that, re-melting the aluminium metal into a new ingot requires much less energy than the primary aluminium production from its ore. Aluminium recycling thus saves tremendous amount of raw materials and energy, and also reduces demands on landfill sites. For instance, it has a reported energy savings of up to 95% achieved per tonne of aluminium produced from scrap compared to primary aluminium (OEA, 2010). According to the European Aluminium Association (EAA, 2008), recyclability of waste aluminium scraps is 76%. It means that 760 kg of recycled aluminium can be obtained from 1 tonne of aluminium scraps. 64.68 kg of aluminium is being recycled in Nonthaburi Municipality for each tonne of waste generated. Recyclable waste aluminium is being sent to the recycling facility, which is situated in Chonburi Province.

For the recycling process, electricity and thermal energy are the main inputs. The International Auminium Institute (IAI, 2007) published data on electricity, thermal energy and other inputs usage for unit process of recycling was taken into account and those data adjusted to the Thailand situation. For instance, the recommended fuel sources for the thermal energy supplement for aluminium industry in Thailand are 37.67% of coal and coal products, 62.33% fuel oil and petroleum products (DEDE, 2008).

There is a potential of producing 49.04 kg of recycled ingot aluminium (64.68 kg of aluminium scraps input) from one tonne of waste generated in Nonthaburi. Thus, the same amount of aluminium production from virgin materials can be avoided and this process can be credited in the LCA perspective. Figure A3 shows the effects of aluminium recycling process on avoidance of virgin production process chain.

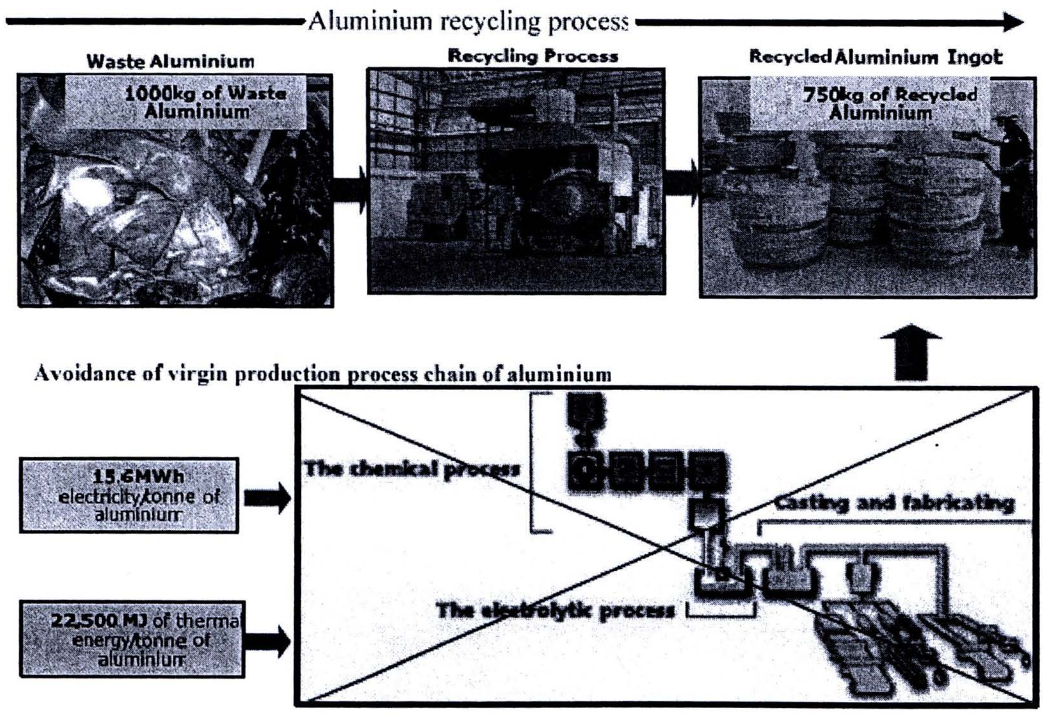


Figure A3: Direct and indirect effects of aluminium recycling process

Virgin production of Aluminium

Bauxite is the main resource of virgin aluminium production. The world average of mined crude ore contains 47.9% of bauxite. 98% of industrial production of aluminium is done by electrolysis of aluminium oxides and that process requires considerable amount of electricity. Basically the aluminium production process involves the following steps such as, bauxite mining, alumina production, anode production, paste production, reduction (electrolysis) and ingot casting. The inventory data for the unit processes of each activity of aluminium production from virgin materials was taken form the International Aluminium Institute (IAI, 2007).

Aluminium production process is highly energy intensive. Electricity and fossil fuel for thermal energy production are the major inputs. In fact, 15.6 MWh of electricity and 22,500MJ of thermal energy are needed to produce 1 tonne of primary aluminium from virgin materials (IAI, 2007). It is important to mention that Thailand is not producing primary aluminium from virgin material and it is imported from Australia. Therefore, IAI reported emissions and energy and electricity consumption data of primary aluminium production were adjusted to the Australian situation. Thus, emissions from Australian grid electricity production as well as from thermal energy production were taken into account for the inventory analysis (Syed et al., 2010; Nunn et al., 2003). Detailed inventory analysis of recycling and virgin production of Aluminium is shown in Table A4.

Table A4: Inputs and outputs of recycling of Aluminium (Note: recycling of 64.68 kg of waste aluminium can be used to replace 49.04 kg of virgin Aluminium)

	Recycling (64.68 kg)		Virgin production (49.04kg)						
	Unit	Total from recycling	Bauxite Mining	Alumina Production	Anode Production	Electrolysis	Ingot casting	Total	Net resource consumption and emissions
Total scrap input		**6.47E+01**							
Life cycle inputs/outputs									
Bauxite	kg	**9.06E-04**	2.58E+02					**2.58E+02**	-2.58E+02
Alumina input	kg							**9.43E+01**	-9.43E+01
Anode	kg							**2.13E+01**	-2.13E+01
Aluminium(liquid metal)	kg							**4.90E+01**	-4.90E+01
Cast ingot	kg	**4.90E+01**						**4.90E+01**	0.00E+00
Electricity and thermal energy									
Total thermal energy	MJ	**2.33E+02**	1.53E+01	9.64E+02	5.49E+01	0.00E+00	7.03E+01	**1.10E+03**	-8.71E+02
Electricity	kWh	**6.24E+00**	4.90E-01	1.19E+01	2.75E+00	7.50E+02	4.07E+00	**7.69E+02**	-7.63E+02
Lignite /brown coal	kg	**1.23E+00**	2.80E-01	1.39E+01	1.20E+00	1.49E+02	1.65E+00	**1.66E+02**	-1.64E+02
Hard coal/Black coal	kg	**3.92E+00**	2.39E-01	1.15E+01	1.04E+00	1.41E+02	1.44E+00	**1.55E+02**	-1.51E+02
Heavy oil and diesel	kg	**3.64E+00**	1.43E-01	8.94E+00	5.19E-01	3.35E+00	6.66E-01	**1.36E+01**	-9.98E+00
Natural gas	m3	**1.08E+00**	1.10E-01	6.09E+00	4.35E-01	3.21E+01	5.81E-01	**3.93E+01**	-3.82E+01
Air emissions									
CO_2	kg	**2.53E+01**	1.80E+00	9.59E+01	7.37E+00	6.89E+02	9.94E+00	**8.04E+02**	-7.78E+02
CO	kg	**2.01E-02**	1.47E-02	9.27E-01	5.28E-02	0.00E+00	6.77E-02	**1.06E+00**	-1.04E+00
N_2O	kg	**1.09E-06**						**0.00E+00**	1.09E-06
HF	kg				2.94E-04	2.70E-02		**2.73E-02**	-2.73E-02
PM	kg	**9.89E-03**	2.47E-01	9.54E-02	9.38E-03	3.47E-01	8.45E-03	**7.06E-01**	-6.96E-01
NOx	kg	**4.46E-02**	3.42E-03	2.38E-01	2.08E-02	2.42E+00	2.59E-02	**2.71E+00**	-2.66E+00
SOx	kg	**2.23E-02**	4.11E-03	5.22E-01	5.93E-02	2.90E+00	2.56E-02	**3.51E+00**	-3.49E+00
NMVOCs	kg	**2.43E-03**	6.93E-05	4.36E-03	2.49E-04	0.00E+00	3.18E-04	**5.00E-03**	-2.57E-03
CH_4	kg	**2.09E-03**	1.14E-03	7.15E-02	4.08E-03	0.00E+00	5.22E-03	**8.19E-02**	-7.98E-02
NH3	kg	**5.76E-06**						**0.00E+00**	5.76E-06

Metal recycling

Iron is the 4th most common element in the earth's crust which basically consists of iron oxides and iron sulfides. Iron ores are mined in China, Brazil and in Australia. Iron and steel scraps have become the steel industry's single largest source of raw material for recycling which involves lower primary energy consumption and gives over lower emissions from that process compared to the blast furnance- converter production route. Thus, recycling has always been an integral part of the steel-making process (Classen et al., 2009).

In Nonthaburi Municipality, approximately 40% of collected recyclables belong to metal and steel category and it amounts to 97.0 kg steel waste for each tonne of waste generated. Therefore, SimaPro 7.1 model was used to estimate the inputs and outputs requirement for recycling as well as for virgin production process of steel (Pré Consultants, 2007b). In order to find the data on steel recycling, the recycling process of tin plated steel without de-tinning from 100% scraps was considered. Tin plated steel production from iron ores is considered to be the representative case for steel production from virgin materials. It should be noted that recyclability of waste steel is 90% and that means 900kg of recycled steel can be produced from 1 tonne of waste steel. When it is calculated for a functional unit, there is a potential of producing 87.8 kg of recycled steel form 97.0 kg of waste steel obtained from each tonne of waste generationed in Nonthaburi. Inventory analysis results are summarized in Table A5.

Table A5: Inventory analysis of steel recycling and virgin production (Note: recycling of 97 kg of waste steel can be used to replace 87.8 kg of steel produce from virgin production)

Life cycle inputs/outputs	Unit	Recycling (97.01kg of steel)	Virgin production 87.80 kg of steel	Net savings
Resources				
Coal, brown, 8 MJ per kg, in ground	kg	2.46E+01	9.31E+00	1.53E+01
Gas, natural, 36.6 MJ per m^3, in ground	m^3	1.12E+01	1.14E+01	-2.63E-01
Coal, 18 MJ per kg, in ground	kg	1.60E+01	1.04E+02	-8.85E+01
Oil, crude, 42.6 MJ per kg, in ground	kg	2.16E+00	7.73E+00	-5.57E+00
Limestone, in ground	kg	0.00E+00	2.49E+01	-2.49E+01
Iron ore, in ground	kg	0.00E+00	2.11E+02	-2.11E+02
Scrap, external	kg	1.04E+02	1.07E+01	9.38E+01
Total energy consumption	MJ	1.49E+03	2.95E+03	-1.46E+03

Emissions to air				
PM	kg	1.03E-01	1.24E-01	-2.11E-02
CH_4	kg	1.78E-01	9.48E-01	-7.70E-01
NMVOC	kg	3.97E-02	8.87E-02	-4.90E-02
CO_2	kg	1.02E+02	2.61E+02	-1.59E+02
CO	kg	4.04E-01	1.62E+00	-1.22E+00
NH_3	kg	1.64E-04	1.73E-04	-8.78E-06
HF	kg	1.33E-03	9.66E-04	3.69E-04
N_2O	kg	5.18E-04	8.43E-04	-3.25E-04
HCl	kg	1.16E-02	7.58E-03	4.01E-03
SO_2	kg	2.56E-01	5.47E-01	-2.92E-01
NO_2	kg	2.36E-01	4.00E-01	-1.64E-01
H_2S	kg		8.69E-04	-8.69E-04
Emissions to water				
Nitrogen, total	kg	1.91E-04	4.85E-04	-2.93E-04
Phosphate	kg	4.25E-03	1.28E-02	-8.57E-03

Glass recycling

The properties of glass provide the attributes for many commercial products. For example, the glass cullets can be re-melted and re-fabricated over and over again without any deterioration of the material properties (Hischier and St. Gallen, 2007).

In Nonthaburi Municipality, 17.8 kg glass is being collected and recycled from each tonne of MSW generated within the Municipality. According to the composition study done by PCD, waste glass can be categorized into three major types such as clear glass, brown glass and green glass which amounts to 37.9%, 60.1% and 2.0% respectively. The collected and sorted waste glass is sent off to a glass recycling factory in Pathumthani Province. At the recycling facility waste glasses are used as the raw material (60% of raw material from waste glass) for glass manufacturing process.

There is no available data in SimaPro 7.1 or Eco-invent databases for recycling of clear and brown glass. Thus, it was assumed that material and energy consumption and emissions from green glass packaging recycling (it consists with 99% form recycling glass and 1% from virgin material) is similar to any type of glass recycling. According to BUWAL 250 in Simapro 7.1 model (Pré Consultants, 2007b), it is possible to produce 952 kg of recycled glass by using 1 tonne of waste glass that means recyclability of glass is 95.2%. It should be noted that recycling of 17.78 kg of glass can avoid the production of 16.93 kg of glass from virgin materials. Inventory analysis of virgin manufacturing of clear glass, brown glass and green class was done separately based on BUWAL 250 in SimaPro 7.1 database, (Table A6).

Table A6: Inventory analysis of glass recycling and virgin production

Life cycle inputs/outputs	Unit	Recycling of 17.78kg of glass	Virgin production inventory (16.93kg of glass)				Net resource consumption and emissions
			White glass (6.418 kg)	Brown glass (10.182 kg)	Green glass (0.332 kg)	Total from virgin production	
Raw materials							
Coal, brown, 8 MJ/ kg	kg	1.41E-01	1.28E-01	2.11E-01	2.76E-03	3.42E-01	-2.01E-01
Gas, natural, 36.6 MJ/ m^3	m^3	4.17E-01	-2.27E-03	-5.95E-02	8.16E-03	-5.36E-02	4.70E-01
Coal, 18 MJ/ kg	kg	2.05E-01	6.64E-01	1.04E+00	4.01E-03	1.71E+00	-1.50E+00
Oil, crude, 42.6 MJ/ kg	kg	2.84E+00	1.32E+00	2.29E+00	5.57E-02	3.66E+00	-8.17E-01
Total energy use	MJ	1.80E+02	9.15E+01	1.56E+02	3.52E+00	2.51E+02	-7.11E+01
Recycling glass	kg	1.78E+01	0.00E+00	0.00E+00	3.48E-01	3.48E-01	1.74E+01
Calumite	kg		1.03E-01	1.62E-01		2.65E-01	-2.65E-01
Dolomite, in ground	kg		1.28E+00	2.01E+00		3.28E+00	-3.28E+00
Limestone, in ground	kg	9.08E-02	1.69E+00	2.57E+00	1.78E-03	4.27E+00	-4.18E+00
Sand, quartz, in ground	kg		4.01E+00	6.35E+00		1.04E+01	-1.04E+01
Sodium chloride	kg	1.14E-01	1.65E+00	2.46E+00	2.23E-03	4.11E+00	-3.99E+00
Emissions to air							
PM	kg	1.20E-02	1.39E-02	1.86E-02	2.35E-04	3.27E-02	-2.07E-02
CH_4	kg	1.32E-02	5.03E-03	8.69E-03	2.58E-04	1.40E-02	-7.85E-04
NMVOC	kg	2.32E-02	1.31E-02	2.21E-02	4.54E-04	3.56E-02	-1.24E-02
CO_2	kg	9.80E+00	6.40E+00	1.12E+01	1.92E-01	1.78E+01	-8.01E+00
CO	kg	4.52E-03	9.96E-03	1.65E-02	8.86E-05	2.65E-02	-2.20E-02
NH_3	kg	4.42E-05	5.81E-04	9.19E-04	8.66E-07	1.50E-03	-1.46E-03
HF	kg	3.96E-04	2.97E-05	1.81E-05	7.76E-06	5.55E-05	3.41E-04
N_2O	kg	2.84E-05	1.65E-05	2.72E-05	5.57E-07	4.43E-05	-1.59E-05
HCl	kg	9.92E-04	5.24E-04	1.45E-03	1.94E-05	1.99E-03	-9.96E-04
SO_x	kg	1.26E-02	3.56E-02	3.99E-02	2.47E-04	7.58E-02	-6.32E-02
NO_x	kg	5.13E-02	8.03E-03	9.41E-03	1.01E-03	1.84E-02	3.29E-02
Emissions to water							
Nitrate	kg	9.70E-05	9.92E-02	1.86E-01	1.90E-06	2.85E-01	-2.85E-01
Ammonium, ion	kg	1.79E-04	4.65E-01	7.65E-01	3.52E-06	1.23E+00	-1.23E+00
Phosphate	kg	1.73E-05	1.93E-02	3.79E-02	3.38E-07	5.73E-02	-5.73E-02

A.2: Background information related to sustainability assessment of landfilling

Collection and transportation of waste and disposing at the sanitary landfill are the major phases of the lifecycle and all the inputs and outputs were compiled for these two phases including fuel production chain, emissions from fuel burning in compactor trucks (PCD, 2009a), HDPE linear manufacturing and waste degradation at landfill.

Emissions and resource consumption for one liter of diesel production is summarized in Table A7. This process includes crude oil extraction in Iran, crude oil transport to Thailand and diesel production at refineries in Thailand (LIPASTO, 2009; Pré Consultants, 2007a).

Table A7: Resource consumption and emissions from diesel production process chain

Resource	amount (g)/L	Emissions	amount (g)/L	Emissions	amount (g)/L	Emissions	amount (g)/L
Baryte	8.64	CO_2	717.58	CH_4	7.73	VOC	14.49
Coal, 18MJ per kg, in ground	19.19	CO	1.01	NO	3.50	SO_4^-	1.11
Coal, brown 8MJ per kg, in ground	14.24	PM	0.41	Nox	1.40	NO_3^-	0.03
Oil cude,42.6MJ per kg	1070.45	H_2	0.01	N_2O	0.01	NH_4	0.06
Iron	4.41	HCl	0.00	SO_2	3.27		

Basic information related to collection of MSW and transportation to Nonthaburi landfill

Total transportation distance from collection to landfill: 50 km

Fuel requirement for 1 tonne of waste transportation: 6.25 L of diesel

Table A 8: Emissions from transportation – Heavy Duty Truck (source: PCD, 2009a)

Emissions	THC	CO	NO_x	CO_2	PM
g/km	4.189	30.239	17.427	1671.54	4.633

Emissions and resource consumptions from HDPE liner manufacturing

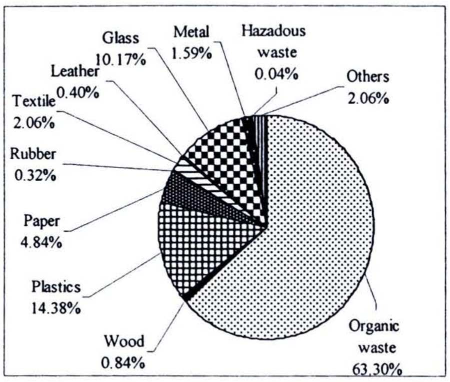
1.5 mm thick HDPE liner is used in Nonthaburi landfill for the bottom area of the landfill and for side walls to a vertical height of 9m. Considering the target filling capacity of the landfill, HDPE liner requirement was calculated for the functional unit and it amounts to 0.126 kg of HDPE/tonne of waste management under the existing situation.

Table A 9: Resource consumption and emissions from HDPE liner manufacturing (Source: Pre Consultants, 2007b)

Materials	Amount (g)/kg of HDPE	Emissions	Emissions (g)/ kg of HDPE
Baryte	7.16	CO_2	2300
Bauxite	0.2	CO	1.03
Coal 18MJ/kg	102	CH_4	9.35
Coal brown 8MJ/kg	119	NO_x	5.8
Iron	8.75	VOC	12.3
Oil crude 42.6MJ/kg	1630	PM	1.06
		SO_x	16.3

Physical and chemical characteristics of MSW

All the emissions during waste degradation period in the landfill depends on the chemical and physical characteristics of waste and characteristics of MSW in Nonthaburi can be summarized as follows (Nonthaburi Municipality, 2010):



Parameter	Value (%)
Moisture content (%)	59.54
Total Solid (%)	39.46
Combustible Solids (%)	97.52
Ash content (%)	9.45
Volatile Solids (%)	29.55
C (%)	16.42
N (%)	1.66
P (%)	0.42
K (%)	0.57
HCV (Kcal/kg)	4917
LCV (Kcal/kg)	1446

Quantification of landfill methane production

CH_4 is the major greenhouse gas which is being emitted from the existing MSW landfills. Intergovernmental Panel on Climate Change (IPCC) waste model was used to calculate methane generation potential from Nonthaburi landfill (IPCC, 2006) (Note: The most updated default values and the information of IPCC model is recomended to use for similar kind of assessment in the future). Based on the waste composition and the landfill conditions, calculated default values for Nonthaburi landfill are; Methane Correction Factor (MCF) –1, Degradable Organic Carbon (DOC) - 0.123, Fraction of DOC Dissimilated (DOC_f)- 0.5, Methane generation rate constant (k)- 0.259, fraction of methane in landfill gases (F)-0.5. Methane oxidation factor in landfill cover was taken as 0.15 (Wangyao et al., 2009). The IPCC waste model showed that the methane emissions from landfill take place significantly over the first 40 years after waste disposal. Based the above default values, the estimated total potential methane generation from one tonne of waste is 34.9 kg. Other emissions from landfill such as NH_3, H_2S, NO_2^-, NO_3^-, VOC etc were estimated based on leachate quality parameter of Nonthaburi landfill and the chemical characteristics of MSW.

Table A 10: Inventory analysis result of the existing landfill-,Nonthaburi

Energy and material use	Fuel production and transportation	Final Disposal	Total
Inputs (kg)			
Coal 18 MJ (per kg)	1.24E-01	1.29E-02	1.37E-01
Coal brown 8MJ (per kg)	9.22E-02	1.50E-02	1.07E-01
Oil Crude	6.94E+00	2.06E-01	7.14E+00
Iron	2.86E-02	1.10E-03	2.97E-02
Bauxite	5.60E-02	9.04E-04	5.69E-02
Emissions (kg)			
CO_2	2.65E+01	0.00E+00	2.65E+01
CH_4	5.13E-02	3.49E+01	3.50E+01
CO	3.85E-01	0.00E+00	3.85E-01
NO_x	2.55E-01	0.00E+00	2.55E-01
N_2O	7.10E-05	0.00E+00	7.10E-05
NH_3	3.56E-04	1.02E+01	1.02E+01
SO_x	2.48E-02	0.00E+00	2.48E-02
H_2S	0.00E+00	4.47E-01	4.47E-01
VOC	1.48E-01	8.34E-05	1.48E-01
PM	6.08E-02	0.00E+00	6.08E-02
NO_3^-	1.50E-04	9.01E-01	9.01E-01

A.3 Background information related to quantification of indicators

Environmental cost calculation: WTP for environmental pollution

In this study, Swedish EPS model (Steen, 2000) was utilized to estimate the environmental cost of the emissions and resource consumption. It is hypothesized that the WTP is proportional to the per capita income (GDP expressed in terms of purchasing power parity – GDP (PPP)) (Nguyen and Gheewala, 2008). For instance, the following equation can be used to estimate WTP for Thailand.

$WTP_{Thailand} = WTP_{Sweden} \times \text{Per capita GDP(PPP)}_{Thailand}/\text{Per Capita GDP(PPP)}_{Sweden}$

Per capita $GDP(PPP)_{Thailand}$/Per capita $GDP(PPP)_{Sweden}$ is the "income elasticity of WTP" and the derived value is 0.21 (GDP(PPP) of Thailand 8400 US$, GDP(PPP) of Sweden, 38200 US$) (CIA, 2008).

Table A11: Derived WTP values for environmental emissions and resource consumption in selected Asian countries

Emissions/Resources	WTP Sweden EUR/kg	WTP Thailand (THB)/kg	WTP Sri Lanka (SLR/kg)	WTP India (INR/kg)
CH_4	2.72	31.47	52.57	13.96
CO_2	0.11	1.25	2.09	0.55
NH_3	1.96	22.67	37.88	10.06
N_2O	38.30	443.08	740.19	196.55
CO	0.33	3.82	6.38	1.69

NO_x	2.13	24.64	41.16	10.93
SO_x	3.27	37.83	63.20	16.78
H_2S	4.96	57.38	95.86	25.45
NOx (NO_3^-)	2.13	24.64	41.16	10.93
VOC	2.14	24.76	41.36	10.98
PM_{10}	36.10	417.63	697.67	185.26
Fossil Oil	0.51	5.85	9.78	2.60
Fossil Coal	0.05	0.58	0.96	0.26

DALYs calculation- Characterization factors

Damage to human health was calculated using characterization factors for different types of emissions as summarized in Table A12. The characterization factors imply the damage to human health occuring due to diseases occurrence through various damage pathways.

Table A12: Characterization factors for DALYs calculation (Source: Steen, 2000).

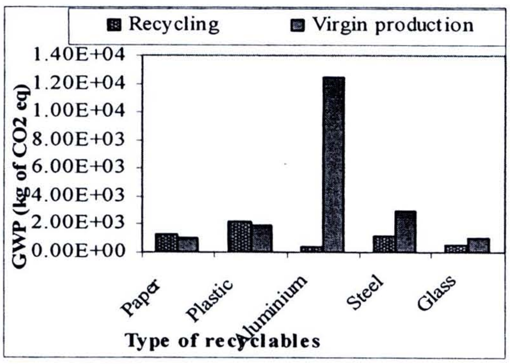
Type of emissions	Mortality (YOLL/kg)	Severe morbidity (YLD)/kg	Morbidity (YLD)/kg
CH_4	1.95E-05	8.65E-06	1.60E-05
CO_2	7.93E-07	3.53E-07	6.55E-07
NH_3	2.64E-05	-4.66E-06	7.22E-06
N_2O	2.87E-04	1.10E-04	2.14E-04
CO	2.38E-06	1.06E-06	1.96E-06
NO_x	2.45E-05	-2.06E-06	3.61E-06
SO_x	3.76E-05	-6.58E-06	1.02E-05
H_2S	5.60E-05	-9.80E-06	1.53E-06
NOx (NO_3-)	2.45E-05	-2.06E-06	3.61E-06
VOC	1.53E-05	4.252E-06	0
PM_{10}	4.24E-04	-2.33E-06	3.61E-06
HCl	2.42E-05	-4.29E-06	6.64E-06

A.4 Environmental sustainability assessment of the existing MSW management system

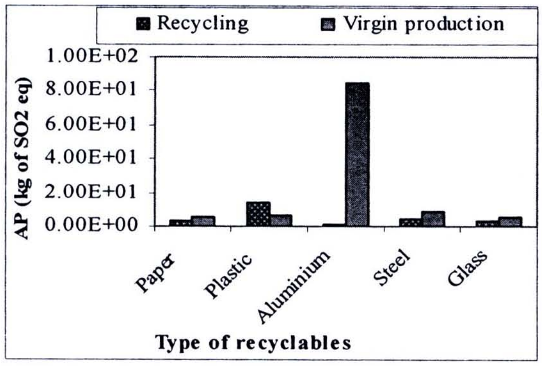
Evaluation of recycling by using midpoint indicators

Major environmental degradation caused by the emissions/resource consumption from recycling and virgin production processes were categorized into several major impact indicators such as global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photo- oxidant formation potential (POFP), abiotic resource depletion potential ADP and Human toxicity potential (HTP). These midpoint indicators were quantified using the inventory analysis results and LCA characterization factors for the different type of emissions (Guinée et al., 2001). The above inventory analysis data was used to quantify the potential environmental impacts from recycling of different types of recyclables as well as from virgin production.

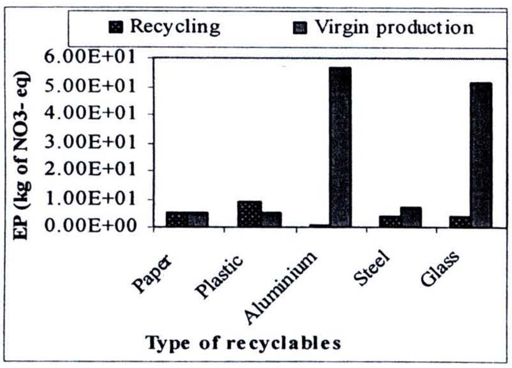
Basic comparison between magnitude of environmental impacts from one tonne of each type of recyclable waste recycling and production of equal amount of primary materials from virgin production process would be really important in the decision making process. For this purpose, quantified midpoint environmental indicators are shown in Figure A4. It should be noticed that, in comparison to other recyclables, the effects of aluminium recycling are remarkable. The aluminium virgin production process is causing severe environmental degradation (see Figure A4) due to the massive amount of fossil fuel consumption and its emissions. Thus, the recycling process would significantly make its influence in avoiding the resource consumption and emissions from the virgin production process.



Global warming potential



Acidification potential



Eutrophication potential

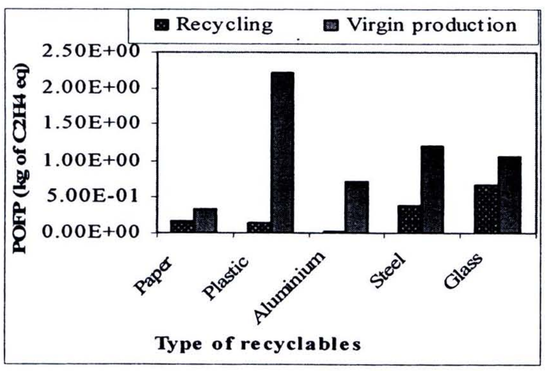
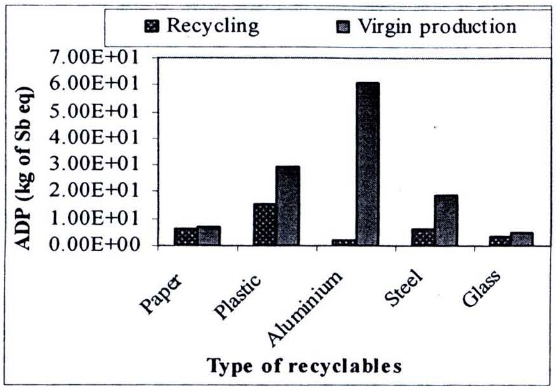
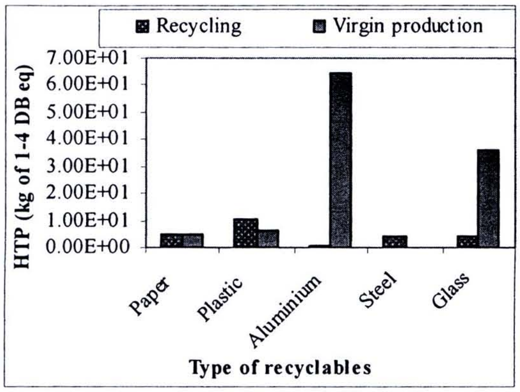


Photo-oxidant formation potential





Abiotic resource depletion potential Human toxicity potential

Figure A4: Quantified midpoint indicators for one tonne of each type of waste recycling and equal amount of primary material production via virgin production process

Furthermore, quantification of environmental impacts from a recyclable mix in Nonthaburi Municipality was calculated giving due consideration to the composition of collected recyclables and the recyclability of different fraction of waste see Table A13. It should be noticed that 66% of collected recyclables, consists of steel and aluminium, thus the effects of recycling of these fractions would considerably influence the sustainability of the existing system. Net impacts of recycling of 243 kg of waste (this is the amount of recycling from each tonne of waste generated in Nonthaburi) has caused a net negative values for all the impact categories due to credited impacts for avoidance of virgin production process. These results reflected that recycling is far more sustainable compared to virgin production, as it consumes less energy and materials and it leads to less emission see Table A13.

Evaluation of landfilling by using midpoint indicators

The same set of midpoint indicators were used to assess the environmental impacts of the sanitary landfill at Nonthaburi. The inventory analysis of the existing sanitary landfill is shown in Table A.10. The impacts were quantified for the major two phases of the life cycle such as the collection and transportation and the final disposal. The result clearly indicate that the existing sanitary landfill is causing enormous environmental damage, see Table A14.

It should be noticed that, the biggest share of all the environmental damage occurs in the final disposal stage except abiotic resource depletion potential. In fact, 98.6% of GWP, 98.9% of AP, 71.3% of EP, 73.2% of POFP and 73.8 % of HTP is results from final disposal due to the massive amount of pollutants emission during the degradation process. In contrast, collection and transportation of waste has contributed to the biggest share of ADP (97.0%) due to the considerable amount of fossil fuel consumption for transportation. It is noticeable that ADP caused from HDPE liner manufacturing is not significant when compared to the potential damage in transportation. Then taking into account the overall impacts from both recycling and landfilling, the midpoint indicators were quantified for the existing situation of Nonthaburi, see Table A15.

Even though, a larger fraction of generated waste is being landfilled in Nonthaburi, the 24% waste recycling has notably influenced the reduction of overall environmental degradation. In fact, as an outcome of credited impacts of recycling, GWP, EP, ADP and HTP have shown net negative values see Table A15.

Table A13: Summary of environmental impacts of recycling, virgin production and net impacts at midpoint level (Note: all the impacts are calculated for the amount of recyclables that have mentioned in the first column)

	Global warming potential (kg of CO_2 eq)		Acidification Potential (kg SO_2 eq.)		Europhication Potential (kg NO_3^- eq.)		Photo Oxidant Formation Potential (kg C_2H_4 eq.)		Abiotic resources Depletion Potential (kg Sb eq.)		HT potential	
Type of waste	Recycling	Virgin Production	Recycling	Virgin production	Recycling	Virgin production	Recycling	Virgin production	Recycling	Virgin production	Recycling	Virgin production
Paper (55.8kg)	7.06E+01	5.41E+01	1.97E-01	2.85E-01	2.86E-01	2.88E-01	9.24E-03	1.81E-02	3.64E-01	3.76E-01	2.62E-01	2.77E-01
Plastic (7.8 kg)	1.72E+01	1.52E+01	1.10E-01	5.89E-02	7.30E-02	4.69E-02	1.18E-03	1.77E-02	1.25E-01	2.35E-01	8.54E-02	4.95E-02
Aluminium (64.86 kg)	2.54E+01	8.08E+02	5.36E-02	5.45E+00	6.03E-02	3.65E+00	2.03E-03	4.56E-02	1.51E-01	3.93E+00	6.39E-02	4.16E+00
Steel (97.02kg)	1.07E+02	2.86E+02	4.33E-01	8.37E-01	3.66E-01	6.80E-01	3.72E-02	1.16E-01	5.78E-01	1.84E+00	3.92E-01	0.00E+00
Glass (17.8 kg)	1.01E+01	1.82E+01	4.86E-02	9.15E-02	6.98E-02	9.14E-01	1.19E-02	1.90E-02	6.80E-02	9.02E-02	7.26E-02	6.35E-01
Total impacts	**2.30E+02**	**1.18E+03**	**8.42E-01**	**6.72E+00**	**8.55E-01**	**5.58E+00**	**6.16E-02**	**2.16E-01**	**1.29E+00**	**6.47E+00**	**8.76E-01**	**5.12E+00**
Net impact from 243 kg of waste recycling	**-9.51E+02**		**-5.88E+00**		**-4.73E+00**		**-1.55E-01**		**-5.19E+00**		**-4.25E+00**	

Table A14: Quantified midpoint indicators for sanitary landfill in Nonthaburi (per tonne of MSW)

Environmental Indicator	Unit	Total impact	Impact from fuel production, collection and transportation	Impact from disposal (HDPE liner manufacturing + dumping)
Global Warming Potential (GWP)	kg of CO_2 equivalents	9.02E+02	2.84E+01	8.74E+02
Acidification potential (AP)	kg of SO_2 equivalents	2.02E+01	2.18E-01	2.00E+01
Eutrophication potential (EP)	kg of NO_3^- equivalents	1.26E+00	3.63E-01	9.01E-01
Photo- Oxidant formation potential (POFP)	kg of C_2H_4 equivalents	3.34E-01	8.95E-02	2.45E-01
Abiotic resource Depletion Potential (ADP)	kg of Sb equivalents	1.48E-01	1.44E-01	4.39E-03
Human toxicity potential (HTP)	kg of 1,4 DB equivalents	1.73E+00	4.53E-01	1.28E+00

Table A15: Net impacts from the existing MSW management system in Nonthaburi

Contribution of treatment methods to overall impacts	Global warming potential kg of CO_2 eg	Acidification Potential kg of SO_2 eq	Europhication Potential kg of NO_3^- eq	Photo Oxidant formation Potential kg of C_2H_4 eq	Abiotic resources Depletion Potential kg of Sb eq	HT potential kg of 1,4 DB eq
Net impact from recycling of **243 kg of recyclables**	-9.51E+02	-5.88E+00	-4.73E+00	-1.55E-01	-5.19E+00	-4.25E+00
Net impact from landfilling of **757 kg of MSW**	6.83E+02	1.53E+01	9.56E-01	2.53E-01	1.12E-01	1.31E+00
Total impacts from 1 tonne of generated MSW	**-2.68E+02**	**9.44E+00**	**-3.77E+00**	**9.82E-02**	**-5.07E+00**	**-2.94E+00**

A.5 Information related to economic sustainability assessment - Detailed LCC calculation at sorting and recycling facilities

-LCC at sorting facility

All financial information related to sorting and preprocessing was collected from the sorting plant at Nonthaburi. The total fixed capital cost was calculated by using cost of land, cost of yard improvement and cost of buildings. It was assumed that the life time of the sorting facility is 50 years when calculating the capital cost per tonne of waste. In order to calculate the present value of the fixed capital cost per tonne of mix recyclable, future value calculation was done for the year 2010, considering 3% of inflation rate in Thailand.

Total movable capital cost was estimated by including the cost of buying and cost of installation of all the equipment. The maximum life time of the machinery is considered as 10 years for the cost estimation for a functional unit. Fixed and movable capital cost was added, to arrive at the total capital cost per tonne of mix recyclable processing at the sorting facility.

However, it was a challenging task to allocate the capital cost among the different types of recyclables. Hence, allocation was done based on net revenues earning potential and the composition from different type of recyclables. It is notable that operational and maintenance costs signify the major share of LCC for a sorting facility (Table A16). That includes all the costs related to buying recyclables, labour wages, electricity and fuel cost, other operating suppliers, insurance and taxes, etc. The highest percentage of operational and maintenance cost comes from buying recyclables (see Table A.16) which contributes to 93%, 87%, 89%, 55% and 96% for paper, plastic, aluminium, glass and metal, respectively in Nonthaburi.

Except the buying cost of various types of recyclables, all other monthly operational and maintenance costs were allocated among the different types of processed recyclables based on the net revenue generation potential. Similarly, estimated total environmental cost for the plant emissions was allocated among the different types of processed recyclables. The cost factors and gross LCC for processing of recyclables at the sorting plant is summarized in Table A.16.

Table A.16: Breakdown of LCC for pre-processing at sorting plant- Nonthaburi (baht/tonne of recyclables)

Summary	Capital cost (baht/tonne)	Operational and maintenance cost			Environmental cost (baht/tonne)	Total LCC at the sorting facility (baht/tonne)
		Buying cost of recyclables (baht/tonne)	Other O & M cost (Baht/tonne)	Total O & M cost (baht/tonne)		
Paper	8.48E+01	4.38E+03	3.25E+02	4.70E+03	1.02E+01	4.80E+03
plastic	2.73E+02	7.28E+03	1.04E+03	8.32E+03	3.28E+01	8.63E+03
Aluminium	1.40E+03	4.50E+04	5.35E+03	5.03E+04	1.68E+02	5.19E+04
Glass	1.29E+02	6.14E+02	4.94E+02	1.11E+03	1.55E+01	1.25E+03
Metal	1.05E+02	1.05E+04	4.01E+02	1.09E+04	1.26E+01	1.10E+04

LCC for the recycling process of different types of recyclables at the recycling facilities

The most reliable financial data (capital cost, operational and maintenance cost) was obtained from some of the best recycling plants in Thailand. Environmental cost was calculated for the emissions and resource consumption, based on inventory analysis data of each type of recyclables. It was noticed that operational and maintenance cost share the major fraction of LCC mainly due to high labour, electricity and the primary energy cost of the recycling processes. LCC breakdown for different types of recyclables is shown in Figure A.5.

A.6 Social Sustainability Assessment

Income based community well-being

The total income generation potential to the community from selling of various types of recyclables in Nonthaburi has been shown is Table A.17. These average buying prices of recyclables were obtained from Wongpaint group, which is one of the biggest waste management/recyclables collecting companies in Thailand.

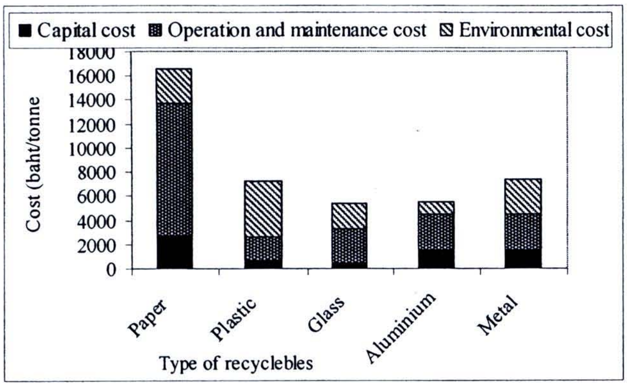


Figure A5: LCC of recycling process at recycling facilities

Table A.17: Daily net income generation potential to the community by selling recyclables

Major recyclable category	Collected amount per day (tonnes)	Different type of recyclables	Weight (tonnes)/day	Average buying price /kg **	Total income (baht/day)
Paper	20.63	Office paper	1.02	7.00	7,131.75
		Newsprint	5.26	5.00	26,319.55
		Laminated paper (magazine)	8.11	3.00	24,324.36
		Kraft paper	4.92	5.00	24,621.51
		Milk carton	1.32	6.00	7,895.86
Plastic	2.96	Plastic bag (PP)	0.77	1.00	766.33
		PET	0.13	13.00	,704.79
		PVC	0.20	10.00	1,967.06
		PS	0.06	1.00	57.37
		Foam(EPS)	0.11	1.00	114.75
		HDPE	1.46	10.00	14,630.02
		LDPE	0.23	10.00	2,294.90
Glass	6.58	Glass clear color	2.49	0.80	1,994.80
		Amber	3.96	0.50	1,978.05
		Green	0.13	0.50	64.43
Aluminium	23.93	Aluminium	23.93	45.00	1,076,969.36
Metal	35.90	Metal	35.90	10.50	376,939.27
Total	**90.00**		**90.00**		**1,569,774.16**
Income generation potential per tonne of mix recyclables (baht/tonne)					**17,442**

(** - Average buying price of recyclables was obtained from Wongpaint group which is one of the biggest waste management/recyclables collecting companies in Thailand)

It should be noted that the highest income generation potential is resulted by selling aluminium and metal. As Wongpaint group is buying such recyclables for a good price, people in the community are putting more effort on collecting valuable recyclables like aluminium than less valuable recyclables like plastic, paper. Due to this reason, still the major share of generated plastic, paper waste goes to the landfill alone with other mix wastes.

APPENDIX B

B1. Inventory analysis of the upgraded MSW system with LFG recovery for electricity production

According to the information obtained from the Nonthaburi Provincial Administration council, the existing landfill will be sufficient to dispose the waste for the period of 5 years (Nonthaburi Municipality, 2010). As Nonthaburi Municipal Administration has already planned to incorporate a LFG recovery system, it was assumed that such LFG recovery project can be initiationed in the second year. According to El Hanandeh and El-Zein (2010) the bulk of the LFG is released within the first few years and the rest being released over an extended period of time. As reported, 75% of generated LFG can be collected using the available technologies (EPA, 2009; Wanichpongpan and Gheewala, 2007). During the peak period of LFG production, excess methane will be flared off to avoid global warming potential. 15% of methane from the fraction that is passing through the landfill cover, can be oxidized due to microbial activities within the landfill cover before it is released to the atmosphere (Wangyao et al., 2009).

IC engine for electricity production

To produce the electricity from the collected LFG, a reciprocating internal combustion (IC) engine can be used. IC engine represents the most employed technology for electric energy generation from LFG. The reason is mainly due to the compatibility of the power with the economic feasibility of the system. Very often, in fact, a suitable system size for acceptable economic revenue is between 1-3MW, and the investment cost of the IC engine for that size is really reasonable (EPA, 2009; Bove and Lunghi, 2006; Shrestha and Narayanan, 2008).

The number of generator sets installed would vary during the life of the project depending on the quantity of LFG available. It was assumed that LFG extraction can be started in the second year while waste tipping continues (Hanandeh and El-Zein, 2010) since methane production is quite fast in the tropical climatic situation. At the beginning only a1.5 MW IC engine would be sufficient. As more LFG is generated, additional engines will be added into the project. In addition, a sufficient LFG flaring system should also be installed to ensure that any surplus LFG is flared, if engine capacity is insufficient or during periods of maintenance or breakdown. According to the IPCC model calculation, the volume of gas is expected to increase after two more years, when the landfill reaches its maximum capacity.

Thus, an additional 1.5 MW IC engine should be incorporated in the system for maximum LFG extraction. As reported by many authors, it was assumed that electricity efficiency of IC engine is 35% (EPA, 2009; Wanichpongpan and Gheewala, 2007; Baratieri et al., 2009). All the onsite information of the existing sanitary landfill was taken for the evaluation purpose. In addition, energy consumption and emissions of the IC engine, capital cost of the IC engine, operational and maintenance cost etc were collected from different sources of literature (Bove and Lunghi, 2006; EPA, 2009). The electricity production process from LFG will significantly reduce GHG emission by replacing the same amount of electricity production via conventional methods. Thus, the data related to emissions and resources consumption of Thai grid electricity production was found to be credited to the electricity production process from LFG recovery (DEDE, 2008).

For financial and social life cycle assessment, additional data related to energy recovery process from LFG was collected from the different sources of literature. In fact, capital cost, operational and maintenance cost of IC engine, sellable price of electricity to the grid etc was collected from reports of EPA and EGAT-Thailand (EPA, 2009; EGAT, 2008). In order to perform a social life cycle assessment, the information related to additional employment opportunities that would be created by the initiated LFG project was taken into account.

Quantification of landfill methane production potential

Based on the characteristics of MSW and the landfill conditions, default values were derived to quantify the methane production potential by using IPCC model (IPCC, 2006). Calculated default values for Nonthaburi sanitary landfill are: Methane Correction Factor (MCF) –1, Degradable Organic Carbon (DOC) - 0.123, Fraction of DOC Dissimilated (DOC_f)- 0.5, Methane generation rate constant (k)- 0.259, fraction of methane in landfill gases (F)-0.5. Methane oxidation factor in the landfill cover was taken as 0.15 (Wangyao et al., 2009). The average waste disposal capacity at Nonthaburi landfill is 900 tonnes/day. Total amount of methane generated and the trend of LFG production, due to waste dumping for the period of 5 years period is shown in Figure B1. In addition, this Figure clearly indicates the amount of methane gas collected, the amount of collected methane use for electricity production and the amount of fugitive methane which could emit to the atmosphere.

For analytical purposes, all the above parameters should be calculated for one tonne of MSW disposed. Thus, the estimated potential methane generation, amount of methane collection, electricity production potential, flared methane and fugitive methane per tonne of disposed waste at the landfill is described in Chapter 6 (Table 6.1).

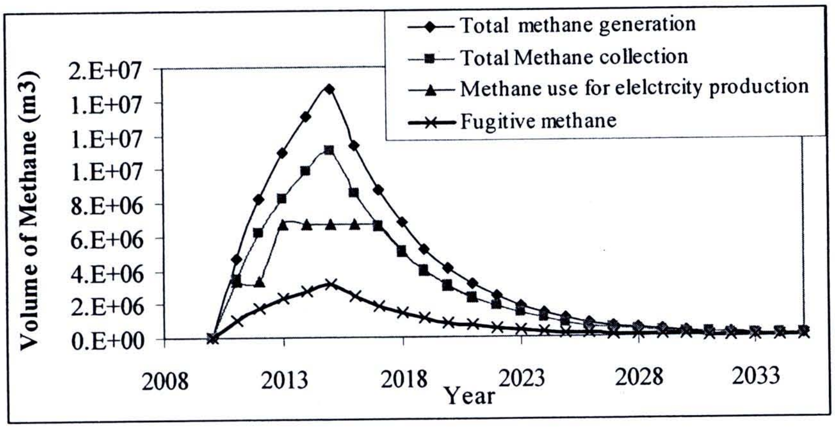


Figure B1: Methane generation potential and usage of methane for electricity production

Life cycle inventory analysis of sanitary landfill with LFG recovery system

The three major phases of fuel production, collection and transportation and final disposal were identified in relation to sanitary landfill with LFG recovery. Inventory analysis results for the three phases are shown in Table B1. In addition, the potential avoid emissions/resources consumption due to credited electricity production from LFG (125.8 kWh/tonne) is also shown in Table B1. For this purpose, emissions and resource consumption from grid mix electricity production in Thailand (DEDE, 2008) was taken into account to estimate the potential credited emissions/resource consumption.

Table B1: Life cycle inventory analysis for the upgraded sanitary landfill in Nonthaburi

Life cycle inputs/ outputs	Resources /Emissions	Resource consumption and emissions from sanitary landfill +LFG collection				Credited resource consumption and emissions	Net Resource consumption and emissions
		Fuel production	Collection + transportation	Final Disposal	Total		
Energy and material use	Coal 18 MJ /kg	1.24E-01	0.00E+00	4.21E-02	1.66E-01		1.66E-01
	Coal brown 8MJ (per kg) /kg	9.22E-02	0.00E+00	4.92E-02	1.41E-01	2.48E+01	-2.47E+01
	Oil Crude	6.93E+00	0.00E+00	6.73E-01	7.61E+00	2.11E-01	7.40E+00
	Natural gas (m^3)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.18E+01	-2.18E+01

	Iron	2.86E-02	0.00E+00	3.62E-03	3.22E-02		3.22E-02
	Bauxite	5.60E-02	0.00E+00	2.96E-03	5.89E-02		5.89E-02
Emissions to air	CO_2	4.56E+00	2.09E+01	1.55E+00	2.70E+01	7.11E+01	-4.41E+01
	CH_4	5.01E-02	0.00E+00	8.74E+00	8.79E+00	5.97E-03	8.78E+00
	CO	6.48E-03	3.78E-01	9.72E-02	4.82E-01	5.80E-02	4.24E-01
	NO_x	2.97E-02	2.18E-01	1.03E-01	3.51E-01	2.23E-01	1.28E-01
	N_2O	6.78E-05	0.00E+00	0.00E+00	6.78E-05		6.78E-05
	NH_3	3.56E-04	0.00E+00	1.02E+01	1.02E+01		1.02E+01
	SO_x	2.04E-02	0.00E+00	7.48E-03	2.78E-02	3.01E-01	-2.73E-01
	H_2S	0.00E+00	0.00E+00	4.47E-01	4.47E-01		4.47E-01
	VOC	9.38E-02	5.24E-02	5.70E-03	1.52E-01		1.52E-01
	PM	2.55E-03	5.79E-02	5.43E-04	6.10E-02	6.82E-02	-7.19E-03
Emissions to water	SO_4^-	7.16E-03	0.00E+00	0.00E+00	7.16E-03		7.16E-03
	NO_3^-	2.06E-04	0.00E+00	1.23E-01	1.23E-01		1.23E-01
	HCl	1.37E-05	0.00E+00	0.00E+00	1.37E-05		1.37E-05
	NH_4^+	3.56E-04	0.00E+00	1.25E-01	1.25E-01		1.25E-01

B2. Evaluation of the upgraded MSW management system using midpoint indicators

Detailed inventory analysis related to recycling processes of various recyclables is shown in Appendix A. As noticed, environmental degradation occurrence and avoidance potential at mid point level from recycling as well as virgin production processes have been already quantified in the Appendix A4. Thus, quantified effects of 24 % of generated MSW recycling on various midpoint impact categories (see Table A.15) was used in this part of research to obtain the end results from the upgraded MSW management system.

Midpoint indicators for sustainability assessment of sanitary landfilling with LFG recovery

The most relevant midpoint indicators such as global warming, acidification, eutrophication, photo-oxidant formation, abiotic resource depletion and human toxicity potential were quantified based on the inventory analysis results of sanitary landfill with LFG recovery. The detail life cycle inventory analysis results of sanitary landfill are shown in Table B1. Based on the inventory analysis, the impacts from sanitary landfilling and the potential credited impacts due to the electricity production (125.8 kWh/tonne) was estimated (Table B2). The net impacts from upgraded landfill were quantified by subtracting the credited impacts from the gross impacts.

It should be noted that in comparison to the existing landfill, LFG recovery process has significantly influenced the reduction of midpoint impacts. In fact, the upgraded system with LFG recovery has reduced 82.4% GWP, 1.91% AP, 41.1% EP, 53.9% POFP, 32.6% ADP and 42.1% HTP when compared to the existing landfill without LFG recovery.

Table B2. Gross and net midpoint impacts from the sanitary landfill + LFG recovery

Environmental Indicator	Unit	Gross impact (collection, transportation+ landfill)	Credited Impacts for electricity production	Net Impacts
Global Warming Potential(GWP)	kg of CO_2 eq/tonne	2.30E+02	7.14E+01	1.59E+02
Acidification potential (AP)	kg of SO_2 eq/tonne	2.03E+01	4.57E-01	1.99E+01
Eutropication potential (EP)	kg of NO_3^- eq/tonne	1.04E+00	3.01E-01	7.43E-01
Photo- Oxidant formation potential (POFP)	kg of C_2H_4 eq/tonne	1.56E-01	2.36E-03	1.54E-01
Abiotic resource Depletion Potential(ADP)	kg of Sb eq/tonne	1.58E-01	4.93E-01	-3.35E-01
Human toxicity potential (HTP)	kg of 14 DB eq /tonne	1.59E+00	5.90E-01	1.00E+00

It would be an interesting point to know the overall impacts from Nonthaburi MSW management, after initiation of LFG recovery system. Thus impacts from both recycling (24 % of generated waste) and landfilling (76% of generated waste) with gas recovery system were merged to arrive at the overall impacts from the upgraded system (Table B3).

Table B3: Net impacts from the upgraded MSW management system in Nonthaburi

Contribution of treatment methods to overall impacts	GWP kg of CO_2 eq/tonne	AP kg of SO_2 eq/tonne	EP kg of NO_3^- eq/tonne	POFP kg of C_2H_4 eq/tonne	ADP kg of Sb eq/tonne	HTP kg of 1-4 DB eq /tonne
Net impact from 240 kg of recycling	-9.51E+02	-5.88E+00	-4.73E+00	-1.55E-01	-5.19E+00	-4.25E+00
Net impact from 760 kg of MSW landfilling + LFG recovery	1.20E+02	1.50E+01	5.63E-01	1.17E-01	-2.54E-01	7.59E-01
Total impact from one tonne of generated waste	**-8.31E+02**	**9.16E+00**	**-4.16E+00**	**-3.81E-02**	**-5.44E+00**	**-3.49E+00**

As already discovered, outcomes from 24% of waste recycling are remarkable and it has significantly influenced the reduction of overall environmental degradations. In addition, it was noticed that upgraded sanitary landfill with LFG recovery system, is far more effective than the presently practiced landfill without gas recovery. Thus, as a whole, the system resulted in net negative values for all the impacts, except the acidification potential (Table B3). The ultimate effects of these midpoint impacts have been discussed in the sustainability assessment in Chapter 6.

B3. Information related to economic sustainability assessment

-Capital cost and operation and maintenance cost of LFG to electricity project

LFG energy project costs may include costs for the collection of gas and flaring, electricity generation. Generally, each LFG energy project will involve the purchase and installation of equipment (capital costs) and the expense of operating and maintaining the project (O&M costs).

The capital costs include costs for the electricity generation equipment as well as costs for typical compression and treatment systems appropriate to the particular technology and interconnection equipments. Operation and maintenance costs include the parts and materials, labour, financing costs, taxes and administration. Estimated operational and maintenance cost for the LFG to energy project is shown in Table B4.

In addition, one necessary component of an LFG energy project is the equipment for gas collection and flare system. This equipment gathers the LFG for combustion in the project's flare, electricity-generating equipment, or direct-use device, and provides a way to combust the gas when the project is not being operated. Capital cost and operational and maintenance cost of flaring system is also included in Table B4.

Table B 4: Capital, operation and maintenance cost of LFG to electricity project (Source: EPA, 2010)

Description	Cost	Unit
Capital cost of IC engine If engine size if more than (800kW)	1,700.00	$/kW
Capital cost of 1.5 MW engine	2,550,000.00	$/1.5 MW engine
Maintenance cost	180.00	$/kW/yr
Maintenance cost for 10 years	2,700,000.00	$/1.5 MW engine
Total cost	5,250,000.00	$/ 1.5 MW engine
Total cost for 2 set of engine	10,500,000.00	$/3 MW
Money Conversion Factor	30.14	baht/$
Total cost	316,470,000.00	Baht
Capital cost of generator	**93.59**	**Baht/tonne**
Operational and maintenance cost	**99.09**	**baht/tonne**
Flaring system		
Capital cost of landfill flaring system	5.93	$/m2
Operational and maintenance cost	1.01	$/m2
Total landfill area	161,600.00	m2
Total tonnage of waste disposal	1,642,500.00	tonnes
Allocation of capital cost for one tonne of waste	**17.59**	**Baht/tonne**
Allocation of operational and maintenance cost	**3.00**	**Baht/tonne**

APPENDIX C

C1. Suitability of technologies for the intended integrated MSW management system

-Recycling: It has been convincingly argued and proved, that recycling is an extremely sustainable option since a significant amount of valuable materials can be recovered from the recycling process (see Chapter 5 and Appendix A). Consequently, this would create tremendous outcomes in the environmental, economic, and social fields. Thus, incorporation of recycling to the integrated system would be the most precious activity to drive the entire system towards sustainability.

-Anaerobic digestion: Among the biological treatment methods, anaerobic digestion (AD) is usually the most cost-effective, due to the potential of high energy recovery linked to the process and its limited environmental impact (Alvarez et al., 2000). Biogas is the major output from AD which has a calorific value of 20-25 MJ/m^3. There are many technologies utilized over the world in the production of electricity from biogas. Decentralized power generation with combined heat and power (CHP) units and feed-in of the excess capacity to the national grid is the most common biogas utilization pathway (Pöschl et al., 2010). It has been noticed that burning of biogas in small engines (<200kW) and large internal combustion engines (up to 1.5 MW) lead to electrical conversion of 25% and 30-35%, respectively (Pöschl et al., 2010). However, electricity production potential can vary since biogas yield is influenced by several process conditions such as temperature, retention time, volumetric loading, degree of pre-treatment of feedstock and so on (Pöschl et al., 2010). Apart from the electricity production process, there is a potential of producing considerable amount of compost from the remaining sludge after the AD process. Thus, this process will have its effect as an additional environmental and economic advantage. However, to improve the compost quality, post treatment of these solids is required (Walker et al., 2009).

-Incineration: MSW incineration plants tend to be among the most expensive solid waste management options, and they require highly skilled personnel and careful maintenance. However, it provides the best way to eliminate methane gas emissions from waste management processes. Furthermore, energy obtained from waste projects provides a substitute for energy obtained from fossil fuel combustion. The most attractive feature of the incineration process is that it can be used to reduce the original volume of combustibles

by 80% to 95% (Rand et al., 2000). Due to all these reasons, incineration has become a popular MSW management method.

In order to achieve success in incineration projects, there are some criteria which should be met. The expected conditions are, a mature and well-functioning waste management system should be in operation for a number of years, the supply of combustibles waste should be stable throughout the year, the lower calorific value must on average be at least 7 MJ/kg, and must never fall below 6 MJ/kg in any season, the community should be willing to absorb the increased treatment cost through management charges, tipping fees, and tax-based subsidies, the possibility of recruitment and maintenance of a skilled staff etc (Rand, et al., 2000).

-*Landfilling:* A landfill is also a necessary treatment method in an integrated MSW management system. It would be needed as a final disposal route for the residual products which cannot be treated by utilizing any of the above technologies.

Incorporating all those technologies, an integrated MSW management system was designed for Nonthaburi Municipality. Detailed evaluation was done for all the individual technologies as well as the intended integrated MSW management system within the designed LCA framework in order to find out the three dimensional sustainability.

C2. Inventory analysis of appropriate technologies

-*Recycling*: It was assumed that there are no changes to the currently practiced recycling option and it will be operated in a similar way as at presents. As seen, a detail inventory analysis of the current recycling process is presented in Appendix A. Thus, the inventory analysis results will be used for quantifying the contribution of recycling for the sustainability of the intended integrated system.

-*Collection and transportation of mixed waste*: As practiced at present, mixed MSW will be collected and transported by compactor trucks. Therefore, transportation distances, fuel consumption efficiency of the vehicles and the emissions from compactor trucks, capital cost of the vehicles, operational and maintenance cost and labour power consumption etc were taken into account.

-*Sorting of waste*: After the collection and transportation, the mixed wastes should be unloaded at the sorting plant. Then, the mix wastes split into the several components. Basically the organic fraction will be separated from the inorganic part (the main flows), and incombustibles part should be separated from remaining combustible fraction. The mechanical equipments combined with manual sorting can be used for the sorting process. Segregation efficiency of waste at the sorting facility is a most important factor. It was assumed that the sorting efficiency of organic fraction of waste at the sorting facility is 75%. Therefore, only a fraction of organic waste can be treated using anaerobic digestion and the remaining food waste can be used for the incineration along with other combustibles. According to the mass balance analysis, the non combustible fraction amounts to 10% of total generated MSW and this is the fraction of waste that should go for landfilling. The mass balance of waste for the intended integrated MSW management system in Nothaburi is shown in Table C1. All the input requirements such as energy, labour power, capital cost, operational and maintenance cost etc at the sorting facility was accounted for in the inventory analysis based on the published data on mix waste sorting at On-Nuch sorting plant, Bangkok, Thailand (Nithikul et al., 2010).

Table C1: Mass balance for the intended integrated MSW management system

Treatment methods	type of treatment method	Mass balance for daily generated waste		Mass balance per functional unit	
	Total waste generation	**370**	tonnes/day	**1**	tonne
Total waste generation	Total point source separated recyclables	90	tonnes/day	243	kg/tonne
	Mix waste collected by LA	280	tonnes/day	757	kg/tonne
	Recycling fraction	24	%	24	%
Recycling	**Total waste for recycling**	**90**	**tonnes/day**	**243**	**kg/tonne**
	Total food waste in mixed MSW composition	178	tonnes/day	481	kg/tonne
Anaerobic digestion	Food waste sorting efficiency	75	%	75	%
	Total waste for anaerobic digestion	**133**	**tonnes/day**	**361**	**kg/tonne**
	Remaining food waste for combustion	44	tonnes/day	120	kg/tonne
	Combustible fraction of MSW	23	%	23	%
	Combustible amount	63	tonnes/day	171	kg/tonne
Incineration	**Total waste for incineration**	**108**	**tonnes/day**	**291**	**kg/tonne**
Land filling	Non combustible fraction	11	%	11	%
	Total waste for landfill	**39**	**tonnes/day**	**105**	**kg/tonne**

-*Inventory analysis of anaerobic digestion*: According to the mass balance, 133 tonne/day of organic waste can be sent to the AD facility. When it is calculated for a functional unit (1 tonne of generated waste treatment), 361 kg of organic waste can be treated by using AD to produce energy from each tonne of waste generated within the Municipality (see

Table C1). In order to do the life cycle inventory for AD technology, all the processes related to AD were studied and the data was gathered from different sources on collection and transportation, sorting, pretreatment, wet digestate preparation, methane production and electricity generation, dewatering of sludge and compost making, etc, (PCD, 2009; Nithikul et al., 2010; Pöschl et al., 2010; Rayong Municipality, 2010). Onsite energy requirement for different operations is an important feature in relation to AD process. For instance, the intended biogas plant in Nonthaburi will require energy mainly for sorting of waste (at sorting facility), particle size reduction, pre-treatment and sterilization, making wet digestate and so forth.

-Energy requirement for pre-treatment and sterilization: energy inputs requirements for pre-treatment and sterilization of food waste is 24 kWh of electricity per tonne and 22.4 kWh per tonne of thermal energy, respectively (Pöschl et al., 2010).

-Energy requirement for making wet digestate - wet digestion process is deployed for feedstock dry matter content of up to 12%, to facilitate the pumping and stirring. Therefore, 1.5 tonnes of additional water have to be added to each tonne of organic waste to make the wet digestate. Energy requirement for making wet digestate is mainly for water pumping and stirring and it amounts to 32MJ of primary energy per tonne of water addition (Pöschl et al., 2010).

-Energy requirement for heating the digesters – Typically it requires 20-25% of total heat component of Combined Heat and Power (CHP) generation and that amount can be supplied using the waste heat from electricity production process.

-Bio gas production from the digester: As reported, there is a potential of producing 308m^3 biogas per tonne of organic waste dry matter in AD process (Pöschl et al., 2010) and it is amounted to 92m^3 of biogas per tonne of wet organic waste. The AD facility implemented at Rayong Municipality- Thailand, has a gas production capacity of 100 m^3 per tonne of wet organic waste (Vanarruk, 2009). These figures indicate that biogas production potential from organic waste would be 90-100 m^3 per tonne of organic waste. This value was considered as the design capacity of intended AD facility and to calculate the potential electricity production from biogas (see Chapter 7, Table 7.1).

-Inventory analysis related to chemical fertilizer production: There is a possibility to produce a significant amount of compost from the digestate. It was assumed that the produced one tonne of compost produced from the digestate can be used to replace chemical fertilizer at the rate of 7.1 kg of N fertilizer, 4.1 kg P_2O_5 and 5.4kg of K_2O fertilizer (Patyk, 1996). Thus production of compost can be credited for avoidance of chemical fertilizer production process. Inventory analysis for chemical fertilizer production process is shown Table C2.

Taking into account all the inputs/outputs and credited processes for valuable by-products production, the life cycle inventory analysis was done for AD process (Table C3).

Table C2: Energy and resource consumption of chemical fertilizer production (Source: Patyk, 1996)

Air emissions	N fertilizer (g/kg)	7.1 kg N equivalent to 1 tonne of compost(g)	P_2O_5 fertilizer (g/kg)	4.1 kg of P_2O_5 equivalent to 1 tonnr of compost(g)	K_2O fertilizer (g/kg)	5.4 kg K_2O equivalent to 1 tonne of compost (g)	total emissions (g) equivalent to 1 tonne of compost
CO_2	2.40E+03	1.71E+04	4.48E+02	1.84E+03	4.43E+02	2.39E+03	2.13E+04
CH_4	4.50E-01	3.20E+00	1.80E-02	7.38E-02	2.00E-02	1.08E-01	3.38E+00
N_2O	9.63E+00	6.84E+01	3.10E-02	1.27E-01	8.90E-03	4.81E-02	6.85E+01
SO_2	3.30E+00	2.34E+01	8.25E+00	3.38E+01	1.20E-02	6.48E-02	5.73E+01
CO	2.15E+00	1.53E+01	4.20E-01	1.72E+00	2.00E-01	1.08E+00	1.81E+01
NOx	9.64E+00	6.84E+01	3.42E+00	1.40E+01	5.40E-01	2.92E+00	8.54E+01
Particles	0.00E+00	0.00E+00	4.10E-02	1.68E-01	2.80E-02	1.51E-01	3.19E-01
HCl	1.10E-01	7.81E-01	1.60E-02	6.56E-02	4.80E-02	2.59E-01	1.11E+00
NH_3	4.93E+00	3.50E+01	1.60E-03	6.56E-03	1.10E-03	5.94E-03	3.50E+01
Dioxins	1.19E-09	8.45E-09	1.70E-10	6.97E-10	2.10E-10	1.13E-09	1.03E-08
Fossil energy requirement (MJ/kg)	6.06E+01	4.30E+02	1.11E+01	4.55E+01	6.70E+00	3.62E+01	5.12E+02

Table C3: Inventory analysis of anaerobic digestion of per tonne of organic waste

Life cycle inputs/ outputs	Collection and transportation (50 km)/tonne of organic waste + sorting	**Anaerobic digestion per tonne of organic waste**			**Composting (production of 125 kg compost /per tonne of organic waste**			Life cycle net resource consumption +emissions
		Fuel production and fuel burning	Credited impact from electricity production (192kWh/tonne)	Net impact	Fuel production + burning + emissions from composting	Credited impact	Net impact	
Inputs (kg)								
Baryte	5.40E-02	1.14E-02	0.00E+00	1.14E-02	6.02E-02	0.00E+00	6.02E-02	1.26E-01
Coal, 18MJ per kg,	1.20E-01	2.53E-02	0.00E+00	2.53E-02	1.34E-01	0.00E+00	1.34E-01	2.79E-01
Coal, brown 8MJ per kg,	1.19E+00	1.88E-02	3.78E+01	-3.78E+01	9.92E-02	0.00E+00	9.92E-02	-3.65E+01
Oil	6.70E+00	1.41E+00	0.00E+00	1.41E+00	7.46E+00	5.88E-01	6.87E+00	1.50E+01

cude,42.6MJ per kg								
Natural gas (m^3)	0.00E+00	0.00E+00	3.33E+01	-3.33E+01	0.00E+00	1.01E+00	-1.01E+00	-3.43E+01
Fuel oil	0.00E+00	0.00E+00	3.21E-01	-3.21E-01	0.00E+00	0.00E+00	0.00E+00	-3.21E-01
Iron	2.76E-02	5.82E-03	0.00E+00	5.82E-03	3.08E-02	0.00E+00	3.08E-02	6.42E-02
Outputs (kg)								
CO_2	2.85E+01	4.42E+00	1.08E+02	-1.04E+02	2.34E+01	2.66E+00	2.07E+01	-5.48E+01
CO	3.87E-01	1.35E-03	0.00E+00	1.35E-03	7.12E-03	2.26E-03	4.86E-03	3.93E-01
PM	6.35E-02	1.15E-03	1.04E-01	-1.03E-01	6.06E-03	3.99E-05	6.02E-03	-3.34E-02
H_2	6.22E-05	1.31E-05	0.00E+00	1.31E-05	6.94E-05	0.00E+00	6.94E-05	1.45E-04
HCl	1.32E-05	2.78E-06	0.00E+00	2.78E-06	1.47E-05	1.38E-04	-1.24E-04	-1.08E-04
CH_4	4.86E-02	1.02E-02	0.00E+00	1.02E-02	5.39E-02	4.22E-04	5.35E-02	1.12E-01
NO	2.19E-02	4.62E-03	0.00E+00	4.62E-03	2.44E-02	0.00E+00	2.44E-02	5.09E-02
NOx	2.37E-01	2.67E-02	3.40E-01	-3.13E-01	1.41E-01	1.07E-02	1.31E-01	5.42E-02
N_2O	6.78E-05	1.43E-05	0.00E+00	1.43E-05	7.56E-05	8.57E-03	-8.49E-03	-8.41E-03
SO_2	3.38E-02	8.67E-03	4.59E-01	-4.51E-01	4.58E-02	7.16E-03	3.87E-02	-3.78E-01
VOC	1.43E-01	2.22E-02	3.40E-01	-3.17E-01	1.18E-01	0.00E+00	1.18E-01	-5.68E-02
SO_4^-	6.91E-03	1.46E-03	0.00E+00	1.46E-03	7.70E-03	0.00E+00	7.70E-03	1.61E-02
NO_3^-	1.99E-04	4.19E-05	0.00E+00	4.19E-05	2.22E-04	0.00E+00	2.22E-04	4.62E-04
NH_3	3.44E-04	7.25E-05	0.00E+00	7.25E-05	1.26E-02	4.38E-03	8.21E-03	8.62E-03

Inventory Analysis of Incineration: According to the waste composition and characteristics of Nonthaburi waste, 291 kg of waste per each tonne of waste generated, can be used for the incineration (Table C1). After the collection and transportation, part of the food waste (75%) is separated at the sorting facility for AD and then, the non-combustible fraction is removed from the waste. This remaining fraction consists of combustible components which can be used for the incineration.

According to the waste characteristics in Nonthaburi, moisture content of the separated combustible fraction for incineration is 33%. Potential electricity production from waste was calculated by using the Low Heating Values (LHV) of different types of combustibles. However, it was noticed that the amount of electricity produced at Phuket incineration plant is lesser than the theoretically estimated electricity production values. Thus, theoretical electricity production values in Nonthaburi were adjusted to the practical potential values by using gross electricity generating efficiency of the Phuket power plant. In Phuket, gross electricity generation efficiency is 8% and the process electricity consumption is 91 kWh/tonne of dry weight.

Further adjustments were done based on the efficiency of Phuket incineration plant. The maximum net electricity production potential is expected from plastics and that amounts to

388 kWh per tonne of dry weight. According to the composition of combustibles in Nonthaburi, the net electricity production potential would be 128kWh per tonne of combustibles since 60 kWh of produced electricity is required for plant operation activities itself, (Table C4). However, produced 188 kWh of gross electricity per tonne of combustibles was credited for avoiding the same amount of conventional electricity production process. The credited resource consumption and emissions from the conventional electricity production process is also shown in Table C5.

In addition to the electricity production process chain, auxiliary material consumption for the incineration was estimated based on the plant specific data of the Phuket incineration plant. Furthermore, theoretical emission values were derived from the combustion process of the combustibles based on the chemical characteristics of waste. Then those theoretical values were adjusted to the potential practical values by using the co-relationship of theoretical and practical values of emissions in the Phuket power plant.

Table C4: Characteristics of the combustibles in Nonthaburi and gross and net electricity production potential per tonne of combustibles

Combustibles	Mass per tonne of combustibles	Moisture content (%)	Dry matter content per tonne of combustibles (kg)	Energy production potential (kWh/tonne DM)	Gross energy production (kWh)	Plant energy requirement (kWh/tonne DM)	Plant energy requirement (kWh)	Saleble electricity production (kWh)
Organic waste	409.29	68.50	128.93	145.48	18.76	91.37	11.78	6.98
Wood	21.64	10.00	19.48	178.10	3.47	91.37	1.78	1.69
Plastics	372.00	9.00	338.52	387.72	131.25	91.37	30.93	100.32
Paper	125.20	14.50	107.05	189.23	20.26	91.37	9.78	10.48
Rubber and leather	18.55	0.00	18.55	311.54	5.78	91.37	1.69	4.08
Textile	53.33	2.00	52.26	169.54	8.86	91.37	4.77	4.09
Total (per tonne of combustibles)	**1000.00**	**33.50**	**664.77**		**188.37**		**60.74**	**127.63**

Table C5: Inventory analysis for intended incineration plant Nonthaburi – combustion and electricity production from one tonne of combustibles

Life cycle inputs/ outputs		Unit	Transportation +sorting	Incineration	Total	Credited resource consumption +emissions (188 kWh electricity	Net Impact
Inputs							
Electricity	Net process electricity input	kWh		6.07E+01	6.07E+01	6.07E+01	0.00E+00
Water	Water	m^3		3.39E-01	3.39E-01		3.39E-01
Diesel	Diesel	L		2.36E-01	2.36E-01	3.15E-01	-7.91E-02
Chemicals	AC_{12} Complexes	kg		1.55E-02	1.55E-02		1.55E-02
	P208 Complexes	kg		1.54E-03	1.54E-03		1.54E-03
	HCl 35%	L		3.49E-02	3.49E-02		3.49E-02
	NaOH 50%	L		3.56E-02	3.56E-02		3.56E-02
	Kalgen147	kg		1.98E-03	1.98E-03		1.98E-03
	Oxynon H-104	kg		1.81E-03	1.81E-03		1.81E-03
	Stemtech AF	kg		2.18E-03	2.18E-03		2.18E-03
	Ca(OH)2	kg		6.00E+00	6.00E+00		6.00E+00
Raw material for diesel production	Coal, 18MJ per kg, in ground	kg	1.20E-01	1.05E+00	1.17E+00		1.17E+00
	Coal, brown 8MJ per kg, in ground	kg	9.25E-01	3.24E-03	9.28E-01	3.71E+01	-3.62E+01
	Oil cude,42.6MJ per kg	kg	6.70E+00	2.44E-01	6.94E+00		6.94E+00
	Natural gas	m^3		9.19E-01	9.19E-01	3.26E+01	-3.17E+01
Outputs							
Electricity	Net electricity output	kWh		1.28E+02	1.28E+02	1.28E+02	0.00E+00
Emissions to air	Waste heat	kWh		2.18E+03	2.18E+03		2.18E+03
	TSP	kg		5.02E-02	5.02E-02		5.02E-02
	CO	kg	3.86E-01	6.14E-01	1.00E+00		1.00E+00
	Dioxin TEQ	kg		2.12E-08	2.12E-08		2.12E-08
	VOC	kg	1.43E-01	3.54E-02	1.78E-01		1.78E-01
	Fossil CO_2	kg	2.78E+01	9.29E+02	9.57E+02	1.06E+02	8.50E+02
	SO_2	kg	3.06E-02	3.88E-02	6.94E-02	4.51E-01	-3.82E-01
	NO_2	kg	2.56E-01	1.82E+00	2.07E+00	3.33E-01	1.74E+00
	NH_3	kg	3.44E-04	4.45E-03	4.79E-03		4.79E-03
	CH_4	kg	4.83E-02	2.52E-04	4.86E-02	8.94E-03	3.96E-02
	Chlorine	kg		1.10E-01	1.10E-01		1.10E-01
	PM	kg	6.04E-02	2.87E-03	6.33E-02	1.02E-01	-3.88E-02
	N_2O	kg	6.78E-05		6.78E-05		6.78E-05
	HCl	kg	1.32E-05	1.10E-01	1.10E-01		1.10E-01
Emissions to water	NO_3^-	kg	1.99E-04	2.68E-01	2.69E-01		2.69E-01
	PO_4^{-3}	kg		1.46E+00	1.46E+00		1.46E+00

-Inventory analysis of landfilling: The objective of designing the final disposal site is to prevent or reduce the negative effects to the environment from the remaining residual waste. Therefore, introduction of stringent technical requirements like landfilling for final disposal is essential as a part of an integrated MSW management. It should be mainly designed and is useful for inert material disposal that would remain after the sorting of waste. For instance, according to the mass balance 105 kg of inert materials should be disposed of at the landfill for every tonne of generated waste (Table C1). Detailed inventory analysis for the landfill which is designed for residual waste disposal is presented in Table C6 where life cycle emissions and resource consumption have been included for all the phases of life cycle.

Table C6: Inventory analysis per tonne of residual waste landfill in Nonthaburi

Inputs	Emissions from fuel production + combustion (kg/tonne of residual waste)	Emission from sorting plant (electricity production)(kg/tonne of residual waste)	Total emissions from landfill (kg/tonne of residual waste
Inputs (kg)			
Baryte	5.60E-02	0.00E+00	5.60E-02
Coal, 18MJ per kg, in ground	1.24E-01	0.00E+00	1.24E-01
Coal, brown 8MJ per kg, in ground	9.22E-02	1.10E+00	1.20E+00
Oil cude,42.6MJ per kg	6.93E-03	9.39E-06	6.94E-03
Natural gas (m^3)	0.00E+00	9.72E-04	9.72E-04
Fuel oil	0.00E+00	0.00E+00	0.00E+00
Iron	2.86E-02	0.00E+00	2.86E-02
Outputs(kg)			
CO_2	2.55E+01	3.17E+00	2.87E+01
CO	3.85E-01	2.58E-03	3.87E-01
PM	6.05E-02	3.04E-03	6.36E-02
H_2	6.45E-05	0.00E+00	6.45E-05
HCl	1.37E-05	0.00E+00	1.37E-05
CH_4	5.01E-02	7.37E-04	5.08E-02
NO	2.27E-02	0.00E+00	2.27E-02
NO_x	2.27E-01	9.92E-03	2.37E-01
N_2O	7.03E-05	0.00E+00	7.03E-05
SO_2	2.12E-02	1.34E-02	3.46E-02
VOC	9.38E-02	0.00E+00	9.38E-02
SO_4^-	7.16E-03	0.00E+00	7.16E-03
NO_3^-	2.06E-04	0.00E+00	2.06E-04
NH_3	3.56E-04	0.00E+00	3.56E-04

C3. Evaluation of intended integrated system via most relevant midpoint indicators

In this session, the most relevant midpoint indicators were used to quantify the impacts from individual technologies which have been incorporated in the intended integrated MSW management system. As noticed, inventory analysis and quantification of midpoint impacts from recycling is shown in Appendix A. In this part of research the focus is to quantify the impacts from other appropriate technologies such as anaerobic digestion, incineration and landfilling that have been incorporated to the integrated system. Furthermore, by considering the fraction of waste treatment done by utilizing the above technologies, the overall impacts from the intended integrated system was estimated.

Quantification of midpoint indicators for anaerobic digestion

Mid point environmental indicators were assessed using the life cycle inventory results of AD. The major valuable by-products from this process are 215.8 kWh of gross electricity and 125 kg of compost per tonne of organic waste (see Chapter 7, Tables 7.1 and 7.2). According to the analysis, credited electricity production process from biogas has favorably influenced in reducing all the environmental impacts and it has been indicated as net negative values for all impact categories (Table C7).

In contrast, the compost making process has contributed for increasing the environmental impacts see Table C7. Although, the compost production process has been credited for avoidance of conventional fertilizer production process, still there is potential for occurrence of damages to the environmental. The basic reason is, the composting production process from sludge, can emit a significant amount of NH_3 and VOC compounds and the reported values are 97.6g per tonne and 3.1g per tonne, respectively (Pöschl et al., 2010). Moreover, this is an energy intensive process. Therefore the energy production process chain and emissions from the fuel combustion process have its influence in increasing the overall environmental burdens. However, it should be noted that for the whole AD process, a net negative value has resulted as the net impact, except for eutrophication potential. This is a reward for the production of significant amount of electricity from biogas.

Table C7: Summary of the quntified midpoint indicators for anaerobic digestion – per tonne of organic waste

Phases of life cycle	Global warming potential (kg of CO_2 eq)	Acidification Potential (kg SO_2 eq.)	Europhication Potential (kg NO_3^- eq.)	Photo Oxidant Formation Potential (kg C_2H_4 eq.)	Abiotic resources Depletion Potential (kg Sb eq.)	Human toxicity potential (kg of 1-4 DB eq)
Transportation and sorting of organic waste	3.05E+01	2.23E-01	3.50E-01	8.73E-02	1.60E-01	3.65E-01
Anaerobic digestion process + credited impacts for electricity production	-1.17E+02	-7.52E-01	-4.73E-01	-1.80E-01	-8.43E-01	-5.65E-01
Compost production	1.94E+01	1.72E-01	2.15E-01	5.94E-02	1.25E-01	1.95E-01
Net impacts	**-6.75E+01**	**-3.57E-01**	**9.22E-02**	**-3.31E-02**	**-5.58E-01**	**-3.87E-03**

Quantification of midpoint indicators for incineration

Midpoint impacts were quantified by using the inventory analysis results. There is a potential of producing 188 kWh of gross electricity per tonne of combustibles. Electricity production process from incineration was credited for avoidance of conventional electricity production process. The estimated midpoint impacts from different types of phases of life cycle and the net impact for overall incineration process is shown in Table C8.

It should be noted that net positive values has been the resulted, for all the midpoint impacts, except abiotic resource depletion. This estimation indicates the possibility of environmental degradation occurrence from incineration. The major pollutants from the incineration process are CO_2, NOx, SOx, PM, etc. For instance, incineration process has emitted as much as 929 kg of fossil CO_2 per tonne of combustibles. Even though, plastic is useful for producing a significant amount of electricity, the major negative aspect of plastic combustion is, its influences on increasing fossil CO_2 emissions. According to analysis, one kilogram of mix plastic waste combustion contributes to 2.5 kg of fossil CO_2 emissions. Therefore, point source separation of plastic for recycling would be the apt option to overcome this problem. To reduce the acidifying (SO_x and NO_x) and eutrophying (NO_x) substances emissions, efficient pollution control measures have to be practiced like adding adequate amount of lime to reduce the SO_x level and maintaining the temperature below 1100 ^{0}C to avoid NO_x formation (Phuket Municipality, 2010).

Table C8: Summary of the quntified midpoint indicators for incineration – per tonne combustibles

Phases of life cycle	Global warming potential (kg of CO_2 eq)	Acidification Potential (kg SO_2 eq.)	Europhication Potential (kg NO_3^- eq.)	Photo Oxidant Formation Potential (kg C_2H_4 eq.)	Abiotic resources Depletion Potential (kg Sb eq.)	Human toxicity potential (1-4 DB eq)
Transportation and sorting of waste	2.97E+01	2.10E-01	3.47E-01	8.72E-02	1.43E-01	3.60E-01
Incineration/combustion process	9.30E+02	1.42E+00	1.80E+01	4.22E-02	3.47E-02	2.19E+00
Credited impacts for electricity production	-1.07E+02	-6.84E-01	-4.50E-01	-6.26E-05	-7.68E-01	-5.16E-01
Net Impacts	**8.53E+02**	**9.42E-01**	**1.79E+01**	**1.29E-01**	**-5.90E-01**	**2.03E+00**

Quantification of midpoint indicators for landfilling

Impacts from landfilling are not as high as other technologies since pollutants emission potential from the residual waste disposal were considered to be negligible. However, in order to experience zero pollutants potential from inert landfill, it is necessary to avoid disposing of incompatible materials such as food waste, chemical containers, and metals (including electrical batteries, organic solvents and petroleum hydrocarbons like oil or grease. All loads arriving at the landfill facility are subjected to inspection. Any waste, which is presented at the landfill not in accordance with the accepted criteria and which cannot be completed on site, should be refused. Thus all the workers and supervisors must adhere to all site safety instructions, and rules and regulations. However, there are some environmental effects which can occur due to fossil fuel and electricity consumption for waste transportation and sorting. The quantified midpoint impacts are presented in Table C9.

Table C9: Summary of the quantified midpoint indicators from landfilling - per tonne of residual waste disposal

Phases of life cycle	Global warming potential (kg of CO_2 eq)	Acidification Potential (kg SO_2 eq.)	Europhication Potential (kg NO_3^- eq.)	Photo Oxidant Formation Potential (kg C_2H_4 eq.)	Abiotic Resources Depletion Potential (kg Sb eq.)	Human Toxicity Potential
Transportation and sorting of waste	3.07E+01	2.25E-01	3.21E-01	8.89E-02	1.67E-01	3.40E-01
Final disposal	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible
Net impacts	**3.07E+01**	**2.25E-01**	**3.21E-01**	**8.89E-02**	**1.67E-01**	**3.40E-01**

Overall effects of intended integrated systems at midpoint impact level

The results of the analysis show that among all technologies analyzed, recycling is the most effective one, followed by anaerobic digestion, landfilling and incineration. It is noticed that, the effects of 24% of waste recycling are remarkable when compared to other technologies. The most advantageous effect of the integrated system is that the effects of both recycling and anaerobic digestion enable to neutralize all of the damages occurrence potential from both incineration and landfiling. Therefore, the intended integrated system has resulted in net negative values for all the midpoint impacts, indicating that the intended integrated system would far more sustainable than the existing or the upgraded MSW management system (Table C10).

Table C.10: Qunitified midpoint indicators of intended integrated system per tonne of MSW treatment

Treatment methods	Amount per tonne	% of waste	GWP (kg of CO_2 eq)	AP (kg SO_2 eq.)	EP (kg NO_3^- eq.)	POFP (kg C_2H_4 eq.)	ADP (kg Sb eq.)	HTP (1-4 DB eq)
Recycling	243.24	24.32	-9.51E+02	-5.88E+00	-4.73E+00	-1.55E-01	-5.19E+00	-4.25E+00
Anaerobic digestion	360.69	36.07	-2.44E+01	-1.29E-01	3.32E-02	-1.19E-02	-2.01E-01	-1.40E-03
Incineration	291.03	29.10	2.48E+02	2.74E-01	7.67E-01	3.77E-02	-1.72E-01	5.91E-01
Landfilling	105.04	10.50	3.22E+00	2.37E-02	3.38E-02	9.34E-03	1.75E-02	3.57E-02
Net impacts	**1000**	**100**	**-7.24E+02**	**-5.71E+00**	**-3.89E+00**	**-1.20E-01**	**-5.54E+00**	**-3.62E+00**

Further analysis was made in order to compare the magnitude of impacts of the integrated MSW management systems with that of the existing or upgraded system since this information would be an interesting point for the decision making process. Notably, the result of the initiation of an integrated MSW management system, with recuperation of maximum amount of energy and materials, would have the potential reduction of 100% of harmful impacts when compared to that of the existing system (Figure C1). For comparison purpose, all corresponding results are graphically displayed as percentages relative to the existing situation. It should be noted that the upgraded MSW management with landfill gas recovery system would be even better than the integrated system as far as global warming and eutrophication potential are concerned. The reason behind this is that the incorporated incineration instead of landfilling with gas recovery has the potential of emitting significant amount of fossil CO_2 and NO_X compounds during the combustion process. Thus, the integrated system has resulted in a high magnitude of global warming and eutrophication potentials.

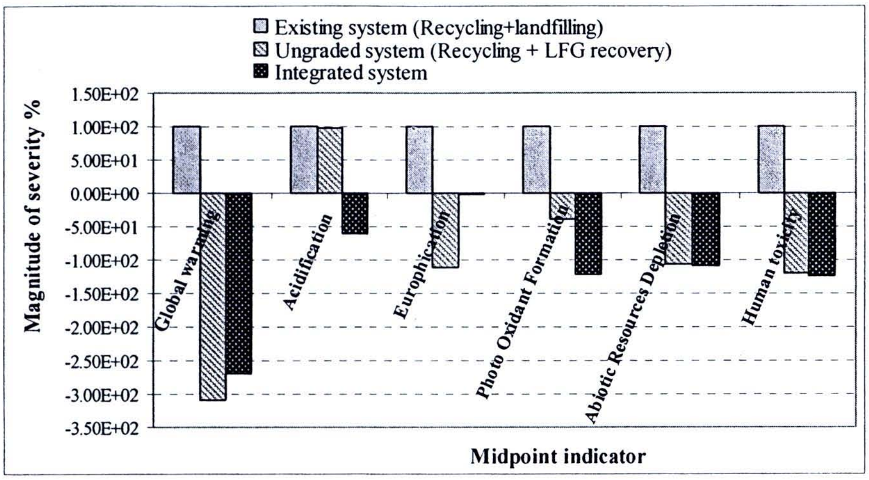


Figure C1: Severity of impacts of integrated system relative to the existing and upgraded system

APPENDIX D

D1. Information related to sustainability assessment of the existing MSW management system –Sri Lanka

Inventory analysis

Inventory data was collected in relation to environmental, economic and social aspects of open dumping. Various literature sources and company/municipality reports were used for gathering the required data (Table D1).

Table D1: Inventory data on MSW management system and data sources

Data required for the assessment	Data source
Specification of MSW collection vehicles (Market price of vehicles, fuel consumption, maximum loading capacity, life time, repair and maintenance cost etc)	Dave Tractors (Pvt) Ltd, Yakkala, Sri Lanka. (personal communication)
Crude oil extraction and its emissions data	ETH-ESU 96 System processes, Sima Pro 7.1
Crude oil transportation from Iran to Sri Lanka by ships	LIPASTO traffic emission. 2009. Available in http://www.lipasto.vtt.fi/info.htm
Crude oil distillation and production of diesel and other products in Sri Lanka	Ceylon Petroleum Cooperation, Colombo, Sri Lanka. (personal communication)
Diesel transportation from Colombo to Kandy using heavy duty trucks (Emissions data from heavy duty trucks, transportation distances)	Shaha et al., 2006
Waste generation rate, composition of waste , no of vehicle and other equipments, labour requirement, annual capital expenditure on MSW management, operational and maintenance cost	Kandy Municipal Council, Sri Lanka. (personal communication)
MSW characteristics in Sri Lanka	Menikpura et al., 2007;Menikpura et al., 2008
Situation of dumpsite, land utilization, disposal rate of waste/day	Pre Feasibility Report, 2009 Solid Waste Management Research Unit. (personal communication)
Greenhouse gas emissions data from open dumping	IPCC, 2006 (default values for Sri Lanka)
Elemental composition of waste in Sri Lanka	Menikpura and Basnayake, 2009
Weighing factors for environmental indicators	Guinée, et al., 2001
VOC emissions, Acidifying and eutrophying substances emissions	Zou et al., 2003; Nielsen and Hauschild, 1998; Banar et al., 2009.
Environmental cost calculation data- (willingness to pay) WTP for emissions	Steen, 2000
Health impacts of environmental emissions, data for DALY calculation	Guinée et al., 2001

Table D2: Major inputs (energy and materials) and outputs (emissions) for one tonne of MSW management under existing situation (open dumping) in Sri Lanka

NS*- Not Significant

Inputs/Outputs	Emissions	Fuel production and fuel transportation	MSW Collection and transportation	Final Disposal	Total
Energy and material use	Coal(g)	4.76E+01	NS	NS	4.76E+01
	Oil Crude(g)	1.27E+03	NS	NS	1.27E+03
	Energy Hydropower (kJ)	9.15E+01	NS	NS	9.15E+01
	Iron(g)	6.62E+00	NS	NS	6.62E+00
	Bauxite(g)	1.15E+01	NS	NS	1.15E+01
Emissions to air(g)	CO_2	9.83E+02	4.04E+03	0.00E+00	5.02E+03
	CH_4	1.03E+01	2.24E-01	2.90E+04	2.90E+04
	CO	1.43E+00	1.69E+01	0.00E+00	1.84E+01
	NO_x	6.36E+00	4.76E+01	0.00E+00	5.40E+01
	N_2O	1.48E-02	1.01E-01	0.00E+00	1.16E-01
	NH_3	NS	NS	4.48E+03	4.48E+03
	SO_x	4.23E+00	6.39E-01	NS	4.87E+00
	H_2S	NS	NS	6.60E+02	6.60E+02
	VOC	2.17E+01	4.56E+00	1.40E-01	2.64E+01
	PM	5.31E-01	2.21E+00	0.00E+00	2.74E+00
Emissions to water(g)	SO_4^-	1.66E+00	NS	1.86E+03	1.86E+03
	NO_3^-	4.77E-02	NS	1.63E+04	1.63E+04
	HCl	2.50E-03	NS	NS	2.50E-03
	NH_4^+	8.25E-02	NS	NS	8.25E-02

D2. Quantification of midpoint impacts of open dumping

Global warming potential

According to IPCC guidelines, the Gohagoda dumpsite can be categorized as deep and unmanaged dump site and thus has a high potential of methane emissions (IPCC, 2006). In addition, the MSW consists of a high fraction of biodegradable waste (88.9% wet basis) and thus, it includes a high fraction of degradable organic carbon (DOC) which directly influences the amount of methane production (IPCC, 2006). Moreover, under the moist and wet tropical climate of Sri Lanka, there is a high potential of producing methane since the conditions are favorable for methanogenesis. IPCC waste model was used to calculate methane generation potential from Gohadoga dumpsite since this model is generally recognized as the most widely used approach for estimating methane generation from the waste sector (Jha et al., 2008).

Based on the composition and dumpsite conditions, calculated IPCC default values for the Gohagoda dump site are; Degradable organic carbon (DOC) - 0.174, fraction of DOC decomposing under anaerobic conditions DOC_f - 0.5, Methane Correction Factor - 0.5 (value for partially aerobic dumpsite (UNFCCC/CCNUCC, 2008)) and fraction of CH_4 by volume in generated landfill gas (F) - 0.5. The IPCC waste model showed that the methane emissions from open dumping take place significantly over the first 40 years after waste disposal. Based on the above default values, the estimated total potential methane generation from one tonne of waste is 29 kg of CH_4. Collection and transportation of MSW is emitting some CO_2 and it effects on GWP.

Acidification potential

According to the characteristic of MSW, it was considered that food waste can be degraded totally and other biodegradable such as garden waste, paper and cardboard can be degraded 50% (Aye and Widjaya, 2006). According to the Nielsen and Hauschild (1998) landfill model, 50% of total nitrogen can be emitted to the atmosphere as NH_3 and 50% of total sulfur can be emitted as H_2S. Using the above, it was estimated that 4.48 kg of NH_3 and 0.65 kg of H_2S are emitted from one tonne of waste. In addition, small amount of NO_x, SO_x, NH_3, HCl like acidifying substances can be emitted from transportation and fuel production (see Table D2). The overall acidification potential is 9.71 kg SO_2 equivalents per tonne, 99.5% of which is from final disposal and the remaining 0.5% is from fuel production, collection and transportation (see Table D3).

Eutrophication potential

According to the chemical composition, nitrogen is the key substance in waste and possibly a major contributor to eutrophication potential. As mentioned earlier, 50% of total nitrogen in waste can be included in leachate as NO_3^- and can contribute a major share to eutrophication (Aye and Widjaya, 2006; Nielsen and Hauschild, 1998). Potential NO_3^- emissions can be estimated based on the chemical composition (Banar et al., 2009). In addition, fuel production, collection and transportation also emit eutrophying substances such as NH_3, NO_x, N_2O and NO_3^-. The overall eutrophication potential per tonne of waste is 16.42 kg of NO_3^- equivalents, 99.5% being contributed by final disposal (see Table D3).

Photo-Oxidant formation potential

Volatile Organic Compounds (VOCs) from open dump and carbon monoxide emissions from collection and transportation of waste are major causes of photo-oxidant formation. In landfills 50% of DOC are decomposed and produce landfill gas which consists of 50-60 % (v/v) CH_4 (Bogner and Matthews, 2003; El Hanandeh and El-Zein, 2010). In this study, a 50% CH_4 fraction was assumed in 89 m^3 of landfill gas being produced per tonne of MSW. CH_4 and non-methane VOCs (NMVOCs – Benzene, Toluene, Ethylbenzene, Styrene, etc.) are the major VOC sources in landfill gas amounting to 29 kg and 140 mg respectively per tonne of waste. In addition, there is a potential of emitting VOC and CO from collection and transportation of MSW up to 26 g and 18 g respectively per tonne of waste. Total photo-oxidant formation potential from one tonne of disposed waste is 0.22 kg of C_2H_4 equivalents (see Table D3), 94% from final disposal and the remaining 6% from collection and transportation.

Human toxicity potential

Emission of H_2S, NO_x, SO_x, NH_3 and PM_{10} compounds from existing MSW management was accounted from collection and transportation and final disposal. Based on the inventory analysis, toxicity creation potential from open dumping amounts to 6.61E-01 1-4 DB equivalents, in which 90% toxicity problem occurs due to final disposal and remaining 10% is from collection and transportation.

Abiotic Resources Depletion Potential

Energy and mineral utilization is the main reason for abiotic resources depletion. Due to insufficient capacities of collection vehicles (1.5 - 2 tonnes/trip), considerable number of trips are necessary to collect the total amount of MSW generated within the municipal limit which requires significant amount of fossil energy. For instance, 1.5 L of diesel is needed for one tonne of waste collection and transportation to the dumpsite which is around 12 km away from collection points. To produce 1.5L of diesel, 1.51 L of crude oil has to be extracted (in Sri Lanka, only 20% of products can be extracted as diesel during crude oil distillation process). According to the existing situation, ADP from one tonne of disposed waste is 2.63E-02 kg of antimony equivalents.

Table D3: Quantification of environmental impacts from the existing MSW management system in Sri Lanka (impacts per tonne of MSW)

Midpoint Indicators	Unit	Total impact	Impact from fuel production, collection and transportation	Impact from disposal (dumping)
Global Warming Potential(GWP)	kg of CO_2 equivalents	7.32E+02	5.68E+00	7.26E+02
Acidification potential	kg of SO_2 equivalents	9.71E+00	4.89E-02	9.66E+00
Eutrophication potential	kg of NO_3^- equivalents	1.63E+01	7.75E-02	1.64E+01
Photo- Oxidant formation potential	kg of C_2H_4 equivalents	2.17E-01	1.39E-02	2.03E-01
Human toxicity potential	kg of 1-4DB equivalents	6.61E-01	6.75E-02	5.93E-01
Abiotic resource Depletion Potential (ADP)	kg of Sb equivalents	2.63E-02	2.63E-02	0.00E+00

D3. Information related to development of sanitary landfill with LFG recovery system as a sustainable solution to the existing crisis

Inventory analysis for sanitary landfill with LFG recovery system

Inventory analysis was done considering all the phases of life cycle. The produced electricity from LFG, (138 kWh/tonne of waste) was credited for avoidance of same amount of electricity from convention production methods.

Table D4: Major inputs (energy and materials) and outputs (emissions) for one tonne of MSW management under sanitary landfill with LFG recovery

NS*- Not Significant

Life cycle Inputs/Outputs	Emissions	Fuel production and transportation	Collection and transportation of MSW	Final disposal	Total emissions	Credited emission/resources for electricity (138 kWh/tonne) production	Net emissions/ resources consumption
Energy and material use (kg)	Coal	6.87E-02	NS	8.87E-02	1.57E-01		1.57E-01
	Oil Crude	1.83E+00	NS	6.54E-01	2.49E+00	1.61E+01	-1.36E+01
	Iron	9.57E-03	NS	3.51E-03	1.31E-02		1.31E-02
Emissions to air(kg)	CO_2	1.38E+00	6.83E+00	1.69E+00	9.91E+00	5.00E+01	-4.01E+01
	CH_4	1.49E-02	0.00E+00	1.23E+01	1.24E+01		1.24E+01
	CO	2.02E-03	1.84E-02	1.37E-01	1.57E-01		1.57E-01

	NOx	8.32E-03	5.94E-02	1.42E-01	2.10E-01	2.24E-01	-1.45E-02
	N_2O	2.14E-05	0.00E+00	0.00E+00	2.14E-05		2.14E-05
	NH_3	0.00E+00	0.00E+00	4.48E+00	4.48E+00		4.48E+00
	SO_x	6.59E-03	0.00E+00	7.51E-03	1.41E-02	5.00E-01	-4.86E-01
	H_2S	0.00E+00	0.00E+00	6.60E-01	6.60E-01		6.60E-01
	VOC	3.14E-02	2.24E-03	5.63E-03	3.93E-02		3.93E-02
	PM	7.56E-04	1.53E-03	5.61E-04	2.84E-03		2.84E-03
Emissions to water(kg)	SO_4^-	2.40E-03	NS	1.86E+00	1.87E+00		1.87E+00
	NO_3^-	6.89E-05	NS	0.00E+00	6.89E-05		6.89E-05
	HCl	3.61E-06	NS	0.00E+00	3.61E-06		3.61E-06
	NH_4^+	1.19E-04	NS	2.18E-01	2.18E-01		2.18E-01

Environmental assessment by using midpoint indicators

Midpoint indicators are also quantified by using the inventory analysis results since this information would be interested at the decision making stage (see Table D5).

Table D5: Estimated midpoint indicators for sanitary landfill with LFG recovery system per tonne of MSW management

Environmental Indicator	**Unit**	**Gross impact**	**Credited impact (for electricity production)**	**Net Impact**
Global Warming Potential(GWP)	kg of CO_2 eq	2.94E+02	5.00E+01	2.44E+02
Acidification potential	kg of SO_2 eq	9.83E+00	6.57E-01	9.17E+00
Eutrophication potential	kg of NO_3^- eq	1.25E+00	3.03E-01	9.51E-01
Photo- Oxidant formation potential	kg of C_2H_4 eq	1.12E-01	0.00E+00	1.12E-01
Human toxicity	kg of 1-4 DB eq	8.49E-01	3.50E-01	4.99E-01
Abiotic resource Depletion Potential(ADP)	kg of Sb eq	5.20E-02	3.43E-01	-2.91E-01

Initiation of sanitary landfill with LFG recovery system can be substantially influenced on improving the environmental sustainability. For instance, in the midpoint level, sanitary landfill with gas recovery system can contribute to reducing global warming potential by 67%, acidification potential by 6%, eutrophication potential by 94%, photo-oxidant formation potential by 48%, human toxicity potential by 25% and abiotic resource depletion potential by 1200%. Electricity production from landfill gas enables to provide a significant benefit from avoiding abiotic resource damage that would have otherwise occurred from corresponding amount of conventional electricity production. This has resulted in huge impact of reducing abiotic resource depletion potential. The above results reveal that even the application of a single technology can substantially reduce the existing burdens associated with MSW management.

D4. Information related to development of an integrated MSW management system as a sustainable solution

Mass balance analysis for intended treatment methods within the integrated system

Mass balance was done according to the composition and the characteristics of waste and it has shown in Table D6. The total waste generation rate is 110 tonnes per day. Thus it was assumed that manual sorting alone with some of the essential machineries would be sufficient to sort out the daily generated waste at the sorting plant.

Table D6: Mass balance of the waste for different treatment technologies

Treatment methods	type of treatment method	Mass balance (for daily generated waste)		Mass balance(per tonne of generated waste	
	Total waste generation	110	tonnes/day	1	tonne
Recycling (assumed 50% of total recyclables in mix waste recovered)	Total recovered recyclables	5	%	5	%
	Recycling amount	**6**	**tonnes/day**	**55**	**kg/tonne**
	Total food waste in composition	85	tonnes/day	774	kg/tonne
	Food waste sorting efficiency	75	%	75	%
Anaerobic digestion	**Food waste for anaerobic digestion**	**64**	**tonnes/day**	**580**	**kg/tonne**
	Remaining food waste for combustion	21	tonnes/day	581	kg/tonne
	Combustibles amount	14	tonnes/day	132	kg/tonne
Incineration	**Total amount for Incineration**	**36**	**tonnes/day**	**325**	**kg/tonne**
Landfilling	Non combustible fraction	4	%	4	%
	Total waste for landfill	**4**	**tonnes/day**	**40**	**kg/tonne**

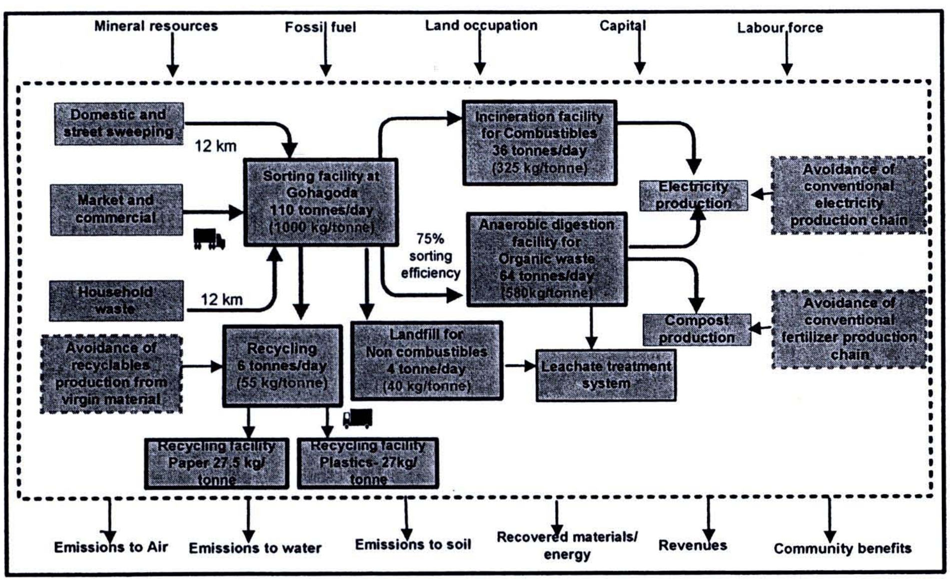


Figure D1: LCA framework for the intended integrated MSW management system in Kandy – Sri Lanka

Inventory analysis of selected appropriate technologies

Recycling

Unlike the situation in Thailand, there is a very lower percentage of recyclables contained in MSW stream in Sri Lanka. For instance, only paper and plastic can be found as the major category of recyclables and there is no significant amount of aluminium, metal and glass etc in the mixed MSW. It was assumed that only 50% of recyclables can be recovered from the mix waste stream for the recycling purpose. The recovered recyclables (paper 27.5 kg per tonne , plastic 27 kg per tonne) at the sorting facility will bailed and sent to the recycling facilities in Colombo (Transportation distance is 110 km by heavy duty trucks). Eco-invent database was used to find the inputs and outputs of recycling (Hischier and St. Gallen, 2007). However, to make a more representative data set for Sri Lanka, country specific data was obtained in relation to the type of fossil energy consumption (heavy fuel oil is the main energy source for thermal energy), the amount of fossil resource requirement, furnace efficiencies, emissions from combustion of fossil resources etc were obtained.

Paper recycling

The composition of the mixed paper waste in Sri Lanka represents approximately, 25% - newsprint, 25% - office paper and 50% - kraft paper. Therefore, point source separated 27.5 kg of paper may consist of 5.75 kg - newsprint, 5.75 kg- office paper and 16 kg - kraft paper. The inventory analysis results for the paper recycling and same amount of paper production from virgin processes are presented in Table D7.

Table D7: Inventory analysis for paper recycling and virgin production in Sri Lanka

	Summary of paper recycling		Production from virgin materials				
Life cycle inputs/ outputs	Unit	Recycling (26.83 kg) waste paper	Newsprint (4.78 kg)	Office paper(4.78 kg)	Kraft paper(15.6 kg)	virgin production of 24.97 kg of paper	Net savings
Water	m^3	2.63E-01	3.40E-01	4.06E-01	1.96E+00	2.70E+00	-2.44E+00
Hard Wood	m^3			8.10E-03	0.00E+00	8.10E-03	-8.10E-03
Soft wood	m^3		4.32E-03	6.51E-03	6.55E-02	7.63E-02	-7.63E-02
Wood chips	m^3		8.55E-04	3.97E-04		1.25E-03	-1.25E-03
Sulphate pulp	kg		8.41E-02	1.67E-01		2.51E-01	-2.51E-01

waste paper mixed from public collection	kg	2.68E+01	3.61E+00			3.61E+00	2.32E+01
Aluminium sulphate powder	kg	1.52E-01	1.29E-02		2.57E-01	2.70E-01	-1.18E-01
Hydrogen peroxide 50% in H_2O	kg	2.02E-01	5.40E-02		1.23E-02	6.63E-02	1.35E-01
H_2SO_4	kg		1.62E-03	8.31E-02	3.24E-02	1.17E-01	-1.17E-01
Energy consumption							
Electricity, at grid	kWh	8.20E+00	7.69E+00	1.76E+00	1.46E+01	2.40E+01	-1.58E+01
Hard coal	kg	4.29E-03	3.39E-04	7.47E-04	3.08E-03	4.16E-03	1.24E-04
Soft coal	kg	0.00E+00	2.58E-04	5.68E-04	2.34E-03	3.17E-03	-3.17E-03
Heavy fuel oil	kg	6.42E+00	1.22E+00	4.04E-01	2.74E+00	4.36E+00	2.06E+00
Natural gas	m3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Output							
Amount of paper produced	kg	2.50E+01	4.78E+00	4.78E+00	1.54E+01	2.50E+01	0.00E+00
Emissions							
CO_2 fossil	kg	2.13E+01	3.82E+00	1.30E+00	8.70E+00	1.38E+01	7.49E+00
NH_3	kg	1.31E-05	1.25E-06	2.40E-06	1.00E-05	1.37E-05	-5.90E-07
CO	kg	1.24E-02	1.03E-03	2.13E-03	8.82E-03	1.20E-02	4.29E-04
CH4	kg	2.30E-03	1.67E-04	3.05E-04	1.28E-03	1.76E-03	5.47E-04
NMVOCs	kg	4.96E-03	4.01E-04	8.84E-04	3.64E-03	4.93E-03	3.59E-05
N_2O	kg	1.35E-04	1.86E-07	4.09E-07	1.69E-06	2.28E-06	1.32E-04
NOx	kg	4.47E-02	1.43E-02	4.86E-03	3.28E-02	5.20E-02	-7.36E-03
SOx	kg	1.20E-01	3.29E-02	9.18E-03	6.79E-02	1.10E-01	1.03E-02
PM >10mm	kg	1.28E-02	7.76E-04	6.64E-04	3.18E-03	4.62E-03	8.16E-03

Plastic recycling

According to the composition of the plastics waste, it consists of 43.5% of PET, 43.5% of PP and the remaining 13% of HDPE. According to the mass balance, it was assumed that 50% of plastic in the mixed MSW could be recovered at the sorting facility thus the recyclable plastic amounts to 27 kg per tonne of waste generated. Inventory analysis of the plastic recycling and equivalent amount of virgin plastic production is presented in Table D8.

Table D8: Inventory analysis for plastic recycling and virgin production in Sri Lanka

Life cycle inputs/ outputs	Recycling Plastics (27 kg)		Virgin production (24.3 kg)					
	unit	Total impacts from recycling (27kg of plastics)	Transportation of crude oil by ships	PP production (10.5 kg)	PET production (10.5 kg)	HDPE production (3.2 kg)	Total virgin production	Net resource consumption
Inputs								
Oil, crude, in ground	kg	1.21E+01	7.74E-01	1.08E+01	8.35E+00	2.86E+00	2.28E+01	-1.06E+01
Gas, natural, in ground	m^3	0.00E+00		6.10E+00	8.15E+00	2.30E+00	1.66E+01	-1.66E+01
Coal, hard, in ground	kg	4.64E-03		8.80E-01	3.09E+00	3.21E-01	4.29E+00	-4.28E+00

Coal, brown, in ground	kg	3.53E-03		1.20E-04	3.02E+00	2.71E-05	3.02E+00	-3.01E+00
Aluminium, 24% in bauxite	kg			5.46E-06	1.94E-02	3.81E-06	1.94E-02	-1.94E-02
Iron, 46% in ore,	kg	1.14E-03		1.74E-03	6.50E-01	5.49E-04	6.53E-01	-6.51E-01
Products								
Total amount of plastic for recycling	kg	2.43E+01		1.06E+01	1.06E+01	3.15E+00	2.43E+01	0.00E+00
Emissions								
PM	kg	1.69E-03	2.57E-03	6.28E-03	2.18E-02	2.39E-03	3.31E-02	-3.14E-02
CO	kg	1.09E-02	2.35E-03	6.43E-02	4.54E-02	3.87E-02	1.51E-01	-1.40E-01
CO_2	kg	3.78E+01	2.84E+00	1.76E+01	2.77E+01	4.90E+00	5.31E+01	-1.53E+01
SO_2	kg	3.69E-01	2.55E-02	4.00E-02	7.38E-02	1.28E-02	1.52E-01	2.17E-01
NOx	kg	1.74E-01	6.55E-02	3.48E-02	5.17E-02	1.02E-02	1.62E-01	1.18E-02
HCl	kg	4.30E-07		5.43E-04	1.27E-03	1.94E-04	2.00E-03	-2.00E-03
NMVOC	kg	7.91E-03	4.69E-04	3.78E-02	2.37E-02	1.36E-02	7.54E-02	-6.75E-02
CH_4	kg	1.77E-03	2.35E-04	1.25E-01	1.35E-01	4.44E-02	3.05E-01	-3.03E-01

Anaerobic digestion

The mass balance analysis results revealed that there is a possibility to treat the biggest share of waste by using AD technology and 581 kg of organic waste can be separated and sent to the AD facility. As explained in Chapter 7 (Table 7.1), the gross electricity production potential from one tonne of organic waste would be 216 kWh and the compost production potential from sludge is 125 kg. Thus, electricity and compost production potential from AD was credited for avoiding conventional process chain. The inventory analysis result for 581 kg of organic waste AD is summarized in Table D9.

Table D9: Inventory analysis of AD of 581 kg of organic waste

Inputs	**Transportation/ per functional unit (15 km by compactor truck)**	**Anaerobic digestion (580.5kg of organic waste and electricity production**	**Composting (production of 72.5kg compost from 581 kg of organic waste**	**Net impacts**
Inputs (kg)				
Baryte	8.35E-03	9.78E-03	3.10E-02	4.92E-02
Coal, 18MJ per kg, in ground	1.96E-02	2.30E-02	7.28E-02	1.15E-01
Coal, brown 8MJ per kg, in ground	1.49E-02	1.75E-02	5.54E-02	8.78E-02
Oil cude,42.6MJ per kg	9.21E-01	1.08E+00	2.60E+00	4.60E+00
Natural gas (m^3)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Heavy oils		-1.30E+01	0.00E+00	-1.30E+01
Iron	4.80E-03	5.63E-03	1.79E-02	2.83E-02
Outputs (kg)				
CO_2	4.64E+00	-3.61E+01	1.16E+01	-1.99E+01

CO	1.16E-02	1.14E-03	2.32E-03	1.51E-02
PM	1.26E-03	1.03E-03	3.24E-03	5.54E-03
H_2	8.57E-06	1.00E-05	3.18E-05	5.04E-05
HCl	1.82E-06	2.13E-06	-7.35E-05	-6.96E-05
CH_4	7.48E-03	8.76E-03	2.75E-02	4.38E-02
NO	3.40E-03	3.98E-03	1.26E-02	2.00E-02
NOx	3.51E-02	-1.56E-01	7.24E-02	-4.84E-02
N_2O	1.07E-05	1.26E-05	-4.93E-03	-4.91E-03
SO_2	3.07E-03	-3.95E-01	2.07E-02	-3.71E-01
VOC	1.71E-02	-1.59E-01	6.83E-02	-7.39E-02
SO_4^-	1.20E-03	1.41E-03	4.47E-03	7.09E-03
NO_3^-	3.46E-05	4.06E-05	1.29E-04	2.04E-04
NH_3	5.99E-05	7.02E-05	4.76E-03	4.89E-03

Incineration

According to the mass balance analysis, 325 kg of combustibles per each tonne of waste generated can be treated by using incineration. As noticed in the Thailand incineration plant, less electricity production efficiencies may be experience in Sri Lanka. Thus, it was assumed that expected electricity production efficiency would be 10%. The reason behind this is the high moisture content of the combustibles which amounts to 41% and the major share of combustibles represents the organic waste which has less LHV. Therefore, gross electricity production potential from one tonne of combustible would be 142 kWh. All incineration plants consume some of the generated energy and sell the remaining energy. In fact, 35% of produced electricity is needed for the onsite operations and the remaining 65% can be sold to the national grid (Phuket Municipality, 2010). The inventory analysis of one tonne of combustibles incineration is presented in Table D10.

D10: Inventory analysis of incineration per one tonne of combustible waste

Inputs/outputs			**Transpor -tation**	**Incineration**	**Total**	**Avoided impact**	**Net Impact**
Inputs							
Electricity	net process electricity	kWh		4.90E+01	4.90E+01	4.90E+01	0.00E+00
Water	Water	m3		2.73E-01	2.73E-01		2.73E-01
Diesel	Diesel	L		6.82E-01	6.82E-01	1.66E+01	-1.59E+01
Auxiliary materials	HCl 35%	L		3.05E-02	3.05E-02		3.05E-02
	NaOH 50%	L		3.11E-02	3.11E-02		3.11E-02
	Stemtech AF	kg		1.64E-03	1.64E-03		1.64E-03
	Ca(OH)2	kg		5.09E+00	5.09E+00		5.09E+00
Raw material for diesel production	Coal, 18MJ per kg,	kg	3.38E-02	3.30E-03	3.71E-02		3.71E-02
	Coal, brown 8MJ per kg,	kg	2.57E-02	2.51E-03	2.82E-02		2.82E-02

	Oil cude,42.6MJ per kg	kg	1.59E+00	1.55E-01	1.74E+00	1.66E+01	-1.48E+01
Outputs							
Electricity	Net electricity output	kWh		9.30E+01	9.30E+01	9.30E+01	0.00E+00
Emissions to air	waste heat	kWh		1.64E+03	1.64E+03		1.64E+03
	TSP	kg		4.05E-02	4.05E-02		4.05E-02
	CO	kg	2.01E-02	4.95E-01	5.15E-01		5.15E-01
	Dioxin TEQ	kg		1.71E-08	1.71E-08		1.71E-08
	VOC	kg	2.94E-02	2.85E-02	5.79E-02		5.79E-02
	Fossil CO_2	kg	7.99E+00	3.46E+02	3.54E+02	5.14E+01	3.02E+02
	SO_2	kg	5.29E-03	3.86E-02	4.39E-02	5.13E-01	-4.69E-01
	NO_2	kg	6.63E-02	1.46E+00	1.53E+00	2.30E-01	1.30E+00
	NH_3	kg	1.03E-04	3.56E-03	3.67E-03		3.67E-03
	CH_4	kg	1.29E-02	0.00E+00	1.29E-02		1.29E-02
	PM	kg	2.17E-03	0.00E+00	2.17E-03		2.17E-03
	N_2O	kg	1.85E-05		1.85E-05		1.85E-05
	HCl	kg	3.13E-06	6.35E-02	6.35E-02		6.35E-02
Emissions to water	NO_3^-	kg	5.96E-05	1.68E-01	1.68E-01		1.68E-01
	PO_4^{-3}	kg		1.88E+00	1.88E+00		1.88E+00

Landfilling

As observed, a landfill is an essential part of the intended integrated system in Kandy, to dispose the residual materials. According to the mass balance, 40 kg of residual waste per each tonne of generated waste has to be landfilled. It was assumed that there is no organic waste remaining in the residual materials so that the environmental impacts would be negligible from the landfill. Diesel fuel is the main input for the landfilling of waste, especially for transportation of waste and operation of heavy machineries to compact the waste at the landfill. Therefore, inventory analysis was done in respect of the diesel fuel production, combustion, etc. (Table D11).

Table D11: Inventory analysis for one tonne of residual waste landfilling

Resources	Amount (kg)	emissions	amount (kg)	emissions	amount (kg)	emission	amount(kg)
Baryte	1.55E-02	CO_2	7.52E+00	CH_4	1.39E-02	VOC	4.49E-02
Coal, 18MJ per kg, in ground	3.63E-02	CO	1.15E-01	NO	6.29E-03	SO_4^{-2}	2.23E-03
Coal, brown 8MJ per kg, in ground	2.76E-02	PM	1.81E-02	NO_x	6.65E-02	NO_3^-	6.41E-05
Oil cude,42.6MJ per kg	1.71E+00	H_2	1.59E-05	N_2O	1.99E-05	NH_3	1.11E-04
Iron	8.90E-03	HCl	3.36E-06	SO_2	5.69E-03		

Evaluation of intended integrated system by using the midpoint indicators

The magnitudes of the net environmental impacts at the midpoint level were estimated for individual technologies and for the intended integrated system, (Table D 12).

Table D 12: Quntified net impacts from the selelcted technologies and intended integrated system

Treatment methods	Amount of waste	Severity of impact per tonne of waste						
		% of mass	Global warming (kg of CO_2 eq)	Acidification (kg SO_2 eq.)	Europhication (kg NO_3^- eq.)	Photo Oxidant Formation (kg C_2H_4 eq.)	Abiotic resources Depletion (kg Sb eq.)	Human Toxicity (kg 1-4 DB eq)
Recycling	54.5	5.5	-2.75E+02	4.23E+00	-1.41E-01	-7.60E-01	-1.05E+01	-2.23E+00
Anaerobic digestion	580.5	58.1	-3.50E+01	-6.45E-01	-5.93E-02	-6.21E-02	-2.94E-01	-1.11E-01
Incineration	325.0	32.5	3.04E+02	5.01E-01	2.15E+01	4.96E-02	-3.02E-01	1.51E+00
Landilling	40.0	4.0	8.07E+00	5.92E-02	9.03E-02	2.72E-02	3.55E-02	9.52E-02
Total impact from the integrated system	**1000**	**100**	**6.38E+01**	**2.16E-02**	**6.96E+00**	**-6.02E-02**	**-8.40E-01**	**3.09E-01**

It should be noted that recycling and anaerobic digestion has significantly influenced the avoidance of all the environmental impacts due to credited energy and material recovery processes, and it is indicated as a net negative values. However, the possibility of avoiding damage from both recycling and AD has not been able to neutralize all the damage occurrence potential from incineration and landfilling within the integrated system. Thus, the overall result of the intended integrated system shows the damage occurrence possibility, to some extent. As a reward for initiation of an integrated system, it will contribute to the reduction of GWP by 91%, acidification by 100%, eutrophication by 57%, photo-oxidant formation by 128%, and human toxicity by 53% than that of the existing MSW management.

APPENDIX E

E1. Information related to sustainability assessment of existing MSW management system in India

Inventory analysis

Table E1: Inventory analysis of open dumping of one tonne of generated MSW at KMC, India (background information for calculation; Pré Consultants, 2007a; LIPASTO, 2009; IPCC, 2006)

Emissions	Fuel production +Transportation (kg)	Open dumping	Total (kg)/tonne
CH_4	1.64E-02	1.82E+01	1.82E+01
CO_2	3.82E+00	NA	3.82E+00
NH_3	8.08E-05	3.30E+00	3.30E+00
N_2O	1.52E-05	NA	1.52E-05
CO	1.97E-02	NA	1.97E-02
NO_x	4.21E-02	NA	4.21E-02
SO_x	6.18E-03	NA	6.18E-03
H_2S	0.00E+00	4.70E-01	4.70E-01
NOx (NO_3^-)	3.41E-05	NA	3.41E-05
VOC	2.13E-02	8.74E-05	2.14E-02
PM 10	2.53E-03	NA	2.53E-03
HCl	2.45E-06	0.00E+00	2.45E-06
Fossil Oil	2.65E+00	NA	2.65E+00
Fossil coal	8.74E-01	NA	8.74E-01

* NA – Not significant

Table E2: Amount of compost production from MSW at Dhapa (background information for calculation Hazra and Goel, 2009; Chattopadhyay et al., 2009; Norbu, et al., 2005)

Description	Amount	Unit
Total MSW receive to the composting plant	700	tonnes/day
Total compostable amount	427	tonnes/day
Moisture content of compostable	69	%
Total dry matter content of compostable	132.37	tonne/day
Dry matter reduction during composting process	20	%
Matured compost (dry basis)	106	tonnes/day
Moisture content of matured compost	40	%
Weight of mature compost (wet basis)	176	tonnes/day
Compost production per tonne of received mix MSW	0.25	tonne of compost/tonne of receive waste

Table E 3: Inventory analysis of compost production process per tonne of generated waste

Emissions	Collection and transportation	Operation and Maintenance	Total kg/ tonne of collected waste	Credited impacts for 0.25 tonne compost production per tonne of collected waste	Net resource consumption and emissions
CH_4	1.64E-02	1.87E-04	1.66E-02	8.44E-04	1.58E-02
CO_2	3.82E+00	3.21E+00	7.03E+00	5.32E+00	1.70E+00
NH_3	8.08E-05	2.38E+00	2.38E+00	8.75E-03	2.38E+00
N_2O	1.52E-05	1.35E-04	1.50E-04	1.71E-02	-1.70E-02
CO	1.97E-02	1.82E-02	3.79E-02	4.52E-03	3.34E-02
NO_x	4.21E-02	5.56E-02	9.77E-02	2.13E-02	7.64E-02
SO_x	6.18E-03	9.98E-04	7.18E-03	1.43E-02	-7.15E-03
NO_x (NO_3^-)	3.41E-05	0.00E+00	3.41E-05	0.00E+00	3.41E-05
VOC	2.13E-02	1.36E-01	1.58E-01	0.00E+00	1.58E-01
PM_{10}	2.53E-03	0.00E+00	2.53E-03	7.98E-05	2.45E-03
HCl	2.45E-06	0.00E+00	2.45E-06	2.76E-04	-2.74E-04
Fossil Oil	2.65E+00	1.99E+00	4.64E+00	2.86E+00	1.78E+00
Fossil coal	8.74E-01	3.59E-02	9.10E-01	0.00E+00	9.10E-01

Evaluation of existing MSW management system by using midpoint environmental indicators

Global warming potential

According to the composition of waste in KMC, dumpsite condition at Dhapa and climatic situation in Kolkata, the IPCC model based default values derived were: DOC (0.109), DOC_f (0.5), k (0.214) and F (0.5). As reported by Hazra and Goel (2009), even though Dhapa dumpsite is considered as a deep and unmanaged dumpsite (17m height), this unmanaged dumpsite is partially aerobic, and therefore the methane correction factor (MCF) was taken as 0.5. The estimated GWP from presently practiced open dumping is 458 kg of CO_2 equivalents per tonne of MSW disposed at the open dump. Out of that, final disposal contributes to 99.1% of GWP which is mainly due to its high methane emission potential under the open dumping situation and remaining 0.9% of GWP from the collection and transportation and fuel production.

In contrast, calculated GWP from composting was -2.85 kg of CO_2 equivalents per tonne of waste. Even though, fuel production, MSW transportation and processing of compost can cause green house gasses emission, net GWP value is negative since compost production from waste was credited for avoiding chemical fertilizer production chain from virgin materials and avoiding its emissions. Considering the fraction of daily generated waste which goes through both open dumping and windrow composting process, (76%

open dumping, 24% composting) the net GWP from existing method is 349 kg of CO_2 equivalent per tonne of MSW generated in KMC.

Acidification potential

According to the chemical composition, one tonne of MSW in KMC has the potential of emitting 3.3kg of NH_3 and 0.47kg of H_2S to the atmosphere in the open dumping situation. In addition, collection and transportation also can release a range of acidifying substances. Due to all the emissions from collection and transportation to final disposal, acidification potential amounts to 7.13kg of SO_2 equivalents /tonne of waste. Moreover, composting of one tonne of MSW has the potential of releasing 4.5kg SO_2 equivalent of acidifying substances to the environment. The most prominent acidifying substance from composting is NH_3 (3.9 kg/tonne of organic waste composting (Cadena et al., 2009) which is released during the decomposition process. In a LCA perspective, composting production process has been credited for avoidance of chemical fertilizer production. However, acidifying substances producing potential from composting is much higher than the amount that can be avoided. Thus, there is a possibility for creation of acidification as a result of composting. Net acidification potential from composting is 4.5 kg SO_2 equivalents per tonne of waste. Considering the aggregated effects from both open dumping and composting processes, acidification potential from one tonne of MSW is 6.51kg of SO_2 equivalents. It should be noted that 24% of generated waste composting in KMC has influenced on reducing 8.7% of acidification potential than just open dumping.

Eutrophication potential

Based on the chemical characteristics of MSW in Kolkata, there is a potential for releasing 194 moles of N as NO_3^- to the environment with leachate. Thus, the potential of eutrophication would be 12.04kg of NO_3^- equivalents per tonne of MSW open dumping. Moreover, MSW transportation and fuel production is also emitting eutrophying substances such as NH_3, NO, NO_2, N_2O. The total eutrophication potential from one tonne of MSW transportation is equal to 0.06 kg of NO_3^- equivalents. Thus, the total eutrophication potential from open dumping at KMC is amounted to 12.1 kg of NO_3^- equivelants. Moreover, eutrophication potential from the composting process is 8.71 kg of NO_3^- equivalents, in which avoided eutrophication potential from chemical fertilizer production has been included. Considering both composting and open dumping, net eutropication potential from one tonne of generated waste is 11.3kg of NO_3^- equivalent due to the existing MSW management in KMC.

Photo oxidant formation potential

IPCC model estimated landfill gas production potential from Dhapa dumpsite is 55.44 m^3/ tonne of MSW. The produced landfill gas includes some of the photo-oxidant formation substances such as methane (18.18 kg/tonne) and NMVOCs (0.03g/tonne). Total photo-oxidant formation potential from open dumping is 0.14 kg of C_2H_4 equivalents per tonne of MSW, and 8.3% of that occurs in the process of transportation. Similarly, windrow composting process can create 0.08 kg of C_2H_4 equivalents of net photo- oxidant formation potential per tonne of MSW. Thus, combining the effects of both open dumping and composting, the net photo–oxidant formation is 0.12 kg of C_2H_4 equivalents per tonne of waste.

Human toxicity potential

Toxicity creating compounds such as H_2S, NO_x, SO_x, NH_3 and PM_{10} emissions were accounted from the entire life cycle of both open dumping and composting. Human toxicity potential from one tonne of waste open dumping in KMC is 0.49 1-4 dichlorobenzene equivalents. In which 90% toxicity problem occurs due to final disposal. In addition composting process is also has the potential of creating human toxicity potential which amounts to 0.33 1-4 dichlorobenzene equivalents. The aggregated effect of human toxicity potential from both open dumping and composting is 0.45 1-4 dichlorobenzene equivalents per tonne of waste management under the existing MSW management.

Abiotic resource depletion potential

The major abiotic resource depletion happens due to the fuel consumption for waste collection and transportation in Kolkata. The estimated fuel consumption for one tonne of waste transportation is 1.46 L of diesel per tonne of waste. Considering the collection and transportation methods in KMC and the fuel production process in India, calculated ADP from open dumping is 5.73E-02 kg of antimony equivalents per tonne of waste.

In addition ADP from the windrow composting process is also calculated, which amounts to 9.47E-02 kg of antimony equivalents. Of this 56.7% ADP occurs due to collection and transportation and remaining 43.3% of ADP is caused from fuel consumption during the processing of compost specially turning of windrows. As reported, 1.85 L of diesel is required per tonne of organic waste composting in the windrow composting process (Lou and Nair. 2009). Moreover, all the possible ways of reducing ADP was counted such as avoidance of mineral usage for chemical fertilizer production through virgin production process chain and avoidance of energy consumption for chemical fertilizer production. Based on those considerations, total avoidance of ADP from composting of one tonne of MSW is 5.86E-02 kg of antimony equivalents. Thus, net ADP potential from composting was 3.61E-02 kg of antinomy equivalents per tonne of waste. When calculated for the existing MSW management method in KMC, taking into account open dumping and composting, potential ADP from one tonne of generated MSW is 4.95E-02 kg of antimony equivalents.

All the environmental indicators quantified for KMC are summarized in Table E4 Environmental impacts have been shown for one tonne of MSW open dumping, and composting by the existing management method (76% - open dumping and 24% - composting). All in all, 24% of composting has a considerable influence in reducing overall environmental damage from existing MSW management than just the open dumping.

Table E4: Quntified midpoint indicators of existing MSW management in Kolkata

Environmental Indicators	Unit	Net impacts from open dumping per tonne of waste	Net impacts from windrow composting per tonne of waste	Net impacts from the existing MSW management
Global Warming Potential	kg of CO_2 equivalents	4.59E+02	-2.90E+00	3.49E+02
Acidification potential	kg of SO_2 equivalents	7.13E+00	4.52E+00	6.51E+00
Eutrophication potential	kg of NO_3^- equivalents	1.21E+01	8.71E+00	1.13E+01
Photo- Oxidant formation potential	kg of C_2H_4 equivalents	1.39E-01	8.02E-02	1.25E-01
Human Toxicity Potential	kg of 1-4 DB equivalents	4.87E-01	3.31E-01	4.50E-01
Abiotic resource Depletion Potential(ADP)	kg of Sb equivalents	5.37E-02	3.61E-02	4.95E-02

E2. Background information on initiation of sanitary landfill with LFG recovery system as a sustainable solution to the present problem

Defining the LCA framework

LCA framework was designed taking onto consideration, all the phases of life cycle and inputs and outputs related to the three pillars of sustainability.

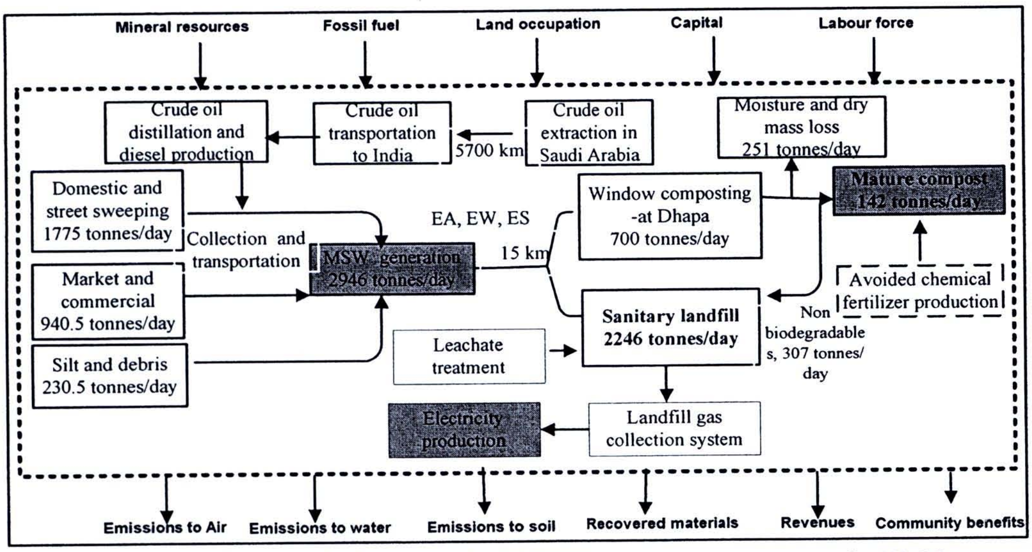


Figure E 1: LCA framework for upgraded MSW management system in KMC

Inventory analysis of sanitary landfill with LFG recovery system

In order to perform an inventory analysis and sustainability assessment of the intended sanitary landfill in KMC, numerous assumptions had to be made as follows.

-The existing vehicles will be replaced with compactor trucks to improve the efficiency of the collection of waste.

-Landfill will be sited adjacent to the existing landfill so that the average transportation distance from the collection points to landfill would be 15 km and the fuel consumption in tipper trucks for transportation would be 1.87 L/tonne of waste.

-Tipping fee should be charged from the local authorities at least 100 INR/tonne of waste disposal at the upgraded system in KMC in order to balance the budget and to initiate a reinforce system (SNG Mercantile Pvt. Ltd, 2007).

-HDPE liner has to be used at the bottom and on the side walls of the landfill to avoid leachate penetration to the ground water table.

-Intended landfill will be used to dispose waste for the period of 5 years.

- Gas collection and flaring systems will be incorporated to collect methane and to flare the excess methane.
- Leachate will be treated to meet the local environmental standards before releasing it to inland water bodies
-Maximum landfill gas extraction would be 75% of generated landfill using available technologies (El Hanandeh and El-Zein, 2010)
- 15% of uncollected methane is oxidized in the landfill cover and electricity efficiency of internal combustion engine is 35% (Baratieri et al., 2009).
- Three sets of 2 MW IC engines would be incorporated to produce electricity out of collected LFG.. Landfill gas extraction will be started in the beginning of the second year since LGF production starts within few months of waste disposal (COGEN Asia, 2010). One set of 2 MW IC would be sufficient in the second year, and the second 2MW engine will be engaged in the 3rd year and the last 2 MW engine in the 4^{th} year in order to extract the maximum amount of LFG. The collected excess LFG will be fared since adding more IC engines would increase the capital and operational cost.
- Average life time of the IC engine is 10 years.
-Produced electricity will be sold to the national grid at the rate of 7 INR/kWh (Ministry of Power, 2009).
- Purchasing new loaders and mobile equipment for more efficient turning of windrows and onsite movement of materials
- Close attention will be paid to generating high quality compost in an efficient, reliable manner. The produced quality compost could be sold at the rate of 3.85 INR/kg (SNG Mercantile Pvt. Ltd, 2007).
-Skilled and efficient labour power will be created to improve the quality of jobs in terms of productivity, average earnings and protection of workers.

Taking into consideration all those assumptions, the total amount of methane that would be used for electricity production and the amount of excess methane which would be flared from the disposed waste during the five year period was estimated (see Figure E2).

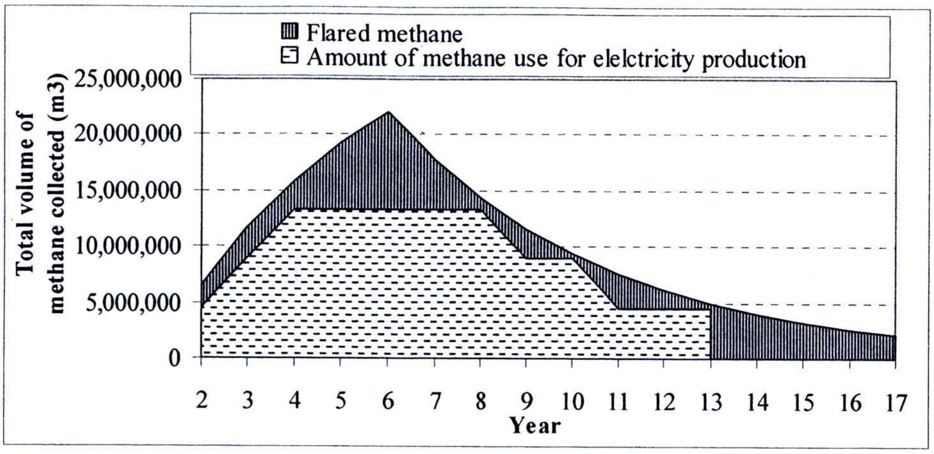


Figure E2: Total methane collection potential from sanitary landfill from the disposed waste for five years

According to the calculation, the electricity production potential from one tonne of disposed waste is 97.58 kWh. The produced electricity from LFG was credited for avoidance of conventional electricity production process and its emissions (see Table E5).

Table E 5: Inventory analysis of sanitary landfill with LFG recovery system

Input/output	Emissions	Fuel production (1.875 L of diesel)	Collection and transportation of MSW	Final Disposal	Total	Credited emissions resource consumption (97.58 kWh/tonne electricity production)	Net emissions/resource consumption
Energy and material use (kg)	Coal	5.94E-02	0.00E+00	8.87E-05	5.95E-02	2.98E+01	-2.97E+01
	Oil Crude	3.29E+00	0.00E+00	6.54E-01	3.95E+00	2.13E-01	3.73E+00
	Iron	8.27E-03	0.00E+00	3.51E-06	8.28E-03		8.28E-03
	Bauxite	1.44E-02	0.00E+00	2.87E-06	1.44E-02		1.44E-02
	Natural gas (m^3)					2.37E+00	-2.37E+00
Emissions to air (kg)	CO_2	1.19E+00	6.27E+00	1.40E+00	8.86E+00	6.32E+01	-5.43E+01
	CH_4	1.29E-02	0.00E+00	7.73E+00	7.75E+00	5.12E-03	7.74E+00
	CO	1.69E-03	1.13E-01	8.61E-02	2.01E-01	1.44E-02	1.87E-01
	NOx	7.64E-03	6.54E-02	9.14E-02	1.64E-01	1.60E-01	4.78E-03
	N_2O	1.93E-05	0.00E+00	0.00E+00	1.93E-05	1.83E-05	1.01E-06
	NH_3	0.00E+00	0.00E+00	3.30E+00	3.30E+00		3.30E+00
	SOx	5.57E-03	0.00E+00	7.15E-03	1.27E-02	4.08E-01	-3.95E-01
	H_2S	0.00E+00	0.00E+00	4.70E-01	4.70E-01		4.70E-01
	VOC	2.72E-02	1.57E-02	5.44E-03	4.83E-02		4.83E-02
	PM	6.75E-04	1.74E-02	5.10E-04	1.86E-02	5.64E-04	1.80E-02
Emissions to water (kg)	SO_4^-	2.07E-03	0.00E+00	1.33E+00	1.33E+00		1.33E+00
	NO_3^-	5.96E-05	0.00E+00	1.73E-01	1.73E-01		1.73E-01
	HCl	3.13E-06	0.00E+00	0.00E+00	3.13E-06		3.13E-06
	NH_4^+	1.03E-04	0.00E+00	1.78E-01	1.78E-01		1.78E-01

Evaluation of the upgraded system in KMC by using the midpoint indicators

Detailed inventory analysis was performed for the sanitary landfill with LFG recovery system at KMC, encompassing all the phases of the life cycle (Table E6). Midpoint indicators were quantified for treatment of one tonne of waste under the sanitary landfill with gas recovery by using the inventory analysis results. In order to find the overall impacts from the upgraded system at KMC, the resulted midpoint impacts from both composting and sanitary landfill technologies were integrated for the fraction of waste. The quantified indicators from one tonne of waste composting, sanitary landfill with the gas recovery system and upgraded integrated system is shown in Table E6.

Table E6: Quantified midpoint indicators for upgraded MSW management in KMC

Environmental Indicator	Unit	Net Impact from sanitary landfill with gas recovery	Net impact from composting	Net impact from upgraded system (76% and land filling +24% composting
Global Warming Potential	kg of CO_2 equivalents	1.24E+02	2.34E+00	9.47E+01
Acidification potential	kg of SO_2 equivalents	6.71E+00	4.55E+00	6.19E+00
Eutropication potential	kg of NO_3^- equivalents	7.98E-01	8.76E+00	2.71E+00
Photo- Oxidant formation potential	kg of C_2H_4 equivalents	8.57E-02	1.08E-01	9.11E-02
Human toxicity potential	kg of 1-4 DB equivalents	4.16E-01	3.90E-01	4.10E-01
Abiotic resource Depletion Potential(ADP)	kg of Sb equivalents	-2.22E-01	6.20E-02	-1.54E-01

It is necessary to understand the factual benefits of this kind of pilot scale project at the design stage prior to the implementation. Thus, to understand the real value of this project, and also to understand the possibilities of achieving sustainability, the results of the upgraded system with LFG recovery were compared with the existing system. The results of the comparison are shown in Figure E3, which clearly reflects the benefits of initiating a landfill gas to energy project. For instance, in the midpoint level, sanitary landfill with the gas recovery system has contributed to reducing global warming potential by 73%, acidification potential by 5%, eutrophication potential by 76%, photo-oxidant formation potential by 27%, human toxicity potential by 9% and abiotic resource depletion potential by 399%. It should be noted that, electricity production from landfill gas and compost production from the biodegradable fraction imparts significant benefits by avoiding abiotic resource damage that would have otherwise occurred from conventional electricity and fertilizer production.

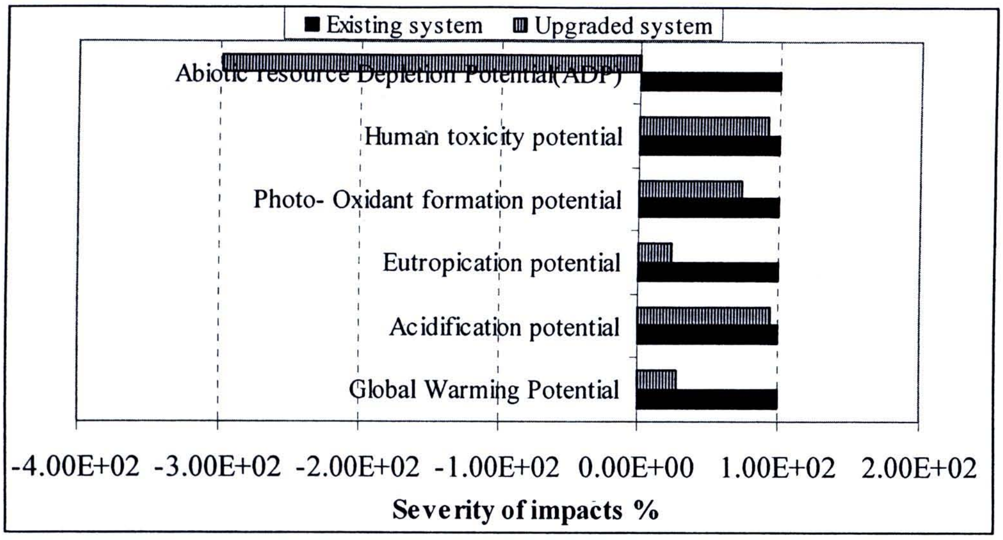


Figure E3: Severity of midpoint indicators of the upgraded system relative to the existing MSW management in KMC

E3 – Background information on sustainability assessment of intended integrated MSW management system at KMC- India

As the first step of sustainability assessment, LCA framework was defined for the proposed integrated system, including all the phases of life cycle such as collection of MSW, transportation of waste to a sorting facility, sorting of waste at a automated sorting plant, treatment of waste using different technologies (recycling of recovered materials, AD of organic waste, incineration of combustibles and landfilling of the residual waste). It was assumed that the existing compost plant will be operated in the usual way. However, part of the recyclables will be separated from the mix waste that would be delivered to the composting facility. The recovered material will be sent to the recycling facilities after preprocessing along with the materials that are recovered at the sorting facility. In addition to the main treatment methods, all the required energy and auxiliary materials production processes were also included within the system boundary. The LCA frame work and the system boundary for the intended integrated MSW management system at KMC are shown in Figure E4.

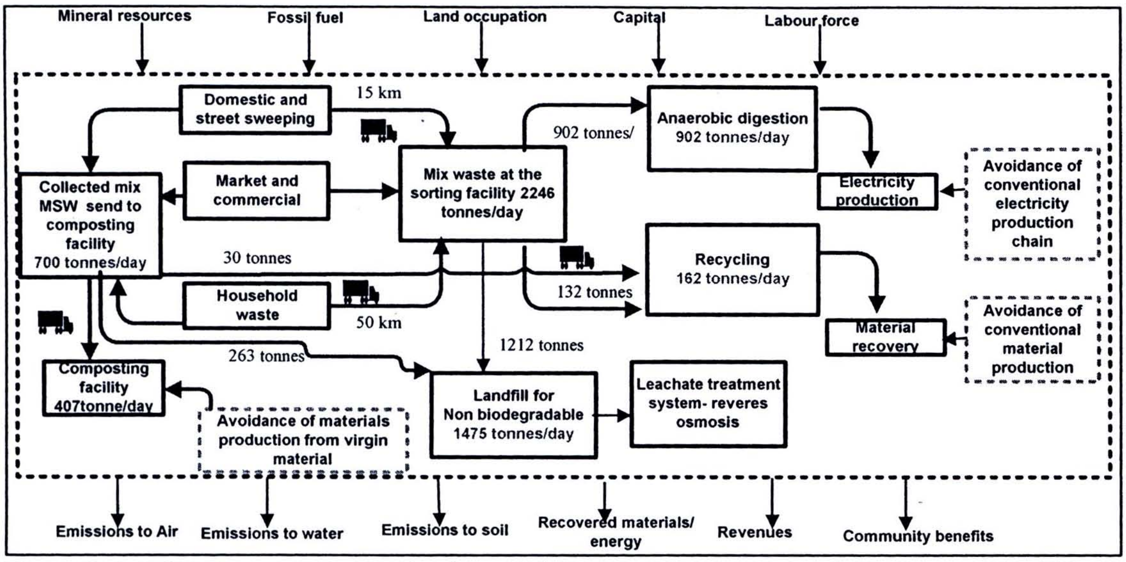


Figure E4: LCA framework for the intended integrated system in KMC for sustainability assessment

The collected waste will be transported to a material recovery facility (MRF). As noticed, total daily waste generation is very high in KMC (around 3000 tonnes/day), so that manual sorting would not be a possible solution. Thus, it was assumed that the operations at the sorting facility will be so designed to make it as automated as possible in order to increase the speed of operation, reduce costs and improve recovery.

Various activities will be performed at the MRF, such as, transporting materials via conveyor belt, ferrous metal separation (removes the ferrous metals), trammel screening (separate food waste from other recyclables), air classification (separate light materials from heavy materials (separate aluminium, plastic from glass), non ferrous metal separation, detect and route systems (to separate glass, plastic and paper separation into various categories), size reduction, compaction and bailing.

Unfortunately, at present there is no functioning mega scale MRF or automated sorting pant in India. Therefore, information related to automated MRF such as efficiencies, capital cost, operational and maintenance cost, etc was collected from the literature sources (Dubanowitz, 2000).

As an initial step of the sustainability assessment, mass balance was done in order to find the amount of waste that can be treated using different technologies. Based on mass balance analysis, it was found that 5.5% of MSW can be recovered and recycled. 30.6% of short term biodegradable waste can be used for anaerobic digestion process. 13.8% of biodegradable waste will be used for composting production process. The biggest share of waste that is 50.1% still goes for landfilling. The reason behind this is, a non -recovered combustible fraction is also disposed at the landfill. As reported all the harnessed incineration plants encountered a lot of problems due to the high volume of organic material, high moisture content and high inert content. Therefore there are no properly functioning incineration plants in India (Sharholy et al., 2008). Therefore, commissioning an incineration plant within the intended integrated system is a doubtful issue.

Thus it was assumed that the unrecovered combustible fraction will also be disposed at the landfill. In addition, the percentage of residual waste is also quite high in the MSW. All together the disposal fractions at the landfill are quite high. It was found that there is a possibility to produce electricity from landfill gas since a considerable amount of organic waste will be disposed of at the sanitary landfill. For instance, 76kWh of electricity production potential was estimated per tonne of waste disposed at the sanitary landfill.

Inventory analysis of the intended integrated system in KMC

Recycling

According to the mass balance analysis, only 5.5% of generated waste can be recovered from the material recovery facility for recycling. It was assumed that only 50% of recyclables can be recovered from the mix waste stream for recycling purposes. Thus, there is a possibility to recover 26.74 kg of paper, 24.40 kg of plastic, 2.55 kg of glass and 1.425 kg of aluminium and metal. It was assumed that recycling facilities will commenced at Kolkata in the near future since it is one of the biggest cities in India. The recovered recyclables at the MRF will be bailed and sent to the recycling facilities in Kolkata (transportation distance was assumed to be 25 km by heavy duty trucks). Eco-invent database was used to find the inputs and outputs of recycling. However, to make a more representative data set for India, country specific data was obtained in relation to the type of fossil energy consumption (50% of thermal energy from coal and coal products and remaining 50% from fuel oil and diesel), the amount of fossil resource requirement, furnace efficiencies, emissions from combustion of fossil resources, emissions from electricity grid mix etc (Ministry of Power, 2009).

Paper recycling

The composition of the mixed paper waste in India represents approximately, 25% - newsprint, 25% - office paper and 50% - Kraft paper. Therefore, recoverable 26.74 kg of paper may consist of 6.68 kg - newsprint, 6.68 kg- office paper and 13.37 kg - Kraft paper. The inventory analysis results for the paper recycling and same amount of paper production through virgin processes are presented in Table E7.

Table E7: Inventory analysis for paper recycling and virgin production in India

Life cycle inputs/outputs	Recycling of 26.74 kg of paper		Virgin production of 23.99 kg of paper				
	Unit	Recycling (26.74 kg) waste paper	Newsprint (6.52 kg)	Office paper(6.52 kg)	Kraft paper(13.04 kg)	virgin production of 23.99 kg of paper	**Net savings**
Inputs							
Hard Wood	m^3			9.42E-03	0.00E+00	9.42E-03	-9.42E-03
Soft wood	m^3		5.03E-03	7.57E-03	5.47E-02	6.73E-02	-6.73E-02
Wood chips	m^3		9.95E-04	4.61E-04		1.46E-03	-1.46E-03
Hydrogen peroxide 50% in H2O	kg	2.34E-01	6.28E-02		1.03E-02	7.31E-02	1.61E-01
H_2SO_4	kg		1.89E-03	9.67E-02	2.70E-02	1.26E-01	-1.26E-01
Energy consumption							
Electricity, at grid	kWh	9.32E+00	8.95E+00	2.05E+00	1.22E+01	2.32E+01	-1.39E+01
Hard coal	kg	1.17E+01	5.57E-01	1.27E+00	4.89E+00	6.71E+00	4.96E+00
Soft coal	kg	0.00E+00	2.73E+00	1.32E-03	3.91E-03	2.73E+00	-2.73E+00
Heavy fuel oil	kg	2.73E+00	2.27E-01	2.93E-01	6.47E-01	1.17E+00	1.56E+00
Natural gas	m^3	2.77E-01	5.88E-03	1.35E-03	8.01E-03	1.52E-02	2.62E-01
Wood chips	MJ						0.00E+00
Outputs							
amount of paper produced	kg	2.40E+01	5.56E+00	5.56E+00	1.29E+01	2.40E+01	0.00E+00
Emissions							
CO_2 fossil	kg	3.80E+01	7.95E+00	4.00E+00	1.31E+01	2.51E+01	1.29E+01
NH_3	kg	5.74E-06	1.90E-06	5.46E-06	1.60E-05	2.33E-05	-1.76E-05
CO	kg	2.87E-02	4.59E-03	7.05E-03	1.96E-02	3.12E-02	-2.54E-03
CH_4	kg	4.02E-03	8.74E-04	9.82E-04	2.99E-03	4.84E-03	-8.24E-04
NMVOCs	kg	2.30E-03	7.13E-04	2.09E-03	6.15E-03	8.95E-03	-6.65E-03
N_2O	kg	1.01E-04	2.01E-06	1.38E-06	5.24E-06	8.63E-06	9.25E-05
NOx	kg	8.02E-02	1.96E-02	1.10E-02	3.75E-02	6.82E-02	1.21E-02
SOx	kg	9.19E-02	4.04E-02	1.23E-02	5.80E-02	1.11E-01	-1.88E-02
PM >10mm	kg	1.77E-02	1.48E-03	2.12E-03	4.79E-03	8.40E-03	9.26E-03

Plastic recycling

It was assumed that 50% of plastic in the mixed MSW could be recovered at the sorting facility; thus the recyclable plastic amounts to 24.4 kg per tonne of waste generated. According to the composition of the plastic waste in India, it consists of 25% of HDPE and 75% LDPE. LDPE plastic is basically the mixture of PET and PP. According to the mass balance, total recovered plastic waste is 24.4 kg, in which 9.15 kg of PP, 9.15 kg of PET and 6.1 kg of HDPE is included. Inventory analysis of the plastic recycling and equivalent amount of virgin plastic production is presented in Table E8.

Table E8: Inventory analysis for plastic recycling and virgin production in India

	Total recycling of 24.4 kg of plastic		Total virgin production of 21.96 kg of plastics					
Life cycle inputs/outputs	unit	Total impacts from recycling (24.4 kg of plastics)	Transportation of crude oil by ships	PP production (9.15 kg)	PET production (9.15kg)	HDPE production (6.1 kg)	Total virgin production of 21.96 kg plastics	Net resource consumption
Inputs								
Oil, crude, in ground	kg	3.28E-01	1.18E+00	8.39E+00	6.50E+00	4.98E+00	2.11E+01	-2.07E+01
Gas, natural, in ground	m3	2.29E+00		4.75E+00	6.35E+00	4.01E+00	1.51E+01	-1.28E+01
Coal, hard, unspecified, in ground	kg	2.87E+01		6.85E-01	2.40E+00	5.60E-01	3.65E+00	2.50E+01
Coal, brown, in ground	kg	2.05E-03		9.38E-05	2.35E+00	4.72E-05	2.35E+00	-2.35E+00
waste managwment landfill	kg			6.91E-02	0.00E+00	5.53E-02	1.24E-01	-1.24E-01
Products								
Total amount of plastic for recycling	kg	2.20E+01		8.24E+00	8.24E+00	5.49E+00	2.20E+01	0.00E+00
Emissions								
PM	kg	1.72E-03	4.00E-03	4.89E-03	1.70E-02	4.17E-03	3.01E-02	-2.84E-02
CO	kg	2.11E-02	3.65E-03	5.00E-02	3.53E-02	6.74E-02	1.56E-01	-1.35E-01
CO_2	kg	6.14E+01	4.42E+00	1.37E+01	2.16E+01	8.54E+00	4.83E+01	1.32E+01
SO_2	kg	3.93E-01	3.96E-02	3.12E-02	5.75E-02	2.24E-02	1.51E-01	2.43E-01
NOx	kg	1.59E-01	1.02E-01	2.71E-02	4.03E-02	1.77E-02	1.87E-01	-2.84E-02
HCl	kg	2.50E-07		4.23E-04	9.87E-04	3.39E-04	1.75E-03	-1.75E-03
NMVOC	kg	5.63E-03	7.31E-04	2.94E-02	1.84E-02	2.36E-02	7.22E-02	-6.65E-02
CH4	kg	5.87E-03	3.65E-04	9.70E-02	1.06E-01	7.74E-02	2.80E-01	-2.74E-01

Glass recycling

It was assumed that 75% of glass in mix MSW can be recovered from the recycling process. Thus only 2.55 kg of glass can be recovered per tonne of mix waste and it can be used for recycling. The recycling process may produce 2.42 kg of recycled glass so that an equivalent amount of virgin glass production can be avoided. Table E9 summarized the inventory data of recycling of 2.55 kg of glass and virgin production of equivalent amount of glass.

Table E9: Inventory analysis for glass recycling and virgin production in India

Life cycle inputs/outputs	Unit	Recycling (2.55 kg)	Virgin production inventory (2.42 kg)				
		Recycling of 2.55 kg of glass recycling production	White glass (1.21 kg virgin production)	Brown glass(0.607 kg virgin production)	Green glass(0.607 kg of virgin production)	Total from virgin production	Net resource consumption and emissions
Inputs							
Coal, brown, 8 MJ per kg,	kg	2.02E-02	2.41E-02	1.26E-02	5.06E-03	4.18E-02	-2.16E-02
Gas, natural, 36.6 MJ per m^3	m^3	5.97E-02	-4.29E-04	-3.55E-03	1.49E-02	1.10E-02	4.88E-02
Coal, 18 MJ per kg, in ground	kg	2.94E-02	1.26E-01	6.19E-02	7.35E-03	1.95E-01	-1.66E-01
Oil, crude, 42.6 MJ per kg	kg	4.08E-01	2.49E-01	1.37E-01	1.02E-01	4.88E-01	-7.96E-02
Total energy use	MJ	2.58E+01	1.73E+01	9.29E+00	6.44E+00	3.30E+01	-7.27E+00
Recycling glass	kg	2.55E+00	0.00E+00	0.00E+00	6.38E-01	6.38E-01	1.91E+00
Outputs							
PM	kg	1.72E-03	2.64E-03	1.11E-03	4.30E-04	4.17E-03	-2.45E-03
CH_4	kg	1.89E-03	9.52E-04	5.18E-04	4.73E-04	1.94E-03	-5.09E-05
NMVOC	kg	3.33E-03	2.47E-03	1.32E-03	8.32E-04	4.62E-03	-1.29E-03
CO_2	kg	1.41E+00	1.21E+00	6.69E-01	3.52E-01	2.23E+00	-8.25E-01
CO	kg	6.48E-04	1.88E-03	9.81E-04	1.62E-04	3.03E-03	-2.38E-03
NH_3	kg	6.34E-06	1.10E-04	5.48E-05	1.58E-06	1.66E-04	-1.60E-04
HF	kg	5.68E-05	5.61E-06	1.08E-06	1.42E-05	2.09E-05	3.59E-05
N_2O	kg	4.08E-06	3.12E-06	1.62E-06	1.02E-06	5.76E-06	-1.68E-06
HCl	kg	1.42E-04	9.91E-05	8.62E-05	3.56E-05	2.21E-04	-7.85E-05
SOx	kg	1.81E-03	6.74E-03	2.38E-03	4.52E-04	9.57E-03	-7.77E-03
NOx	kg	7.36E-03	1.52E-03	5.61E-04	1.84E-03	3.92E-03	3.44E-03

Aluminium recycling

According to the composition of waste in KMC, the percentage of aluminium is quite less and it amounts to 0.71 kg per tonne of waste generated. Recycling of this amount of waste aluminium can replace the production 0.54 kg of virgin aluminium. Inventory analysis data for aluminium recycling and equivalent amount of virgin aluminium production is presented in Table E10.

Table E10: Inventory analysis for aluminium recycling and virgin production in India

Life cycle inputs and outputs	Recycling (0.71 kg)		Virgin production (0.54kg)		
	Unit	Total from recycling	emissions from electricity production and thermal energy providing	Total	Net resource consumption and emissions
Inputs					
Total thermal energy	MJ	2.57E+00	1.22E+01	1.22E+01	-9.60E+00
Electricity	kWh	1.20E-01	8.47E+00	8.47E+00	-8.35E+00
Lignite /brown coal	kg	7.95E-05	0.00E+00	0.00E+00	7.95E-05
Hard coal/Black coal	kg	1.17E-01	2.97E+00	2.97E+00	-2.85E+00
Heavy oil and diesel	kg	3.61E-02	1.58E-01	1.58E-01	-1.22E-01
Natural gas	m^3	1.67E-03	2.06E-01	2.06E-01	-2.04E-01
Outputs					
CO_2	kg	4.49E-01	6.96E+00	6.96E+00	-6.51E+00
CO	kg	5.27E-04	2.41E-03	2.41E-03	-1.88E-03
N_2O	kg	5.99E-08		0.00E+00	5.99E-08
HF	kg		0.00E+00	3.00E-04	-3.00E-04
PM	kg	1.76E-04	8.46E-04	5.84E-03	-5.67E-03
NOx	kg	9.24E-04	2.81E-03	1.79E-02	-1.69E-02
SOx	kg	3.67E-04	2.31E-03	4.97E-02	-4.94E-02
HCl	kg			4.86E-06	-4.86E-06
NMVOCs	kg	1.20E-04	1.92E-05	1.92E-05	1.01E-04
CH_4	kg	6.90E-05	1.29E-04	5.74E-04	-5.05E-04
NH_3	kg	3.19E-07		0.00E+00	3.19E-07

Metal recycling

It should be noted that the metal content of the MSW in KMC is quite low. Estimated recoverable metal content for recycling would be 0.71 kg per tonne of waste generated and this amount would be sufficient to replace 0.64 kg of metal production from the virgin process chain. Inventory analysis was done for recycling of recovered metal and production of equivalent amount of metal through virgin production process, (see Table E11).

Table E11: Inventory analysis for metal recycling and virgin production in India

Life cycle inputs/ outputs	Unit	0.71 kg recycled steel production	0.64 kg of virgin steel production	Net resource consumption and emissions
Inputs				
Coal, brown, 8 MJ per kg, in ground	kg	1.81E-01	6.83E-02	1.12E-01
Gas, natural, 36.6 MJ per m3, in ground	m^3	8.19E-02	8.38E-02	-1.93E-03

Coal, 18 MJ per kg, in ground	kg	1.17E-01	7.67E-01	-6.50E-01
Oil, crude, 42.6 MJ per kg, in ground	kg	1.59E-02	5.67E-02	-4.09E-02
Limestone, in ground	kg	0.00E+00	1.83E-01	-1.83E-01
Iron ore, in ground	kg	0.00E+00	1.55E+00	-1.55E+00
Outputs				
PM	kg	7.54E-04	9.09E-04	-1.55E-04
CH_4	kg	1.31E-03	6.96E-03	-5.65E-03
NMVOC	kg	2.91E-04	6.51E-04	-3.60E-04
CO_2	kg	7.48E-01	1.92E+00	-1.17E+00
CO	kg	2.97E-03	1.19E-02	-8.96E-03
NH_3	kg	1.21E-06	1.27E-06	-6.45E-08
HF	kg	9.80E-06	7.09E-06	2.71E-06
N_2O	kg	3.80E-06	6.19E-06	-2.39E-06
HCl	kg	8.51E-05	5.56E-05	2.95E-05
SO_2	kg	1.88E-03	4.02E-03	-2.14E-03
NO_2	kg	1.73E-03	2.94E-03	-1.21E-03

Inventory analysis of intended anaerobic digestion facility

It was assumed that 75% of food waste in MSW can be separated using available technologies at the sorting facility. According to the mass balance analysis, 306 kg of food waste can be sorted out per tone of waste received to the MRF and this amount can be treated using the intended AD facility. After the digestion process is over, the remaining sludge can be used for compost production. 38 kg of compost can be produced using the remaining sludge from 306 kg of organic waste. The inventory analysis was done for AD process which includes collection and transportation of organic waste, anaerobic digestion process and electricity production and compost production process from the remaining sludge as shown in Table E12.

Table E12: Inventory analysis of AD process

Life cycle inputs/outputs (kg)	Total emission from collection and transportation (15 km)	Anaerobic digestion (306 kg of organic waste per functional unit)			Composting (production of 38 kg compost per functional unit			Total net impact
		Fuel production and fuel burning	Credited impact electricity production	Net impact	fuel production, burning composting	Credited impact	Net impact	
Inputs(kg)								
Baryte	4.70E-03	5.16E-03		5.16E-03	1.64E-02		1.64E-02	2.62E-02
Coal, 18MJ per kg	1.10E-02	1.21E-02	1.79E+01	-1.79E+01	3.84E-02		3.84E-02	-1.79E+01
Coal, brown 8MJ per kg,	8.39E-03	9.22E-03	0.00E+00	9.22E-03	2.92E-02		2.92E-02	4.68E-02
Oil	5.19E-01	5.70E-01	1.28E-01	4.42E-01	1.81E+00	2.04E-01	1.60E+00	2.57E+00

crude,42.6MJ per kg								
Natural gas (m^3)	0.00E+00		1.43E+00	-1.43E+00		2.48E-01	-2.48E-01	-1.68E+00
Fuel oil			1.28E-01	-1.28E-01			0.00E+00	-1.28E-01
Iron	2.70E-03	2.97E-03		2.97E-03	9.42E-03		9.42E-03	1.51E-02
Outputs (kg)								
CO_2	2.31E+00	2.20E+00	3.81E+01	-3.59E+01	6.98E+00	8.15E-01	6.16E+00	-2.74E+01
CO	3.53E-02	6.13E-04	8.66E-03	-8.05E-03	1.94E-03	6.92E-04	1.25E-03	2.85E-02
PM	5.54E-03	5.54E-04	3.39E-04	2.15E-04	1.76E-03	1.22E-05	1.74E-03	7.50E-03
H2	4.83E-06	5.30E-06		5.30E-06	1.68E-05		1.68E-05	2.70E-05
HCl	1.02E-06	1.12E-06		1.12E-06	3.56E-06	4.23E-05	-3.88E-05	-3.66E-05
CH_4	4.21E-03	4.63E-03	3.08E-03	1.54E-03	1.47E-02	1.29E-04	1.45E-02	2.03E-02
NO	1.91E-03	2.10E-03		2.10E-03	6.67E-03		6.67E-03	1.07E-02
NOx	2.06E-02	1.33E-02	9.61E-02	-8.28E-02	4.23E-02	3.27E-03	3.90E-02	-2.31E-02
N_2O	6.32E-06	6.95E-06	1.10E-05	-4.10E-06	2.20E-05	2.62E-03	-2.60E-03	-2.60E-03
SO_2	1.82E-03	4.23E-03	2.45E-01	-2.41E-01	1.34E-02	2.19E-03	1.12E-02	-2.28E-01
VOC	1.37E-02	1.13E-02	0.00E+00	1.13E-02	3.60E-02		3.60E-02	6.11E-02
SO_4^-	6.77E-04	7.44E-04		7.44E-04	2.36E-03		2.36E-03	3.78E-03
NO_3^-	1.95E-05	2.14E-05		2.14E-05	6.79E-05		6.79E-05	1.09E-04
NH_3	3.37E-05	3.70E-05		3.70E-05	3.85E-03	1.34E-03	2.51E-03	2.58E-03

Landfilling

As noticed, in the intended integrated system, the biggest share of waste (50.1%) still should be disposed at a sanitary landfilling. The waste received at the landfill includes a considerable amount of food waste, and un-recovered combustibles. For instance, total biodegradable fraction of disposed waste at the landfill is 28%, and it might contribute to produce a significant amount of methane. In addition, as the daily disposal capacity is high at the sanitary landfill, there is a possibility to collect a considerable amount of LFG. Therefore, inventory analysis was done for the sanitary landfill, including landfill gas recovery system. The collected LFG (there is a possibility to collect 14.3kg of CH_4/tonne of disposed waste) can produce 77 kWh of electricity. Thus the electricity production process from recovered LFG was credited. Table E13 summarizes the inventory analysis of sanitary landfill with a LFG recovery system.

Table E13: Inventory analysis of sanitary landfill with gas recovery system per tonne of waste

Life cycle inputs/outputs	Emissions from fuel production (1.875 L) collection and transportation	Inputs/ outputs landfill (kg/tonne)	Credited resources/ emissions from electricity	Net emissions and resource consumption from final disposal	Net resource consumption and emissions from landfilling
Inputs (kg)					
Baryte	1.44E-02	5.04E-03		5.04E-03	1.94E-02
Coal, 18MJ per kg, in ground	3.38E-02	4.60E-02	2.35E+01	-2.34E+01	-2.34E+01
Coal, brown 8MJ per kg, in ground	2.57E-02	5.16E-02		5.16E-02	7.73E-02
Oil cude,42.6MJ per kg	1.59E+00	8.94E-01	1.68E-01	7.26E-01	2.31E+00
Iron	8.27E-03	4.76E-03		4.76E-03	1.30E-02
Natural gas (m^3)		0.00E+00	1.87E+00	-1.87E+00	-1.87E+00
Outputs (kg)					
CO_2	8.02E+00	1.85E+00	4.99E+01	-4.80E+01	-4.00E+01
CO	2.01E-02	4.55E-02	1.13E-02	3.41E-02	5.42E-02
PM	2.20E-03	6.58E-04	4.45E-04	2.14E-04	2.42E-03
H_2	1.48E-05	2.23E-06		2.23E-06	1.70E-05
HCl	3.13E-06	4.72E-07		4.72E-07	3.60E-06
CH_4	1.29E-02	4.05E+00	4.04E-03	4.05E+00	4.06E+00
NO	5.86E-03	8.82E-04		8.82E-04	6.74E-03
NOx	6.12E-02	5.27E-02	1.26E-01	-7.32E-02	-1.20E-02
N_2O	1.93E-05	2.91E-06	1.45E-05	-1.16E-05	7.80E-06
SO_2	5.57E-03	1.77E-03	3.21E-01	-3.20E-01	-3.14E-01
VOC	2.94E-02	9.69E-03		9.69E-03	3.91E-02
SO_4^{-2}	2.07E-03	3.12E-04		3.12E-04	2.38E-03
NO_3^-	5.96E-05	7.42E-01		7.42E-01	7.42E-01
NH_4^+	1.03E-04	1.67E+00		1.67E+00	1.67E+00
H_2S	0.00E+00	2.41E-01		2.41E-01	2.41E-01

Evaluation of the intended integrated system by using midpoint composite indicators

All the calculations were done per tonne of waste treatment under each technology. The impacts from the intended integrated system were calculated as follows:.

The impacts from the intended integrated system = Impacts from recycling/tonne × fraction of waste recycling + Impacts from AD/tonne × fraction of waste AD + Impacts from composting/tonne × fraction of waste composting + Impacts from landfilling/tonne × fraction of waste landfilling.

The quantified midpoint indicators from the individual treatment methods and the intended integrated system are summarized in Table E14. It should be noticed that environmental damage from the intended integrated system is not significant compared to the existing MSW management system.

Table E 14: Quantified midpoint indicators for individual treatment methods and intended integrated system

Treatment methods	% of mass	Global warming (kg of CO_2 eq)	Acidification (kg SO_2 eq.)	Europhication (kg NO_3^- eq.)	Photo Oxidant Formation (kg C_2H_4 eq.)	Abiotic resources Depletion (kg Sb eq.)	Human toxicity (1-4 DB eq)
Paper		4.81E+02	-3.87E-01	2.10E-01	-1.28E-01	2.83E+00	7.58E-01
Plastic		2.70E+02	9.13E+00	-1.57E+00	-1.66E+00	-1.42E+01	-4.86E+00
Glass		-3.26E+02	-2.22E+00	-3.44E+01	-2.91E-01	-8.97E-01	5.31E-01
Aluminium		-9.15E+03	-8.66E+01	-3.21E+01	-3.96E-02	-3.89E+01	-3.60E+01
Metal		-1.85E+03	-4.16E+00	-3.23E+00	-8.11E-01	-7.36E+00	-2.50E+00
Total recycling	5.51	1.95E+02	2.58E+00	-2.64E+00	-8.23E-01	-5.55E+00	-2.26E+00
Anaerobic digestion	30.63	-9.02E+01	-7.44E-01	-4.81E-02	1.04E-01	-3.74E-01	-9.93E-02
Composting	13.80	4.12E+00	2.16E-01	4.14E-01	1.96E-01	1.17E-02	1.02E-01
Landilling	50.06	5.35E+01	3.28E+00	7.34E-01	5.01E-02	-2.81E-01	-3.55E-02
Total from the integrated system	**100.00**	**1.05E+01**	**1.59E+00**	**2.64E-01**	**3.86E-02**	**-5.60E-01**	**-1.58E-01**

To understand the improvements of the sustainability as a result of initiating an integrated system, results of the existing and the upgraded MSW management system were compared. In Figure E5, the reduction of the severity of midpoint impacts compared to the existing situation can be clearly noticed.

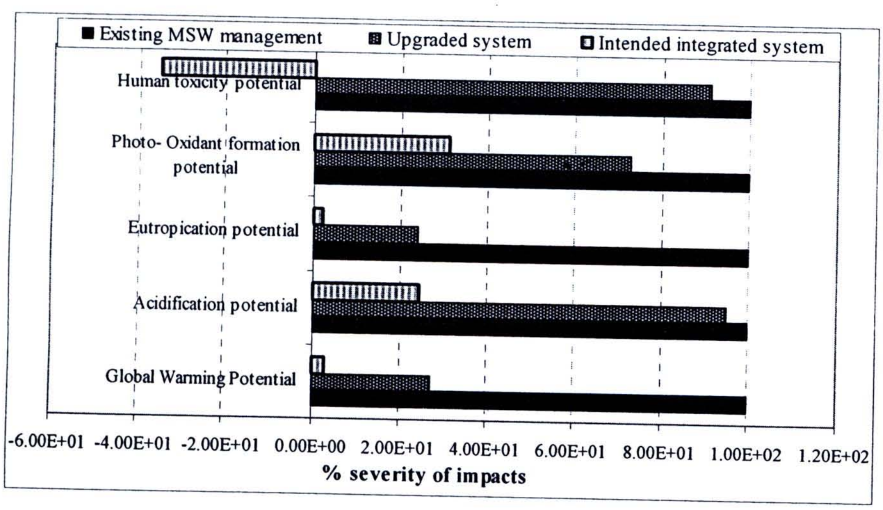


Figure E5: Comparison of severity of impacts of the intended integrated system relative to the existing MSW management

For instance, the intended integrated system has a favorable influence on reducing global warming potential by 97%, acidification potential by 76%, eutrophication potential by 98%, photo-oxidant formation potential by 69%, human toxicity potential by 135% and abiotic resource depletion potential by 1210%. It should be noted that the recovered materials from recycling and composting and recuperated energy from AD and sanitary landfilling have their significant influences in reducing the mid point impacts and in driving the entire system towards the sustainability. Moreover, the developed endpoint indicators were also used to assess the sustainability, especially to quantify the ultimate damage/effects from the intended integrated system.