UNIVERSITY OF ATHENS, A' LABORATORY OF PATHOLOGIC ANATOMY

PROGRAM OF POSTGRADUATE STUDIES

"ENVIRONMENT AND HEALTH. CAPACITY BUILDING FOR DECISION MAKING"

MASTER THESIS

HEALTH RISK ASSESSMENT OF MUNICIPAL SOLID WASTE INCINERATION (MSWI) WITH ENERGY RECOVERY IN ATHENS, GREECE

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BSc. ENVIRONMENTAL SCIENTIST

SUPERVISOR: PROF. DR. LUC HENS, VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK (VITO)

2013

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2013

Table of Contents

List of Figures

List of Tables

Preface

This thesis is submitted in partial fulfillment of the requirements for the degree "Master of Science" at the National and Kapodistrian University of Athens, Athens, Hellenic Republic.

The work was carried out at the Faculty of Medicine at the A' Laboratory of Pathologic Anatomy, with Prof. Dr. Luc Hens and Assist. Prof. Nicolopoulou-Stamati Polyxeni as supervisors.

This work has been part of the "Environment and Health. Capacity Building for Decision Making" program of postgraduate studies. The author expresses his gratitude to both supervisors for an exemplary cooperation.

I wish to thank Prof. Dr. Luc Hens for his constant guidance and thoroughness throughout the project, as well as Assist. Prof. Nicolopoulou-Stamati Polyxeni for her support and kindness, when they were needed most. Your professionalism and expertise have equipped me with all necessary tools to successfully evolve as a professional and become a better person; for that they are deeply appreciated.

I would like to also express my gratitude to my family, my mother Maria, my father Stratos and my beloved sister Eliza for never giving up their efforts to constantly encourage me to make one step at a time so as to accomplish my studies and successfully broaden my sphere of knowledge without fear for obstacles that may not be overcome. Nothing would be possible without you.

Lastly, my special thanks go to my beloved fiancée, Jenny, the woman in my life; without her presence, this endeavour would not have been the same. She always stands by me with her smile making every minute invested on my studies and our future worth the effort. Your compassion and understanding are admirable and indeed commendable.

Title and Abstract (English)

Thesis Title

Health Risk Assessment of Municipal Solid Waste Incineration (MSWI) with Energy Recovery in Athens, Greece

Abstract

In the present master thesis, the European legal framework of waste incineration has been mentioned, while followed by a short prospect of investment potential in municipal solid waste incineration in Athens focusing on waste characteristics and financial data. Reference has been made on incineration's expected social, environmental and health impacts by scoping conventional combustion, gasification and pyrolysis of wastes. The objectives of the study, the used materials and the method of research have been defined to present the thesis' rationale. The health risk assessment for incineration's air emissions has been developed in accordance to the Codex Alimentarius Commission standards; hazard identification, risk estimation and risk evaluation were integrated within a master thesis' context. Hazard characterization was based on the hazards' classification list of World Health Organization's International Agency for Research on Cancer Monographs and the minimum risk levels of the Agency for Toxic Substances and Disease Registry of the United States' Department of Health and Human Services. Exposure assessment revealed the magnitude of incineration risk by incorporating a part of literature review, while risk characterization was focused on the necessity for interdisciplinary approach. The author's personal opinion has been placed in a separate chapter for the avoidance of confusion with scientific data.

Title and Abstract (Greek)

Τίτλος Διπλωματικής

Εκτίμηση Υγειονομικού Κινδύνου της Αποτέφρωσης Αστικών Στερεών Αποβλήτων (ΑΣΑ) με Ανάκτηση Ενέργειας στην Αθήνα

Περίληψη

Στην παρούσα μεταπτυχιακή διατριβή, έγινε αναφορά στο Ευρωπαϊκό νομικό πλαίσιο που διέπει την αποτέφρωση απορριμμάτων και επακολούθησε σύντομη διερεύνηση της επενδυτικής προοπτικής επί της αποτέφρωσης αστικών στερεών αποβλήτων στην Αθήνα εστιάζοντας στα χαρακτηριστικά των απορριμμάτων και σε οικονομικά δεδομένα. Αναφέρθηκαν οι αναμενόμενες κοινωνικές, περιβαλλοντικές και υγειονομικές επιπτώσεις της αποτέφρωσης με πεδίο εφαρμογής τη συμβατική καύση, την αεριοποίηση και την πυρόλυση των απορριμμάτων. Οι στόχοι της μελέτης, τα υλικά που χρησιμοποιήθηκαν και η ερευνητική μέθοδος ορίστηκαν ώστε να παρουσιάσουν τη λογική πίσω από τη διατριβή. Η εκτίμηση του υγειονομικού κινδύνου των αερίων εκπομπών της αποτέφρωσης αναπτύχθηκε σύμφωνα με τα πρότυπα της Επιτροπής του Κώδικα Τροφίμων· η αναγνώριση του, η εκτίμηση της διακινδύνευσης και η αξιολόγηση της διακινδύνευσης ενσωματώθηκαν στα πλαίσια μιας μεταπτυχιακής διατριβής. Ο χαρακτηρισμός των κινδύνων βασίστηκε στη λίστα κατάταξης των κινδύνων των Μονογραφιών του Διεθνούς Οργανισμού για την Έρευνα του Καρκίνου του Παγκόσμιου Οργανισμού Υγείας και στα επίπεδα ελάχιστης διακινδύνευσης της Υπηρεσίας Καταγραφής Τοξικών Ουσιών και Ασθενειών του Τμήματος Υγείας και Ανθρωπίνων Υπηρεσιών των Ηνωμένων Πολιτειών. Η εκτίμηση της έκθεσης ανέδειξε το μέγεθος της διακινδύνευσης από την αποτέφρωση ενσωματώνοντας ένα μέρος βιβλιογραφικής ανασκόπησης, ενώ ο χαρακτηρισμός της διακινδύνευσης εστίασε στην αναγκαιότητα για διεπιστημονική προσέγγιση. Η προσωπική άποψη του συγγραφέα τοποθετήθηκε σε ξεχωριστό κεφάλαιο για την αποφυγή της σύγχυσης με τα επιστημονικά δεδομένα.

1. Introduction

Recent national and international developments force the Greek Government towards the application of sustainable waste management practices, including biological and thermal municipal solid waste treatment.[1] Incineration represents only a part of this discussion. Modern waste management practices are complex systems that include minimization of waste generation and maximization of waste differentiated collection, re-usability, materials and energy recovery, as well as controlled final disposal.[2] The rising concern on applying new and innovative waste management methods in Athens, in accordance with the EU regulation, underlines the need to establish relevant studies prior to likely investment.

This report focuses on the health impacts of incineration of *municipal solid waste* (MSW), a term referring to household, commercial and non-hazardous waste[3] of similar nature and composition to waste from households[4] that is collected by or on behalf of local authorities from any source.[5] Incineration is an option for waste treatment aiming to volume and hazard reduction, potentially harmful substances' capture-concentration-destruction and energy recovery through waste combustion.[6]

According to the European *Waste Incineration Directive* (WID),[7] an incineration plant has been defined as:

> *'Any stationary or mobile technical unit and equipment dedicated to the thermal treatment of wastes with or without recovery of the combustion heat generated. This includes the incineration by oxidation of waste as well as other thermal treatment processes such as pyrolysis, gasification or plasma processes in so far as the substances resulting from the treatment are subsequently incinerated.'*

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1 Papageorgiou A. et. al. (2009)

2 WHO (2007)

3 Strange K. (2002)

4 EC (2000)

5 Strange K. (2002)

6 WHO (2007)

7 EC (2000)

A typical waste incineration plant consists of a several sections (Figure 1), some of which are described in short below:

- the delivery section, where garbage trucks go to release their content in the bunker;
- the bunker, a place where garbage is stored until it is used as fuel for the incineration process;
- the steam generator or incineration section, where the activity incineration takes place reducing waste volume collected as bottom ash and generating power;
- the gas cleaning section, where waste gas deriving from incineration is processed and cleaned so as to be compatible with legal emission standards prior to release in the atmosphere;
- and the chimney section, which is a system of pipes, filters and monitoring instruments used to monitor gas quality and the quantity of air pollutants as the gas is being released in the atmosphere.

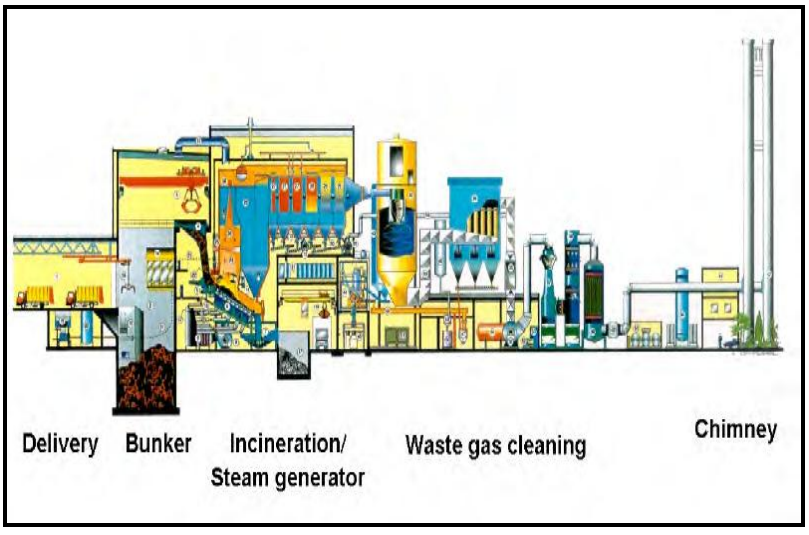

Figure 1. Standard Technical Scheme of Waste Incineration[8]

The WID's transposition in the EU member states deadline had been set at 28.12.2002.[9] However, regulation of emission limits may differ significantly from

[8] UBA (2001)

[9] EC (2000)

country to country and from province to province.[10] Regarding the operation of municipal solid waste incinerators the European Directive foresees that wastes must be incinerated at a minimum combustion temperature of 850 °C for at least 2 seconds, while emission limits for various emissions, such as SO_2, NO_X, HCl, VOCs, CO, PMs (fly ash), heavy metals and dioxins are regulated (Annex II: Tables 1-A & 1-B). The directive also sets the prerequisite for bottom ash, which in no case never exceed the value of 3% of the total organic carbon content.[11]

The European legal frame setting the requirements for regulated waste incineration of different technologies can be summed up to the following:[12]

- ATEX Guidelines of the European Union
- Directive 73/23/EC (Low Voltage Directive)
- Directive 1994/9/EC (ATEX 95)
- Directive 1997/23/EC (Pressure Equipment Directive)
- Directive 1998/37/EC (Machinery Directive)
- Directive 1999/92/EC (ATEX 137)
- Directive 2000/76/EC (Waste Incineration Directive - WID)
- EMC – Guideline 2004/108/EC
- Others

The key advantages of *municipal solid waste incineration* (MSWI), in comparison to alternative waste treatment options, include the significant reduction of MSW weight and volume, as well as the opportunity to recover energy and materials – about 30% is left as residue available for materials' recovery. The key disadvantages of MSWI are the production of hazardous solid waste, the discharge of contaminated waste water and the emission of toxic pollutants, heavy metals and combustion products.[13] Part of

[10] Schaffernak B. (2006)

[11] DEFRA[2] (2007)

[12] Lettner F. & Timmerer H. (2006)

[13] Rushton L. (2003)

the emissions might negatively affect health and worsen the living standards of exposed population.[14]

In the present project, the expected hazardous air emissions of MSWI will be assessed to determine the health risks for the population in the conurbation of Athens. The study aims to provide answers on related questions and contribute to scientific thought on environment and public health by outlining the health impact of waste incineration in Athens. The completion of this project will facilitate any future research on public health impact associated with waste incineration close to densely populated regions.

Basic information and supplementary data required for the paper's thorough understanding is provided on Chapter 1, while the researcher's objectives are presented in Chapter 2. The methodology followed for the development of this project is described in Chapter 4 and incineration health risk assessment's outcomes are summarized for discussion in Chapter 5. Other relative conclusions are presented separately in Chapter 6.

[14] NRC (2000)

1.1 Incineration in Athens

Official European data[15] show that the yearly volume of municipal waste generated in Greece is on average 478 kg/person or ~1.31 kg/day per capita. Athens has a population of 2,664,776 inhabitants, while the population density amounts to 7,367 inhabitants per sq. km.[16] On average each resident generates 1.31 kg of wastes per day, resulting in a total amount of ~3,500 tons/day (~9,650 kg/km^2 per day) or ~1,274,000 tons/year of waste generated in the conurbation. The composition of MSW of Attica reflects composition of wastes in Athens and consults of 40% kitchen and garden waste, 29% paper and card, 14 % plastic, 3% glass, 3% metals, 3% inerts, 2 % leather, wood, textiles, rubber and 6% other materials (Annex II: Table 2).[17]

Recent data indicate that ~82% of the Greek MSW is deposited in landfills, while from the remaining ~18% collected waste, ~16.5% is recycled and ~1.5% is composted (see Annex II: Table 3).[18] Landfilling is a main cause of greenhouse gas emissions in comparison to other available MSW management practices.[19] The national waste treatment policy needs to comply with the European Landfill Directive and by 2016[20] has to develop measures considerably reducing landfilling.[21]

At present, no thermal treatment of MSW takes place in Greece.[22] Incineration of waste is one of the options which can potentially reduce the amount of landfill waste[23] and it can be coupled with energy recovery in *waste-to-energy* (WTE) plants.[24] This practice is preferred in the EU.[25] It produces steam or hot water[26] for electricity[27] or

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15 Eurostat 2011)

16 NSSG (2009)

17 Papageorgiou A. et. al. (2009)

18 Eurostat (2011)

19 EEA (2011), Data and maps – Maps and graphs: Emissions from municipal waste management in the EU-27, excluding Cyprus, plus Norway and Switzerland, 1990 and 2008, CO2-equivalents.

20 EEA (2011), Data and maps – Maps and graphs: Biodegradable municipal waste landfilled in 2006 (% of biodegradable municipal waste generated in 1995), compared to targets of the European Landfill Directive.

21 EEA (2011), Data and maps – Maps and graphs: Trends and outlook for management of municipal waste in the EU-27 (excluding Cyprus) plus Norway and Switzerland, baseline scenario.

22 EIPPCB (2006)

23 UNEP (2003)

24 Klein A. & Themelis N.J. (2003)

25 Bontoux L. (1999)

combined heat and power (CHP) generation – a term referring to an energy recovery plant that produces both heat and power via a steam boiler.[28] Energy recovery also generates an attractive - in particular in periods of financial crisis - income (e.g. ~14% of total costs according to Annex II: Table 4) [29] that can be used to counterbalance the operational costs. Apart from the generation of a steady income, the combination of waste thermal treatment with energy recovery results in reduced air and water emissions and contributes to reducing dependence on fossil fuels for electricity generation. [30]

Incinerator capacities determine investment costs (Figure 2) and may range from about 100,000 to over 1 million tons/year[31] with a minimum waste input of about 240 tons/day (10 tons/hour) set as requirement per incineration line.[32] A medium sized plant with a capacity of ~400,000 tons/year requires an investment of 75M to 150M €,[33] which means that investing in maximal incineration with energy recovery in Athens would require an investment of almost 130M € in year 2000.[34] Investing in a MSWI plant of about 320,000 tons throughput per year, built with the *best available technologies* (BAT), may cost as much as the indicative sum of 230M € - incl. planning and 25.5M € of infrastructure measures.[35] The so-called operational treatment fees range from 64 €/ton[36] to 460 €/ton depending on incinerator's waste capacity, [37] while the typical average cost of bulk MSW incineration is estimated to range between 64 €/ton[38] and 70 €/ton.[39] Informative detailed breakdowns of

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[26] Smith A. et al. (2001)

[27] UNEP (2003)

[28] DEFRA[2] (2007)

[29] Eunomia (2001)

[30] Klein A. & Themelis N.J. (2003)

[31] Smith A. et al. (2001)

[32] The World Bank (1999)

[33] Smith A. et al. (2001)

[34] Sedee C. et al. (2000)

[35] UBA (2001)

[36] Smith A. et al. (2001)

[37] EIPPCB (2006)

[38] Smith A. et al. (2001)

[39] Bontoux L. (1999)

indicative incineration costs and a comparison of the costs for different practices in various member states of EU are displayed in Annex II: Tables 5, 6 & 7.

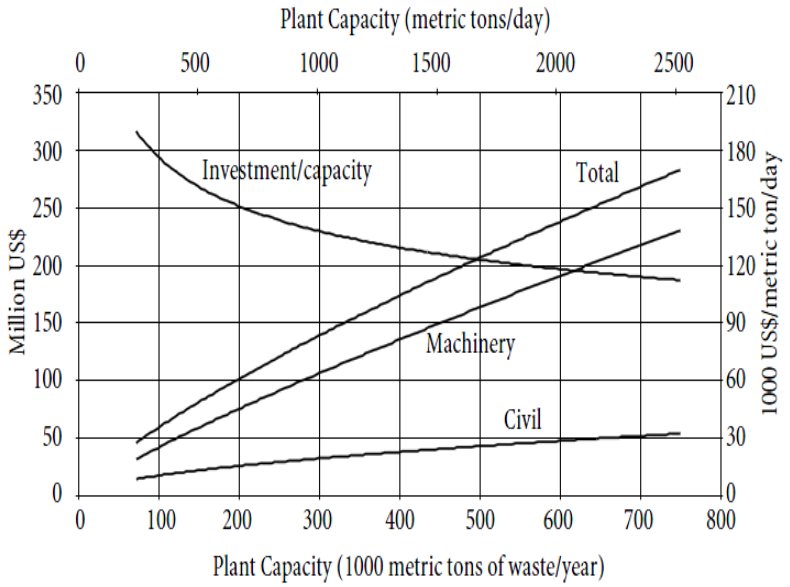

Figure 2. Indicative Investment Costs for MSWI[40]

Although the energy output is almost constant throughout a day, the incinerator's design and layout are based on continuous operation at 100 percent load.[41] Many installations are considered to operate on a 24 hours/day basis for nearly 365 days/year,[42] but the incinerator's actual availability has been calculated to an average of 312.5 days/year (7500 hours/year), while the remaining ~0.14% (51.5-52.5 days) of the year is dedicated to rest and maintenance purposes.[43] The operational life of an incinerator is about 20-30 years.[44]

Taking in consideration the government's current financial difficulties,[45] the option of MSWI appears to be an expensive solution to Athenian waste management problems, which can be supported through the contribution of the private sector, either as *Public Private Partnerships* (PPPs) or complete private funding. However, the difficulty in

[40] The World Bank (1999)

[41] Ibid.

[42] EIPPCB (2006)

[43] The World Bank (1999)

[44] Smith A. et al. (2001)

[45] Bank of Greece (2012)

calculating the benefit-cost ratio (BCR) due to incineration's *'negative benefits'* [46] may prove to be discouraging for relative private investment.

Successfully locating an incineration facility in the conurbation of Athens is a difficult and quite ambitious task. Depending on their size, municipal waste incinerators may be major industrial facilities with the potential to become significant sources of pollution[47] and as such they should better be located in spacious, industrial areas. Scarce green lands and hardly polluting industrial areas, along with the *not-in-my-backyard* (Nimby) syndrome, make the effort of determining the scope of this study even harder. The specified possible locations of such a facility will most probably be selected according to the availability of industrial space and their position in the conurbation. Therefore, as potential locations of installing an incineration plant can be considered the following: one in the centre of Athens (Eleonas), one at the NW line of the conurbation (Acharnes) and one at the SE outskirts (Koropi).

[46] Sedee C. et al. (2000)

[47] UNEP (2003)

1.2 Environmental and Health Hazards

Waste incineration potentially results in human exposure via the atmospheric emissions, solid ash residues or water cooling process.[48] Residues and emissions from MSWI can be distinguished to *primary pollutants*, which include particulate matter (PM), nitrogen oxides ($NO_{X)}$, sulfur oxides (SO_X), volatile organic compounds (VOCs) and carbon monoxide (CO); *secondary pollutants*, such as nitrates (NO_X), sulfates (SO_X) and ozone (O_3); and *micropollutants*, including heavy metals and dioxins.[49]

Provided that solid ash residues and cooling water can be effectively controlled through appropriate handling and disposal methods, this study is limited to determining the health impacts of airborne pollutants.[50] Mass burn, gasification and pyrolysis (Annex I) are examined for potential unhealthy releases to the environment that derive from their activity in the form of air emissions (Annex II: Table 8). These emissions may affect public health and include air pollutants, such as HCl,[51] NO_X, SO_2, inorganic and combustible PMs, [52] dioxins and furans, other carcinogens, such as PAHs,[53] dust, odor and micro-organisms.[54]

The precautionary principle advises that the health and environmental impacts need to be examined prior to establishing a waste incinerator. An appropriate cost/benefit study weights the health and environmental impacts against the costs. However, the present study will be only assessing the potential health risks of such activity so as to be integrated in future relevant studies.

Many health problems are related to pollutants released in the atmosphere from the incinerator's stack, including organic (HC, VOCs, PCDD/Fs, PCBs, PAHs) and

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48 HPA (2010)

49 Rabl A., Spadaro J.V. & McGavran P.D. (1998)

50 HPA (2010)

51 Smith A. et al. (2001)

52 Sedee C. et al. (2000)

53 HPA (2010)

54 DEFRA (2004)

inorganic compounds (CO_X, SO_X, NO_X) as well as particles of all sizes (Annex II: Table 9).[55]

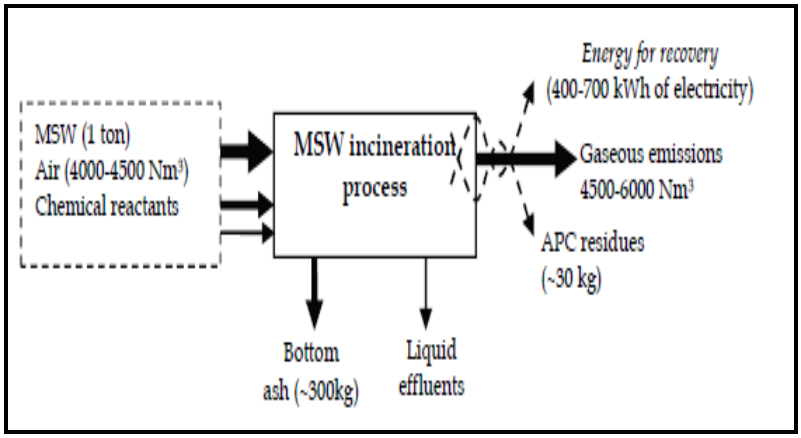

Figure 3. Main Inputs and Outputs of MSWI[56]

The potential environmental and health hazards from MSWI derive from four sources of exposure (Figure 3):[57]

- air emissions of dust, HCl, SO_X, Hf, NO_X, C, CO, NH_3, Cd, Tl, Hg, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V, Sn, PCDD/PCDF, benzo(a)pyrene, PCBs, PAHs and N_2O,
- water emissions, including, Hg, Cd, Tl, As, Pb, Cr, Cu, Ni, Zn, Sn, fluoride, N, P, temperature, pH, sulfate and C,
- ash residues that contain C, PCDD/PCDF, Ar, Pb, Cd, Cr, Cu, Ni, Hg, Zn, as well as SO_4^{2-} and Cl^- as products of elution,
- noise emissions (for 24 hours a day and seven days a week all year round)[58] as high as 36-57 dB(A) during day and 29-45 dB(A) at night.

Throughout the study stack emissions are examined. The most important achievement with BAT incinerators is that the flue–gas multistage cleaning treatment *guarantees* that emissions are within the WID's limits.[59]

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55 WHO (2007)

56 Quina Margarida J. et al. (2011)

57 UBA (2001)

58 The World Bank (1999)

59 WHO (2007)

1.3 Social, Health and Environmental Impacts

Incineration is related to social disamenity due to intense environmental and health impacts in nearby regions that contribute in the creation of locally undesirable land uses (LULUs) with decreased property values - house price depreciation has been estimated to ascend ~10.5% within 1 km distance from a waste treatment facility.[60]

Waste combustion raises environmental concerns related to its impacts on global climate change and other global effects, provided that pollutants from MSWI have been reported to contribute in acidification,[61] ecosystem toxicity, global warming, ozone depletion, tropospheric smog formation,[62] eutrophication[63] and contamination of water bodies, depletion of non-renewable resources, noise, accidents etc.[64]

According to the United Kingdom's Health Protection Agency[65] there is *'no significant pollution from modern incineration facilities and relevant study is not recommended'*. However, it has been reported that populations working at or living near incinerators are exposed to incineration hazards through inhalation of contaminated air, consumption of contaminated foods and water, or even dermal contact with contaminated soil.[66] The incinerator's location and employees' specialization are deemed as *'critical factors'* in terms of public health.[67] Amongst the reported hazards, heavy metals, such as Cd, Pb, Hg, dioxins and furans,[68] as well as PMs, fly ash and organic compounds,[69] are of primary concern since they have the potential to cause the adverse health effects to the facility workers and the nearby residents.[70]

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60 Sedee C. et al. (2000)

61 Olofsson M. et al. (2005)

62 Bontoux L. (1999)

63 Olofsson M. et al. (2005)

64 Smith A. et al. (2001)

65 HPA (2010)

66 Franchini M. et al. (2004)

67 WHO (2007)

68 NRC (2000)

69 WHO (2007)

70 NRC (2000)

Exposure to incineration pollutants, such as oxides and VOCs, is expected to cause public health deterioration. Incineration activity has been directly related to the release of carcinogens (e.g. dioxins and furans), as well as to human toxicity due to heavy metals emissions, lung irritation due to SO_X respiration and other direct or indirect human health effects resulting because of bioaccumulation and biomagnification through the food chain.[71] Non-Hodgkin's lymphoma (NHL), soft tissue sarcoma (STS), lung and esophageal cancer, childhood cancer, high blood PCDD/F levels and an increased risk's of producing urinary mutagens has been laso reported to be associated with waste incineration.[72] Exposure to incineration hazards may be eventually related to the occurrence of other cancers, such as those of the digestive system, the liver, kidneys, pancreas,[73] skin and the respiratory system. Low birth weight and thyroid hormones' reductions - due to PCBs and heavy metals - have been reported, but further investigation is deemed necessary.[74]

[71] Bontoux L. (1999)

[72] Franchini M. et al. (2004)

[73] Rushton L. (2003),

[74] Franchini M. et al. (2004)

2. Objectives

This study aims to validate UK HPA's statement (see p.21 §2) by addressing and assessing the health risks of mass burn, gasification and pyrolysis in Athens, so that *source-pathway-receptor*[75] linkages to be developed for air emissions. Provided that in an integrated risk analysis system the stakeholders are engaged in every stage of development (Figure 4), the paper is intended to support the stakeholders throughout the procedure. That can be accomplished by contributing to the understanding of MSWI health impacts and by further supporting integrated MSWI health risk management projects through the availability of relevant data to decision-makers and waste management policy-makers.

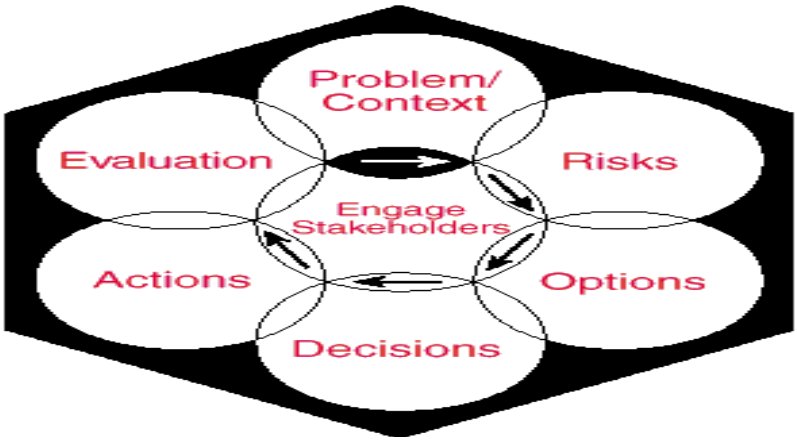

Figure 4. The Engagement of Stakeholders in Integrated Risk Analysis[76]

This work aims to raise awareness on literature evidence of MSWI health impacts and the WID's implication, as well as to support future efforts of determining *risk acceptability*[77] related to these specific incineration technologies, thus effectively contributing to risk communication. Following the risk analysis paradigm, this health risk assessment may be included in future integrated risk analysis projects as one of the necessary components.[78] The paper is equally a source report for the developing of individual risk assessments or waste management strategies involving any of the technologies described for implications close to densely populated regions.

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[75] HPS & SEPA (2009)

[76] P/CCRARM (1997)

[77] Kruk G. (1999)

[78] CAC (2011)

3. Materials and Method

Data from both printed and digital sources have been used. Bibliographies from previous projects of personal work, articles from peer-reviewed journals and magazines, research documents and models developed by governmental agencies have been accessed through local libraries and various digital sources. Digital sources include scientific internet search engines, such as Google Scholar, Microsoft Academic Search, Scirus and Open Archives, digital libraries, such as Pub Med and DSpace NTUA, as well as scientific trade publications' databases, such as Science Direct (Elsevier) and Sage Pub. The research evolved around several key phrases and words, such as *municipal solid waste treatment, municipal waste incineration, mass burn combustion, gasification, pyrolysis, conventional incineration, incineration health impacts, waste-to-energy technologies* etc. Although sporadic references to earlier bibliography have been made, the main body of research is constituted of bibliography published after 1997.

Sites of (scientific) international organizations, such as the World Health Organization (WHO), non-profit research institutions, such as the National Research Council (NRC), and governmental authorities, such as Ministries and Departments, the European Commission (EC) and the US - Environmental Protection Agency (USEPA), as well as specific sites dedicated to their projects have been accessed. The Integrated Risk Information System (IRIS) of USEPA has also been used. Publications of environmental non-governmental organizations' (NGOs) and private companies have been avoided as much as possible, although unintended reference to their projects may have been made through their collaboration with international and governmental bodies. Academic advisors have been consulted for guidance on the development of this paper, while contact with interested professional experts was not deemed as necessary.

From a statistical point of view, a review of a little more than a thousand of papers resulted in a potential bibliography constituted by relevant papers at a ratio of approximately 1/12, from which only a part of almost 1/2 has been actually used for the development of this research.

This risk assessment will be developed, according to the Codex Alimentarius Commission (CAC) standards,[79] by incorporating the following steps (Figure 5):

1. Hazard Identification

   Hazard Identification – a process aiming to identify the harmful substances for human health.

2. Risk Estimation

   a. Hazard Characterization – a process investigating dose-response relations and MRLs, as well as classifying hazards for carcinogenicity according to IARC Monographs.

   b. Exposure Assessment – a process aiming to quantify hazard emissions and to estimate the severity of exposure.

3. Risk Evaluation

   Risk Characterization – a process of integrating information from previous steps that aims to assess the total risk by evaluating the overall quality of data, specific assumptions and uncertainties in each step.

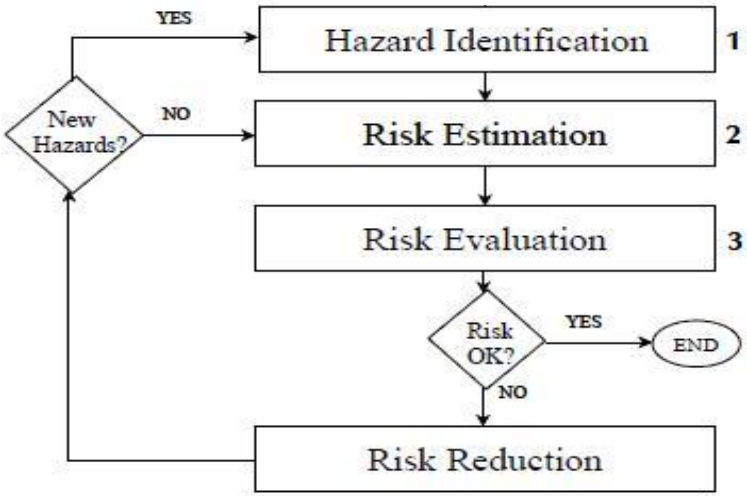

Figure 5. Outline Risk Assessment Decision-Making Flow Chart[80]

[79] CAC (2011)

[80] Cusco L. (2006)

4. Results

4.1 Hazard Identification

Most major health hazards in incineration stack emissions have already been regulated by respective authoritative bodies and can be categorized to PM, CO, acid gases (SO_2, NO_X, HCl, HBr, HF), TOCs (PCDD/Fs, PAHs, PCBs, other VOCs), heavy metals and other pollutants (Annex II: Table 10).

4.1.1 Particles

According to the Greening EPA Glossary: [81]

> *'Particulate matter is a complex mixture of extremely small particles and liquid droplets made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles.'*

Waste combustion emits particulate matter,[82] which is broadly distinguished by particle size to PM_{10}, PM_5, $PM_{2.5}$, microns and ultrafine.[83] Flue-gas delivers particles out of the furnace, where as the gases cool down, inorganic compounds may condense on particle surfaces forming metal chlorides, such as ZnC_{l2}, PbC_{l2} and CdC_{l2},[84] as well as aluminum and silicon oxide particles.[85]

Emissions of PM are not expected to be a problem in gasification though. However, the grinding process as well as the fuel's high moisture may contribute to potential fine particulate carryover.[86] The same applies to pyrolysis as well.[87]

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81 USEPA[1] (2013)

82 Quina Margarida J. et al. (2011)

83 WHO (2007)

84 The World Bank (1999)

85 Quina Margarida J. et al. (2011)

86 Barbour J. (2011)

87 Khoo H.H. (2009)

4.1.2 CO

Insufficient amount of O_2 in the combustion chambers or lower temperature to what is required for full reaction to CO_2 may result in incomplete combustion, which contributes to CO presence in flue-gas. [88] The CO concentration in flue-gas can be measured to assess incineration efficiency,[89] as well as possible presence of PAHs in stack emissions.[90]

Residues of CO may be existent in cases of insufficient carbon oxidization to CO_2,[91] but due to combustion process's efficiency in most gas engines, presence of CO cannot serve as an indicator to measure PAH emissions; which in gasification are usually non-existent.[92] In regards to pyrolysis, emissions of CO may occur at the high temperatures of the pyrolytic process,[93] but they will most probably be in low levels.[94]

4.1.3 Acid Gases

SO_2

Sulfur dioxide (SO_2) is an inorganic substance. It is a colorless gas with a pungent odor quite soluble in the water.[95] It is a highly reactive gas, with short half life indoors, that tends to condense on fine particle surfaces. During combustion, sulfur contained in MSW is oxidized releasing SO_2 in the flue-gas which ends up as another component of stack gases.[96]

Sulfur can generally be maintained in low levels with higher incineration temperatures. In gasification, sulfur is largely converted to H_2S. The H_2S concentration is normally too high, thus control techniques are necessary to meet SO_2

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88 EIPPCB (2006)

89 Quina Margarida J. et al. (2011)

90 Knoef H. (2006)

91 EIPPCB (2006)

92 Knoef H. (2006)

93 Conesa J.A. et al. (2008)

94 Khoo H.H. (2009)

95 ATSDR[1] (1998)

96 Quina Margarida J. et al. (2011)

emission standards set for waste incineration.[97] Releases of SO_2 have been observed also in pyrolysis,[98] but in very low concentrations.[99]

NO_X

Nitrogen contained in air and wastes, usually in temperatures higher than 1300 °C and in conditions where oxygen is not a 'limiting reagent', tends to react with present oxygen to form *thermal* and *fuel* NO_X respectively. In MSWI with energy recovery, *thermal* NO_X is significantly greater in comparison to *fuel* NO_X. Nitrogen oxides may also be produced through radical reactions of organic matter – these are widely known as *prompt* NO_X.[100]

The high temperature of the gasification process results in considerable NO_X stack releases. Lowering the temperature by ~100 °C, may reduce NO_X emissions from biomass up to 50%.[101] Nitrogen is mainly converted to NH_3 which results in the waste-water stream and can be handled by appropriate filters.[102] However, NO_X emissions are also expected in high concentrations in the pyrolytic gas,[103] thus constituting a major concern.[104]

Halogens

Plastics, such as PVC, salty food wastes and other inorganic chlorides possibly to be found in MSW, when combusted release chlorine. Plastics, such as PTFE, fluorinated textiles and other inorganic fluorides, in waste incineration conditions produce fluorine in significant quantities. These substances in furnace conditions are usually

97 Faaij A. et al. (1997)

98 Lin K.-H. et al. (2009)

99 Khoo H.H. (2009)

100 Quina Margarida J. et al. (2011)

101 Barbour J. (2011)

102 Faaij A. et al. (1997)

103 Lin K.-H. et al. (2009)

104 Khoo H.H. (2009)

transformed into acid hydrogen halides, HCl and HF, and then they are partly converted into metal chlorides.[105]

Chlorine in MSW is highly volatile and during the gasification process may react to form hydrogen chloride gas. If uncontrolled, high concentration of HCl can be found in stack air emissions.[106] However, nearly all of chlorine is removed as HCl tends to react well with particles, which then are collected by respective filters, and lime, thus attaining absorption levels of more than 90%. Any remaining HCl is dissolved in the scrubber water.[107] Similarly to chlorine, bromine is transformed into HBr in concentrations much lower (30 – 200 ppm) when compared to chlorine (3,000-6,000 ppm).[108] In short, halogens, such as HCl, HF and HBr, are expected in every MSWI process and it is essential to be effectively controlled.[109]

4.1.4 TOC

Dioxins / Furans

In the pure form, chlorinated dibenzodioxins (CDDs) are crystals or colorless solids and enter the environment as mixtures containing a number of individual components. They are released into the air in emissions from municipal solid waste and industrial incinerators.[110] Chlorinated dibenzofurans (CDFs), are a family of chemicals that contain one to eight chlorine atoms attached to the carbon atoms of the parent chemical, dibenzofuran, they do not dissolve in water easily and appear to be in the form of colorless solids. They can also be released from incinerators.[111]

The different forms of dioxins and furans are known as congeners.[112] Polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) compose a

[105] Quina Margarida J. et al. (2011)

[106] Barbour J. (2011)

[107] Faaij A. et al. (1997)

[108] Klein A. & Themelis N.J. (2003)

[109] Khoo H.H. (2009)

[110] ATSDR[2] (1998)

[111] ATSDR (1994)

[112] Environment Australia (1999)

'well-known environmental contaminant family'[113] whose various congeners tend to condense on particle surfaces. Specifically in MSWI, 75 dioxin and 135 furan congeners[114] may be formed in trace quantities[115] of which the 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD) is considered the most toxic.[116] It is odorless and the odors of the rest CDDs remain unknown.[117] Analysis of PCDD/F profiles from MSWIs identifies the de novo synthesis as the dominant formula irrespectively of the type of thermal process to be considered.[118]

MSWI plants appear to be a sink of dioxins, as PCDDs and PCDFs may be either present in furnace feedstock or formed during the various incineration processes.[119] Especially in temperatures ranging between 300–400 °C, PCDD/PCDF formation is expected to be maximized.[120] Even though conventional MSWI plants used to be major sources of air PCDD/PCDF contamination,[121] after the WID's enforcement, their contribution is significantly lower.[122]

Dioxins and furans are also to be found in gasification. Although there have been several studies developed for combustion, relative data for pyrolysis is not enough for safe conclusions to be made.[123] The lack of experimental studies available obstructs greatly the evaluation of the environmental impact of pyrolysis.[124] However, it is already known that traces of PCDD/Fs may be present in stack emissions depending on waste composition (Figures 6 & 7) and the temperature of the pyrolytic process.[125]

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[113] Hites R.A. (2011)

[114] Quina Margarida J. et al. (2011)

[115] UNEP Chemicals (2005)

[116] Quina Margarida J. et al. (2011)

[117] ATSDR[2] (1998)

[118] Everaert K. & Baeyens J. (2002)

[119] Quina Margarida J. et al. (2011)

[120] McKay G. (2002)

[121] Olie K. et al. (1998)

[122] Quina Margarida J. et al. (2011)

[123] Garcia-Perez M. (2008)

[124] Everaert K. & Baeyens J. (2002)

[125] Conesa J.A. et al. (2008)

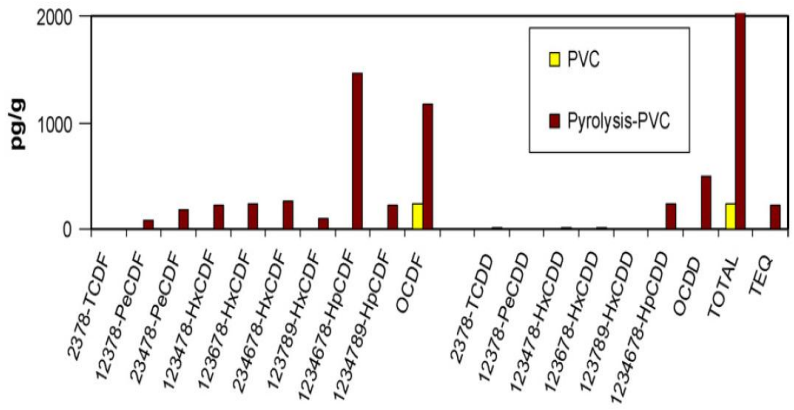

Figure 6. 2,3,7,8-Substituted PCDD/Fs of PVC (raw material) and emissions produced by pyrolysis at 850 °C[126]

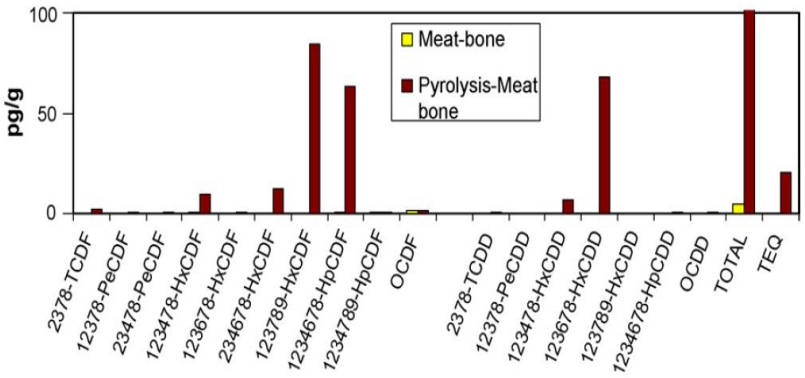

Figure 7. 2,3,7,8-Substituted PCDD/Fs of meat bone (raw material) and emissions produced by pyrolysis at 850 °C[127]

Other Organic Compounds

Incomplete combustion in MSWI results in traces of PAHs and PCBs, which are mostly adsorbed into particles. Other organic compounds of high vapor pressure, a group of substances generally known as VOCs, such as methane (it can only be formed in the waste bunker, because of the anaerobic conditions developed during long-term storage), ethane, propane, butane, pentane, hexane, heptane, ethylene, BTX, ethylbenzene, acetylene, formaldehyde and acetone are also released in the flue-gas. All of them are quantified as *total organic carbon* (TOC).[128]

[126] Conesa J.A. et al. (2008)

[127] Ibid.

[128] Quina Margarida J. et al. (2011)

Polychlorinated biphenyls (PCBs) are mixtures of up to 209 congeners not released by natural sources. They are colorless to light yellow substances in the form of oily liquids or solids and some PCBs can exist as a vapor in air. They have no known smell or taste so far and many of those commercial mixtures are known in the US by the trade name Aroclor. They have been used as coolants and lubricants in transformers, capacitors and other electrical equipment, because they don't burn easily and are good insulators. The US stopped manufacturing PCBs in 1977, because of evidence that they build up in the environment and can cause harmful health effects.[129] They are extremely persistent in the environment because they do not readily break down into less harmful chemicals.[130]

Polycyclic aromatic hydrocarbons (PAHs) are a group of over 100 different chemicals that can be formed during incomplete waste combustion. Some PAHs are manufactured and usually exist as colorless, white or pale yellow-green solids. PAHs can be found in dyes, plastics and pesticides among other products.[131]

Ethylbenzene is a colorless liquid with an aromatic odor and is flammable and combustible that smells like gasoline.[132] It can be found in insecticides,[133] gasoline, paints and varnishes, inks, pesticides and carpet glues, as well as automotive and tobacco products among others.[134] Emissions of ethylbenzene and other PAHs have been traced also in gasification[135] and pyrolysis,[136] as they tend to occur in large quantities at temperatures over 700 °C.[137] Fluorene, phenanthrene, pyrene and especially naphthalene are drawing much of the attention (Figure 8).[138]

Aromatics, parafins and olefins coexist in pyrolytic gas with the latter consisting the main fraction. The major VOCs to be found are propene, propane, toluene, benzene

[129] ATSDR[1] (2000)

[130] USEPA[4] (2013)

[131] ATSDR (1995)

[132] ATSDR (2011)

[133] ATSDR (2010)

[134] ATSDR (2011)

[135] Lin K.-H. et al. (2009)

[136] Garcia-Perez M. (2008)

[137] Ledesma E.B. et al. (2002)

[138] Conesa J.A. et al. (2008)

and 1-butene, while the compounds with expected higher concentrations are benzene, toluene, ethylbenzene and xylene.[139] Benzene is a colorless liquid with a sweet odor that evaporates into the air very quickly and dissolves slightly in water.[140] It is also highly flammable.[141] It is used to make other chemicals which are used to make plastics, resins, and nylon and synthetic fibers,[142] as well as for the manufacturing of some types of rubbers, lubricants, dyes, detergents, drugs and pesticides.[143] Benzene is also a natural part of cigarette smoke. [144]

Xylene is a colorless, flammable liquid with a somewhat sweet odor that evaporates and burns easily.[145] There are three forms of xylene in which the methyl groups vary on the benzene ring, namely meta-xylene, ortho-xylene, and para-xylene (m-, o-, and p-xylene), which are referred to as isomers.[146] Many xylenes (mixtures of the isomers) are used as solvents and synthetic intermediates.[147] They are frequently used as solvents and in the printing, rubber and leather industries. Xylene is also used as a cleaning agent, a thinner for paint, as well as in paints and varnishes.[148]

Toluene is a clear, colorless liquid with a distinctive smell that is used in making paints, fingernail polish, rubber, some printing and leather tanning processes etc.[149] Naphthalene is a white solid with a strong, but not unpleasant smell, that evaporates easily and has been used in moth repellents and toilet deodorant blocks. The major commercial use of naphthalene is in the manufacture of PVC plastics. Burning tobacco or wood also produces naphthalene.[150] Formaldehyde is a flammable,[151] colorless water-soluble gas with a distinct, pungent odor that is detected at levels of

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[139] Lin K.-H. et al. (2009)

[140] ATSDR[1] (2007)

[141] ATSDR[3] (2007)

[142] ATSDR[1] (2007)

[143] ATSDR[3] (2007)

[144] ATSDR[1] (2007)

[145] ATSDR[4] (2007)

[146] ATSDR[2] (2007)

[147] ATSDR[4] (2007)

[148] ATSDR[2] (2007)

[149] ATSDR[2] (2000)

[150] ATSDR[1] (2005)

[151] ATSDR[1] (1999)

about 100 ppb. It is included in some building materials, furnishing and some consumer products,[152] such as antiseptics, medicines, cosmetics and as a preservative in foods. It is used in the production of fertilizer and paper.[153] Ethylene and acetylene, as well as CH_4 and other HCs, may also provide reason for concern.[154]

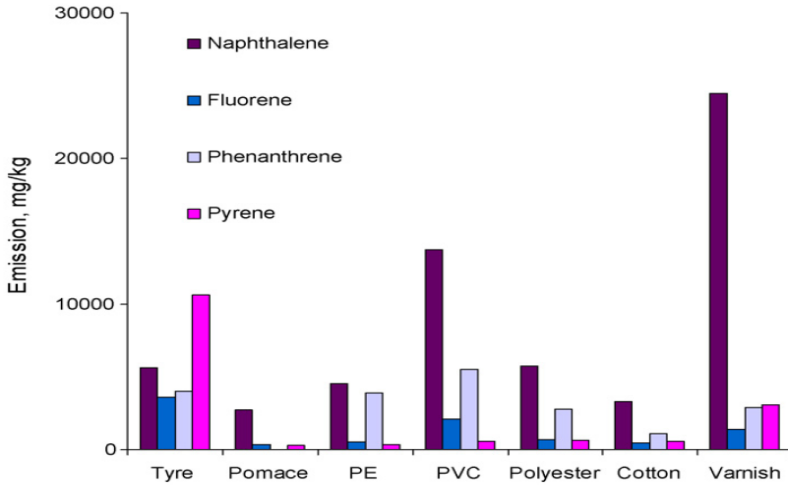

Figure 8. Emissions of PAHs from pyrolysis at 850 °C[155]

4.1.5 Heavy Metals

As per the definition of the EU Directive 67/548/EEC, the term heavy metals refers to antimony (Sb), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), selenium (Se), tellurium (Te), thallium (Tl), tin (Sn), as well as their compounds, while manganese (Mn) and zinc (Zn) are often included. Concentrations of heavy metals in MSW fractions vary significantly depending on MSW composition and definitions (Annex II: Table 11).[156]

Arsenic is a highly poisonous semi-metallic element.[157] Inorganic As is mostly used as wood preservative[158] while organic As compounds are used as pesticides. When As

[152] USEPA[5] (2013)

[153] ATSDR[1] (1999)

[154] Conesa J.A. et al. (2008)

[155] Ibid.

[156] Becidan M. (2007)

[157] USEPA[6] (2013)

[158] ATSDR[5] (2007)

is combined with O, Cl and S forms inorganic As compounds.[159] Cadmium is another thermally mobile metal with high toxicity that can be found in MSW, due to discarded electronic devices, paints, batteries and plastics, which is usually detected in the flue-gas in the form of $CdCl_2$.[160] It is usually found as a mineral combined with O, Cl and S. Cadmium does not corrode easily and has many uses,[161] including batteries, pigments, coatings and platings, stabilizers for plastics and photovoltaic devices.[162]

Chromium exists with other elements forming various compounds. The main forms of Cr are Cr(0), Cr(III) and Cr(VI). It is used to make metal alloys, such as stainless steel and in MSW, it can be found in many consumer products, such as treated wood, tanned leather and stainless steel cookware among other.[163] Lead has many different uses. Its properties, such as corrosion resistance, density, and low melting point, make it a familiar metal in pipes, weights and storage batteries,[164] as well as other commercial and industrial products. However, because of several health concerns, lead from gasoline, paints and ceramic products, caulking and pipe solder has been dramatically reduced.[165]

Mercury exists in several forms as elemental, metallic or a compound.[166] It combines with other elements, such as Cl, S, or O, to make inorganic Hg compounds or "salts" appearing as white powders or crystals, as well as C to form organic Hg compounds. More releases of Hg in the environment can increase the amounts of methylmercury that these small organisms make. Skin lightening creams, antistiseptic creams and ointments,[167] as well as other MSW, such as batteries, thermometers, fluorescent light bulbs, some electrical switches and other electrical devices, may contain amounts of Hg.[168] Metallic Hg is a dense liquid that is not easily absorbed into unbroken skin, but

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[159] ATSDR[6] (2007)

[160] Quina Margarida J. et al. (2011)

[161] ATSDR[3] (2012)

[162] ATSDR[2] (2012)

[163] ATSDR[4] (2012)

[164] ATSDR[7] (2007)

[165] ATSDR[8] (2007)

[166] USEPA[1] (2013)

[167] ATSDR[2] (1999)

[168] USEPA[1] (2013)

vaporizes even at room temperature.[169] It is a thermally mobile metal which is highly toxic and in temperatures above 357 °C is usually entirely volatilized into the flue-gas in the form of Hg^0 and $HgCl_2$.[170] Mercury vapors are colorless and odorless and the higher the temperature, the more vapors are released.[171]

Nickel is a hard, silvery-white metal that may combine with other metals, such as iron, copper, chromium, and zinc, to form alloys used for coins, jewelry, items such as valves and heat exchangers, as well as stainless steel. It can combine with other elements, such as Cl, S and O to form Ni compounds. Compounds of Ni are used for electroplating, to color ceramics, as catalysts that increase the rate of chemical reactions and in battery production. Many of them can dissolve fairly easy in water and have a green color. Neither Ni nor its compounds have any characteristic odor or taste.[172]

Elemental Se (else referred to as Se dust) is in the form of metallic grey to black hexagonal crystals. Most processed Se is used in electronics because of its semiconductor and photoelectric properties. It is used in the glass industry and as a component of pigments in plastics, paints, enamels, ink, and rubber. It is used in pharmaceutical products, in pesticides and fungicides, as well as an ingredient in antidandruff shampoos.[173]

Thallium in MSW, if any, is almost non-existent and most of times not detectable. Stack gases of MSWI may also include highly toxic Sb, Co, Cu, Mn and V emissions depending on the combustion temperature in the furnace. As the gases cool down, oxides and chlorides in the flue-gas may condense on particle surfaces.[174]

Very high heavy metal concentrations have been reported for gasification, especially in regards to Zn, Cu, Cr, Ni and Pb, while concentrations of As need as well to be monitored in this process. Reducing atmosphere conditions of gasification promotes evaporation of heavy metals in metallic form. Heavy metals with a low melting point,

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[169] ATSDR[2] (1999)

[170] Quina Margarida J. et al. (2011)

[171] ATSDR[2] (1999)

[172] ATSDR[3] (2005)

[173] ATSDR[3] (2003)

[174] Quina Margarida J. et al. (2011)

such as Cd, Hg, Pb, will most probably evaporate in the gasifier, while the rest will be discarded to the gasifier ash. Any metals present in the gas stream will normally be cooled to 140 °C so as to condense on particles and be later removed by respective filters. This way stack emissions of heavy metals can be controlled to very low levels.[175] Not enough relative data was found specifically for pyrolysis in literature, but it can be perceived that no significant differences result when compared to gasification.

4.1.6 Other Pollutants

GHGs

Releases of CO in the atmosphere are gradually transformed into CO_2. [176] Moreover, although methane (CH_4) is expected in high oxidative conditions, such as mass burn combustion, it can be also formed in the storage bunker due to the anaerobic conditions developed during long periods of waste storage. In such cases, if the primary air is supplied from the storage bunker, the oxidation of CH_4 will produce H_2O and CO_2. Carbon dioxide (CO_2) is also produced directly from organic waste combustion,[177] as well as during the gasification[178] and pyrolysis processes at high temperatures;[179] however, emissions of CH_4 need to be monitored both in MSW gasification[180] and pyrolysis plants.[181] Control techniques aiming to reduce NO_X emissions may result in N_2O releases in the flue-gas.[182] Nitrous oxide is a clear, colorless gas with slightly sweet odor. Due to its long atmospheric lifetime (approximately 120 years) and heat trapping effects - about 310 times more powerful

[175] Faaij A. et al. (1997)

[176] EIPPCB (2006)

[177] Quina Margarida J. et al. (2011)

[178] Kwon E. et al. (2009)

[179] Conesa J.A. et al. (2008)

[180] Kwon E. et al. (2009)

[181] Conesa J.A. et al. (2008)

[182] Quina Margarida J. et al. (2011)

than CO_2 on a per molecule basis – it is considered a greenhouse gas that contributes to global climate change.[183]

$\underline{NH_3}$

Control techniques aiming to reduce NO_X emissions may also result in NH_3.[184] Ammonia is a colorless gas, soluble in the water with a distinct sharp odor widely used as fertilizer, as well as in many household cleaners and window-cleaning products.[185]

[183] USEPA[1] (2013)

[184] EIPPCB (2006)

[185] ATSDR[1] (2004)

4.2 Hazard Characterization

So far 953 agents have been studied and classified from the IARC as per their carcinogenicity (Annex II: Table 12), while research is constant and the index is steadily growing.[186] Some hazards already studied that can potentially be found in MSWI stack emissions include, but are not limited to the substances of the following list (Annex II: Table 13):[187]

- Group 1
    - 2,3,7,8-TCDD
    - 2,3,4,7,8-PeCDF
    - As and its compounds
    - Benzene
    - Cd and its compounds
    - Cr(VI) compounds
    - Formaldehyde
    - Ni compounds
- Group 2A
    - Pb compounds, inorganic
    - PCBs
- Group 2B
    - CH_3Hg^+ compounds
    - Ethylbenzene
    - Naphthalene
    - Ni, metallic and alloys
    - Pb

[186] IARC Monographs[1] (2013)

[187] IARC Monographs[2] (2013)

- Group 3
    - Cr, metallic
    - Cr(III) compounds
    - Ethylene
    - Fluorene
    - Fluorides
    - HCl
    - Hg and its inorganic compounds
    - Pb compounds, organic
    - PCDD/Fs (excluding 2,3,7,8-TCDD and 2,3,4,7,8-PeCDF)
    - Phenanthrene
    - Pyrene
    - Se and its compounds
    - SO_2
    - Toluene
    - Xylenes

Many of the aforementioned hazards have been thoroughly studied by health and environmental organizations (e.g. WHO, USEPA, ATSDR). Specific tolerable levels of exposure (e.g. MRL) have derived for those substances (Annex II: Table 14), which are further discussed in the next pages.

4.2.1 Particles

Particles are related to breathing problems.[188] Their properties depend on their size and their toxicity on the respective chemical composition. Fine particles ($PM_{2.5}$) and

[188] Becidan M. (2007)

particulate matter of even smaller size cause the greatest concern as they are capable to penetrate deep into the respiratory tract.[189]

Therefore, neither MRLs can be derived for inhalation exposure to PMs in general nor there can be any generic classification for human carginogenicity.

4.2.2 CO

CASRN: 630-08-0

It is already known that exposure to CO can lead to respiratory problems.[190] Its toxicity may affect the heart and the cardiovascular system, the central nervous system, the fetus and the neonate. Severe poisoning from CO may be life-threatening and is related to cardiac arrhythmias, myocardial ischemia, cardiac arrest, hypotension, respiratory arrests, noncardiogenic pulmonary edema, seizures and coma among other symptoms. Moderate poisoning may lead to confusion, syncope, chest pain, dyspnea, weakness, tachycardia, tachypnea and rhabdomyolysis, while mild poisoning may cause headache, nausea, vomiting, dizziness and blurred vision.

According to animal studies, exposure to CO during pregnancy may result in decreased fetal weight, adverse central nervous system development, altered peripheral nervous system development, cardiac effects, altered sexual behavior, immunological effects and hematological effects. Exposure to high levels of CO during pregnancy may result in miscarriage, while exposure to low levels may lead to developmental impairment of the child. Moreover, asthmatic children appear to be more vulnerable to respiratory effects associated with CO.[191]

No MRLs for inhalation exposure have been derived for CO and the IARC has not classified the hazard for human carginogenicity.

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[189] Quina Margarida J. et al. (2011)

[190] Becidan M. (2007)

[191] ATSDR[1] (2012)

4.2.3 Acid Gases

SO_2

CASRN: 7446-09-5

It has been reported that SO_2 affects breathing[192] as it is respiratory irritant and a bronchoconstrictor.[193] Apart from causing respiratory problems,[194] it may aggravate cardiovascular diseases.[195] Although sensitivity to SO_2 varies, exposure to SO_2 is expected to mostly affect asthmatics, people with bronchitis[196] or emphysema, children, and elderly. Emissions of sulfur in the air also contribute to aquatic acidification and visibility impairment.[197]

A minimal LOAEL of 0.1 ppm has resulted in a MRL of 0.01ppm (UF 9) derived for acute-duration (<14 days) inhalation exposure to SO_2. No cancer effects have been noted so far, but exposure to SO_2 is known to affect the immunological and respiratory organ systems.[198] The IARC has classified the hazard in Group 3 for human carginogenicity.[199]

NO_X

CASRN: 10102-43-9 (NO)

CASRN: 10102-44-0 (NO_2)

NO and NO_2 may indirectly affect health through the occurrence of acid rain[200] and other environmental problems, such as smog and eutrophication of coastal waters.[201] Acute-duration (<14 days) inhalation exposure to NO_2 may induce adverse respiratory

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[192] USEPA[2] (2013)

[193] Katsouyanni et al. (1997)

[194] Becidan M. (2007)

[195] USEPA[2] (2013)

[196] Katsouyanni et al. (1997)

[197] USEPA[2] (2013)

[198] ATSDR[1] (1998)

[199] IARC Monographs[2] (2013)

[200] Becidan M. (2007)

[201] USEPA[3] (2013)

effects including airway inflammation in healthy people and increased respiratory symptoms in people with asthma.[202]

At present, no MRLs for inhalation exposure have been derived for NO_X and the IARC has not yet classified the hazards for human carginogenicity.

Halogens

CASRN: 7647-01-0 (HCl)

CASRN: 7664-39-3 (HF)

CASNR: 10035-10-6 (HBr)

Halogens may cause severe respiratory problems.[203] While no NOAEL exists for HCl, a $LOAEL_{HEC}$ of 6.1 mg/m^3 for hyperplasia of nasal mucosa, larynx and trachea has resulted in a RfC of 0.02 mg/m^3 (UF 300) derived for chronic-duration (>365 days) exposure to HCl.[204]

Hydrogen fluoride is a colorless, fuming liquid or gas with a strong, irritating odor that readily dissolves in water to form colorless hydrofluoric acid solutions. Even though HF is not directly related to any specific cancer effects,[205] it mostly affects human health from direct contact. Noticeable effects include bronchiolar ulceration, pulmonary hemorrhage, as well as burns to the eyes and skin.Childern under the age of 8 are susceptible to dental fluorosis, but other than that it is not known yet if they are more vulnerable to hydrogen fluoride than adults.[206]

A minimal LOAEL of 0.5 ppm fluoride as hydrogen fluoride for upper respiratory tract irritation has resulted in a MRL of 0.02 ppm (UF 30) derived for acute-duration (<14 days) inhalation exposure to HF.[207] No intermediate or chronic-duration MRLs

[202] USEPA[9] (2013)

[203] Becidan M. (2007)

[204] USEPA (1995)

[205] ATSDR[1] (2003)

[206] ATSDR[2] (2003)

[207] ATSDR[1] (2003)

have been derived for HF.[208] The IARC has classified HCl in Group 3 for human carginogenicity.[209]

4.2.4 TOC

Dioxins / Furans

CASRN: 1746-01-6 (2,3,7,8-TCDD)

CASRN: 57117-31-4 (2,3,4,7,8-PeCDF)

Dioxins and furans are usually emitted in traces, [210] but they are highly toxic. In most cases, PCDD/Fs enter in the human organization through the food chain.[211] CDDs are associated with an increased risk of chloracne and hyperpigmentation, changed liver function and lipid metabolism, changes in activities of various liver enzymes, depression of the immune system, as well as endocrine -and nervous- system abnormalities. The PCDDs are potent teratogenic and fetotoxic chemicals in animals and specifically 2,3,7,8-TCDD is considered a very potent promoter of carcinogenesis for the liver of rat. There have also been reports of soft-tissue sarcomas and non-Hodkin's lymphomas occurrence in populations occupationally exposed to CDDs.[212]

2,3,7,8-TCDD is considered one of the most toxic of PCDDs and primarily affects the dermal, the developmental, the immunological and the reproductive organ systems.[213] It has been observed that 2,3,7,8-TCDD concentration in human tissue is decreasing by about a factor of 7 over a period of 25 years.[214]

A NOEL of 0.005 μg/kg and a LOAEL of 0.01 μg/kg for impaired resistance in mice have resulted in a MRL of 0.0002 (2×10^{-4}) μg/kg/day (UF 21) derived for acute-duration (<14 days) oral exposure to 2,3,7,8-TCDD. A NOAEL of 0.0007 μg/kg/day and a LOAEL of 0.005 μg/kg/day for decreased thymus weight in guinea pigs have

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[208] ATSDR[2] (2003)

[209] IARC Monographs[2] (2013)

[210] Quina Margarida J. et al. (2011)

[211] Becidan M. (2007)

[212] Quina Margarida J. et al. (2011)

[213] USEPA (2012)

[214] Hites R.A. (2011)

resulted in a MRL of 0.00002 (2×10^{-5}) μg/kg/day (UF 30) for intermediate-duration (15-364 days) oral exposure to this dioxin. A LOAEL of 1.2×10^{-4} μg/kg/day for altered social behavior in monkeys have resulted in a MRL of 0.000001 (1×10^{-6}) μg/kg/day (UF 90) for chronic-duration (>365 days) oral exposure to the same dioxin.[215] Decreased sperm count and motility in men exposed to TCDD as boys and increased TSH in neonates have also been observed after chronic-duration (>365 days) oral exposure to 2,3,7,8-TCDD.[216]

2,3,4,7,8-PeCDF affects the hepatic and the immunological organ systems and is especially harmful. A MRL of 0.001 μg/kg/day (UF 3000) for acute-duration (<14 days) oral exposure to the CDF has been set in regards to the immunological organ system and a MRL of 0.00003 μg/kg/day (UF 3000) for intermediate-duration (15-364 days) oral exposure to the 2,3,4,7,8-PeCDF has been set in regards to the hepatic organ system.[217]

2,3,7,8-TCDD and 2,3,4,7,8-PeCDF are known human carcinogens that according to IARC Monographs are classified in Group 1 for human carginogenicity. The same authority has classified other PCDD/Fs in Group 3 for human carcinogenicity.[218]

Other Organic Compounds

CASRN: 50-00-0 (Formaldehyde)

CASRN: 71-43-2 (Benzene)

CASRN: 91-20-3 (Naphthalene)

CASRN: 100-41-4 (Ethylbenzene)

CASRN: 108-88-3 (Toluene)

CASRN: 83-32-9, 120-12-7 (PAHs)

CASRN: 1330-20-7 (Xylenes)

CASRN: 1336-36-3, 11097-69-1 (PCBs)

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[215] ATSDR[2] (1998)

[216] USEPA (2012)

[217] ATSDR (1994)

[218] IARC Monographs[2] (2013)

PCBs affect the dermal, developmental, endocrine, hepatic, immunological and neurological organ systems,[219] while PAHs affect mostly the dermal, hepatic and immunological organ systems.[220]

A less serious LOAEL of 0.0075 mg/kg/day of PCBs for neurobehavioral toxicity in monkeys has resulted in a MRL of 0.03 μg/kg/day (UF 300) derived for intermediate-duration (15-364 days) oral exposure to these substances. A LOAEL of 0.005 mg/kg/day for decreased antibody response also in monkey has resulted in a MRL of 0.02 μg/kg/day (UF 300) for chronic-duration (>365 days) oral exposure to PCBs.[221]

Ethylbenzene affects the developmental and neurological organ system.[222] In high levels, it can cause eye and throat irritation, vertigo and dizziness. In animals, the auditory system is the most sensitive target. Specifically, a potentially irreversible damage to cochlear hair cells and hearing loss have been observed in rats following acute and intermediate-duration inhalation exposure and acute-duration oral exposure. Intermediate-duration oral exposure, according to animal studies, can be hepatotoxic, while inhalation exposure to high levels of ethylbenzene can lead to developmental effects, such as decreases in growth and increased skeletal variations. Children are expected to be affected by ethylbenezene poisoning as much as adults.[223]

The ATSDR has reached to a MRL of 5ppm (UF 30) derived for acute (<14 days), a MRL of 2 ppm (UF 30) for intermediate (15-364 days) and a MRL of 0.06 ppm (UF 300) for chronic-duration (>365 days) inhalation exposure to ethylbenzene. A NOAEL of 75 mg/kg/day and LOAEL of 250 mg/kg/day of ethylbenzene for hepatotoxicity, especially in males, have resulted in a MRL of 0.4 mg/kg/day (UF 30) for intermediate-duration (15-364 days) oral exposure to this substance.[224]

Acute exposure to benzene mostly affects the hematological, immunological and neurological organ systems,[225] while the adverse systemic effects of low-level chronic

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[219] ATSDR[1] (2000)

[220] ATSDR (1995)

[221] ATSDR[1] (2000)

[222] ATSDR (2010)

[223] ATSDR (2011)

[224] ATSDR (2010)

[225] ATSDR[1] (2007)

exposure to benzene are focused to the hematological system. Moreover, according to animal studies, benzene exposure may be associated with reproductive and developmental effects. At present, it is not known if children are more susceptible to benzene poisoning than adults.[226]

The ATSDR has reached to a MRL of 0.009 ppm (UF 300) derived for acute (<14 days), a MRL of 0.006 ppm (UF 300) for intermediate (15-364 days) and a MRL of 0.003 ppm (UF 10) for chronic-duration (>365 days) inhalation exposure to benzene as well as a MRL of 0.5 μg/kg/day (UF 30) derived for chronic-duration (>365 days) oral exposure to the same substance.[227]

Exposure to toluene primarily affects the cardiovascular and the neurological system. A NOAEL of 40 ppm for neurological effects in human has resulted in a MRL of 1 ppm (UF 10) for acute (<14 days), while a LOAEL of 35 ppm for alcohol - and age - adjusted color vision impairment in human has resulted in a MRL of 0.08 ppm (UF 100) for chronic-duration (>365 days) inhalation exposure to toluene. Moreover, a LOAEL of 250 mg/kg/day for neurological effects in rat has resulted in a MRL of 0.8 mg/kg/day (UF 300) for acute-duration (<14 days), while a LOAEL of 5 mg/kg/day for neurological effects in mouse has resulted in a MRL of 0.02 mg/kg/day (UF 300) intermediate-duration (15-364 days) oral exposure to toluene.[228]

Xylenes affect the nervous system by all routes of exposure, the respiratory tract by inhalation exposure, and, at higher oral exposure levels, hepatic, renal, and body weight effects. The nervous system effects include subjective symptoms of intoxication at higher concentrations and impaired performance on tests of short-term memory, reaction time and equilibrium at lower concentrations. Xylene vapors cause nose, eye and throat irritation and dermal exposure to xylene causes skin irritation, dryness and scaling of the skin, as well as vasodilation. Animal studies have shown that high concentrations of xylene may have developmental effects. Although no sufficient data is available, it is expected that children would be equally affected by exposure to xylenes as adults. However, children may be more susceptible to

[226] ATSDR[3] (2007)

[227] ATSDR[1] (2007)

[228] ATSDR[2] (2000)

respiratory impairment from inhalation exposure to xylenes than adults, because of their narrower airways.[229]

A LOAEL of 50 ppm m-xylene for slight respiratory effects and subjective symptoms of neurotoxicity in human has resulted in a MRL of 2 ppm (UF 30) for acute-duration (<14 days) inhalation exposure to xylenes. A minimal LOAEL of 50 ppm for statistically significant decrease in the mean latency of the paw-lick response in rat has resulted in a MRL of 0.6 ppm (UF 90) for intermediate (15-364 days), while a LOAEL of 14 ppm for subjective symptoms of neurotoxicity, respiratory toxicity and eye irritation has resulted in a MRL of 0.05 ppm (UF 300) for chronic-duration (>365 days) inhalation exposure to the xylenes. In regards to oral exposure to xylenes, a NOAEL of 125 mg/kg/day for alteration of visual evoked potentials in rats has resulted in a MRL of 1 mg/kg/day (UF 100) for acute (<14 days) and a NOAEL of 500 mg/kg/day for hyperactivity in both male and female mice ($NOAEL_{ADJ}$: 360 mg/kg/day) has resulted in a MRL of 0.4 mg/kg/day (UF 1000) for intermediate-duration exposure. A NOAEL of 250 mg/kg/day ($NOAEL_{ADJ}$: 179 mg/kg/day) for neurological effects in rat has resulted in a MRL of 0.2 mg/kg/day (UF 1000) for chronic-duration of oral exposure to xylenes.[230]

Naphthalene affects the hematological, hepatic, neurological, ocular and the respiratory organ systems. A LOAEL in both sexes of rats of 10 ppm for nonneoplastic lesions in nasal olfactory epithelium and respiratory epithelium has resulted in a MRL of 0.0007 ppm (UF 30) for chronic-duration (>365 days) inhalation exposure to the agent. A minimal LOAEL of 50 mg/kg/day for transient clinical signs of toxicity in pregnant rat dams has resulted in a MRL of 0.6 mg/kg/day (UF 90) for acute (<14 days) and intermediate-duration (15-364 days) oral exposure to naphthalene.[231]

Formaldehyde causes acute eye burning and irritates mucous membranes as well as the respiratory tract.[232] Exposure to formaldehyde may affect the dermal, gastrointestinal, immunological and the respiratory organ systems. A minimal

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[229] ATSDR[4] (2007)

[230] ATSDR[2] (2007)

[231] ATSDR[1] (2005)

[232] USEPA[5] (2013)

LOAEL of 0.4 ppm for nasal and eye irritation in human has resulted in a MRL of 0.04 ppm (UF 9) for acute-duration (<14 days), while a NOAEL of 0.98 ppm and a LOAEL of 2.95 ppm for nasopharyngeal irritation and lesions in nasal epithelium in cynomolgus monkey have resulted in a MRL of 0.03 ppm (UF 30) for intermediate-duration (15-364 days) inhalation exposure to formaldehyde. In addition, a minimal LOAEL of 0.24 ppm for clinical symptoms of mild irritation of the eyes and upper respiratory tract as well as of mild damage to the nasal epithelium have resulted in a MRL of 0.008 ppm (UF 30) for chronic-duration (>365 days) inhalation exposure to the agent. A NOAEL of 25 mg/kg/day for gastrointestinal effects in rats has resulted in a MRL of 0.3 mg/kg/day (UF 100) for intermediate-duration (15-364 days) oral exposure, while a NOAEL of 15 mg/kg/day for gastrointestinal effects in male rats has resulted in a MRL of 0.2 mg/kg/day (UF 100) for chronic-duration (>365 days) oral exposure to formaldehyde.[233]

As PCBs are reasonably anticipated to be human carcinogens,[234] the IARC has classified them in Group a 2A for human carcinogenicity. PAHS are also reasonably anticipated to be human carcinogens and as such some of them have already been classified by the IARC, including benzene,[235] which is associated with leukemia and especially acute myelogenic leukemia,[236] and formaldehyde in Group 1, ethylbenzene and naphthalene in Group 2B, as well as ethylene, fluorene, phenanthrene, pyrene, toluene and xylenes in Group 3.[237]

[233] ATSDR[1] (1999)

[234] ATSDR[1] (2000)

[235] IARC Monographs[2] (2013)

[236] ATSDR[3] (2007)

[237] IARC Monographs[2] (2013)

4.2.5 Heavy Metals

CASRN: 7439-92-1 (Pb)

CASRN: 7439-97-6 (Hg)

CASRN: 7440-02-0 (Ni)

CASRN: 7440-38-2 (As)

CASRN: 7440-43-9 (Cd)

CASRN: 7440-47-3 (Cr)

CASRN: 7782-49-2 (Se)

Heavy metals are health hazards[238] strongly associated with carcinogenicity. In addition, they may provoke respiratory damages.[239]

Arsenic affects the dermal, gastrointestinal, hepatic, neurological and respiratory organ systems.[240] According to ATSDR:

> *'Inhalation of inorganic arsenic may cause respiratory irritation, nausea, skin effects and increased risk of lung cancer, while acute high dose oral exposure to inorganic arsenic may cause nausea, vomiting, diarrhea, cardiovascular effects and encephalopathy. Long term oral exposure to low levels of inorganic arsenic may cause dermal effects (such as hyperpigmentation and hyperkeratosis, corns and warts) and peripheral neuropathy characterized by a numbness in the hands and feet that may progress to a painful "pins and needles" sensation. There may also be an increased risk of skin cancer, bladder cancer and lung cancer etc.'* [241]

[238] Becidan M. (2007)

[239] Quina Margarida J. et al. (2011)

[240] ATSDR[6] (2007)

[241] ATSDR[5] (2007)

Inorganic As in children is less efficiently metabolized than in adults. When children are exposed to high levels of arsenic, it is expected to exhibit similar symptoms to those seen in adults.[242]

A LOAEL of 0.05 mg/kg/day for gastrointestinal effects in human has resulted in a MRL of 0.005 mg/kg/day (UF 10) for acute-duration (<14 days) oral exposure, while a NOAEL of 0.0008 mg/kg/day for dermal effects in human has resulted in a MRL of 0.3 μg/kg/day (UF 3) for chronic-duration (>365 days) oral exposure to As.[243]

Cadmium can potentially affect the cardiovascular, neurological, renal, reproductive and respiratory organ systems.[244] Cadmium poisoning following oral exposure primarily affects the kidney and bone, while following inhalation exposure, it affects the kidney and lung. Observed effects from long term exposure include renal tubular damage, glomerular damage, decreases in bone mineralization, increased risk of bone fractures, decreased lung function and emphysema. These effects typically occur after long term exposure to cadmium.There are also reports of increased risk of lung cancer for population occupationally exposed to Cd. Children and adults are most likely effected the same way. However, provided that Cd is a cumulative toxin with a very long half-time in the body, exposure to children in even low amounts may have long-term consequences. Moreover, animal studies suggest that children may be more susceptible on Cd-induced bone damage than adults, as well as that Cd causes decreases in fetal or pup body weight, skeletal malformations and behavioral alterations.[245]

A LOAEL of 0.088 mg/m^3 for affecting the respiratory organ system in rats resulted in a MRL of 0.03 μg/m^3 (UF 300) for acute-duration (<14 days) inhalation exposure, while a MRL of 0.01 μg/m^3 (UF 9) has also derived for chronic-duration (>365 days) inhalation exposure to Cd after some renal effects in human. Musculoskeletal organ system effects in rat have resulted in a MRL of 0.5 μg/kg/day (UF 100) for intermediate-duration (15-364 days) oral exposure and renal organ system effects in

[242] ATSDR[5] (2007)

[243] ATSDR[6] (2007)

[244] ATSDR[3] (2012)

[245] ATSDR[2] (2012)

human resulted in a MRL of 0.1 μg/kg/day (UF 3) for chronic-duration (>365 days) oral exposure to this substance.[246]

Exposure to Cr can affect the immunological and respiratory organ systems.[247] It is known that compounds of Cr(VI) are more toxic than compounds of Cr(III). Primary targets of Cr(VI) are the respiratory, gastrointestinal, hematological and reproductive organ systems, while the primary targets of Cr(III) compounds are the respiratory and immunological organ systems. At present, it remains unknown whether children are more vulnerable to Cr poisoning than adults, but animal studies indicate that Cr(VI) causes miscarriages, low birth weight and changes in development of skeleton and reproductive system. These developmental effects may be partly related to maternal Cr toxicity.[248]

A LOAEL of 0.002 mg/m^3 Cr(VI) aerosol and mists for nasal irritation, mucosal atrophy and other effects on the respiratory organ system in human have resulted in a MRL of 5×10^{-6} mg/m^3 (UF 100) for intermediate (15-364 days) and chronic-duration (>365 days) inhalation exposure to Cr(VI). Observed alterations in lactate dehydrogenase levels in bronchoalveolar lavage in rats after exposure to Cr(VI) PMs have resulted in a MRL of 0.3 $\mu g/m^3$ (UF 30) for intermediate-duration (15-364 days) inhalation exposure to Cr(VI) particulates. Microcytic and hypochromic anemia in rats after exposure to Cr(VI) has resulted in a MRL of 0.005 mg/kg/day (UF 100) for intermediate-duration (15-364 days) oral exposure, while the occurrence of diffuse epithelial hyperplasia of the duodenum in mice has resulted in a MRL of 0.9 μg/kg/day (UF 100) for chronic-duration (>365 days) oral exposure to Cr(VI).

In regards to Cr(III), a LOAEL of 3 mg/m^3 ($LOAEL_{ADJ}$: 0.54 mg/m^3, $LOAEL_{HEC}$: 0.43 mg/m^3) insoluble Cr(III) PMs for trace-to-mild septal cell hyperplasia in rats and chronic interstitial inflammation of the lung have resulted in a MRL of 0.005 mg/m^3 (UF 30) for intermediate-duration (14-364 days) inhalation exposure to this agent. Moreover, a LOAEL of 3 mg/m^3 ($LOAEL_{ADJ}$: 0.54 mg/m^r, $LOAEL_{HEC}$: 0.04 mg/m^3) soluble Cr(III) PMs for nasal and larynx lesions in rats has resulted in a MRL of 0.1

[246] ATSDR[3] (2012)

[247] ATSDR[5] (2012)

[248] ATSDR[4] (2012)

μg/m^3 (UF 300) for intermediate-duration (15-364 days) inhalation exposure to these substances.[249]

Lead is hazardous to health if breathed or swallowed,[250] which can bioaccumulate in fish and wildlife.[251] Exposure to Pb may affect the cardiovascular, developmental, gastrointestinal, hematological, musculoskeletal, neurological, ocular, renal and reproductive organ systems.[252] Although MRLs have not been derived for Pb, because a clear threshold for some of the more sensitive effects in humans has not been identified, the ATSDR has developed an advisory framework based on blood lead levels (PbBs).[253] These are presented in short as follows:

- PbB <10 μg/dL may affect the hematological (decreased activity of several heme biosynthesis enzymes), the cardiovascular (elevated blood pressure) and the neurological (cognitive and neurobehavioral effects in children) organ system,
- PbB <20 μg/dL may affect the renal (decreased glomerular filtration) organ system,
- PbB 40 μg/dL may affect the neurological (peripheral neuropathy) organ system,
- PbB >40 μg/dL may affect the reproductive (reduced fertility) organ system,
- PbB 40-80 μg/dL may affect the neurological (neurobehavioral and neuropsychological effects in adults) organ system,
- PbB 60-100 μg/dL may affect the gastrointestinal (colic in children) organ system and
- PbB 70–100 μg/dL (children) and 100-120 μg/dL (adults) may affect the neurological (encephalopathy) organ system.

[249] ATSDR[5] (2012)

[250] USEPA[8] (2013)

[251] USEPA[7] (2013)

[252] ATSDR[8] (2007)

[253] ATSDR[7] (2007)

It is already known that children are more vulnerable to lead effects than adults. Lead exposure during infancy or childhood may result in various symptoms, such as anemia, renal alterations, colic, impaired metabolism of vitamin, delays or impairment of neurological development, neurobehavioral deficits including IQ deficits, low birth weight, low gestational age, growth retardation, and delayed sexual maturation in girls. A diet that is nutritionally adequate in Ca and Fe may decrease the absorbed dose of Pb.[254] Use of Pb in several products has been sharply restricted or eliminated by respective laws and regulations.[255]

Mercury may affect the developmental, gastrointestinal, neurological, ocular and renal organ systems depending on the route of exposure. A LOAEL of 0.026 mg/m^3 for increased frequency of tremors in human has resulted in a MRL of 0.2 $\mu g/m^3$ (UF 30) derived for chronic-duration (>365 days) inhalation exposure to Hg vapors. A NOAEL of 0.93 mg/kg/day for no renal effects in rats has resulted in a MRL (UF 100) of 0.007 mg/kg/day for acute-duration (<14 days) oral exposure, while a NOAEL of 0.23 mg/kg/day for no renal effects in rats has resulted in a MRL of 0.002 mg/kg/day (UF 100) for intermediate-duration (15-364 days) oral exposure to inorganic Hg (mercuric chloride). In addition, a NOAEL of 0.0013 mg/kg/day CH_3Hg^+ no developmental effects in human has resulted in a MRL of 0.3 μg/kg/day (UF 4.5) derived for chronic-duration (>365 days) oral exposure in such compounds.[256]

Nickel may affect the cardiovascular, dermal, immunological and respiratory organ systems depending on the route of exposure.[257] Lung inflammation is the predominant noncancerous respiratory effect related to Ni exposure. The toxicity of nickel in the respiratory tract depends on the Ni compounds' solubility; soluble compounds are the most toxic and may cause atrophy of the nasal epithelium. Studies on rats exposed to Ni in drinking water indicate also decreased survival as a potential impact. At present,

[254] ATSDR[7] (2007)

[255] USEPA[8] (2013)

[256] ATSDR[2] (1999)

[257] ATSDR[3] (2005)

it remains unknown whether children are more susceptible to Ni poisoning than adults.[258]

A NOAEL of 0.06 mg/m^3 for chronic active inflammation in rats has resulted in a MRL of 0.2 μg/m^3 (UF 30) for intermediate-duration (15-364 days) inhalation exposure and a NOAEL of 0.03 mg/m^3 for chronic active inflammation and lung fibrosis in rats has resulted in a MRL of 0.09 μg/m^3 (UF 30) for chronic-duration (>365 days) inhalation exposure to Ni.[259]

Exposure to Se may affect the dermal, developmental and reproductive organ systems.[260] More specifically, short-term inhalation exposure to high levels of elemental Se or SeO_2 in the air can induce respiratory tract irritation, bronchitis, difficulty breathing and stomach pain, while longer-term exposure to either of these forms can cause respiratory irritation, bronchial spasms and coughing. Short-term oral exposure to high concentrations of Se may cause nausea, vomiting and diarrhea, while long-term oral exposure to high concentrations of Se can cause selenosis, a disease characterized by hair loss and brittle nails. In addition, according to some animal studies, exposure to extremely high doses of Se may cause neurological abnormalities ranging from unsteady gait to partial paralysis. Selenium has also been found in placental tissue, umbilical cord blood, fetal tissues and breast milk.[261] A NOAEL of 0.015 mg/kg/day for nail disease (selenosis) in human has resulted in a MRL 0.005 mg/kg/day (UF 3) for chronic-duration (>365 days) of oral exposure to elemental Se.[262]

The IARC has classified several heavy metals for their carcinogenicity, including As (and its inorganic compounds), Cd (and its compounds), Cr(IV) compounds and Ni compounds in Group 1, inorganic Pb compounds in Group 2A, CH_3Hg^+ compounds, Pb and Ni in Group 2B, as well as Cr (and Cr(III) compounds), organic Pb

[258] ATSDR[2] (2005)

[259] ATSDR[3] (2005)

[260] ATSDR[4] (2003)

[261] ATSDR[3] (2003)

[262] ATSDR[4] (2003)

compounds, Hg (and its inorganic compounds) and Se (and its compounds) in Group 3.[263]

4.2.6 Other Pollutants

GHGs

CASRN: 74-82-8 (CH_4)

CASRN: 124-38-9 (CO_2)

CASRN: 10024-97-2 (N_2O)

Methane and CO_2 are not toxic, but they are both known asphyxiants. Although CH_4 is not harmful in low concentrations, when in high concentrations, it can displace oxygen in the air inducing various symptoms, such as rapid breathing, rapid heart rate, clumsiness, emotional upsets and fatigue. In even higher concentrations, it may cause nausea and vomiting, collapse, convulsions, coma and in some occasions death.[264] Exposure to N_2O may decrease mental performance, audiovisual ability and manual dexterity, while animal studies indicate it may also cause adverse reproductive effects. Studies of workers exposed to N_2O have reported adverse health effects, such as reduced fertility, spontaneous abortion, as well as neurological, renal and liver disease.[265]

No MRLs for inhalation exposure have been derived for any of these substances and the IARC has not classified these hazards for human carginogenicity.

NH_3

CASRN: 7664-41-7

Exposure to NH_3 may affect the dermal, ocular and respiratory organ systems.[266] It is an upper respiratory irritant in humans causing immediate irritation to the nose and throat upon exposure. Acute exposure to NH_3 gas can lead to human death due to

[263] IARC Monographs[2] (2013)

[264] CCOHS (2013)

[265] DHHS – NIOSH (2013)

[266] ATSDR[1] (2004)

airway obstruction or infections and other secondary complications. The skin is also extremely sensitive to both airborne NH_3 and NH_3 dissolved in water, thus exposure can produce cutaneous burns, blisters, and lesions. Exposure of children to NH_3 is expected to have similar effects to those of adults.[267]

A LOAEL of 50 ppm for mild irritation to the eyes, nose and throat in human has resulted in a MRL of 1.7 ppm (UF 30) for acute-duration inhalation exposure, while a NOAEL of 9.2 ppm for no significant alterations in lung function in human has resulted in a MRL of 0.1 ppm (UF 30) for chronic-duration inhalation exposure in NH_3.[268]

The IARC has not yet classified NH_3 for human carginogenicity.

[267] ATSDR[2] (2004)

[268] ATSDR[1] (2004)

4.3 Exposure Assessment

As already mentioned in Chapter 1.1, the conurbation of Athens generates ~3,500 tons/day or ~1,274,000 tons/year of waste, which are composed by 40% kitchen and garden waste, 29% paper and card, 14% plastic, 3% glass, 3% metals, 3% inerts, 2 % leather, wood, textiles, rubber and 6% other materials (Annex II: Table 2).[269] Density of Athenian MSW has been estimated to ~200.43 kg/m^3 or ~0.2 tons/m^3 (Annex II: Table 15). Conversion of waste measurement from tons/day to m^3/day, by multiplying the generated amounts of MSW with the density price, results to ~700 m^3/day or 254,800 m^3/year wastes generated in Athens.

According to EU provisions, in year 2013, almost 20% of wastes should be incinerated[270] so as to meet the European Landfill Directive target set[271] for member countries, including Greece. Taking this parameter in account, ~140 m^3/day or ~50,960 m^3/year of Athens MSW may have to be incinerated in the direct future. Provided that an incineration plant functions almost 24h per day[272] for an average of 312.5 days per year,[273] the amount of at least ~140 m^3/day of MSW incinerated needs to adjust to the incinerator's maintenance schedule, thus resulting to the incineration of at least ~163.5 m^3/day (140*365/312.5) of MSW generated from the conurbation's inhabitants.

The WID has regulated legal limits for MSWI emissions (Annex II: Table 16) as follows:

- For Particles: 10 mg/m^3
- For CO: 50 mg/m^3
- For TOC: 10 mg/m^3
- For HCl: 10 mg/m^3

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[269] Papageorgiou A. et. al. (2009)

[270] EEA (2011), Data and maps – Maps and graphs: Trends and outlook for management of municipal waste in the EU-27 (excluding Cyprus) plus Norway and Switzerland, baseline scenario.

[271] EEA (2011), Data and maps – Maps and graphs: Biodegradable municipal waste landfilled in 2006 (% of biodegradable municipal waste generated in 1995), compared to targets of the European Landfill Directive.

[272] EIPPCB (2006)

[273] The World Bank (1999)

- For HF: 1 mg/m^3
- For SO_2: 50 mg/m^3
- For NO_X: 200 mg/m^3

  (95% NO, 5% NO_2)
- For Hg: 0.05 mg/m^3
- For Cd and Tl: 0.05 mg/m^3
- For other heavy metals: 0.5 mg/m^3
- For PCDD/Fs: 0.1 ng I-TEQ/m^3

Provided that incineration plants comply with the limits set by the WID, the magnitude of contamination from MSWI in Athens (Annex II: Table 17) can be estimated to:

• Particles:	1635 mg/day	or	509,600 mg/year
• CO:	8175 mg/day	or	2,548,000 mg/year
• TOC:	1635 mg/day	or	509,600 mg/year
• HCl:	1635 mg/day	or	509,600 mg/year
• HF:	16.35 mg/day	or	50,960 mg/year
• SO_2:	8175 mg/day	or	2,548,000 mg/year
• NO_X: (95% NO, 5% NO_2)	32700 mg/day	or	10,192,000 mg/year
• Hg:	8.175 mg/day	or	2,548 mg/year
• Cd and Tl:	8.175 mg/day	or	2,548 mg/year
• Other heavy metals:	81.75 mg/day	or	25,480 mg/year
• PCDD/Fs:	16.35 ng I-TEQ/day	or	5,096 ng I-TEQ/year

It is important to be mentioned that incineration hazards may be carcinogenic or noncarcinogenic toxic substances and when inhalation exposure above MRLs occurs, there is considerable risk of severe toxicity of the respiratory, immunological, renal

and neurologic organ systems. Oral exposure to hazard concentrations above MRLs can be harmful to almost every human organ system (Annex II: Table 14).

Light and very small particulate matter, such as fine particles ($PM_{2.5}$) and particles of even smaller size, tend to persist in the atmosphere for long periods travelling long distances. Heavy metals and PCDD/Fs can be spread in the surroundings of the plant, thus the health of nearby population may be adversely affected by the carcinogenic and noncarcinogenic compounds.[274] Moreover, legal limits for emissions of CH_4, NH_3, N_2O, benz(a)pyrene, PAHs and PCBs are not included in WID.[275]

Even though environmental health risks may derive from a volume of improperly cleaned stack gases, most hazards are under constant regulatory observation. In addition, according to some very specific studies (see Chapter 5, in Quina Margarida J. et al., 2011), it has been concluded that modern MSW incinerators cannot be associated with relevant health problems, as well as that the health risk of incineration is not higher than that of landfilling. However, there is also suggested that there is some potential in further lowering emission limits, if overall incineration costs permit.[276]

[274] Quina Margarida J. et al. (2011)

[275] EPD BC – Stantec Consulting Ltd. (2011)

[276] Quina Margarida J. et al. (2011)

4.4 Risk Characterization

Most recent bibliography deriving from acknowledged scientific authorities and individual researchers has been used for the health assessment of MSWI in Athens, thus achieving a satisfactory level of overall quality of the data used throughout the project. However, it has been noticed that waste ATT technologies, excluding conventional gasification, have not been thoroughly studied as of yet. Therefore, available data for ATT technologies, such as pyrolysis and plasma arc practices, is scarce and the quality of data used requires further scientific verification. In cases where provided data has not been addressed separately for each technology, sometimes a necessity due to absence of available sources or because of information not in accordance to the selection criteria set in Chapter 3, it has been assumed that all technologies behave in a similar way. In regards to the MRLs derived for hazards, it needs to be noted that some of them are based to animal studies, as well as that they are accompanied by an uncertainty factor (UF). The WID's legal limits have been used to determine the magnitude of exposure, under the assumption that no incineration plant will ever violate regulated limits, thus no concentrations of hazards will exceed the legal maximum prices.

The health risk of MSWI with energy recovery in Athens greatly depends on the incineration technology used and the efficiency of air pollution control (APC) practices. Provided that ATT are preferred to conventional combustion technologies and the APC measures are effective, the health impact of the activity can be significantly reduced. However, it must be noted that the health risk also depends on various other parameters, such as local meteorological conditions, staff specialization, stakeholders' engagement and the incineration plant's location.

In addition, the environmental aspect of waste incineration, which has been excluded of the present study, needs to be investigated prior to investment on this section. Incineration appears to significantly contribute on environmental effects with an impact on public health, such as the climate change, global warming, acid rain and more. Moreover, it is important to be noted that the project has been limited to examining air contamination through stack emissions, while other contamination sources, such as the disposal of ash residues, have been excluded.

In conclusion, incineration of MSW may release carcinogenic and noncarcinogenic health hazards through the stack and pose a threat to public health, if not all necessary precautionary measures, as they will be described by an integrated risk management study, have been taken to properly control and monitor emissions. In case of exposure above MRLs almost every organ system can be harmed, when the most vulnerable appears to be the respiratory.

5. Discussion

Incineration of MSW with energy recovery is considered to be an environmental solution, especially when dealing with the rising problem of landfilling, because it bears the significant advantage of reducing dependence on conventional energy production practices. Although this perception may be partly accurate, it must be noted that there should be no confusion as per the activity's dimension of public health. Incinerators are complex and potentially hazardous installations where simple malfunctions can mean disastrous consequences for public health. Investment on the latest technology, careful planning and constant monitoring provide some assurances, but these are not always enough for a successful model's implication.

Filters, catalysts and other APC measures can ensure air emissions are within the WID's set limits; site location may deal with the Nimby issues; however, the human parameter appears to be critical for safe MSWI and education is the only way to deal with it. Educated staff and alerted citizens can cooperate for a successful model of waste incineration and so further ensure that every harmful aspect of MSWI has been investigated. Therefore, public deliberation and engagement of the stakeholders are deemed necessary for efficient risk management.

Lastly, it must be underlined the importance of developing a dispersion model for stack emissions specifically for Athens so as to better estimate the hazard concentrations from the source to the receptor and be included in any future integrated risk assessment project.

6. Conclusions

The technologies of municipal solid waste incineration addressed in this study, more specifically the conventional combustion, gasification and pyrolysis, will most probably emit different quantities of the same hazards, including particulate matter, carbon oxides, acid gases, total organic compounds, heavy metals and other.

The advanced thermal treatment technologies of gasification and pyrolysis appear to be somewhat cleaner solutions in terms of total hazard emissions, but health risk associated with exposure to heavy metals, polycyclic aromatic hydrocarbons and other volatile organic compounds provides some reasons of concern. Gasification can also be associated with increased nitrogen oxides releases. Conventional combustion is already associated with many known carcinogenic and noncarcinogenic health hazards, such as dioxins and furans. Temperature and the amount of oxygen used in incineration practice is the major reason behind the noticed emission diversity in stack releases.

Despite the various hazards in stack emissions, relevant studies have suggested that no significant health risks exist, when the waste incineration directive's legal limits are respected and the appropriate air pollution control measures have been implemented. Emission legal limits can be revised so as to be more consistent to new scientific developments on health hazards.

In the case of Athens, incineration appears to be a costly, potentially hazardous, but quite effective - in terms of waste reduction - solution to landfilling problems. Health risks of severe air contamination can not be ruled out with absolute confidence, but they will have to be reassessed after the incinerator's location in the conurbation has been specified.

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USEPA[1] (2013), *Greening EPA Glossary*, (http://www.epa.gov/oaintrnt/glossary.htm#p , last access 19/2/2013)

USEPA[2] (2013), *Terminology Services: Vocabulary Catalog List Detail - Green Power Partnership Glossary (Sulfur Dioxide),* (http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details=&glossaryName=GPP%20Glossary , last access 17/2/2013)

USEPA[3] (2013), *Terminology Services: Vocabulary Catalog List Detail - Acid Rain Glossary (Nitrogen Oxides),* (http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details=&glossaryName=Acid%20Rain%20Glossary , last access 17/2/2013)

USEPA[4] (2013), *Terminology Services: Vocabulary Catalog List Detail - Region 5 Cleanup Sites Glossary (Polychlorinated Biphenyls),* (http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details= , last access 17/2/2013)

USEPA[5] (2013), *Terminology Services: Vocabulary Catalog List Detail - Indoor Air Quality Glossary (Formaldehyde),* (http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details= , last access 17/2/2013)

USEPA[6] (2013), *Terminology Services: Vocabulary Catalog List Detail – Clean Energy Glossary (Arsenic),* (http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details=&glossaryName=Clean%20Energy%20Glossary , last access 18/2/2013)

USEPA[7] (2013), *Terminology Services: Vocabulary Catalog List Detail – Lake Erie Lakewide Management Plan (LaMP) Glossary (Lead),* (http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details= , last access 18/2/2013)

USEPA[8] (2013), *Terminology Services: Vocabulary Catalog List Detail – Terms of Environment (Lead),* (http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details= , last access 18/2/2013)

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(http://www.epa.gov/air/nitrogenoxides/health.html , last access 18/2/2013)

Glossary

Symbols

~	More or less approximately
2,3,7,8-TCDD	2,3,7,8-tetrachlorodibenzo-*p*-dioxin
2,3,4,7,8-PeCDF	2,3,4,7,8-pentachlorodibenzofuran

A

Ar	Argon
As	Arsenic
APC	Air Pollution Control
ATSDR	Agency for Toxic Substances and Disease Registry (United States)
ATT	Advanced Thermal Treatment

B

BAT	Best Available Technique
BCR	Benefit-Cost Ratio
BTX	Benzene, Toluene, Xylene; refers to mixtures of benzene, toluene, and the three xylene isomers (p-, m-, o- xylene)

C

C	Carbon
CAC	Codex Alimentarius Commission
CASRN	Chemical Abstract Service Registry Number
Cd	Cadmium
CDD(s)	Chlorinated Dibenzodioxin(s)
CDF(s)	Chlorinated Dibenzofuran(s)
CHP	Combined Heat and Power

CH_3Hg^+	Methylmercury; else $MeHg^+$
CH_4	Methane
Cl-	Chloride Ion
CO	Carbon Monoxide
Co	Cobalt
Cr	Chromium
Cu	Copper

D

dB(A)	Decibels (A-weighted)
DEFRA	Department for Environment, Food and Rural Affairs (United Kingdom)
DHHS	Department of Health and Human Services (United States)
DOC	Degradable Organic Carbon

E

EC	European Commission
EEA	European Environment Agency
EIPPCB	European Integrated Pollution Prevention and Control Bureau
EPD BC	Environmental Protection Division - Government of British Columbia
EU	European Union

F

G

GHG(s)	Greenhouse Gas(es), CO_2, CH_4, N_2O

H

HC	Hydrocarbons
HCl	Hydrogen Chloride
HF	Hydrogen Fluoride
Hf	Hafnium
Hg	Mercury
HPA	Health Protection Agency
HPS	Health Protection Scotland

I

IBA	Incineration Bottom Ash
IRIS	Integrated Risk Information System

J

K

L

LOAEL	Lowest Observed Adverse Effect Level
$LOAEL_{ADJ}$	LOAEL adjusted to continuous exposure duration from an intermittent regimen by hour/day and days/7 days
$LOAEL_{HEC}$	LOAEL adjusted for dosimetric differences across species to a human equivalent concentration
LULU(s)	Locally Undesirable Land Use(s)

M

Mn	Manganese
MRL(s)	Minimal Risk Level(s)

MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incineration

N

N	Nitrogen
NCV	Net Calorific Value
NH_3	Ammonia
NHL	Non-Hodgkin's Lymphoma
Ni	Nickel
Nimby	Not-in-my-backyard
NIOSH	National Institute for Occupational Safety and Health (United States)
Nm^3	Normal cubic meter (at 0 °C and 1 atm)
NO_X	Nitrogen Oxides, NO / NO_2
NOAEL	No Observed Adverse Effect Level
N_2O	Nitrous Oxide
NRC	National Research Council
NSSG	National Statistical Service of Greece

O

P

P	Phosphorus
PAH(s)	Polycyclic Aromatic Hydrocarbon(s)
Pb	Lead
PbB(s)	Blood Lead Level(s)
PCB(s)	Poly-Chlorinated Biphenyl(s)

P/CCRARM	Presidential / Congressional Commission on Risk Assessment and Risk Management
PCDD/F	Polychlorinated Dibenzodioxin and Polychlorinated Dibenzofuran
PCDD(s)	Polychlorinated Dibenzodioxin(s)
PCDF(s)	Polychlorinated Dibenzofuran(s)
PM(s)	Particulate Matter(s)
POP(s)	Persistent Organic Polutant(s)
PPP(s)	Public Private Partnership(s)

Q

R

RfD	Oral Reference Dose
RfC	Inhalation Reference Concentration

S

Sb	Antimony
Se	Selenium
SEPA	Scottish Environment Protection Agency
Sn	Tin
SO_X	Sulfur Oxides
SO_2	Sulfur Dioxide
SO_4^{2-}	Sulfate Ion
STS	Soft Tissue Sarcoma

T

Tl	Thallium
TOC	Total Organic Carbon

U

UBA	German Federal Environment Agency (Umweltbundesamt)
UF	Uncertainty Factor
UNEP	United Nations Environment Programme
US-EPA	United States Environmental Protection Agency

V

V	Vanadium
VOC(s)	Volatile Organic Compound(s)

W

WID	Waste Incineration Directive
WHO	World Health Organization
WTE	Waste-to-Energy

X

Y

Z

Zn	Zinc

Annexes

Annex I: Incineration Technologies

Options of Different Technologies

The thermal treatment technologies which are examined in this study include both combustion (in conditions of excess air) and non-combustion (in starved air conditions) processes; specifically, the widely encountered mass burn incineration (conventional combustion),[277] gasification and pyrolysis techniques.[278] The main difference between conventional combustion and advanced thermal treatment technologies is the amount of air present in the incineration process, as well as the timing of gas cleaning in the processes' sequence (Figures 9 & 10).

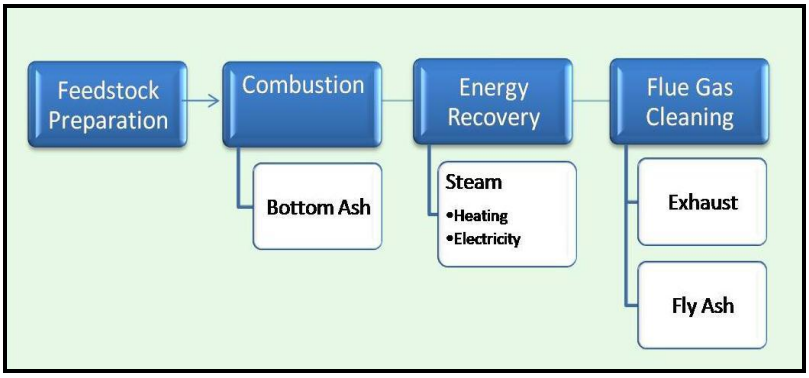

Figure 9. Conventional WTE Incineration[279]

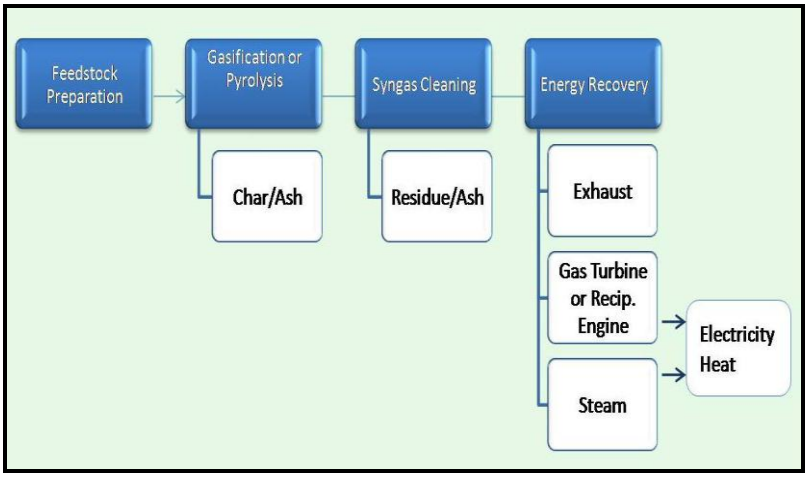

Figure 10. Advanced Thermal Treatment WTE[280]

Gasification and pyrolysis are considered *Advanced Thermal Treatment* (ATT) technologies that use high temperatures to process waste and require less oxygen than

[277] EPD BC – Stantec Consulting Ltd. (2011)

[278] EIPPCB (2006)

[279] EPD BC – Stantec Consulting Ltd. (2011)

[280] Ibid.

conventional mass burn incineration,[281] since the only air required in these technologies is used by the engines.[282] The volume of exhaust gas sent for cleaning in ATT technologies is lower than in conventional incineration, resulting in considerably reduced emissions.[283] Gasification refers to the partial oxidation of waste and as such it can be seen as an option between pyrolysis and mass combustion (Figure 11).[284]

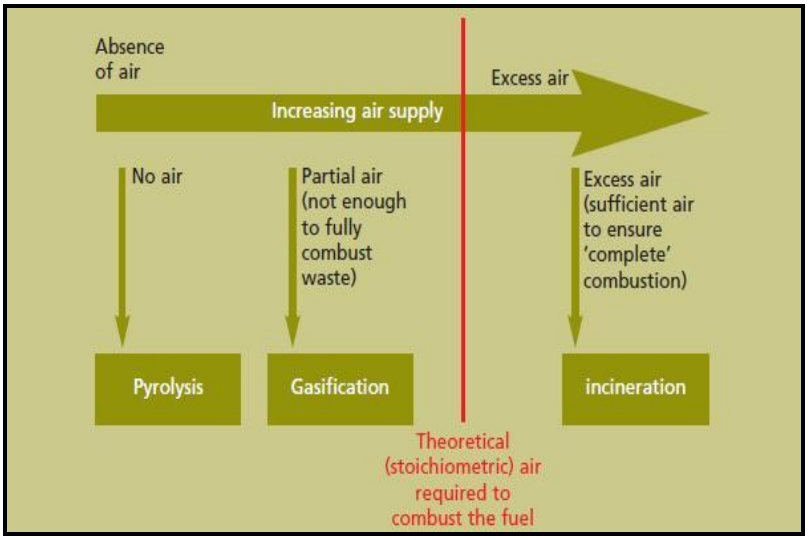

Figure 11. Air Requirement for Relative MSWI Processes[285]

The plasma arc technologies are not addressed in the present study because of their high capital and operational costs, which make them 'not commercially proven'.[286] Other processes, based on gasplasma, thermal cracking, thermal oxidation and waste-to-fuels technologies are also unaddressed since they are still considered as emerging and scientific knowledge on their impacts remains limited.[287]

Combustion (Mass Burn)

Energy recovery from conventional combustion is more efficient than from gasification or pyrolysis.[288] Mass burn is the most frequently applied MSWI technique

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[281] DEFRA[1] (2007)

[282] Smith A. et al. (2001)

[283] Ibid.

[284] DEFRA[2] (2007)

[285] Ibid.

[286] EPD BC – Stantec Consulting Ltd. (2011)

[287] Ibid.

[288] DEFRA[2] (2007)

and refers to a *full oxidative combustion process*[289] of unprepared MSW. It usually takes place on a moving grate[290] and less often on rotary kilns,[291] regularly in temperatures between 850-1200 °C,[292] during which combustible materials are mostly converted into carbon dioxide and water.[293] Incinerator bottom ash (IBA) is consisted of remaining materials and contains some residual carbon.[294] Conventional combustion's typical throughput ranges between 120-720 tons/day.[295] The generic processes of mass burn can be summarized to waste preparation, combustion and gas cleaning, while residue and ash handling is an important aspect to be considered in an efficient system. A more detailed overview of the aforementioned processes is presented schematically in the following flow diagram (Figure 12).

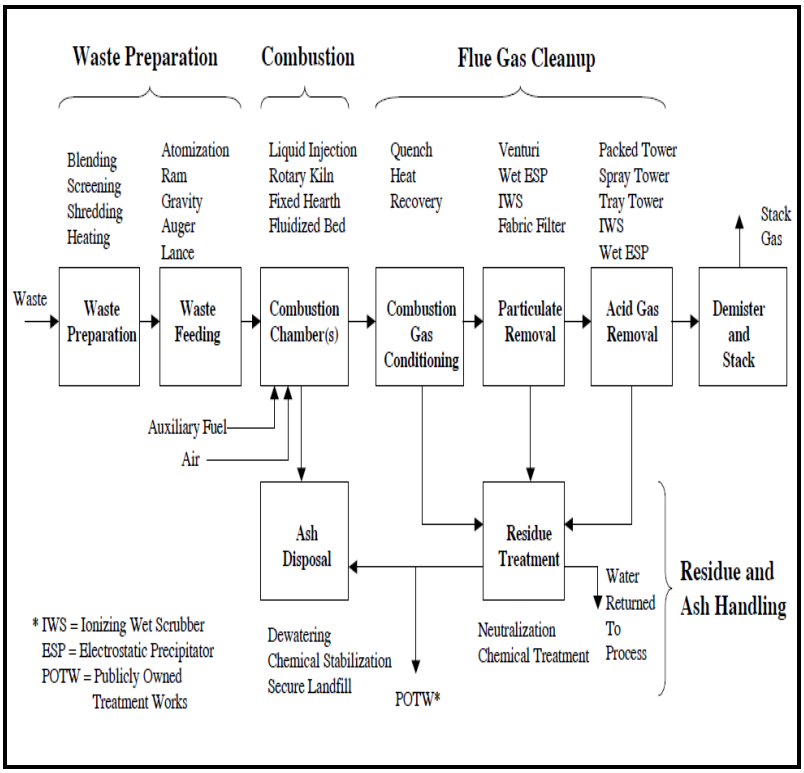

Figure 12. Mass Burn Process Flow Diagram[296]

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289 EIPPCB (2006)

290 Exergia S.A. et al. (2002)

291 The World Bank (1999)

292 Arena U. (2012)

293 DEFRA[2] (2007)

294 Ibid.

295 EIPPCB (2006)

296 Orr D. & Maxwell D. (2000)

Gasification

Gasification is rarely applied for MSW treatment[297] and it can take place in modular plants[298] at temperatures of 550-1,600 °C.[299] There are three main types of gasification (the directly heated air, the directly heated oxygen and the indirectly heated gasification)[300] in which steam appears to be the most commonly used gasification agent.[301] Gasification of MSW is mainly processed in fluidized bed reactors for larger plants and in fixed bed reactors[302] for smaller plants respectively.[303]

This technique differs from conventional combustion in that the waste is heated with a very restricted quantity of air[304] not sufficient to allow the complete oxidation of waste and the occurrence of full combustion.[305] The starting point is a solid feedstock (waste) that is converted into a gaseous combustible homogeneous fuel,[306] known as synthesis gas (syngas),[307] to be used in engines or turbines.[308] The syngas has a 4-10 MJ/Nm^3 net calorific value (NCV) and it is mostly consisted of carbon monoxide, hydrogen and methane. However, the gas also contains ashes of relatively low levels of carbon[309] and slag,[310] necessitating that it is cleaned and cooled down prior to utilization in engines or turbines.[311]

The typical throughput of gasification applications ranges between 250-500 tons/day.[312] The generic processes of gasification are similar to mass burn and can be

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297 EIPPCB (2006)

298 DEFRA[1] (2007)

299 Arena U. (2012)

300 Bauen A. (2004)

301 Belgiorno V. et al (2003)

302 Chen C. et al (2011)

303 Bauen A. (2004)

304 Smith A. et al. (2001)

305 DEFRA[2] (2007)

306 Knoef H. (2006)

307 DEFRA[2] (2007)

308 Knoef H. (2006)

309 DEFRA[2] (2007)

310 Orr D. & Maxwell D. (2000)

311 Knoef H. (2006)

312 EIPPCB (2006)

summarized to waste preparation, gasification and gas cleaning, after which the clean gas is usually used for energy production. A schematic overview follows in the flow diagram below (Figure 13).

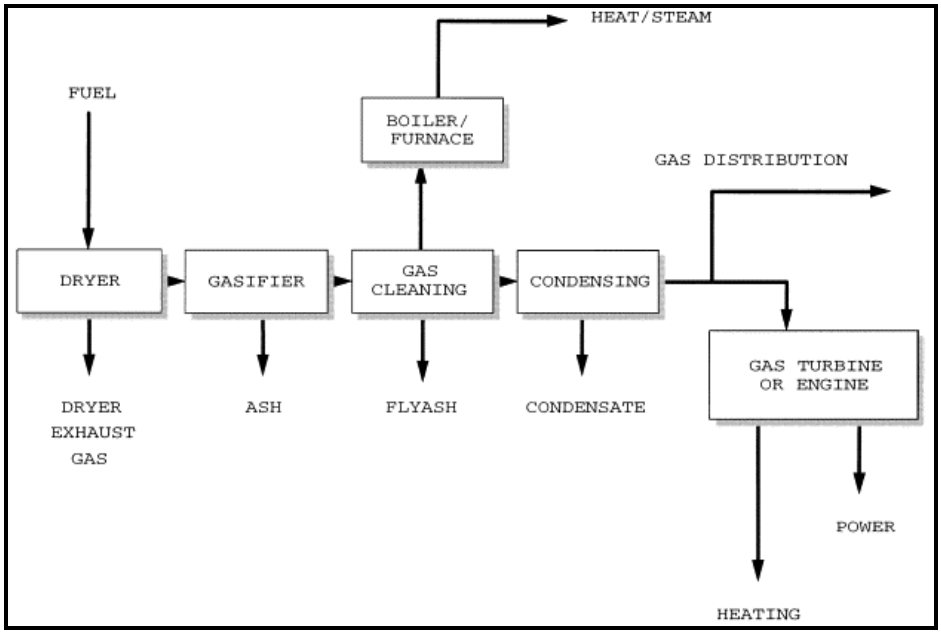

Figure 13. Gasification Process Flow Diagram[313]

Pyrolysis

Pyrolysis is one of the technologies that can take place in plants of modular structure[314] mostly at temperatures of 500-800 °C[315] and it is rarely applied for MSW treatment.[316] It differs from conventional combustion in that the waste is first heated in conditions of complete absence of air.[317] The thermal degradation of organic material in starved air conditions converts waste into solid residue (char) - this residue consists of a mixture of non-combustible materials and carbon - as well as into syngas with a NCV of 10-20 MJ/Nm^3; the syngas is composed by combustible gas constituents and condensable oils, waxes and tars.[318] The typical throughput of a pyrolysis plant ranges between 10-100 tons/day,[319] but wastes are treated faster than

[313] Morris M. & Waldheim L. (1998)

[314] DEFRA[1] (2007)

[315] Arena U. (2012)

[316] EIPPCB (2006)

[317] Smith A. et al. (2001)

[318] DEFRA[2] (2007)

[319] EIPPCB (2006)

in gasification.[320] The generic processes of pyrolysis are no exemption to the widely used methods and can also be summarized to waste preparation, pyrolysis and gas cleaning. A typical plant's structure can be examined in the following figure (14).

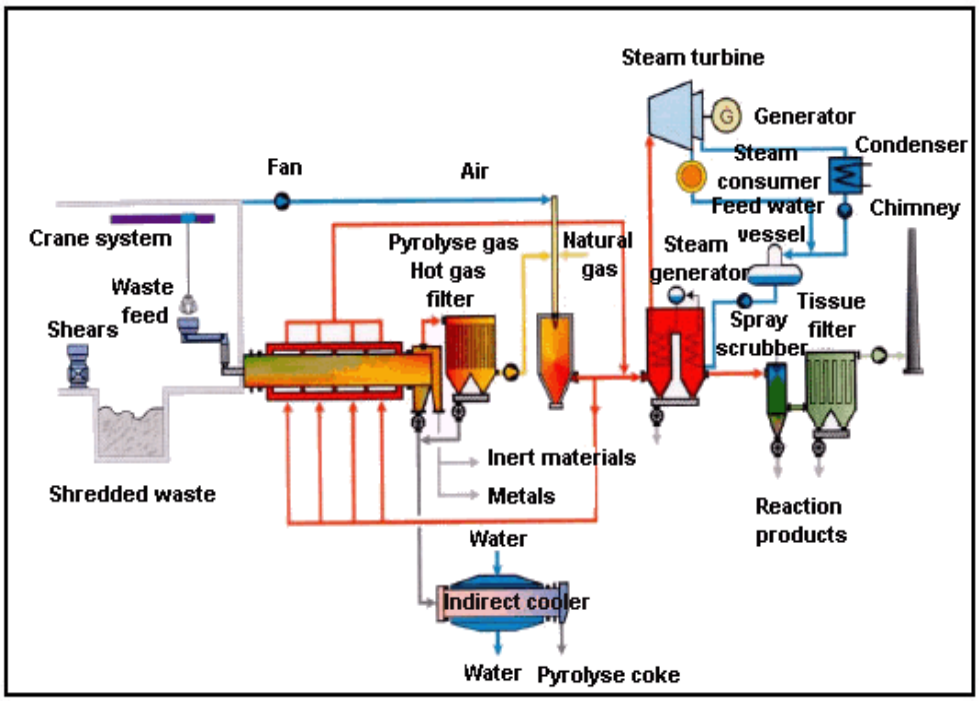

Figure 14. Typical Structure of a Pyrolysis WTE Plant for MSW Treatment[321]

[320] Bridgewater A.V. et al. (1999)

[321] UBA (2001)

Annex II: Tables 1A - 17

Table 1-A. European WID's Regulated Standards[322]

Contaminant Emissions to Air (mg/Nm^3 unless stated)	WID	
	Daily Average ELV	Half Hourly (100%/97% of the time)
Total Particulate	10	30/10
HCl	10	60/10
SO_2	50	200/50
NO_x (as NO_2)	<200 to <500 (size/new/existing dependant)	400/200
VOC (as Total Organic Carbon)	10	20
CO	50	150 (10 min avg) (some alternatives)
Hg	0.05 (non-continuous sample)	
Cd/Tl	0.05 (non-continuous sample)	
PCDD/F	0.1 ng/m^3 (non-continuous sample)	
Ammonia	Not included in WID	
N_20		
Benz(a)pyrene		
PAHs		
PCBs		

Table 1-B. Complementary European WID's Regulated Standards[323]

POLLUTANT	LIMIT (mg/Nm^3 s)	POLLUTANT	LIMIT (mg/Nm^3 s)
Total dust	10–30	TOC[1]	10–20
HCl[2]	10–60	Cd[3], Tl[4], Hg[5]	0.05*
HF[6]	1–4	Sb[7], As[8], Pb[9], Cr[10], Co[11], Cu[12], Mn[13], Ni[14], V[15]	0.5
SO_2	50–200	PAH	-
NO_2[16]	200–400	PCDD + PCDF (ng/Nm^3)	0.1**
CO	50–100		

Note: the double limit value is: daily average and maximum (hourly or 30 minutes average).
[1]Total organic compound; [2]Hydrogen chloride; [3]Cadmium; [4]Thallium; [5]Mercury; [6]Hafnium; [7]Antimony; [8]Arsenic; [9]Lead; [10]Chromium; [11]Cobalt; [12]Copper; [13]Manganese; [14]Nickel; [15]Vanadium; [16]Nitrogen dioxide.
*Limit for (Cd+Tl) and Hg separated.
**Calculated using the concept of toxic equivalence factors referred to 2,3,7,8 T_4CDD.

[322] Papageorgiou A. et. al. (2009)

[323] WHO (2007)

Table 2. Composition of MSW in Attica[324]

	MSW (wet)	Packaging waste (wet)	Residual waste (wet)			Residual waste (dry)		
	Weight (% w/w)	Fraction of packaging waste in MSW (% w/w)	Weight (% w/w)	Moisture (% w/w)	NCV (GJ t^{-1})	Carbon content (%w/w)	Degradable organic carbon (DOC) (%w/w)	Fossil carbon (%w/w)
Category								
Paper and card	29	8.1	26.7	10	14.2	46	46	0
Kitchen and garden waste	40	0	44.2	60	4.5	43	43	0
Plastic	14	6.1	13.9	0	29.3	75	0	100
Other	6	0	6.5	40	7.3	38	19	50
Inerts	3	0	3.3	10	0	0	0	0
Leather, wood, textiles, rubber	2	1.2	2	20	13.6	55	44	20
Glass	3	3	1.4	0	0	0	0	0
Ferrous metals	2.47	2.4	1.4	0	0	0	0	0
Non-ferrous Metals	0.53	0.5	0.6	0	0	0	0	0
Total	100	21.3	100	32.5	10.6	31.5	–	–

[324] Papageorgiou A. et. al. (2009)

Table 3. MSW in EU-27 and EFTA (2009)[325]

Municipal waste, 2009 Municipal waste generated, kg per person		Total municipal waste treated, kg per person	Municipal waste treated, %			
			Landfilled	Incinerated	Recycled	Composted
EU-27	**513**	**504**	**38**	**20**	**24**	**18**
EU-15						
Austria	591	591	1	29	30	40
Belgium	491	486	5	35	36	24
Denmark	833	833	4	48	34	14
Finland	481	481	46	18	24	12
France	536	536	32	34	18	16
Germany	587	564	0	34	48	18
Greece	478	474	82	-	17	2
Ireland	742	730	62	3	32	4
Italy	541	594	45	12	11	32
Luxembourg	707	707	17	36	27	20
Netherlands	616	520	1	39	32	28
Portugal	488	488	62	19	8	12
Spain	547	547	52	9	15	24
Sweden	485	480	1	49	36	14
United Kingdom	529	538	48	11	26	14
EU-12						
Bulgaria	468	450	100	-	-	-
Cyprus	778	778	86	-	14	-
Czech Republic	316	274	83	12	2	2
Estonia	346	285	75	0	14	11
Hungary	430	427	75	10	13	2
Latvia	333	333	92	0	7	0
Lithuania	360	342	95	-	3	1
Malta	647	643	96	-	4	-
Poland	316	264	78	1	14	7
Romania	396	308	99	-	1	0
Slovakia	339	311	82	10	2	6
Slovenia	449	495	62	1	34	2
EFTA						
Iceland	554	520	73	11	14	2
Norway	473	467	14	42	28	16
Switzerland	706	706	-	49	34	17

Data for the EU-27, Denmark, Germany, Spain, France, Italy, Cyprus, Luxembourg, Netherlands, Romania, Portugal and the United Kingdom are estimated.
0 equals less than 0.5%, "-"indicates a real zero

[325] Eurostat (2011)

Table 4. Revenues from Energy Recovery, SCR/SCNR Incinerator (Flanders)[326]

	Grate Incinerator SNCR	Grate Incinerator SCR
COSTS		
Capital Cost per Tonne	€ 34.58	€ 37.08
Operational Cost	€ 38.79	€ 40.00
Fixed	€ 30.54	€ 31.76
Variable	€ 8.24	€ 8.24
Overhead	€ 9.23	€ 9.80
Total	€ 82.57	€ 86.88
REVENUES		
Materials	€ 0.00	€ 0.00
Electricity production	-€ 11.88	-€ 11.76
Total	-€ 11.88	-€ 11.76
NET COST	**€ 70.69**	**€ 75.12**

Table 5. Mass-Burn Incinerator Costs (200,000 tons/year, Ireland)[327]

Capital investments	**EUR**
Civil works and buildings	23741660
Mech. and Electrical Equipment	45388468
Other	15108329
Total	**84238458**
Operating costs	**EUR**
Fixed	
Personnel	954297
Maintenance and replacement	890522
Unforeseen	125527
Total	**1988422**
Variable	
Maintenance and replacement	839782
Chemicals	890522
Other (consumables and residues)	1174520
Other (unspecified)	293630
Total	**3198454**
Variable costs per tonne	16

[326] Eunomia (2001)

[327] Ibid.

Table 6. Mass-Burn Incinerator Costs (200,000 tons/year, Germany)[328]

TOTAL INVESTMENT	Investment (EUR)	Payback Period (y/s)	Rate %	Annualised cost (EUR/yr)	Specific costs (EUR/t)
Site costs	368000		7	25700	0.13
Development of site	341000	25	7	29200	0.15
Construction costs	21629000	25	7	1856000	9.28
Technical installations and machinery	69740000	15	7	7657100	38.29
Electro technical installations	13280000	15	7	1458000	7.29
Fees	7349000	17	7	752800	3.76
Pre-financing	9219000	17	7	944200	4.72
TOTAL	**121925000**			**12723000**	**63.61**
OPERATIONAL COSTS, independent of input	EUR	Percentage		Annual costs EUR/yr	Specific costs EUR/t
Construction	21970000	1		219700	1.10
Technical installations and machinery	69740000	4		2789600	13.95
Electro technical installations	13280000	2.5		332000	1.66
Taxes and insurance	105357000	1		1053600	5.27
Management	2863000	10		286300	1.43
Auxiliary materials	3341000	5		167100	0.83
		number	EUR/person		
Labour		80	35790	2863200	14.32
TOTAL				**7711500**	**38.56**
OPERATIONAL COSTS, input dependent					
		EUR per m^3/yr	EUR/m^3		
Process water		51200	0.15	7900	0.04
Gas		1381440	0.20	282500	1.41
		t/yr	/t		
CaO		1000	79.2	79200	0.40
Ammonia		400	97.1	38900	0.19
	kg/t input				
Treatment of slag	334	66800	28.1	1878500	9.39
Treatment of ashes	8	1600	255.6	409000	2.05
Treatment of filter dust	22	4400	255.6	1124800	5.62
TOTAL				**3820800**	**19.10**
	MWh/t input	MWh/yr	EUR/MWh	EUR/yr	EUR/t
Credits for electricity	0.35	70700	46.0	3253300	16.27
TOTAL Cost Per Year				21002000	105
Cost per tonne input					

[328] Eunomia (2001)

Table 7. Comparative Incineration Costs in EU[329]

	Pre-tax Costs Net of Revenues	Tax (for plant with energy recovery)	Revenues from Energy Supply (per kWh)	Costs of Ash Treatment
AU	326 @ 60ktpa 159 @ 150ktpa 97 @ 300ktpa		Electricity 0.036 Heat 0.018	Bottom ash €63/t Flue gas residues €363/t
BE	€71-75 @ 150ktpa €83 per tonne *	€12.7/tonne (Flanders)	Electricity 0.025	Not available
DK	€30-45/tonne	€44/tonne	Electricity 0.05	Bottom ash €34 /t Flue gas residues €134/t
FI	None		For gasification, Electricity 0.034 Heat 0.017	
FR	€118-129 @ 18.7 ktpa €91-101 @ 37.5ktpa €86-101 @ 37.5ktpa €80-90 @ 75ktpa €67-80 @ 150ktpa		Electricity 0.023	€13-18 per tonne input
GE	€250 (50 ktpa and below) €105 (200ktpa) €65 @ 600ktpa		Electricity €0.046	Bottom ash €28.1 /t Fly ash / air pollution control residues €255.6/t
GR	None		Not known	Not known
IR	€46 (200 kt, est)		Not known	Not known
IT	€41.3 – 93 (350kt, depends on revenues for energy and packaging recovery)		Electricity €0.14 (old) €0.04 (market) €0.05 (green cert.)	Bottom ash €75/t Fly ash and air pollution control residues €129/t
LUX	€97 (120kt)		Electricity €0.025 (est)	Bottom ash €16/t input waste Flue gas residues €8/t input waste
NL	€71-110* (VVAV) €70-134* (OVAM)		Electricity €0.05/t (est)	
PO	€46-76 (est)			No data
SP	€34-56		Electricity €0.036	
SW	€21-53		Electricity €0.03 Heat €0.02	
UK	€69 @ 100ktpa €47 @ 200ktpa		Electricity 0.032	Bottom ash recycled (net cost to operator) Fly ash circa €90/t

** These figures are gate fees, not costs*

[329] Eunomia (2001)

Table 8. Main Characteristics of WTE Technologies[330]

	Combustion	Gasification	Pyrolysis
Aim of the process	To maximize waste conversion to high temperature flue gases, mainly CO_2 and H_2O	To maximize waste conversion to high heating value fuel gases, mainly CO, H_2 and CH_4	To maximize thermal decomposition of solid waste to gases and condensed phases
Operating conditions			
Reaction environment	Oxidizing (oxidant amount larger than that required by stoichiometric combustion)	Reducing (oxidant amount lower than that required by stoichiometric combustion)	Total absence of any oxidant
Reactant gas	Air	Air, pure oxygen, oxygen-enriched air, steam	None
Temperature	Between 850 °C and 1200 °C	Between 550–900 °C (in air gasification) and 1000–1600 °C	Between 500 °C and 800 °C
Pressure	Generally atmospheric	Generally atmospheric	Slight over-pressure
Process output			
Produced gases	CO_2, H_2O	CO, H_2, CO_2, H_2O, CH_4	CO, H_2, CH_4 and other hydrocarbons
Pollutants	SO_2, NO_x, HCl, PCDD/F, particulate	H_2S, HCl, COS, NH_3, HCN, tar, alkali, particulate	H_2S, HCl, NH_3, HCN, tar, particulate
Ash	Bottom ash can be treated to recover ferrous (iron, steel) and non-ferrous metals (such as aluminium, copper and zinc) and inert materials (to be utilized as a sustainable building material). Air Pollution Control residues are generally treated and disposed as industrial waste	As for combustion process. Bottom ash are often produced as vitreous slag that can be utilized as backfilling material for road construction	Often having a not negligible carbon content. Treated and disposed as industrial special waste
Gas cleaning			
	Treated in air pollution control units to meet the emission limits and then sent to the stack	It is possible to clean the syngas to meet the standards of chemicals production processes or those of high efficiency energy conversion devices	It is possible to clean the syngas to meet the standards of chemicals production processes or those of high efficiency energy conversion devices

[330] Arena U. (2012)

Table 9. MSWI Hazardous Emissions[331]

Stack Pollutants	**Inorganic Compounds**	**Water (Vapour)**	**Carbon Oxide (CO)**	**Carbon Dioxide (CO2)**
		Sulphur Oxides (SO_X)	**Nitrogen Oxides (NO_X)**	
		Products of Incomplete Combustion ***[Silicates, Inorganic Ash, Soot, Metal Elements and their Oxides, Salt (i.e. Hg and other metals with high vapour pressure)]***		
	Organic Compounds	**VOCs**	**Hydrocarbons (HC)**	**Dioxins (PCDDs)**
		Furans (PCDFs)	**Polychlorinated Biphenyls (PCBs)**	**Polycyclic Aromatic Hydrocarbons (PAHs)**
	Particles	**PM_{10}**	**PM_5**	**$PM_{2.5}$**
		Microns	**Ultrafine**	
Non-Stack Pollutants		**Ash**	**Bottom Ash**	**Fly ash**
		Noise	**Odor**	**Pests**
		Transport–related Emissions	**Dusts**	**Spores**

Table 10. Occurrence of Pollutants in MSWI Stack Emissions

Pollutant \ **Technology**		**Combustion (Mass Burn)**	**Gasification**	**Pyrolysis**
Particles		+	<	<
CO		+	+	<
Acid Gases	*SO_2*	+	<	<
	NO_X	+	>	>
	Halogens (HCl, HBr, HF)	>	+	+
TOC	*PCDD/Fs*	+	+	?
	Other (VOCs, PAHs, PCBs)	<	>	+
Heavy Metals		+	>	n.d.
Other Pollutants	*GHGs (CO_2 CH_4, N_2O)*	+	+	+
	NH_3	?	?	?
Marks Explanation		+ – Expected presence / – Expected absence ? – Possible presence < – Low levels expected > – High levels expected n.d. – No sufficient data		

[331] WHO (2007)

Table 11. Typical Heavy Metals Concentrations in MSW (wet basis, ppm)[332]

	Pb	Cr	Cd	Hg
MSW	12	6.5	.45	.12

Table 12. IARC Monographs Classification Groups[333]

Group	Description	Agents
1	*Carcinogenic to humans*	*109*
2A	*Probably carcinogenic to humans*	*65*
2B	*Possibly carcinogenic to humans*	*275*
3	*Not classifiable as to its carcinogenicity to humans*	*503*
4	*Probably not carcinogenic to humans*	*1*

[332] Kathirvale S. et al. (2004)

[333] IARC Monographs[1] (2013)

Table 13. Typical MSWI Hazards Classified by IARC Monographs[334]

Agent Group	Agent Subgroup	Agent Name	Classification
Acid Gases	Halogens	*HCl*	*3*
		Fluorides	*3*
	Other	*SO_2*	*3*
TOC	BTX	*Benzene*	*1*
		Toluene	*3*
		Xylenes	*3*
	PAHs	*Ethylene*	*3*
		Ethylbenzene	*2B*
		Fluorene	*3*
		Formaldehyde	*1*
		Naphthalene	*2B*
		Phenanthrene	*3*
		Pyrene	*3*
	PCDD/Fs	*2,3,7,8-TCDD*	*1*
		2,3,4,7,8-PeCDF	*1*
		Other	*3*
	Other	*PCBs*	*2A*
Heavy Metals		*As*	*1*
		Cd	*1*
		Cr, metallic	*3*
		Hg	*3*
		Ni, metallic and alloys	*2B*
		Pb	*2B*
		Se	*3*
		Arsenic inorganic compounds	*1*
		Cadmium compounds	*1*
		Chromium(III) compounds	*3*
		Chromium(VI) compounds	*1*
		Lead inorganic compounds	*2A*
		Lead organic compounds	*3*
		Mercury inorganic compounds	*3*
		Methylmercury compounds	*2B*
		Nickel compounds	*1*
		Selenium compounds	*3*

[334] IARC Monographs[2] (2013)

Table 14. List of MRLs for Health Hazards Expected from MSWI[335]

ATSDR Minimal Risk Levels (MRLs)							
Substance	Route	Duration	MRL	UF	Endpoint	Date	CASRN
AMMONIA	*Inh.*	*Acute*	*1.7 ppm*	*30*	*Resp.*	*2004*	*7664-41-7*
		Chr.	*0.1 ppm*				
ARSENIC	*Oral*	*Acute*	*0.005 mg/kg/day*	*10*	*Gastro*	*2007*	*7440-38-2*
		Chr.	*0.0003 mg/kg/day*	*3*	*Dermal*		
BENZENE	*Inh.*	*Acute*	*0.009 ppm*	*300*	*Immuno.*	*2007*	*71-43-2*
		Int.	*0.006 ppm*				
		Chr.	*0.003 ppm*	*10*			
	Oral	*Chr.*	*0.0005 mg/kg/day*	*30*			
CADMIUM	*Inh.*	*Acute*	*0.00003 mg/m^3*	*300*	*Resp.*	*2012*	*7440-43-9*
		Chr.	*0.00001 mg/m^3*	*9*	*Renal*		
	Oral	*Int.*	*0.0005 mg/kg/day*	*100*	*Musculo.*		
		Chr.	*0.0001 mg/kg/day*	*3*	*Renal*		
CHROMIUM(III) INSOL. PARTICULATES	*Inh.*	*Int.*	*0.005 mg/m^3*	*90*	*Resp.*	*2012*	*16065-83-1*
CHROMIUM(III) SOLUBLE PARTICULATES			*0.0001 mg/m^3*	*300*			
CHROMIUM(VI)	*Oral*	*Int.*	*0.005 mg/kg/day*	*100*	*Hemato.*	*2012*	*18540-29-9*
		Chr	*0.0009 mg/kg/day*		*Gastro.*		
CHROMIUM(VI), AEROSOL MISTS	*Inh.*	*Int.*	*0.000005 mg/m^3*		*Resp.*		
		Chr.					
CHROMIUM(VI), PARTICULATES		*Int.*	*0.0003 mg/m^3*	*30*			
ETHYLBENZENE	*Inh.*	*Acute*	*5 ppm*	*30*	*Neurol.*	*2010*	*100-41-4*
		Int.	*2 ppm*				
		Chr.	*0.06 ppm*	*300*	*Renal*		
	Oral	*Int.*	*0.4 mg/kg/day*	*30*	*Hepatic*		
FORMALDEHYDE	*Inh.*	*Acute*	*0.04 ppm*	*9*	*Resp.*	*1999*	*50-00-0*
		Int.	*0.03 ppm*	*30*			
		Chr.	*0.008 ppm*				
	Oral	*Int.*	*0.3 mg/kg/day*	*100*	*Gastro.*		
		Chr.	*0.2 mg/kg/day*				
HYDROGEN FLUORIDE	*Inh.*	*Acute*	*0.02 ppm*	*30*	*Resp.*	*2003*	*7664-39-3*
MERCURY	*Inh.*	*Chr.*	*0.0002 mg/m^3*	*30*	*Neurol.*	*1999*	*7439-97-6*
METHYLMERCURY	*Oral*	*Chr.*	*0.0003 mg/kg/day*	*4.5*	*Develop.*	*1999*	*22967-92-6*
NAPHTHALENE	*Inh.*	*Chr.*	*0.0007 ppm*	*300*	*Resp.*	*2005*	*91-20-3*
	Oral	*Acute*	*0.6 mg/kg/day*	*90*	*Neurol.*		
		Int.	*0.6 mg/kg/day*				
NICKEL	*Inh.*	*Int.*	*0.0002 mg/m^3*	*30*	*Resp.*	*2005*	*7440-02-0*
		Chr.	*0.00009 mg/m^3*				
2,3,4,7,8-PENTACHLORODIBENZOFURAN	*Oral*	*Acute*	*0.001 ug/kg/day*	*3000*	*Immuno.*	*1994*	*57117-31-4*
		Int.	*0.00003 ug/kg/day*		*Hepatic*		
POLYCHLORINATED BIPHENYLS (PCBs)	*Oral*	*Int.*	*0.03 ug/kg/day*	*300*	*Neurol.*	*2000*	*11097-69-1*
		Chr.	*0.02 ug/kg/day*		*Immuno.*		
SELENIUM	*Oral*	*Chr.*	*0.005 mg/kg/day*	*3*	*Dermal*	*2003*	*7782-49-2*
SULFUR DIOXIDE	*Inh.*	*Acute*	*0.01 ppm*	*9*	*Resp.*	*1998*	*7446-09-5*
2,3,7,8-TETRACHLORODIBENZO-P-DIOXIN	*Oral*	*Acute*	*0.0002 ug/kg/day*	*21*	*Immuno.*	*1998*	*1746-01-6*
		Int.	*0.00002 ug/kg/day*	*30*	*Lymphor.*		
		Chr.	*0.000001 ug/kg/day*	*90*	*Develop.*		
TOLUENE	*Inh.*	*Acute*	*1 ppm*	*10*	*Neurol.*	*2000*	*108-88-3*
		Chr.	*0.08 ppm*	*100*			
	Oral	*Acute*	*0.8 mg/kg/day*	*300*			
		Int.	*0.02 mg/kg/day*				
XYLENES, MIXED	*Inh.*	*Acute*	*2 ppm*	*30*	*Neurol.*	*2007*	*1330-20-7*
		Int.	0.6 ppm	90			
		Chr.	0.05 ppm	300			
	Oral	Acute	1 mg/kg/day	100			
		Int.	0.4 mg/kg/day	1000			
		Chr.	0.2 mg/kg/day				

[335] ATSDR[1] (2013)

Table 15. Density of Athenian MSW (kg/m^3)

Waste Category	Waste Material	Waste Density[336]	Average Material Density Estimation	Average Category Density Estimation	MSW Composition[337]	MSW Density Estimation
Kitchen and Garden Waste	Food Waste	*120-480*	*300*	*221.25*	*40%*	*88.5*
	Garden Trimmings	*60-225*	*142.5*			
Paper and Card	Cardboard, Corrugated Paper Box	*30-80*	*55*	*135*	*29%*	*39.15*
	Paper	*30-130*	*80*			
Plastic	Plastic	*30-156*	*93*	*93*	*14%*	*13.02*
Glass	Glass	*90-260*	*175*	*175*	*3%*	*5.25*
Metals	Metal-Ferrous	*120-1200*	*660*	*405*	*3%*	*12.15*
	Metal-Non Ferrous	*60-240*	*150*			
Inerts	Asphalt	*680*	*680*	*915*	*3%*	*27.45*
	Brick/ Concrete/ Tile/ Dirt	*800-1500*	*1150*			
Leather, Wood, Textiles and Rubber	Leather	*90-450*	*270*	*261.6*	*2%*	*5.232*
	Sawdust	*250-350*	*300*			
	Wood	*156-900*	*528*			
	Textile	*30-100*	*65*			
	Rubber	*90-200*	*145*			
Other Materials	Electronic Equipments	*105*	*105*	*161.25*	*6%*	*9.675*
	Other MSW/ Biomedical waste	*87-348*	*217.5*			
Approximate MSW Density Estimation					**100%**	**200.43**

[336] Chandrappa R. & Das D.B. (2012)

[337] Papageorgiou A. et. al. (2009)

Table 16. Average Air Emissions of MSWI[338]

Hazard	Before Treatment		After Treatment	Legal Limits
	According to EC[339]	According to relevant studies[340]		According to WID[341]
Dust (mg/Nm^3)	1000-5000	2000-10000	0.1-4	10
CO (mg/Nm^3)	5-50		2-45	50
TOC (mg/Nm^3)	1-10		0.1-5	10
HCl (mg/Nm^3)	500-2000	400-1500	0.1-6	10
HF (mg/Nm^3)	5-20	2-20	0.01-0.1	1
SO_2 (mg/Nm^3)	200-1000	200-800	0.2-20	50
$NO+NO_2$ (mg/Nm^3)	250-500	200-400	20-180	200 #
NO (mg/Nm^3)	<40			not defined
Hg (mg/Nm^3)	0.05-0.5	0.3-0.8	0.0002-0.05	0.05
Cd,Tl (mg/Nm^3)	<3	3-12	0.0002-0.03	0.05
Other heavy metals (Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V)	<50		0.0002-0.05	0.5
Dioxins and Furans (ng I-TEQ/Nm^3)	0.05-10	<1-5	0.0002-0.08	0.1
CO_2	5-10%			not defined
H_2O	10-20%			not defined

 # for nominal capacity ≥ 6 tons/hour or new incineration plants

Notice: Stack NO_X emissions are 95% NO and 5% NO_2.[342]

[338] Quina Margarida J. et al. (2011)

[339] EIPPCB (2006)

[340] Achternbosch M. & Richers U. (2002)

[341] EC (2000)

[342] EIPPCB (2006)

Table 17. Estimation of Contamination Magnitude

Hazard	Daily Burden (mg/day)	Annual Burden (mg/year)
Particles	1635	509,600
CO	8175	2,548,000
TOC	1635	509,600
HCl	1635	509,600
HF	16.35	50,960
SO_2	8,175	2,548,000
NO_X *(95% NO, 5% NO_2)*	32,700	10,192,000
Hg	8.175	2,548
Cd and Tl	8.175	2,548
Other heavy metals	81.75	25,480
PCDD/Fs	16.35 *(ng I-TEQ/day)*	5,096 *(ng I-TEQ/year)*

Annex III: About Classification Groups of the IARC Monographs

Presented as described in the Preamble of “IARC Monographs on the Evaluation of Carcinogenic Risks to Humans” developed by the World Health Organization’s International Agency for Research on Cancer.

WORLD HEALTH ORGANIZATION
INTERNATIONAL AGENCY FOR RESEARCH ON CANCER

IARC Monographs on the Evaluation of Carcinogenic Risks to Humans

PREAMBLE

LYON, FRANCE
2006

Group 1: The agent is *carcinogenic to humans*

This category is used when there is *sufficient evidence of carcinogenicity* in humans. Exceptionally, an agent may be placed in this category when evidence of carcinogenicity in humans is less than *sufficient* but there is *sufficient evidence of carcinogenicity* in experimental animals and strong evidence in exposed humans that the agent acts through a relevant mechanism of carcinogenicity.

Group 2

This category includes agents for which, at one extreme, the degree of evidence of carcinogenicity in humans is almost *sufficient*, as well as those for which, at the other extreme, there are no human data but for which there is evidence of carcinogenicity in experimental animals. Agents are assigned to either Group 2A (*probably carcinogenic to humans*) or Group 2B (*possibly carcinogenic to humans*) on the basis of epidemiological and experimental evidence of carcinogenicity and mechanistic and other relevant data. The terms *probably carcinogenic* and *possibly carcinogenic* have no quantitative significance and are used simply as descriptors of different levels of evidence of human carcinogenicity, with *probably carcinogenic* signifying a higher level of evidence than *possibly carcinogenic*.

Group 2A: The agent is probably carcinogenic to humans

This category is used when there is *limited evidence of carcinogenicity* in humans and *sufficient evidence of carcinogenicity* in experimental animals. In some cases, an agent may be classified in this category when there is *inadequate evidence of carcinogenicity* in humans and *sufficient evidence of carcinogenicity* in experimental animals and strong evidence that the carcinogenesis is mediated by a mechanism that also operates in humans. Exceptionally, an agent may be classified in this category solely on the basis of *limited evidence of carcinogenicity* in humans. An agent may be assigned to this category if it clearly belongs, based on mechanistic considerations, to a class of agents for which one or more members have been classified in Group 1 or Group 2A.

Group 2B: The agent is possibly carcinogenic to humans

This category is used for agents for which there is *limited evidence of carcinogenicity* in humans and less than *sufficient evidence of carcinogenicity* in experimental animals. It may also be used when there is *inadequate evidence of carcinogenicity* in humans but there is *sufficient evidence of carcinogenicity* in experimental animals. In some instances, an agent for which there is *inadequate evidence of carcinogenicity* in humans and less than *sufficient evidence of carcinogenicity* in experimental animals together with supporting evidence from mechanistic and other relevant data may be placed in this group. An agent may be classified in this category solely on the basis of strong evidence from mechanistic and other relevant data.

Group 3: The agent is not classifiable as to its carcinogenicity to humans

This category is used most commonly for agents for which the evidence of carcinogenicity is *inadequate* in humans and *inadequate* or *limited* in experimental animals.

Exceptionally, agents for which the evidence of carcinogenicity is *inadequate* in humans but *sufficient* in experimental animals may be placed in this category when there is strong evidence that the mechanism of carcinogenicity in experimental animals does not operate in humans.

Agents that do not fall into any other group are also placed in this category.

An evaluation in Group 3 is not a determination of non-carcinogenicity or overall safety. It often means that further research is needed, especially when exposures are widespread or the cancer data are consistent with differing interpretations.

Group 4: The agent is probably not carcinogenic to humans

This category is used for agents for which there is *evidence suggesting lack of carcinogenicity* in humans and in experimental animals. In some instances, agents for which there is *inadequate evidence of carcinogenicity* in humans but *evidence suggesting lack of carcinogenicity* in experimental animals, consistently and strongly supported by a broad range of mechanistic and other relevant data, may be classified in this group.

Annex IV: About Minimal Risk Levels (MRLs)

Presented as described in Toxic Substances Portal – Minimal Risk Levels (MRLs)[343] of the Agency for Toxic Substances and Disease Registry of the U.S. Department of Health and Human Services.

[343] ATSDR[2] (2013)

What is Minimal Risk Levels (MLRs)?

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) [42 U.S.C. 9604 et seq.], as amended by the Superfund Amendments and Reauthorization Act (SARA) [Pub. L. 99 499], requires that the Agency for Toxic Substances and Disease Registry (ATSDR) develop jointly with the U.S. Environmental Protection Agency (EPA), in order of priority, a list of hazardous substances most commonly found at facilities on the CERCLA National Priorities List (NPL) (42 U.S.C. 9604(i)(2)); prepare toxicological profiles for each substance included on the priority list of hazardous substances, and to ascertain significant human exposure levels (SHELs) for hazardous substances in the environment, and the associated acute, subacute, and chronic health effects (42 U.S.C. 9604(i)(3)); and assure the initiation of a research program to fill identified data needs associated with the substances (42 U.S.C. 9604(i)(5)).

The ATSDR Minimal Risk Levels (MRLs) were developed as an initial response to the mandate. Following discussions with scientists within the Department of Health and Human Services (HHS) and the EPA, ATSDR chose to adopt a practice similar to that of the EPA's Reference Dose (RfD) and Reference Concentration (RfC) for deriving substance specific health guidance levels for non-neoplastic endpoints. A MRL is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse non-cancer health effects over a specified duration of exposure. These substance specific estimates, which are intended to serve as screening levels, are used by ATSDR health assessors and other responders to identify contaminants and potential health effects that may be of concern at hazardous waste sites. It is important to note that MRLs are not intended to define clean up or action levels for ATSDR or other Agencies.

The toxicological profiles include an examination, summary, and interpretation of available toxicological information and epidemiologic evaluations of a hazardous substance. During the development of toxicological profiles, MRLs are derived when ATSDR determines that reliable and sufficient data exist to identify the target organ(s) of effect or the most sensitive health effect(s) for a specific duration for a given route of exposure to the substance. MRLs are based on non-cancer health effects only and are not based on a consideration of cancer effects. Inhalation MRLs are exposure concentrations expressed in units of parts per million (ppm) for gases

and volatiles, or milligrams per cubic meter (mg/m3) for particles. Oral MRLs are expressed as daily human doses in units of milligrams per kilogram per day (mg/kg/day). Radiation MRLs are expressed as external exposures in units of millisieverts.

ATSDR uses the no observed adverse effect level/uncertainty factor (NOAEL/UF) approach to derive MRLs for hazardous substances. They are set below levels that, based on current information, might cause adverse health effects in the people most sensitive to such substance-induced effects. MRLs are derived for acute (1-14 days), intermediate (15-364 days), and chronic (365 days and longer) exposure durations, and for the oral and inhalation routes of exposure. Currently MRLs for the dermal route of exposure are not derived because ATSDR has not yet identified a method suitable for this route of exposure. MRLs are generally based on the most sensitive substance-induced end point considered to be of relevance to humans. ATSDR does not use serious health effects (such as irreparable damage to the liver or kidneys, or birth defects) as a basis for establishing MRLs. Exposure to a level above the MRL does not mean that adverse health effects will occur.

MRLs are intended to serve as a screening tool to help public health professionals decide where to look more closely. They may also be viewed as a mechanism to identify those hazardous waste sites that are not expected to cause adverse health effects. Most MRLs contain some degree of uncertainty because of the lack of precise toxicological information on the people who might be most sensitive (e.g., infants, elderly, and nutritionally or immunologically compromised) to effects of hazardous substances. ATSDR uses a conservative (i.e., protective) approach to address these uncertainties consistent with the public health principle of prevention. Although human data are preferred, MRLs often must be based on animal studies because relevant human studies are lacking. In the absence of evidence to the contrary, ATSDR assumes that humans are more sensitive than animals to the effects of hazardous substances that certain persons may be particularly sensitive. Thus the resulting MRL may be as much as a hundredfold below levels shown to be nontoxic in laboratory animals. When adequate information is available, physiologically based pharmacokinetic (PBPK) modeling and benchmark dose (BMD) modeling have also been used as an adjunct to the NOAEL/UF approach in deriving MRLs.

Proposed MRLs undergo a rigorous review process. They are reviewed by the Health Effects/MRL Workgroup within the Division of Toxicology and Environmental Medicine; an expert panel of external peer reviewers; the agency wide MRL Workgroup, with participation from other federal agencies, including EPA; and are submitted for public comment through the toxicological profile public comment period. Each MRL is subject to change as new information becomes available concomitant with updating the toxicological profile of the substance. MRLs in the most recent toxicological profiles supersede previously published levels. To date, 142 inhalation MRLs, 249 oral MRLs and 8 external radiation MRLs have been derived. A listing of the current published MRLs by route and duration of exposure is provided as follows.

ATSDR Contact Person for MRLs:

Further information can be obtained by contacting the ATSDR Information Center at:

Agency for Toxic Substances and Disease Registry

Division of Toxicology and Human Health Sciences

1600 Clifton Road NE, Mailstop F-57

Atlanta, GA 30333

Phone: 1-800-CDC-INFO 888-232-6348 (TTY)

Email: cdcinfo@cdc.gov

Appendices

Appendix I: Why Incineration in Athens?

Waste Incineration in Athens: A Facts-Assumptions Approach

The complexity of composition and the volume of generated MSW, as well as the best available way with which they should be treated, have always been composing a great challenge for communities, authorities and scientists causing most of times social turmoil and headaches to decision-makers.

The prolonged neglect of the question on effective MSW treatment in Athens has resulted in many social, economical and political issues most of which are best reflected on public health and environmental decadence. This delay has brought up the necessity of further researching the available MSW treatment options in Athens, despite of what is nowadays broadly believed such as there is a one-way solution to the existent problem pointing out the benefits of thermal treatment processes.

It is common knowledge that MSW is generated from several different kinds of sources, such as houses, offices, shops, institutions and industries, making the choice of best available treatment method an even more difficult task. However, the reasoning behind the prevailing opinion of thermal treatment, on which the specific study is based, are presented below as "simple and short"[344] as possible.

Some of the facts on which the opinion is based are being presented below:

Fact 1. Power generation in Greece is mainly based on lignite combustion.[345]

Fact 2. Landfilling is the number one factor for greenhouse gases emissions in comparison to available MSW management practices.[346]

Fact 3. National waste treatment policy needs to comply with the European Landfill Directive in order to reach the target of reduced landfilling[347] as set for 2016.[348]

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[344] The analysis of reason behind the prevailing opinion is not within the interests of the specific study, thus only a small reference is preferable over an extensive presentation of argument.

[345] PPC S.A.

[346] EEA (2011), Data and maps – Maps and graphs: Emissions from municipal waste management in the EU-27, excluding Cyprus, plus Norway and Switzerland, 1990 and 2008, CO2-equivalents.

[347] EEA (2011), Data and maps – Maps and graphs: Trends and outlook for management of municipal waste in the EU-27 (excluding Cyprus) plus Norway and Switzerland, baseline scenario.

[348] EEA (2011), Data and maps – Maps and graphs: Biodegradable municipal waste landfilled in 2006 (% of biodegradable municipal waste generated in 1995), compared to targets of the European Landfill Directive.

Fact 4. The amount of total wastes treated in Greece is less than the respective amount in rest countries of former WEU and EFTA, plus Austria, Sweden, Finland, Denmark, Ireland, Slovenia and Cyprus (see Appendix II: Map 1).

Fact 5. Greek legislation needs to be regulated in order to be attuned with the respective Community Directives on urban solid waste.[349]

Fact 6. The power generation from renewable sources rate in Greece needs to be increased in order to be in line with the most developed countries of EU-27 and EFTA (see Appendix II: Map 2).

Fact 7. Volume of generated MSW per capita in Greece is estimated as the lowest among former EU-15 countries and in comparison with other wealthy countries of Europe, such as Switzerland, Iceland, Malta and Cyprus (see Appendix II: Map 3 & Table 1), as well as considerably below the average generation of respective wastes in US.[350]

Fact 8. Modern politics in Greece have set environmental issues as first in governmental and social prioritization as indicated by a set of actions, such as the recent implementation of the "Kallikratis" operational program[351] on reorganization of ministries and municipalities (for a more effective environmental governance among other purposes), the recent revision[352] of the national environmental legislation (introduction of energy inspectors, new law on environmental licensing procedures), the occurrence of the "Keratea" incident[353] ('not in my backyard' syndrome for the siting of a new residue landfill), the several funded environmental programs[354] on solid, hazardous and urban waste management (NSRF: Priority Axis 4) etc.

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[349] Ministry for Development, Competitiveness and Shipping (Greece)

[350] EPA

[351] Greek Government (2010)

[352] Greek Government (2011)

[353] Athens News; Proto Thema

[354] Ministry for Development, Competitiveness and Shipping of Greece

Fact 9. Most countries of EU-27 have already resorted to MSWI while respective investment in Greece is nonexistent (see Appendix II: Map 4 & Table 1).[355]

Fact 10. Composition of MSW in Greece can be summarized to 47% fermentable (biomass), 20.0% paper, 8.5% plastic, 4.5% metal, 4.5% glass and 15.5% other materials.[356]

According to the aforementioned facts, there can be made some related assumptions, which are concluded to:

Assumption 1. The old fashioned ways of power generation in Greece dignifies the need of turning to alternative more ecological ways and energy recovery from waste incineration seems to be an option. Lignite combustion is strongly related to several environmental and health issues so it is only a matter of time before it is replaced by a different method of power generation.

Assumption 2. Landfilling must be replaced with a "cleaner" practice of solid waste management and incineration is again one of the available options.

Assumption 3. National waste treatment policy will soon have to project a way to decrease the amount of wastes sent to landfills in order to comply with the European Landfill Directive and waste incineration is the sole effective method to reduce landfilling percentage so much as to reach the target set for 2016.

Assumption 4. The necessity for a considerably increased rate of total waste treatment determines the big importance of treatment modernization and due to the fact that incineration facilities can treat a huge amount of wastes, it seems that incineration is the ideal choice.

Assumption 5. The alignment of Greek legislation with the Community Directives will most probably have to integrate the European MSW treatment patterns that include investment in waste incineration facilities.

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[355] EEA (2007)

[356] Greek Government (2003)

Assumption 6. A waste incineration facility used for power generation seems to be a solution for both the increased rate of waste landfilling and the reduced rate of power generation from renewable sources, while at the same time lignite combustion is partially being replaced by a more eco-friendly method.

Assumption 7. Due to the relatively low volume of generated MSW per capita in Greece, an incineration facility is assumed to treat a higher percentage of daily waste generation per capita in comparison to other European and US applications so far. That, along with the economical and spatial planning advantages of this type of treatment, makes not difficult to conclude that an incineration facility of MSW in Athens may be associated with maximum profit, which has always been the driving-force for investment.

Assumption 8. Environmental policy in Greece is currently under revision and intense debate. Therefore, alternative practices of waste treatment, including incineration for generating power, will most probably be sought.

Assumption 9. Incineration has already been proven a common practice of waste treatment for the developed countries of EU-27, thus it is only a matter of time before this practice is applied in Greece. High urbanization rate in Greece has lead to 24.30% of total population (2,664,776 inhabitants) to be found in the prefecture of Athens in a density of 7,367 inhabitants per sq. km. (Census 2001)[357] High waste demand of an incineration facility makes Athens an ideal place for investment on this type of treatment, while dealing with many landfilling concerns that have been raised during the last decade.

Assumption 10. The high rate of biomass to be found in Greek MSW indicates that, if not all the appropriate precautionary measures are taken, there is high risk for several endocrine disruptors to be released in the atmosphere resulting in several health problems to the population

[357] NSSG (2009)

of Athens. Moreover, due to MSW composition, the incineration process is most probable to take place in high temperatures.

Summarizing the presented facts and assumptions, there is high possibility that MSWI is a waste treatment practice that is going to be applied in Greece within the next few years with the first plant most probably built in the broader region of Athens. Furthermore, the peculiar circumstances under which the Greek (EU forced environmental-friendly) urban development policy-making takes place, combined with the current preferable method of power generation in Greece, illustrate the importance of exploiting MSWI for energy recovery for public benefit.

The above ratiocination constitutes the reason to develop a case study on the risks related to potential MSWI with energy recovery in Athens so as to generally assess the risks of incinerating waste of high organic load in a densely populated urban area. In addition, the intriguing economical aspect of MSWI for power generation, as well as the social and environmental footprint of such an activity, makes incineration an interesting subject of scientific thought.

This study aims to provide further scientific knowledge on the risks associated with waste incineration in similar conditions by determining, as well as properly and scientifically assessing, the environmental and health impacts of potential investment on such operation with Athens on scope, thus providing fundamental knowledge for risk management to policy decision-makers, while also contributing to scientific thought.

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Glossary

~	More or less approximately
EEA	European Environment Agency
EFTA	European Free Trade Association
EU	European Union
EU-12	European Union (of 12 member states)
EU-15	European Union (of 15 member states)
EU-27	European Union (of 27 member states)
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incineration
NSSG	National Statistical Service of Greece
US	United States of America
WEU	Western European Union

Appendix II: Maps – Tables – Graphs

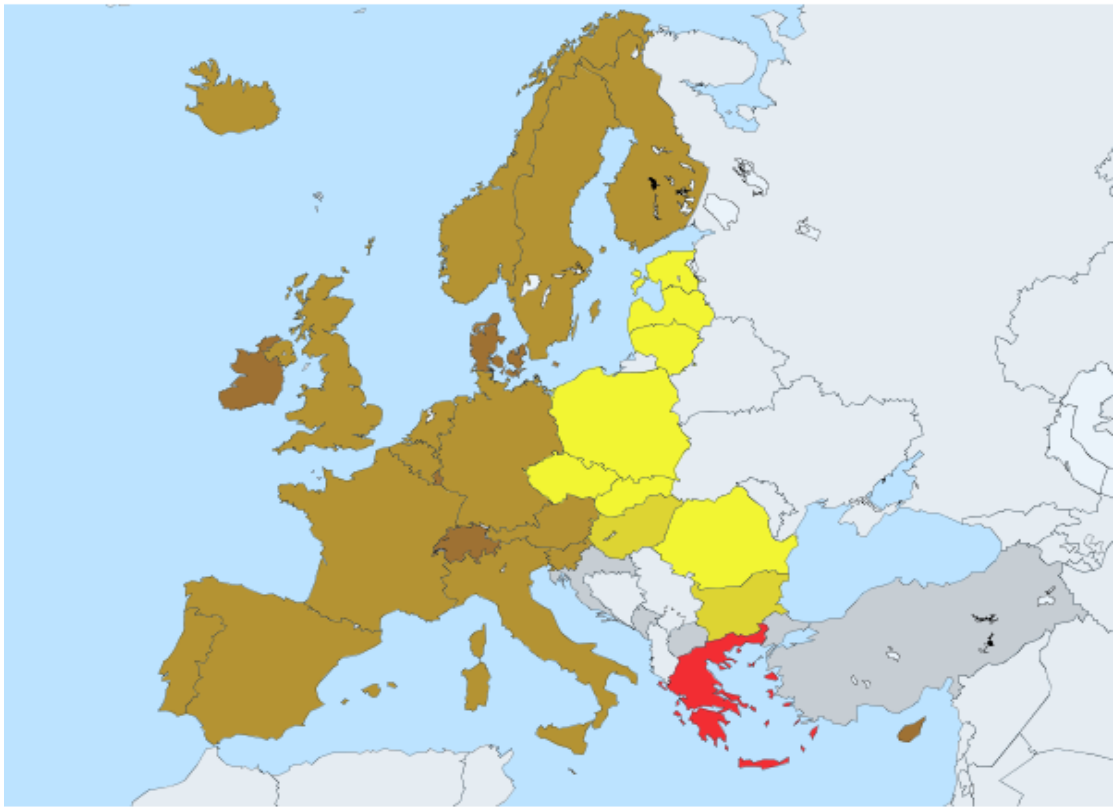
Map 1. Comparative map of total MSW treatment per capita in EU-27 and EFTA (2009)

Municipal waste generation and treatment, by type of treatment method

kg per capita - 2009

Total waste treatment

Based on a comparison with:Greece



Legend

0.5777 - 0.7888 | 0.7888 - 0.9999 | 1.0000

1.0001 - 1.348 | 1.348 - 1.6958 | N/A

Minimum value:0.578 Maximum value:1.696

Source of Data:: Eurostat

Copyright of administrative boundaries: ©EuroGeographics, commercial re-distribution is not permitted

Last update: 09.02.2012

Date of extraction: 17 Feb 2012 15:56:27 MET

Hyperlink to the map: http://epp.eurostat.ec.europa.eu/tgm/mapToolClosed.do?tab=map&init=1&plugin=1&language=en&pcode=tsdpc240&toolbox=legend

Disclaimer: This map has been created automatically by Eurostat software according to external user specifications for which Eurostat is not responsible.

General Disclaimer of the EC: http://europa.eu/geninfo/legal_notices_en.htm

Short Description: Municipal waste consists to a large extent of waste generated by households, but may also include similar wastes generated by small businesses and public institutions and collected by the municipality; this part of municipal waste may vary from municipality to municipality and from country to country, depending on the local waste management system.
For areas not covered by a municipal waste collection scheme the amount of waste generated is estimated.

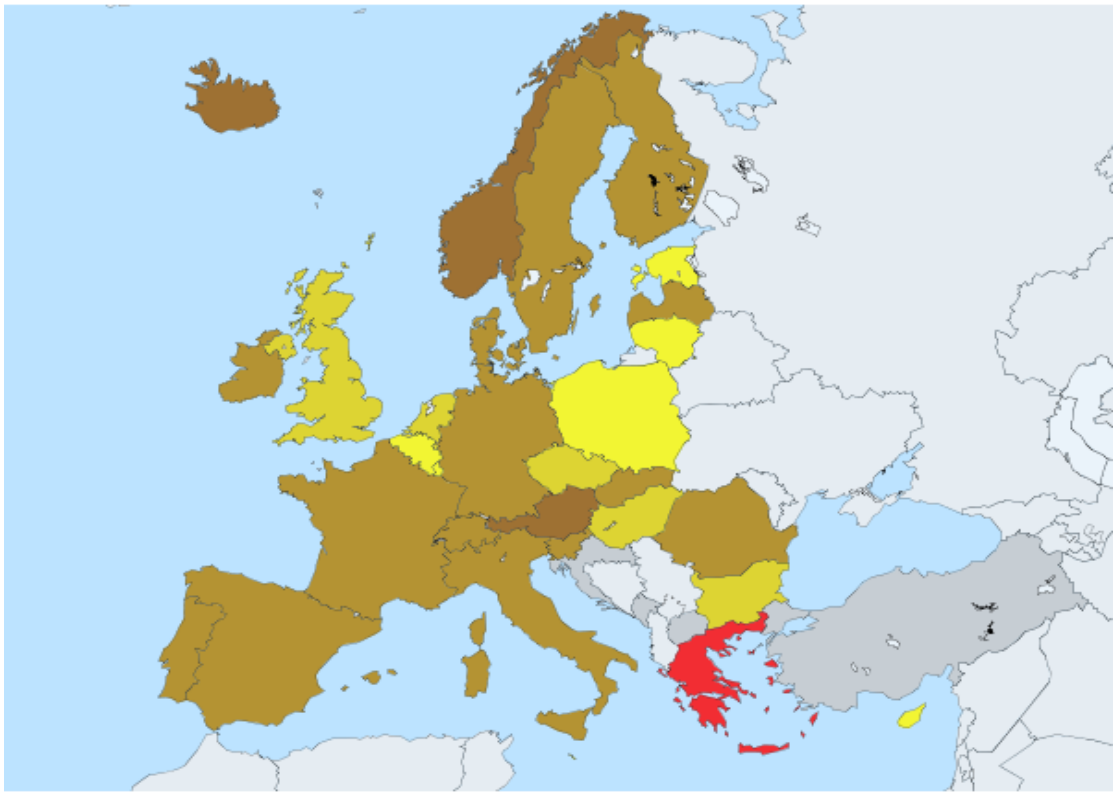
Code: tsdpc240

Map 2. Comparative map of electricity generated from renewable sources in EU-27 and EFTA (2009)

Electricity generated from renewable sources

% of gross electricity consumption

Based on a comparison with:Greece



Legend

0.0 - 0.5 | 0.5 - 0.9999 | 1.0000

1.0001 - 4.6935 | 4.6935 - 8.3869 | N/A

Exceptions: IS(1997)

Minimum value:0.0 Maximum value:8.387 eu25:18.135 eu15:Not available

Source of Data:: Eurostat

Copyright of administrative boundaries: ©EuroGeographics, commercial re-distribution is not permitted

Last update: 09.02.2012

Date of extraction: 17 Feb 2012 16:05:49 MET

Hyperlink to the map: http://epp.eurostat.ec.europa.eu/tgm/mapToolClosed.do?tab=map&init=1&plugin=1&language=en&pcode=tsien050&toolbox=legend

Disclaimer: This map has been created automatically by Eurostat software according to external user specifications for which Eurostat is not responsible.

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Short Description: This indicator is the ratio between the electricity produced from renewable energy sources and the gross national electricity consumption for a given calendar year. It measures the contribution of electricity produced from renewable energy sources to the national electricity consumption. Electricity produced from renewable energy sources comprises the electricity generation from hydro plants (excluding pumping), wind, solar, geothermal and electricity from biomass/wastes. Gross national electricity consumption comprises the total gross national electricity generation from all fuels (including autoproduction), plus electricity imports, minus exports.

Code: tsien050

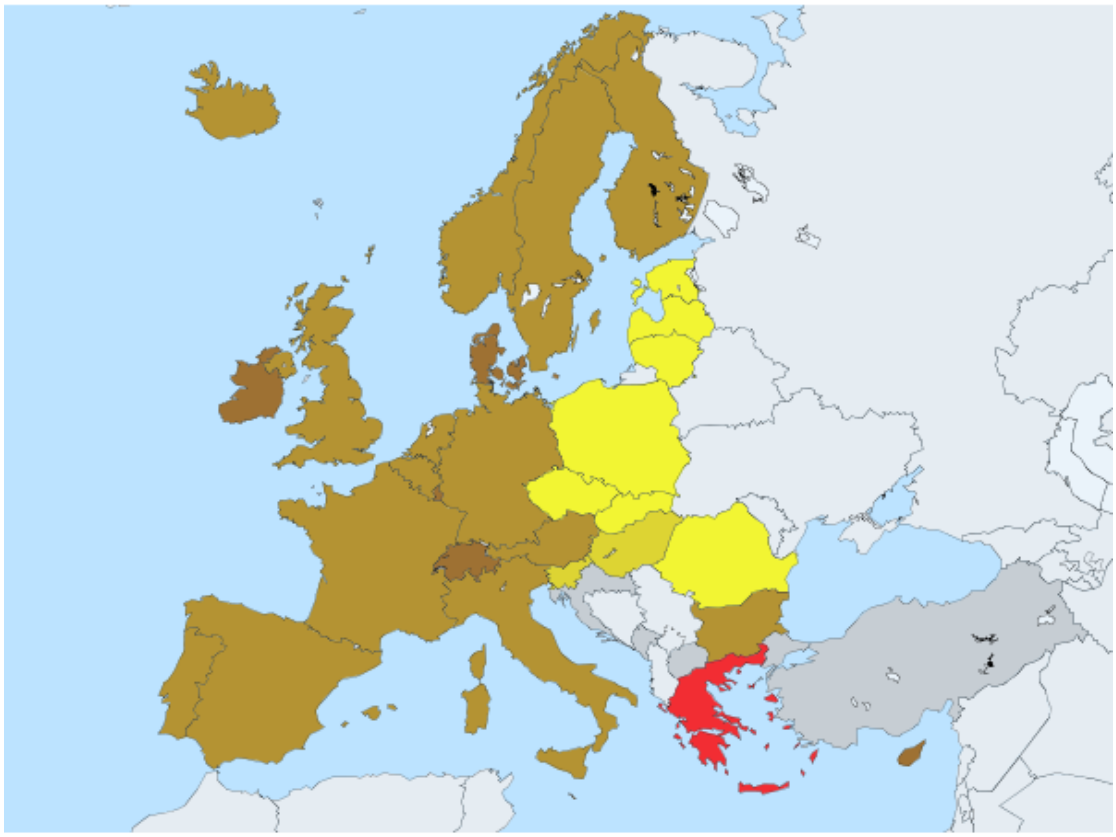
Map 3. Comparative map of MSW generation per capita in EU-27 and EFTA (2009)

Municipal waste generation and treatment, by type of treatment method

kg per capita - 2009

Waste generated

Based on a comparison with:Greece



Legend

0.6915 - 0.8457 | 0.8457 - 0.9999 | 1.0000

1.0001 - 1.348 | 1.348 - 1.6958 | N/A

Minimum value:0.691 Maximum value:1.696

Source of Data:: Eurostat

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Last update: 09.02.2012

Date of extraction: 17 Feb 2012 15:58:29 MET

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Short Description: Municipal waste consists to a large extent of waste generated by households, but may also include similar wastes generated by small businesses and public institutions and collected by the municipality; this part of municipal waste may vary from municipality to municipality and from country to country, depending on the local waste management system.
For areas not covered by a municipal waste collection scheme the amount of waste generated is estimated.

Code: tsdpc240

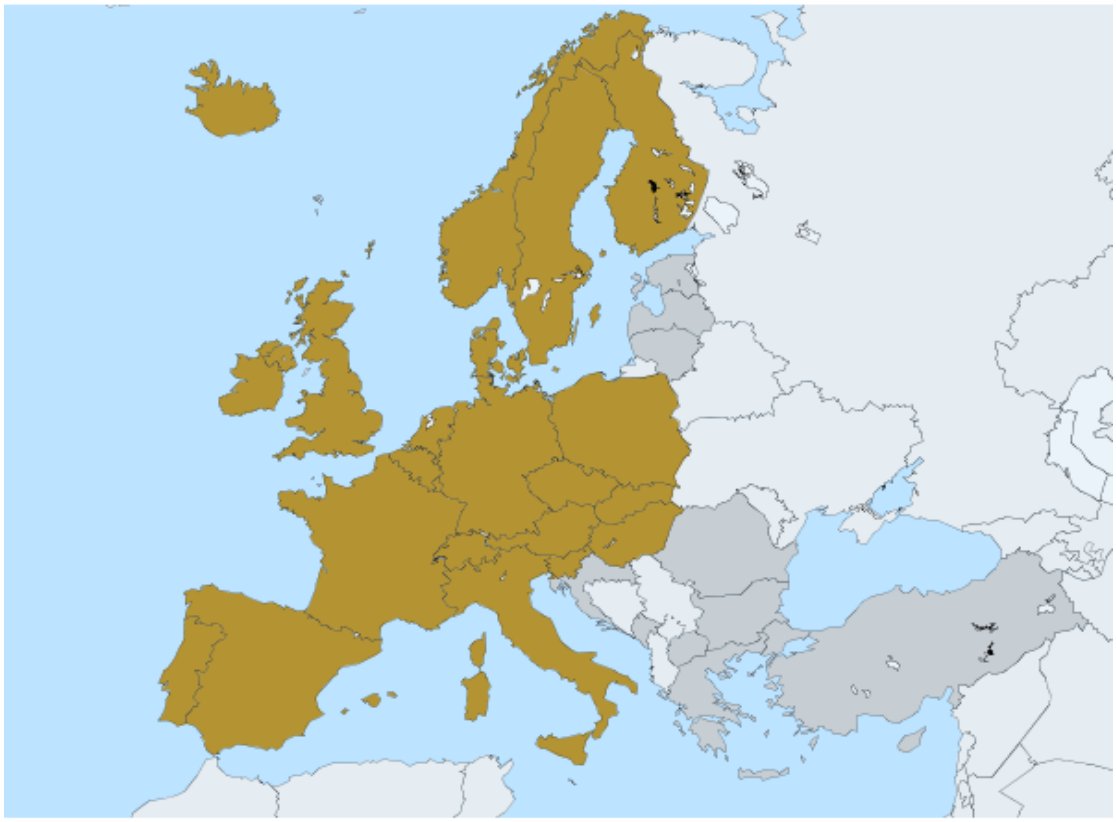
Map 4. Indicative map of countries already resorted to MSWI (including energy recovery) in EU-27 and EFTA (2009)

Municipal waste generation and treatment, by type of treatment method

kg per capita - 2009

Total incineration (including energy recovery)

Based on a comparison with:Greece



Legend

0.9997 - 0.9998 | 0.9998 - 0.9999 | 1.0000

1.0001 - 9.223372036854776E14 | 9.223372036854776E14 - 0.0 | N/A

Minimum value:9.223372036854776E15 Maximum value:9.223372036854776E15

Source of Data:: Eurostat

Copyright of administrative boundaries: ©EuroGeographics, commercial re-distribution is not permitted

Last update: 09.02.2012

Date of extraction: 17 Feb 2012 15:52:11 MET

Hyperlink to the map: http://epp.eurostat.ec.europa.eu/tgm/mapToolClosed.do?tab=map&init=1&plugin=1&language=en&pcode=tsdpc240&toolbox=legend

Disclaimer: This map has been created automatically by Eurostat software according to external user specifications for which Eurostat is not responsible.

General Disclaimer of the EC: http://europa.eu/geninfo/legal_notices_en.htm

Short Description: Municipal waste consists to a large extent of waste generated by households, but may also include similar wastes generated by small businesses and public institutions and collected by the municipality; this part of municipal waste may vary from municipality to municipality and from country to country, depending on the local waste management system.
For areas not covered by a municipal waste collection scheme the amount of waste generated is estimated.

Code: tsdpc240

Table 1. MSW in EU-27 and EFTA (2009)[358]

Municipal waste, 2009 Municipal waste generated, kg per person		Total municipal waste treated, kg per person	Municipal waste treated, %			
			Landfilled	Incinerated	Recycled	Composted
EU-27	**513**	**504**	**38**	**20**	**24**	**18**
EU-15						
Austria	591	591	1	29	30	40
Belgium	491	486	5	35	36	24
Denmark	833	833	4	48	34	14
Finland	481	481	46	18	24	12
France	536	536	32	34	18	16
Germany	587	564	0	34	48	18
Greece	478	474	82	-	17	2
Ireland	742	730	62	3	32	4
Italy	541	594	45	12	11	32
Luxembourg	707	707	17	36	27	20
Netherlands	616	520	1	39	32	28
Portugal	488	488	62	19	8	12
Spain	547	547	52	9	15	24
Sweden	485	480	1	49	36	14
United Kingdom	529	538	48	11	26	14
EU-12						
Bulgaria	468	450	100	-	-	-
Cyprus	778	778	86	-	14	-
Czech Republic	316	274	83	12	2	2
Estonia	346	285	75	0	14	11
Hungary	430	427	75	10	13	2
Latvia	333	333	92	0	7	0
Lithuania	360	342	95	-	3	1
Malta	647	643	96	-	4	-
Poland	316	264	78	1	14	7
Romania	396	308	99	-	1	0
Slovakia	339	311	82	10	2	6
Slovenia	449	495	62	1	34	2
EFTA						
Iceland	554	520	73	11	14	2
Norway	473	467	14	42	28	16
Switzerland	706	706	-	49	34	17

Data for the EU-27, Denmark, Germany, Spain, France, Italy, Cyprus, Luxembourg, Netherlands, Romania, Portugal and the United Kingdom are estimated.
0 equals less than 0.5%, "-"indicates a real zero

[358] Eurostat Press Office (2011)