CHEMICAL ENGINEERING TRANSACTIONS Volume 25, 2011
Editors Jiří Jaromír Klemeš, Petar Sabev Varbanov, Hon Loong Lam
Copyright © 2011, AIDIC Servizi S.r.l., ISBN 978-88-95608-16-7 ISSN 1974-9791
DOI: 10.3303/CET1125086

Waste-to-Energy Technologies Performance Evaluation Techniques

Andreja Nemet, Petar Sabev Varbanov*, Jiří Jaromír Klemeš

Centre for Process Integration and Intensification – CPI[2], Research Institute of Chemical and Process Engineering, Faculty of Information Technology, University of Pannonia, Veszprém, Hungary
varbanov@cpi.uni-pannon.hu

This paper overviews the techniques for evaluating the environmental and economic performance of the technologies for generation and utilisation of energy from waste. The issues of waste management and energy supply are analysed within a common context which includes the reduction of environmental footprint, as well as improvement of the energy security and efficiency, and also accounting for the synergies and the major risk. The sustainability indicators and procedures are analysed with the goal to outline the main challenges and directions for future research.

1. Introduction

Waste treatment has become a significant problem due to the large volumes generated worldwide and its impact on the environment (Eurostat, 2010). The main impacts relate to atmospheric emissions and aqueous effluents from landfills and activities for waste collection, transportation, and processing. The growing energy demands present enormous challenges for securing cleaner supplies (EIA, 2011). The most significant problem is to achieve maximum savings of fossil fuels at minimum Carbon Footprint (CFP) in an economically viable way.

Waste to Energy (WTE) is an important tool capable of reducing simultaneously the problems in energy supply and pollution prevention. It may be implemented as either incineration with direct heat recovery or as a more complex system involving logistics and intermediate waste treatment steps for deriving fuels. It fits in only one of the priorities in the waste management hierarchy. Managing waste properly usually follows the established priorities of avoiding generation, reusing, recycling and recovering materials, followed by utilisation of the waste energy value and finally treatment and safe disposal (EUROPA, 2011). However, WTE processes have also impact on the environment. For incineration: (i) Auxiliary heating with fossil fuels is often needed, potentially reducing the savings from fossil energy and CO_2. (ii) The side products usually contain toxic contaminants. This indicates that WTE technology itself does not guarantee the reduction of environmental impact and proper evaluation of the processes is required. A number of indicators relevant to the evaluation of the impacts of WTE processes are reviewed and the analyses are further extended to the scope of supply chain and life cycle for the case of WTE, providing a more global view of the tools of

Please cite this article as: Nemet A., Varbanov P. and Klemes J.J., 2011, Waste-to-energy technologies performance evaluation techniques, Chemical Engineering Transactions, 25, 513-520
DOI: 10.3303/CET1125086

the system performance. The evaluation should be performed within the framework of an overall strategy for improving the performance of WTE processes.

2. Strategy for improving WTE performance

The choice of indicators depends on the waste management method and the goals of applying WTE. There can't be a totally uniform methodology for designing WTE processes with inherently reduced environmental impacts. Mathematical programming and comparative environmental impact assessments of process alternatives are used.

2.1. Synergies and risks of WTE

The waste management hierarchy (EUROPA, 2011) has several goals. The most obvious is to minimise the pollution caused by waste. Minimising the use of fossil energy sources is another goal of similar importance. After the higher priority measures have been applied, exploiting WTE generation can be very advantageous by reducing the amount of waste intended for disposal while decreasing the consumption of fossil energy sources (Figure 1**Errore. L'origine riferimento non è stata trovata.**) and the related Carbon Footprint (CFP).

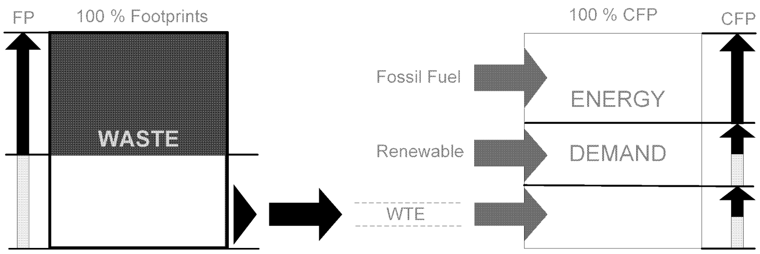

Figure 1: Advantages of Waste to Energy

At the same time WTE processes may release various toxic side streams (Psomopoulos et al., 2009; Consonni et al., 2005), which have to be limited to minimise the risk of dispersing pollutants. Another risk is that the amount of auxiliary fossil energy added to a WTE process may be so large, as to increase the CFP of the entire system instead of reducing it (Mühle et al., 2010). This reveals the need for a systematic procedure for maximising the fossil energy saving through WTE generation while minimising the risks and impacts of environmental harm. Two main approaches can be distinguished: Mathematical Programming, as well as evaluation and ranking of process alternatives.

2.2. Mathematical Programming

Many approaches use Mathematical Programming to mainly maximise the profit. Waste minimisation is only one of the objectives. In (Li et al., 2009) the environmental impact indicators are combined into the second objective to be minimised. The resulting formulation is MINLP, model reduction is applied combined with careful initialisation. Another class of methods integrates the environmental impacts into the constraints – e.g. (Chakraborty et al., 2004) for minimising waste generation for batch process planning. It takes as inputs forecasts for (i) The market conditions and demands, and (ii) The waste and emission regulations. The outputs are schedules for plant operation as well as for making investments within the planning horizon. The optimisation model is a MILP, minimising the net present cost with items estimating the operating, investment and maintenance cost. The environmental impacts are constrained within the regulation limits by explicit inequalities. It is possible to combine the above approaches by assigning monetary penalties to the violations of the environmental limits, thus obtaining a weighted monetary objective function. An example of can be seen in (Varbanov et al., 2005) accounting for greenhouse gas emissions.

2.3. The WAR Algorithm

The waste reduction (WAR) algorithm (Hilaly and Sikdar, 1994; Barrett Jr et al., 2011) is based on the potential environmental impact (PEI) for the investigated process. The US-EPA offers a software implementation for download (EPA, 2011). The method relies on process simulators for computing the relevant emission rates and environmental impacts. As noted by Cabezas et al. (1999), the environmental impacts are caused by the energy and material that the process takes from or emits to the environment. Various pollution indexes can be used within the framework of the WAR algorithm. Some of them are discussed in Section 3. The WAR algorithm has the following steps (Hilaly and Sikdar, 1994; Cabezas et al., 1999): (i) Identification of the process flowsheet and calculation of its material and energy balances. (ii) Generation of alternative process flowsheets. (iii) Calculation of the environmental impact indices and ranking of the alternatives. The ranking is performed by both PEI and cost. (iv) Selection of the most favourable process flowsheet. From all these steps, the most critical and difficult to implement is the generation of the alternatives. This step has been performed mostly by engineering experience and little systematic insights.

3. Performance Indicators

A WTE system can be evaluated in terms of economic and environmental performance. The economic indicators usually employed are cost or profit. There are many environmental indicators and here is presented only a selection of those which are likely to play important role in evaluating WTE processes.

3.1. Indicators used by the WAR algorithm

The recent implementations of the WAR algorithm employ environmental impact indicators rather than specific emissions. The overall potential environmental impact of a waste stream is determined by summing up its weighted contributions over all defined impact categories classified as global atmospheric and local toxicological impacts. The published WAR algorithm applications usually define four global atmospheric impact categories: global warming potential (GWP), ozone depletion potential (ODP), acidification or acid-rain potential (AP), and photochemical oxidation or smog formation potential (PCOP). The four local toxicological impact categories used are human toxicity potential by ingestion (HTPI), human toxicity potential by either inhalation or dermal exposure (HTPE), aquatic toxicity potential (ATP), and terrestrial toxicity potential (TTP). All impacts are normalized within each impact category.

3.2. WTE process evaluation–Primary Energy Saving

The common indicators for evaluating the energy recovery in incineration plants proposed by Pavlas and Touš (2009) are applicable only to the comparison of municipal solid waste (MSW) incinerators and similar facilities. To evaluate and compare the energy performance of diverse WTE options beyond incineration, a more comprehensive indicator is needed. Generating energy from waste reduces the fossil fuel use. Pavlas et al. (2010) have introduced the Primary Energy Savings Index (**pes**), as a quantification of this substitution. It is calculated as a fraction of the energy saving from the introduction of the evaluated system over the sum of the energy used to operate it (Figure 2). The WTE process would save primary energy when **pes > 0.**

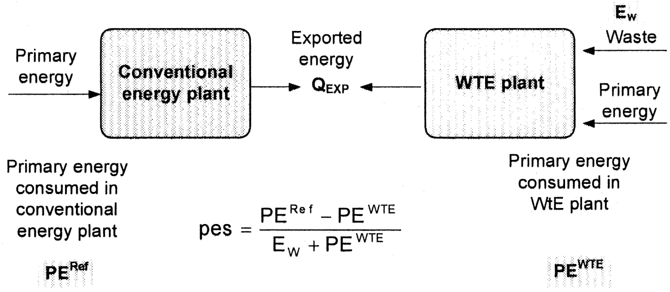

*Figure 2: Primary Energy Savings (**pes**) Index (after Pavlas et al., 2010)*

Pavlas et al. (2010) applied the index to the evaluation of several energy technologies: WTE CHP plant (**pes** = 0.76), natural gas based CHP (**pes** = 0.61), biomass-fired heating facility (0.84), biomass-fired power plant based on ORC (**pes** = 0.74), and ORC biomass-fired CHP plant (**pes** = 1.16). Note that this index is relative to the chosen base efficiencies of the state of the art energy technologies and it is important to compare the index values among the considered options rather than to take the values as absolute. The same authors considered also other relevant indicators – as NO_x, SO_x, CO and particulates emissions to provide a complete evaluation.

3.3. Footprints

The environmental impact of various processes including WTE can be evaluated by various footprints (FP). The idea is that larger values reflect stronger impacts and smaller values are desirable. Ecological footprints are usually estimated over the full life cycle of a system but footprint contributions of significant elements could be used too. The widely known is the Carbon Footprint – CFP (POST, 2006) defined as the total amount of CO_2 and other greenhouse gases emitted over the full life cycle of a process or product. The CFP has become an important environmental impact indicator as most industrialised countries have commitment to reduce their CO_2 emissions. Exploitation of renewable energy sources as well as WTE generate some CFP, contrary to the popular belief that they are completely carbon-neutral. Another indicator of this type is the Water Footprint – WFP (Hoekstra, 2008). It is defined as an indicator of direct and indirect water use measured in terms of water volumes consumed, evaporated, and/or polluted. Although WFP may not be very important for waste incineration, other WTE routes, as generation of biogas or alcohol fermentation, it may be significant. The water footprint reflects volumes of water consumption and pollution and also the type of water use as well as where and when the water was used. WFP is frequently applied in the framework of a life-cycle assessment (Hoekstra and Chapagain, 2007; Hoekstra, 2008). It is possible to define other footprints – e.g. by adapting some of the indicators used by the WAR algorithm concerning impact on human health. Other specific issues can be covered, including impact on the economy or society, which are also part of the system boundary for sustainability definition.

3.4. Strategic Environmental Performance Indicator (SEPI)

There is a large number of possible indicators to apply to WTE processes and at least CFP and some work environment footprints should be used. At the same time the economic sustainability of such systems has to be also ensured in order to provide viable and practical solutions. This brings up the need to employ a composite indicator to enable efficient strategic decision-making. A composite indicator is the Strategic Environmental Performance Indicator (SEPI) formulated by De Benedetto and Klemeš (2009). It combines the system cost with a set of normalised deviations from targets of the environmental footprints represented by a spider diagram. It constitutes a pyramid, the base represents the combined normalised deviation of the process impacts from the acceptable targets. The height of the pyramid corresponds to the system cost.

4. Defining the system boundaries

4.1. Supply Chains

A supply chain can be defined as a network of actors (organisations, people) which perform certain activities on the delivery of some products or services. The term is intended to include all significant actors and activities of relevance. Applied to WTE systems, the system boundary should be carefully selected considering upstream and downstream operations. Regarding upstream operations the possible waste sources should be accounted for. There can be residential sources generating MSW and also industrial sources. Although the share if industrial waste on a global scale (Eurostat, 2010) is overwhelming, the generated volumes of the MSW are still enormous and justify supply chain analysis. Downstream the WTE system are logistics and disposal sites, which should also be included in the analyses. Zhang et al. (2011) presented an example of an optimisation of a complete MSW management supply chain.

4.2. Life cycle assessment (LCA)

Life cycle assessment (LCA) is a “cradle-to-grave” approach for evaluating various processes and products. The life cycle is considered as the complete network of states, activities and operations concerning the product under consideration. It can be thought of as including the complete supply chain, extended with the activities and impacts resulting from the product use, maintenance, decommissioning, and disposal. LCA has been standardised (ISO, 1997; ISO, 1998; ISO, 2000a,b) and it involves several phases (Figure 3): (i) Definition of the goals and scope, (ii) Life Cycle Inventory (LCI) analysis, (iii) Life Cycle Impact Assessment (LCIA), and (iv) Interpretation and reporting. It should be noted that the ISO standard leaves the exact implementation details to the practitioners and mainly provides a framework within which these elements can be developed and used. LCA enables the estimation of cumulative environmental impacts from all stages of a product's life. The indicators to be employed are also left to the implementers and in the case of WTE they could be chosen from the ones discussed in Section 3.

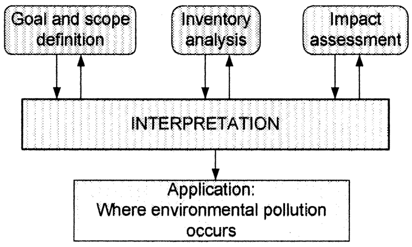

Figure 3: Phases and application of LCA

5. Conclusions

The present paper provides a review analysis of the tools for evaluating the performance of WTE systems. It reveals a wealth of performance indicators defined in the literature, as well as some optimisation models and studies. Regarding the methods for improving WTE performance, there is a lack of a systematic procedure for identifying actions for impact reduction. In the MP approaches this lack is inherent, as they rely on total system models and the trade-offs defined by the relevant model equations. In the WAR algorithm, the step which for generation of the alternative flowsheets plays this role. The current state of the art includes mostly formulating the alternatives based on engineering experience and very limited systematic insights. Concerning performance indicators, there is no convenient indicator for directly evaluating the CFP effect of applying the various WTE options. The closest to this concept is the "**pes**" index (Pavlas et al., 2010). As a result, the important directions for future work should address the needs for a novel indicators as well as tools for targeting the various WTE performance characteristics as efficiency of energy recovery relative to the waste energy content, the maximum CFP saving and minimal residual impact on the environment and human health. This can gap can be filled by applying the techniques of Process Integration (Klemeš et al., 2010; Friedler, 2009; Friedler, 2010, Almutlaq et al., 2005) and thermodynamic principles, as well as innovative graph-theoretic approaches based on the P-graph framework (Friedler et al., 1992; Varbanov and Friedler, 2008).
Accounting for the regional and global scale of the problems related to waste management and WTE, appropriate methodologies for handling them are also needed, combined with optimal choices of equipment types and designs. Examples of steps in this direction can be found in (Stehlík, 2009a,b; Stehlík., 2011; Ucekaj et al., 2010).

Acknowledgements
The financial support is gratefully acknowledged from the EC FP7 project "Intensified Heat Transfer Technologies for Enhanced Heat Recovery - INTHEAT", Grant Agreement No. 262205

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