

A Comparative Analysis of Solid Waste Treatment Technologies on Cost and Environmental Basis

Nesli Aydin

Abstract—Waste management decision making in developing countries has moved towards being more pragmatic, transparent, sustainable and comprehensive. Turkey is required to make its waste related legislation compatible with European Legislation as it is a candidate country of the European Union. Improper Turkish practices such as open burning and open dumping practices must be abandoned urgently, and robust waste management systems have to be structured. The determination of an optimum waste management system in any region requires a comprehensive analysis in which many criteria are taken into account by stakeholders. In conducting this sort of analysis, there are two main criteria which are evaluated by waste management analysts; economic viability and environmentally friendliness. From an analytical point of view, a central characteristic of sustainable development is an economic-ecological integration. It is predicted that building a robust waste management system will need significant effort and cooperation between the stakeholders in developing countries such as Turkey. In this regard, this study aims to provide data regarding the cost and environmental burdens of waste treatment technologies such as an incinerator, an autoclave (with different capacities), a hydroclave and a microwave coupled with updated information on calculation methods, and a framework for comparing any proposed scenario performances on a cost and environmental basis.

Keywords—Decision making, economic viability, environmentally friendliness, stakeholder, waste management systems.

I. INTRODUCTION

THE determination of an optimum waste management scenario in any region requires a comparison of a range of proposed scenarios. There is an increasing number of studies in the literature which carry out this sort of analysis in different regions across the world. For example, Colon et al. evaluated different scenarios from the point of their influence of transport, fugitive methane emissions in Catalonia [1]. Another study conducted by Deus et al. in Brazil determined the future environmental impact of household solid waste management scenarios for a region in terms of carbon dioxide emission and energy requirement [2]. Ciplak has also identified the best possible health care waste management option in the West Black Sea Region by taking into account different healthcare waste management scenarios that consist of different technology alternatives [3].

The waste management analysts have always included two main criteria, economic viability and environmentally friendliness in their analysis. It is because a central

characteristic of sustainable development is economic-ecological integration from an analytical point of view. Environmental systems provide resources for economic development; in return, economic development has an impact on the environment, which provides the economic foundation for environmental protection [4]. Since the models aimed at structuring decision making systems generally have far reaching economic and ecological consequences, there is a strong body of research focusing particularly on the mechanism of environment-economy systems, e.g. Sugiyama et al. presented an assessment on how economic and environmental assessment results change when different process options or evaluation settings are taken into account [5]. Therefore, this study aims to provide data considering the cost and environmental burdens of a diverse range of waste treatment technologies including an incinerator, an autoclave (with different capacities), a hydroclave, and a microwave and also updated information on calculation methods with assumptions in the scope of system boundaries. This will help comparing any proposed scenario performances on a cost and environmental basis for Turkish cities and beyond.

II. METHODOLOGY

The scope of this research includes waste treatment technologies which have been adopted commonly in setting waste management scenarios in the literature so far. These are namely: (1) An incinerator with 1 ton/hour capacity, (2) An oil fired autoclave with 0.45 ton/hour capacity, (3) An oil fired autoclave with 0.20 ton/hour capacity, (4) An electrical autoclave with 0.07 ton/hour capacity, (5) A microwave with 0.250 ton/hour capacity and (6) A hydroclave with 0.09 ton/hour capacity. These systems are designed to work in continuous process.

Since this study deals with the environmental and cost burdens of different waste management technologies, two different methodologies have been adopted.

- 1) In terms of assessing the environmental burdens (CO₂ and CH₄ emissions), the calculation methods have been gathered from international sources, such as the Intergovernmental Panel on Climate Change [6]. The data regarding the process emissions from the plants and their water requirements have also been collected from the manufacturers in Turkey, Europe, the United States and Canada.
- 2) In terms of determining the cost values of these technologies, cost analyses of different technologies remained limited with the data provided by some private

Nesli Aydin is with Karabuk University, Department of Environmental Engineering, Faculty of Engineering, Karabuk, Turkey (e-mail: nesli.ciplak.aydin@gmail.com)

companies as the investment costs of various treatment technologies are commercially confidential.

The environmental burdens of landfills have also been assessed from the sources outlined above as the treated waste is sent to landfill sites after being treated at alternative technologies, such as autoclaves, hydroclaves, and microwaves.

III. RESULTS AND DISCUSSION

Investment costs consist of the costs relating to the purchase of mechanical equipment, including boilers if required,

construction of a plant, infrastructure, and technological installations such as temporary containers, waste container washing units, cooling units, etc. On the other side, operation costs consist of three parts; (A) the consumables, such as electricity, water and fuel costs to run the facility; (B) the salary of employees, any replacement cost for the equipment; and (C) the maintenance cost which is involved in a cash flow after the equipment completes its service life as the technology requires additional maintenance and renovation after its service life completed.

TABLE I
INVESTMENT AND ANNUAL OPERATING COSTS OF THE PLANTS

Treatment Option	Capacity (ton /hour)	Operating Cost-A (TL/year)	Operating Cost-B (TL/year)	Operating Cost-C (TL/year)	Investment Cost (TL)
Incinerator	1.00	1184227	4320748	**	7577600
Oil fired autoclave	0.45	223936	611240	38362	3711485
Oil fired autoclave	0.20	100640	495800	38362	1346800
Electrical autoclave	0.07	58164	183520	4795	627372*
Micro-wave	0.25	162800	615704	310800	2077920
Hydroc-lave	0.09	78440	161438	16000	469042*

TL: Turkish Lira * with boiler **As the service life of the incinerator is usually assumed to be 25 years, the operating cost (C) is not included.

Table I shows operating costs and investment costs of the waste treatment technologies as detailed in the methodology section. These values were estimated as present values (base year 2016) by taking into account Turkish inflation rate, staffing costs, the consumables, etc.

In environmental assessments, a lifecycle approach is the technique which is used very commonly, especially for the comparison of the waste management scenarios on atmospheric greenhouse gas emissions over a project time. In order to compare performances of these scenarios on the basis of functional equivalence, the functional unit is usually defined as *one ton of collected waste*. All emissions and energy uses, for example, are expressed as “per ton of waste” [3].

The lifecycle of the waste, in waste management projects, begins when materials become waste and are disposed of. It focuses on environment impacts in terms of greenhouse gas emissions, and energy recovery from incineration and landfill. These emissions are the emissions due to transport, the consumption of fuels and electricity requirement for the treatment of wastes and the combustions of wastes for each waste management scenario [7].

The system boundary includes collection processes until disposal in the incineration or alternative treatment plant. Emissions produced from the construction of facilities, nitrous oxide (N₂O) released from landfills and the fuel consumption for on-site operations such as spreading and compaction of the waste, and energy requirements for leachate treatment are not included as it is considered that these emissions are small in comparison to those released during the use of the facilities [8].

In inventory analysis of the assessment, greenhouse gas emissions from several sources are evaluated as follows;

- Transport Emissions: The transportation of the waste to

the plants depends on the distances travelled by each truck.

- Process Emissions: These are the greenhouse gas emissions from the processing of the waste. They occur through combustion in the incineration and through the escape of methane from wastes degrading in landfill sites.

Regarding greenhouse gas emissions due to landfilling the waste after alternative treatment process, the following approximations are assumed;

1. Intergovernmental Panel on Climate Change (2006) on greenhouse gas assessment states that biogenic carbon should be excluded when the conducting assessments related to emissions from waste because of that biogenic emissions are sourced from biomass and therefore treated, like biomass renewables, as having a zero-carbon emission factor [6].
2. When a gas collection system is in place, the landfill is fitted with a system to prevent the release of gas in combination with a system of wells and pumps used to extract the gas for combustion in a gas engine. The results of the study conducted by Spokas et al. show 35% gas recovery for an operating cell with an active gas recovery system; 65% for a temporary covered cell with an active recovery system and 85% for a cell with clay final cover [9].
3. Landfill gas (50% CH₄ and 50% CO₂) is generated during the waste acceptance lifetime of the landfill and for some considerable time after waste has ceased being accepted [10]. As landfill gas production will continue even after the landfill stops accepting waste, the landfill gas, which is emitted over a hundred-year period, is taken into account in the context of life cycle analysis.
4. First order decay method (FOD) provides formulations for the estimation of the emissions from landfilled waste [11]

and it is frequently applied to estimate landfill gas production [12]. The FOD also meets the requirement of a "conservative approach", which is adopted in technical assumptions underpinning the Clean Development Mechanism (CDM) [13], [14]. The CDM is one of the "flexibility" mechanisms along with emissions trading (ET) and joint implementation (JI) as defined in the Kyoto Protocol in order to promote sustainable development [15].

According to the FOD method, the generation rate of the landfill gas depends on a number of factors, including gas generation rate as a function of the available waste in a landfill site, gas generation potential (L_0), gas generation rate constant (k), and age of the waste. The rate k is a function of the moisture content (precipitation, leachate circulation), while L_0 is a function of waste composition.

The produced electricity from the waste could be assumed to displace electricity drawn from the national grid, which is comprised of coal, oil, and renewable origins. The $CO_{2,e}$ emissions are not generated at the point of electricity used, but they are emitted in the process of power generation.

While some of these power plants operate as a base-load supply, such as fossil fueled power plants; the others are intermediate and peaking plants, whose operation can be altered to meet the desired load at a given time of day, such as natural gas plants. As each of the plants have a different level of emissions rate, it is necessary to account for all these sources in the emission factors. There are mainly two approaches: (1) the average emission rate, which equals the total carbon equivalent emissions over total electricity consumption of the grid; and (2) the marginal emission factor, which excludes the base-load electricity sources and compares incremental changes that occur in the margin by a project that decreases the electricity demand from existing plants (operating margin). However, the grid operation is extremely complex, determining the sources of electricity offset by a given project poses a major challenge [16]. Therefore, several methods and models have been developed to simulate the emission offsets. One approach to estimating average and marginal emission rates for a grid is to use generation planning models, e.g., Ader, that simulate future grid operation in order to meet a forecasted hourly load [17], [18]. In the international scale, the CDM proposes the marginal emission factor to be used in calculating the contribution of reducing CO_2 emissions from the grid power [19]. Nevertheless, in the complex nature of the sources in the grid power, specifying the marginal emission factor is subject to considerable uncertainty in the long-term, particularly in the electricity sector where it is unclear what type/mix of generation will constitute the marginal source of electricity supply [20].

Table II illustrates the electricity and fuel oil requirements of alternative technologies. The data in Table II were sourced from the private companies as mentioned in the methodology section. It is seen in Table II that the electricity requirement of hydroclave is considerably high. The reason for that is the hydroclave takes more electricity than the autoclave to warm

up since it has to transfer the heat from the outer jacket into the vessel chamber. Once the hydroclave is hot, it will require considerably less energy. The high energy requirement is only for the first run, and then diminishes. The value in Table II represents the worst-case scenario [21].

TABLE II
ENERGY REQUIREMENT OF ALTERNATIVE TECHNOLOGIES

Treatment Option	Capacity (ton/hour)	Electricity Requirement (kW)	Fuel-Oil Requirement (Liter/ton)
Oil fired autoclave	0.45	27.5	15.6
Electrical autoclave	0.07	29.4*	-
Microwave	0.25	80	-
Hydroclave	0.09	364	-

*Requires external boiler and the values includes the electricity requirement of the external boiler

The Intergovernmental Panel on Climate Change (IPCC 2006) provides an approach for estimating the emissions due to incineration [6]. In this approach, only CO_2 emissions from the incineration of fossil carbon (i.e. plastics, certain textiles, rubber, liquid solvents, and waste oil) need to be taken into account (biogenic CO_2 emissions from the combustion of wastes are excluded).

TABLE III
WATER CONSUMPTION OF THE TREATMENT OPTIONS

Treatment Option	Water Consumption (Liter/hour)
Incineration	2500
Autoclave	200
Microwave	*
Hydroclave	228**

* Dry heat processes do not use water or steam. ** On average, the steam used per batch is 91 kg. However, 97% of this steam is returned to the boiler. Therefore, water loss per cycle is 2.7 kg. This is not included in the 228 Liter used for the condenser bottle

The data regarding to the electricity requirement to run the incinerator were sourced from Moynihan as 55 kWh/ton [22]; and Fisher et al. has reported that the fuel input per ton of material throughput is 1.2 kg fuel [23]. The data on water usage for each treatment technology option were also supplied by the companies and illustrated in Table III.

IV. CONCLUSION

It is known that environmental decisions usually involve conflicting objectives and various types of information and several individuals. Therefore, environmental decision making using a multi-dimensional way leads to more rational decision making. At this point, for decisions to be effective, it is necessary to set a balance between the environmental sustainability, economically viability, technically soundness and the social acceptability of the system.

Turkey is as a candidate country of the European Union and therefore it is highly important for it to make its national legislation compatible with European waste related regulations. Frequently adopted improper waste management practices in Turkey, such as open burning and open dumping have to be abandoned urgently, and robust waste management

systems have to be built up. This will inevitably require significant effort coupled with the cooperation between the stakeholders from a range of backgrounds. In this context, this study will pioneer a direction for the process of building a new waste management system in Turkish cities and beyond by providing the necessary data, information, and approach. This is a significant step for developing countries such as Turkey since it is considered that there is currently an important gap regarding the supply of reliable information and data in the waste management literature so far.

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REFERENCES

- [1] J. Colon., E. Cadena, A.B. Colazo, R. Quiros, A. Sanchez, X. Font, and A. Artola (2015). "Toward the implementation of new regional biowaste management plans: Environmental assessment of different waste management scenarios in Catalonia" *Resources, Conservation and Recycling* (Online). (95) pp. 143–155.
- [2] R.M. Deus, R.A.G. Battistelle and G.H.R. Silva (2016). "Current and future environmental impact of household solid waste management scenarios for a region of Brazil: carbon dioxide and energy analysis" *Clean Techn Environ Policy*. (Online). Pp. 1-10 doi:10.1007/s10098-016-1205-0
- [3] N. Ciplak, (2015) "Assessing future scenarios for healthcare waste management using a multi- criteria decision analysis tool: A case study in the Turkish West Black-Sea Region". *The Journal of Air and Waste Management Association* (Online). 65(8) pp. 919-929 Available: <https://www.ncbi.nlm.nih.gov/pubmed/26211633> (access date: 21st December 2016)
- [4] J. Tao, "The research of environment economy decision supportive system based on GIS". *1st International Conference on E-Business and E-Government*, ICEE 2010, 7-9 May, Guangzhou, China, IEEE Computer Society.
- [5] H. Sugiyama, U. Fischer, E. Antonijuan, V.H. Hoffmann, M. Hirao, and K. Hungerbuhler (2009) "How do different process options and evaluation settings affect economic and environmental assessments? A case study on methyl methacrylate (MMA) production processes." *Process Safety and Environmental Protection* 87(6) pp. 361-370.
- [6] IPCC (2006). Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste. Chapter 5: Incineration and Open Burning of Waste. (Online): <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html> (access date: 19th December 2016)
- [7] S. Critten, (2007). "Exeter Energy from Waste Facility". Carbon Analysis Final. (Online) <http://www.devon.gov.uk/graceroad-carbonanalysis.pdf> (access date: 21st December 2016)
- [8] N. Ritchie and C. Smith (2009). "Comparison of Greenhouse Gas Emissions from Waste-to-Energy Facilities and the Vancouver Landfill". Technical Memorandum. (Online) <http://pentz.com/NoIncinerator/greenhouse%20Emmissions.pdf>
- [9] K. Spokas, J. Bogner, J.P. Chanton, M. Morcet, C. Aran, C. Graff, Y. Moreau-Le Golvan, and I. Hebe (2006). "Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?" *Waste Management* 26(5) pp516-525.
- [10] S. Manfredi, T.H. Christensen, H. Scharff and J. Jacobs (2010). "Environmental assessment of low-organic waste landfill scenarios by means of life-cycle assessment modelling (Easewaste)." *Waste Management & Research* 28(2) pp. 130-140.
- [11] IPCC (2000). Intergovernmental Panel on Climate Change United Nations Framework Convention on Climate Change (UNFCCC). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Chapter 5 Waste Section. Montreal. Accessed from: <http://www.ipccnggip.iges.or.jp/public/gp/english/> (access date: 1st December 2016)
- [12] M. Ritzkowski and R. Stegmann, (2010). "Generating CO₂-credits through landfill in situ aeration." *Waste Management* 30(4) pp. 702-706.
- [13] R. Couth, C. Trois, J. Parkin, L.J. Strachan, A. Gilder and M. Wright, (2011). "Delivery and viability of landfill gas CDM projects in Africa-A South African experience." *Renewable and Sustainable Energy Reviews* 15(1) pp. 392-403.
- [14] F.J. Maciel and J.F.T. Juca, (2011). "Evaluation of landfill gas production and emissions in a MSW large-scale Experimental Cell in Brazil." *Waste Management* 31(5) pp. 966-977.
- [15] UNFCCC (1998). United Nations Framework Convention on Climate Change. Kyoto Protocol Article 12. <http://unfccc.int/resource/docs/convkp/kpeng.pdf>
- [16] Sathaye, J., Murtishaw, S., Price, L., Lefranc, M., Roy, J., Winkler, H. and SpadingFecher, R. (2004). "Multiproject baselines for evaluation of electric power projects." *Energy Policy* 32(11): 1303-1317.
- [17] E.H. Rau, R.J. Alaimo, P.C. Ashbrook, S.M. Austin, N. Borenstein, M.R. Evans, H.M. French, R.W. Gilpin, J. Hughes, S.J. Hummel, A.P. Jacobsohn, C.Y. Lee, S. Merkle, T. Radzinski, R. Sloane, K.D. Wagner and L.E. Weaner (2000). "Minimization and management of wastes from biomedical research." *Environmental Health Perspectives* 108 pp. 953-977.
- [18] T. Kerr, R. Morgan, J. Haydel. And B. Thapa, (2002). Average Displaced Emissions Rate (ADER): Approach and Methodology. <http://www.epa.gov/ttnchie1/conference/ei11/poster/morgan.pdf> (access date: 1st December 2016)
- [19] S. Sharma and R.M. Shrestha (2006). "Baseline for electricity sector CDM projects: Simplifying estimation of operating margin emission factor." *Energy Policy* 34(18) pp 4093-4102.
- [20] T. Lelyveld and P. Woods (2010). Carbon emission factors for fuels – Methodology and values for 2013 & 2016. <http://www.zerocarbonhub.org> (access date: 21st December 2016)
- [21] Wallis, T. (2010). Personal Communication. Mr Wallis is a project manager for Hydroclave Systems Corp. Ltd, Kingston, Ontario, Canada
- [22] Moynihan, M. (2010). Personal Communication Mr Moynihan is a general manager for Incinco Limited, Welwyn, Hertfordshire, UK.
- [23] K. Fisher, M. Collins, S. Aumônier, B. Gregory (2006). Carbon Balances and Energy Impacts of the Management of UK Wastes. Defra R&D Project WRT 237. <http://randd.defra.gov.uk/> (access date: 21st December 2016)

Dr. Nesli Aydin completed her bachelor degree in Civil Engineering Department, Dokuz Eylul University, Izmir, Turkey in 2006. She then won a scholarship of the Turkish Ministry of Education to pursue her studies in the UK. Under this scholarship, she completed her master and PhD research in the School of Civil Engineering-Sustainable Waste Management Department, University of Leeds, the UK. She came back to Turkey and started working in the Faculty of Engineering, Environmental Engineering Department, Karabuk University.

Dr. Aydin supervises a postgraduate student on a project- "Solid Waste Management in the provinces of Ankara, Karabuk and Zonguldak of Turkey with an overview to the progress in environmental sector particularly in municipal waste management in the context of the European Union membership" and also delivers Advanced Solid Waste Management 1-2 courses to undergraduate and postgraduate students at the department. She has also acted as a leader of a project financed by Scientific and Technological Research Council of Turkey, titled "System Dynamics Approach to Healthcare Waste Management in The West Black Sea Region" since 2014. Assist. Prof. Dr. Aydin has acted an administrative role as a Vice Chair and an Erasmus Student/Staff Exchange Program Coordinator at the department so far.