

# Benefits and Trade-Offs Between Energy Conservation and Releases of Unintentionally Produced Persistent Organic Pollutants

A STAP advisory document



**Scientific and Technical Advisory Panel**

The Scientific and Technical Advisory Panel, administered by UNEP, advises the Global Environment Facility



# Benefits and Trade-Offs Between Energy Conservation and Releases of Unintentionally Produced Persistent Organic Pollutants

A STAP advisory document

**Scientific and Technical Advisory Panel**

The Scientific and Technical Advisory Panel, administered by UNEP, advises the Global Environment Facility



## **Benefits and Trade-Offs Between Energy Conservation and Releases of Unintentionally Produced Persistent Organic Pollutants, A STAP advisory document:**

Prepared on behalf of the Scientific and Technical Advisory Panel (STAP) of the Global Environment Facility (GEF) by:

Siegmund Böhmer, Federal Environment Agency, Industry and Power Plants, Wien, Austria

William Carroll, Occidental Chemical Corporation, Dallas, Texas

Emmanuel Fiani, ADEME - Agence de l'Environnement et de la Maîtrise de l'Energie, Angers, France

Hans Hartenstein, Energy & Environmental Consultants GmbH, Nümbrecht, Germany

Ute Karl, European Institute for Energy Research (EIFER), Karlsruhe, Germany

### **Reviewed by:**

Patrick Finlay, Environmental Consultant, Ottawa, Canada

Sfeffi Richter, Federal Environment Agency, Dessau-Roblau, Germany

### **Acknowledgements**

STAP wishes to thank several other reviewers of the Advisory Document. Staff of the United Nations Environment Program, the United Nations Industrial Development Organization, particularly Heinz Leuenberger (Director of the Environmental Management Branch, UNIDO), and the Climate Change team of the GEF Secretariat all provided constructive comments that helped to improve the Advisory Document and refine recommendations. The STAP Secretariat (Lev Neretin, Guadalupe Duron and Douglas Taylor) edited the revised version.

Design & Layout: Jinita Shah, UNON Publishing Services Section, Nairobi, ISO 14001:2004-certified.

Cover photo: 2007. Manfred Steinbach. Image from Bigstock.com

Please use the following reference for this publication: GEF-STAP (2009). Benefits and trade-offs between energy conservation and releases of unintentionally produced persistent organic pollutants, A STAP advisory document by S.Böhmer, W.Carroll, E.Fiani, H. Hartenstein, and U.Karl. Global Environment Facility, Washington, D.C.

### **About STAP**

The Scientific and Technical Advisory Panel comprises six expert advisers supported by a Secretariat, which are together responsible for connecting the Global Environment Facility to the most up to date, authoritative and globally representative science.

<http://stapgef.unep.org/>

## Preface

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) emphasized a need for capturing synergies and avoiding trade-offs when addressing greenhouse gases (GHG) mitigation and air pollution control. The efficiency of a framework depends on the choice and design of the policy instruments and their integration.

Air pollutants and GHGs are often emitted by the same sources, and, therefore, a single set of technologies or policy measures (an integrated approach) has co-benefits for emission reduction. However, there are situations when energy efficiency improvements may have limited or negative impact on the release of air pollutants (trade-offs).

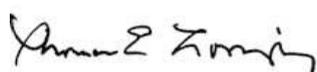
Annex C of the Stockholm Convention on persistent organic pollutants (POPs) lists twenty source categories which may have significant global impacts on the formation and release of so-called unintentionally produced POPs to the environment. Many of these categories also account for a significant part of global energy consumption and GHG emissions.

As the Stockholm Convention now moves from enabling activities, such as developing National Implementation Plans into actual implementation, it becomes increasingly important that the measures taken and investments made are compatible with the aims of other conventions, in particular the United Nations Framework Convention on Climate Change.

The report was commissioned following the request from the Global Environment Facility (GEF) to the Scientific and Technical Advisory Panel (STAP) to explore the relationship between management of unintentionally produced POPs and climate change mitigation strategies in GEF operations. Specifically, the report addresses whether the implementation of best available techniques and best environmental practices (BAT/BEP), in the context of the Stockholm Convention, has synergistic effects on GHG emissions, or whether there are trade-offs.

This report from STAP, while showing in many instances that co-benefits do occur also provides recommendations to the GEF, clearly demonstrating the need for careful consideration of Annex C sources that involve significant combustion for heat or energy generation or destruction of waste and gives some guiding principles for analysis of benefits and trade-offs. The report also cautions that some unresolved issues could benefit from further work that considers life cycle analyses.

Finally, while this report offers succinct and well targeted advice to the GEF, it also suggests some next steps to take, and it is hoped that with the assistance of the STAP report the continued implementation of the UNFCCC and the Stockholm Convention will take place with increased benefits to both conventions in pursuing the aim of a sustainable future.



Thomas E. Lovejoy  
Chair, Scientific and Technical Advisory Panel



Bo Wahlström  
STAP member

# Table of contents

Preface.....	iii
Acronyms.....	v
Executive summary.....	1
Recommendations to the GEF.....	4
I. Introduction.....	7
II. Review of Part II and III in Annex C sources of unintentionally produced POPs of the Stockholm Convention.....	11
II.1. Waste Incineration, firing installations for wood and other biomass fuels, residential combustion.....	11
II.1.1. Incineration of municipal solid waste, hazardous waste, sewage sludge and medical waste.....	11
II.1.2. Firing installations for wood and other biomass fuels.....	16
II.1.3. Residential Combustion Sources.....	18
II.2. Crematoria.....	19
II.3. Cement kilns firing hazardous waste.....	21
II.4. Fossil fuel-fired utility and industrial boilers.....	23
II.5. Motor vehicles, particularly those burning leaded gasoline.....	25
II.6. Production of pulp using elemental chlorine or chemicals generating elemental chlorine, specific chemical production processes releasing Annex C chemicals, textile and leather dyeing and finishing.....	26
II.6.1. Production of pulp using elemental chlorine.....	26
II.6.2. Specific chemical processes releasing unintentionally produced POPs, especially production of chlorophenols and chloranil.....	27
II.7. Smoldering of copper cables and opening burning of waste.....	29
II.7.1. Smoldering of copper cables.....	29
II.7.2. Open burning of waste.....	29
II.8. Thermal processes in the metallurgical industry in Parts II and III of Annex C.....	30
II.8.1. Secondary copper, aluminum, zinc and lead production.....	30
II.8.2. Sinter plants in the iron and steel industry.....	31
II.8.3. Thermal processes in the metallurgical industry not mentioned in Annex C Part III: Primary aluminum production, magnesium production, primary base metals smelting.....	33
II.8.4. Other thermal processes in the metallurgical industry not mentioned in Annex C Part III: Secondary steel production.....	34
III. Cross-cutting considerations (waste management, training and awareness raising, testing, monitoring and reporting).....	37
IV. Discussion on capturing benefits and avoiding trade-offs in the promotion of energy conservation and unintentionally produced POPs reduction.....	43
V. Conclusions.....	49
List of References.....	51

# Acronyms

AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)
BAT	Best Available Techniques
BEP	Best Environmental Practices
BF	Bagfilter
BFBC	Bubbling Fluidized Bed Combustion
BIGCC	Biomass Integrated Gasification Combined Cycle
CEIT	Countries with Economies in Transition
CFBC	Circulating Fluidized Bed Combustion
CHP	Combined Heat and Power
EAf	Electric Arc Furnace
ECF	Elemental Chlorine-Free (process)
ESP	Electrostatic Precipitator
EU	European Union
FBC	Fluidized Bed Combustion
FGD	Flue Gas Desulphurization
GEF	Global Environment Facility
GHG	Green House Gas
GWP	Global Warming Potential
HCb	Hexachlorobenzene
HCl	Hydrochloric Acid
HM	Heavy Metals
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
KRS	Kayser Recycling System
LCA	Life Cycle Assessment / Analysis
LULUCF	Land Use, Land-Use Change and Forestry
MSW	Municipal Solid Waste
NO <sub>x</sub>	Nitrogen Oxides
OECD	Organization for Economic Co-operation and Development
ORC	Organic Rankine Cycle

PAH	Polycyclic Aromatic Hydrocarbons
PCB	Polychlorinated Biphenyls
PCDD	Polychlorinated Dibenzop-dioxins
PCDF	Polychlorinated Dibenzofurans
PFC	Perfluorocarbons
PM	Particulate Matter
POP	Persistent Organic Pollutant
PTS	Persistent Toxic Substance
SAICM	Strategic Approach to International Chemicals Management
SCM	Sound Chemicals Management
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
STAP	Scientific and Technical Advisory Panel
SO <sub>2</sub>	Sulfur Dioxide
TAL	Tetraalkyllead
TEQ	Toxic Equivalent
TCF	Totally chlorine-free (process)
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
UNFCCC	United Nations Framework Convention on Climate Change



## Executive summary

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) emphasized a need for capturing synergies and avoiding trade-offs when addressing greenhouse gases (GHG) mitigation and air pollution control. The efficiency of a framework depends on the choice and design of the policy instruments and their integration. Air pollutants and GHGs are often emitted by the same sources, and, therefore, a single set of technologies or policy measures (an integrated approach) has co-benefits for emission reduction. However, there are situations when energy efficiency improvements may have limited or negative impact on the release of air pollutants (trade-offs).

This report is commissioned following the request from the Global Environment Facility to the Scientific and Technical Advisory Panel (STAP) to utilize the relationship between management of unintentionally produced POPs and climate change mitigation strategies in GEF operations. This request also addresses recipient country needs in capturing multiple benefits of the Strategic Approach to International Chemicals Management (SAICM). Specifically, the report addresses the question as to whether implementation of best available techniques and best environmental practices (BAT/BEP) in the context of the Stockholm Convention<sup>1</sup> has synergistic effects on GHG emissions or whether there are trade-offs.

Annex C of the Stockholm Convention lists twenty source categories having significant global impacts on the formation and release of unintentionally produced persistent organic pollutants (unintentionally produced POPs)<sup>1</sup> to

---

1. In the Stockholm Convention context, BAT and BEP may be modified by socioeconomic considerations and may be different, country to country, depending upon state of development and other considerations. As part of the treaty implementation, BAT/BEP guidelines and guidance document was generated by an Expert Group. The technology in this document is best viewed as "state-of-the-art," presented as an aid to countries on the way to full development. In this paper, the state-of-the-art, as described in the BAT/BEP guidelines and guidance [UNEP, 2006] is taken as the benchmark for comparisons.

the environment. Many of these categories account for a significant part of global energy consumption and GHG emissions. Since by definition all GHG are emitted to the earth's atmosphere, the analysis mainly centered on air emissions of unintentionally produced POPs; however, there are many Stockholm Annex C processes with significant potential for direct unintentionally produced POPs emissions to water (pulp and paper) and land (ash and residue from various processes). Guidelines on BAT and Provisional Guidance on BEP relevant to Article 5 and Annex C of the Stockholm Convention (BAT/BEP guidelines and guidance) generally takes those issues into consideration and specifies best practices for all media, i.e., air, water and land; thus the reader is referred to the BAT/BEP guidelines and guidance [UNEP, 2006].

**Waste incineration**, as part of an environmental sound waste management system is an accepted technique for minimizing the impacts on the environment of the whole system – provided that BAT and BEP is effectively implemented. BAT and BEP for the process includes the implementation of operational (primary) measures, effective end-of-pipe techniques and appropriate treatment/disposal options for solid residues (especially, for fly ash). Primary measures both reduce GHG and POPs emissions, be it by the prevention of POPs formation or by providing the basis for high energy efficiency and reduced process demand of energy. In addition, the application of BAT and BEP helps to optimize the process by increasing the efficiency of end-of-pipe techniques over the life-time of the plant. A very limited number of end-of-pipe techniques exist for the sole reduction of POPs emissions; the majority of these techniques have the co-benefit of minimizing the emissions of a variety of pollutants (including Particulate Matter (PM), Nitrogen Oxides (NO<sub>x</sub>), Sulfur Dioxide (SO<sub>2</sub>), Hydrochloric Acid (HCl) and Heavy Metals (HM)). The operation of end-of-pipe techniques is in general accompanied by energy consumption and an overall increase of GHG emissions. However, from a total perspective this drawback of energy consumption is far outweighed by the benefits, in terms of energy efficiency and emission reduction (including GHG) achieved by BAT and BEP. The goals of POPs and GHG emission reduction should be seen in the context of an integrated approach to protect the environment as a whole. More emphasis should be given to the application of the principles of the waste reduction and hierarchy.

Unintentionally produced POPs can be generated in **firing installations for wood and other biomass** fuels, particularly when using contaminated biomass. BAT to reduce PCDD/PCDF emissions include the control of fuel quality (including exclusion of treated woods and non-virgin biomass and other waste), optimized combustion technology, optimized air supply, mixing and residence time as well as optimized plant operation. Combustion of virgin biomass is considered CO<sub>2</sub>-neutral in many government policies. However, combustion of non-virgin biomass or non-biomass combustible material, results in the emission of additional GHGs, mostly in form of CO<sub>2</sub>. Other GHGs can be formed through incomplete combustion (nitrous oxide, methane). In general, fuel efficiency and conservation can reduce GHG emissions when combustion is used to generate electricity, particularly via combined heat and power (CHP) applications.

Efficient combustion of clean, chemically untreated fuels for cooking and heating is of primary importance for reducing the formation and release of POPs in **the residential combustion** sector. BAT and BEP for residential combustion include ensuring separation of household waste from fuel to avoid burning of such waste in cooking and heating appliances. GHG can be reduced in the residential sector by increasing the share of virgin biomass fuel and by increasing energy efficiency, and by reductions on the demand side. Coal and biomass burning stoves dominate energy supply for households in rural areas of developing countries. Improved stoves can save from 10 to 50% of fuel consumption for the same cooking service at the same time reducing indoor air pollution. In industrialized countries, there is a risk of increasing POPs releases in the case of a switch from efficient liquid, or gaseous fossil fuels to solid biomass. Unintentionally produced POPs are best avoided by appropriate technology, such as, stoves and boilers with automatic fuel supply, and standardized for at least dry and homogenized biomass fuels.

**Cremation** is a religiously and culturally important and accepted practice for many cultures and countries as a way of dealing with the death of human beings. Due to the small size of crematories, environmental impacts are restricted to the local area and can be effectively minimized by application of BAT and BEP. GHG emissions of cremation are negligible by comparison to national or global emissions. Energy consumption of end-of-pipe techniques for the removal of particulates, mercury (Hg) and POPs is low due to the comparable small scale of crematoria.

2. Annex C of the Stockholm Convention applies to the following persistent organic pollutants when formed and released unintentionally from anthropogenic sources: Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDF), Hexachlorobenzene (HCB), and Polychlorinated biphenyls (PCB).

BAT and BEP to avoid POPs emissions from **cement kiln** operation include comprehensive primary measures such as fuel quality control, process control and rapid cooling of flue gases. End-of-pipe measures are mainly installed to reduce emissions of PM, SO<sub>2</sub> or NO<sub>x</sub> and control of POPs emissions is a welcome side effect of such measures. The main options for the reduction of greenhouse gas emissions include technology improvements, clinker substitutes for cement production, the use of low carbon fossil fuels, and also certain types of waste as a fuel. Technology improvements with an increase of energy efficiency of the process show the highest GHG emission reduction potential and a clear co-benefit of GHG and POPs emission reduction. Depending on the type of waste, its use as a fuel can create adverse effects. The use of such fuels requires careful input and process control to avoid an increase of POPs and/or heavy metals emissions. The benefit of GHG emission reduction through substitution of fossil fuels by wastes should be assessed on a site specific basis.

**Fossil fuel fired utility and industrial boilers** are one of the largest sources of GHG emissions worldwide. Even though the amounts of POPs emitted are small compared to other sources and the primary purpose of correct application of BAT/BEP is the reduction of PM, SO<sub>2</sub>, NO<sub>x</sub>, and HMs, the correct design and operation of proper flue gas cleaning equipment will also further reduce the emissions of POPs. BEP combined with necessary secondary BAT flue gas cleaning systems (ESP or baghouses for particulate control, selective catalytic reduction (SCR) for NO<sub>x</sub>-control and flue gas desulphurization (FGD) for SO<sub>2</sub> control) further reduce the emissions of unintentionally produced POPs. Additionally, improvements in power generation efficiency reduce the amount of fossil fuel consumed per unit energy generated, leading to reductions of GHG and unintentionally produced POPs emissions.

As leaded gasoline in **motor fuels** has been phased out in most regions, this is a smaller source of POPs. The difference between leaded- and unleaded-gasoline in generation of GHG is not significant compared to other differences in engine technologies.

BAT for elimination of **production of pulp using elemental chlorine** is described as Elemental Chlorine Free (ECF) or Totally Chlorine Free (TCF) bleaching. The two are distinguished by the use of chlorine dioxide as bleaching agent in the former along with various other steps which may also use oxygen, peroxide and ozone. ClO<sub>2</sub> is derived from sodium chlorate which requires more energy to produce than elemental chlorine or sodium hypochlorite; ozone

is generated electrochemically from oxygen. The bleaching process is a small component of energy used in making pulp and paper. BAT application may carry a 1% penalty in GHG in exchange for virtual elimination of POPs in the process.

BAT for **specific chemical production** processes involves purification of intended product and isolation of POPs in a waste stream that can be destroyed by hazardous waste incineration. When integrated into a manufacturing facility, waste process heat can be used for the purification step and the inherent fuel value of the waste may sustain its combustion. Slightly increased GHG emissions (as CO<sub>2</sub>) result from combustion of 1-2% waste from the processes; process energy use—with or without waste destruction—is a much larger source.

**Smoldering of copper cables** should be eliminated; such elimination is a significant reduction in POPs generation and also results in reduced GHG emissions since waste material is not combusted.

**Secondary steel, copper, aluminum, zinc and lead productions** are significant sources of unintentionally produced POPs. However, secondary production of metals generally consumes significantly less energy than primary production from ores. BAT/BEP measures can generate low GHG impacts which are largely outweighed by very high positive impacts in terms of minimization of unintentionally produced POPs and other pollutants. Some BAT/BEP primary measures should be carefully considered and their specific impacts on energy consumption should be assessed on a plant-by-plant basis.

**Primary metal production** (from ores) is very energy intensive. Hence BAT/BEP measures for sinter plants in the iron and steel industry and for primary base metal production are considered to be neutral to low. Alternative processes are likely to generate low-to-high impacts in terms of CO<sub>2</sub> emissions. However, these impacts should be assessed on a plant-by-plant basis as they are strongly dependant on the availability of appropriate fuels and metallic raw materials.

**Other source categories of unintentionally produced POPs** which are specified in the Stockholm Convention Annex C were not considered in detail in the Advisory Document, because they are relatively insignificant sources of unintentionally produced POPs and GHGs. These sources include destruction of animal carcasses, textile and leather dyeing and finishing, shredder plants for the treatment of end of life vehicles, and waste oil refineries.

For GHG and unintentionally produced POPs emissions consideration, it is recognized that for some GHG sectors, the sources within that sector which contribute to unintentionally produced POPs, may be relatively small. For example, in the iron and steel sector, sintering plants are relatively small generators of GHG but are relatively major sources of unintentionally produced POPs. Similarly, for the chemical sector, potential unintentionally produced POPs sources are relatively small generators of GHGs.

There are three ways to classify unintentionally produced POPs and GHG reduction strategies: 1) approaches to unintentionally produced POPs reduction which also reduce GHGs; 2) unintentionally produced POPs reduction methods which increase GHGs; or 3) situations where the two emissions are not closely related.

Many of the unintentionally produced POPs reduction technologies corresponding to Stockholm Convention recommended BAT and BEP aim at improving the combustion conditions, increasing energy efficiency, raising energy recovery rates (e.g. by use of combined heat and power (CHP) systems) and improving the quality of solid residues from emission reduction systems.

There are a few cases where application of BAT and BEP requires (in most cases a minor) increase in the energy demand. This is the case for air pollution control equipment (end-of-pipe techniques). Only a couple of these techniques are installed solely for the reduction of unintentionally produced POPs (e.g. quenching, afterburner). The majority has the co-benefit of reducing other pollutants, such as particulates, sulfur dioxide, nitrogen oxides and metals. Another example where energy is required is the treatment and disposal of solid residues from flue gas cleaning (e.g. fly ash from waste incineration plants). These treatment/disposal techniques target not only POPs but also metals and other compounds.

In some cases, reduction of POPs comes from application of a technology that does not require additional energy and results in no additional GHG (e.g. fuel switch, use of chlorine free bleaching agents).

In some cases, elimination of a process such as open burning of waste or smoldering of copper cables can, on its face, eliminate generation of GHG such as CO<sub>2</sub> as well as unintentionally produced POPs. However the need to deal with the waste by some means remains. Every waste management activity should be optimized concerning energy consumption and emissions of

CO<sub>2</sub> and methane (CH<sub>4</sub>) according to waste hierarchy principles (i.e., prevention, reduction, reuse, recycling, recovery, incineration including reuse, recycling and/or recovery of incineration by-products and final disposal in the landfill). Modern incineration is often accompanied by energy recovery from the process or by heat and electricity co-generation. This leads to a significant offset in the use of other fuels. The net result is a reduction in GHG emissions. Substitution of modern incineration for open burning may reduce generation of POPs but present no significant benefit in GHG reduction unless the energy is recovered. Substitution of recycling or composting for a significant fraction of the waste otherwise incinerated will reduce POPs but the impact on GHG is uncertain and requires life cycle analysis/assessment (LCA). Similarly, a fuller consideration of life cycle issues than is possible in this study may be needed to analyze options for fuel substitution, waste management systems or complex process changes.

BAT and BEP is the implementation of an effective waste management system which at the end reduces the waste throughput. The implementation of the waste hierarchy and integrated life cycle principles will, in general, reduce emissions of all polluting substances (including GHGs and unintentionally produced POPs) by providing the basis for a longer life time of goods, with increased reuse of products, higher recovery and recycling rates.

## Recommendations to the GEF

The advisory document is relevant to all Strategic Objectives of the GEF-4 Climate Change Focal Area with inter-linkages to source categories of polychlorinated dibenzo-dioxins/polychlorinated dibenzo-furans (PCDD/PCDF) and other air-born Persistent Toxic Substances (PTS) (particularly, to Strategic Objective 2 "To promote energy-efficient technologies and practices in industrial production and manufacturing processes"). It is also relevant to the Strategic Objective 1 of the GEF-4 POPs Focal Area "To reduce and eliminate production, use and releases of POPs" for projects dealing with BAT/BEP for the reduction of releases of unintentionally produced POPs. Reduction of land-based sources of PTS other than POPs in coastal and marine environments (foremost, of heavy metals) is a priority in the International Waters Focal Area. The Sound Chemicals Management (SCM) framework strategy emphasizes integration of SCM in GEF projects, inter alia, through activities that bring co-benefits to other focal areas<sup>3</sup>.

3. Focal area strategies and strategic programming for GEF-4.  
Available at: [http://gefweb.org/uploadedFiles/Focal%20Area%20Strategies\\_10.04.07.pdf](http://gefweb.org/uploadedFiles/Focal%20Area%20Strategies_10.04.07.pdf)

The analysis of benefits and trade-offs between GHG and unintentionally produced POPs emissions for the sectors with significant global impacts (waste incineration, firing installations for wood and other biomass fuels, residential combustion, cement kilns, fossil fuel fired utilities and industrial boilers) concluded that GEF climate mitigation projects that aim at maximizing thermal efficiency of fuel combustion (including improved fuel efficiency, increased carbon efficiency of fuel mixes and higher energy recovery [combined heat and power]) will also lead to reduced unintentionally produced POPs releases. Furthermore, the GEF's significant investments on the demand side of the energy efficient market (e.g., buildings and appliances, industrial energy efficiency and sustainable transport) tend to be also beneficial for the reduction of unintentionally produced POPs as these interventions aim at reducing the emission generating activity. Complementing these interventions with the application of end-of-pipe techniques represent no-regret measures with a minor penalty on energy demand (i.e., GHG emissions), but substantial co-benefits of reducing unintentionally produced POPs and other pollutants such as PM, NO<sub>x</sub>, SO<sub>2</sub>, HCl, HF and heavy metals including mercury.

Experience gained in prevention and control of pollution by developed countries should be utilized. Environmental performance guidance and standards for many industrial and other sectors are reflected in the World Bank Group (WBG) International Finance Corporation (IFC) Environmental, Health and Safety Guidelines (EHS). These comprehensive WBG IFC Guidelines take a multi-pollutant, multi-media approach to sources, and include energy efficiency considerations.

**Recommendation I:** GEF should continue promoting energy efficiency investments for Annex C source categories and complement these primary measures with support for air pollution control such as end-of-pipe techniques. Increased financial support is required for the development of the integrated national/regional climate mitigation and multi-pollutant prevention and control plans and strategies reflecting upon source- and site-specific information. GEF recipients should also consider potential synergies and trade-offs between GHG emissions and unintentionally produced POPs releases in the process of developing National unintentionally produced POPs Action Plans, or similar strategies.

The Stockholm Convention recommended BAT/BEP that have multi-pollutant reduction benefits of cleaner production activities with no, or insignificant, GHG emissions penalty.

**Recommendation II:** GEF projects dealing with Annex C source categories should comply in full with the provisions of BAT/BEP guidelines and guidance of the Convention, taking into account source-specific considerations provided in the Advisory Document.

**Recommendation III:** GEF should support training in available environmental methodologies, practices and tools at both managerial and technical or operating levels in public and private sector organizations involved in the implementation of the BAT/BEP guidelines and guidance. The BAT/BEP guidance and guidelines, the WBG/IFC EHS Guidelines, and this Document could be the basis for developing user-friendly training tools.

Eliminating open burning of waste (including smoldering of copper cables) should be one of the GEF priorities, because open burning is a significant global source of unintentionally produced POPs and elimination of this practice results also in a direct reduction of GHG emissions. STAP notes that these interventions have to be considered as an integral part of a waste management hierarchy, because mitigation of POPs emissions in one source category involves the potential to switch POPs release and GHG emissions to another source category (waste incineration vs. open burning vs. landfilling vs. composting).

**Recommendation IV:** GEF should place increased emphasis on the promotion of waste management and strategies and concepts that take a full account of the waste management hierarchy. Final decision to support a particular waste management practices including treatment and disposal should take into account potential energy conservation (reduced GHG emissions) and unintentionally produced POPs reduction.

Material conservation and energy consumption are often directly linked and in most cases offer higher environmental benefits than implementation of energy efficiency measures alone. Capturing synergies and avoiding trade-offs between energy conservation and release of unintentionally produced POPs is only part of a broader development framework towards sustainable production and consumption. The latter requires a range of tools and strategies to be applied to

all stages of life cycle of goods and services, including awareness raising, capacity building, design of policy frameworks, market-based and voluntary instruments, and consumer information tools. Although demanding and sophisticated, life cycle analysis for the industrial process optimization is the first step towards this goal. The UNIDO/UNEP Resource Efficient and Cleaner Production network could be instrumental in this regard. Due its multistakeholder nature GEF could be instrumental in establishing baseline information and building necessary skills and capacity to conduct LCA.

**Recommendation V:** GEF should promote capacity building and awareness raising activities in developing countries and CEIT on the use of integrated LCA at the regional and national levels. No assumptions should be made about comparative impacts of alternatives; there is no substitute for characterizing actual impacts in each situation. GEF projects dealing with fuel, or technology switch, should include LCAs to consider cumulative impact on GHG emissions, and unintentionally produced POPs releases.





## I. Introduction

The Fourth Assessment Report of the IPCC (AR4) emphasized a need for capturing synergies and avoiding trade-offs when addressing GHG mitigation and air pollution control. Climate mitigation policies, including interventions aimed at increased energy efficiency, if designed independently from air pollution control, can lead to increased air pollution and may be cost-ineffective due to increased pollution control costs, higher burden of disease, and costs of environmental degradation [Sims et al., 2007].

Inefficient fuel combustion processes may emit complex mixtures of organic pollutants, metals and fine particles resulting in global public health and environmental problems. As a rule, combustion technology, efficiency of combustion, and the use of a particular fuel determine the physical scale and chemical composition of combustion by-products. These by-products may include unintentionally produced POPs, such as PCDD/PCDF.

In 2004 energy supply accounted for 26% of the global GHG emissions, industry – 19%, land use change and forestry – 17%, agriculture – 14%, transport – 13%, residential, commercial and service sectors – 8%, and waste – 3%. However, no reliable global release inventories exist for PCDD/PCDF. While open burning of waste in some developing countries may be the major source category of PCDD/PCDF, this may not be the case for developed countries and countries with economies in transition (CEIT).

However developed countries may have other significant sources of unintentionally produced POPs such as metallurgical industries and residential combustion sources. Nevertheless, available national inventories indicate the source categories of Annex C of the Stockholm Convention as main contributors to national total emissions [Fiedler, 2007].

There is large uncertainty in the scientific literature and among policy makers about the possible

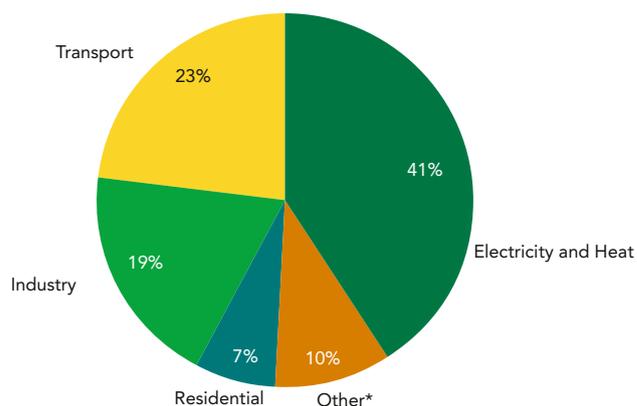
benefits and trade-offs between energy conservation practices and releases of unintentionally produced POPs and other air-born PTS. This analysis is meant to address the benefits and trade-offs uncertainty.

Annex C of the Stockholm Convention lists twenty source categories having significant impact on the formation and release of unintentionally produced POPs to the environment, including PCDD/PCDF, polychlorinated biphenyls (PCBs) and hexachlorobenzene (HCB). Unintentionally produced POPs are formed and released from thermal processes involving organic matter and chlorine as a result of incomplete combustion or chemical reactions [Stockholm Convention, 2001]. This study deals primarily with PCDD/PCDF. Formation mechanisms of PCDD/PCDF are described in details both in the Guidelines on BAT and Provisional Guidance on BEP Relevant to Article 5 and Annex C of the Stockholm Convention on Persistent Organic Pollutants (BAT/ BEP guidelines and guidance) [UNEP, 2006] and in the Standardized Toolkit for Identification and Quantification of Dioxin and Furan Releases (the Toolkit) [UNEP, 2005b].

## GHG Sources

Most of the source categories listed under Annex C of the Stockholm Convention are sectors, or parts of sectors, which account for a significant part of global CO<sub>2</sub> emissions (Figure 1).

Fig. 1. Shares of global CO<sub>2</sub> emissions by sector in 2006 [OECD, 2008].



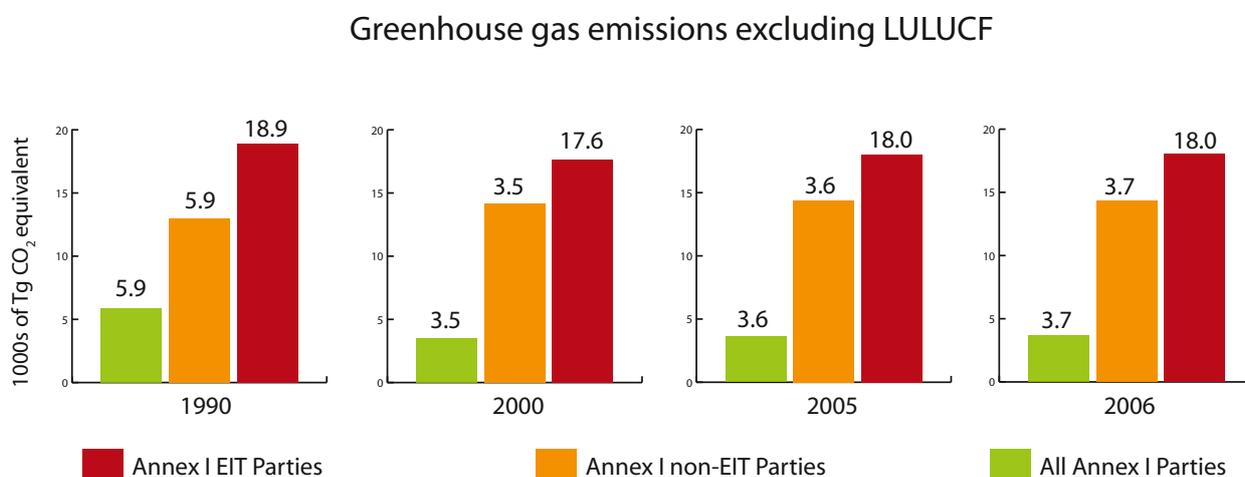
\* Other includes commercial/public services, agriculture/forestry, fishing, energy industries other than electricity and heat generation, and other emissions not specified elsewhere.

With regard to the sectors discussed here, the United Nations Framework Convention on Climate Change (UNFCCC) provides GHG emission inventories for Annex I countries only<sup>4</sup>. Total aggregate GHG emissions excluding emissions/removals from LULUCF for all Annex I parties amounted to about 18 Gt CO<sub>2</sub> equivalents in 2006 [UNFCCC, 2008]. Figure 2 provides an overview of these data indicating a decrease of 4.7% since 1990.

## Energy Statistics

In 2005 the total primary energy supply amounted to 479.7 EJ (exajoules) world-wide. For the period 1990 -

Fig. 2. GHG emissions from Annex I Parties, 1990, 2000, 2005 and 2006 [UNFCCC 2008] (EIT: Economies in Transition)



4. Annex I Parties: The industrialized countries listed in this annex to the Convention which were committed return their greenhouse-gas emissions to 1990 levels by the year 2000 as per Article 4.2 (a) and (b). They include the 24 original OECD members, the European Union, and 14 CEIT.

Table 1. Annual GHG emissions of UNFCCC Annex I countries by selected categories, in Gg CO<sub>2</sub> equivalent<sup>5</sup>

Category	Annex I 1990	Annex I 2006	Difference
1.A.1 Energy Industries	5.688.688,21	5.909.365,96	3,90%
1.A.2 Manufacturing Industries and Construction	2.566.490,16	2.299.694,51	-10,40%
1.A.3 Transport	3.212.919,40	3.718.192,22	15,70%
1.A.4 Other Sectors (including Residential)	2.060.741,30	1.830.538,34	-11,20%
2.A.1 Cement Production	240.504,31	246.156,12	2,30%
2.C.1 Iron and Steel Production	392.232,18	302.845,58	-22,80%
2.C.3 Aluminum Production	89.745,57	52.438,02	-41,60%
4.E Prescribed Burning of Savanna	6.611,50	11.477,65	73,60%
4.F Field Burning of Agricultural Residues	3.489,18	3.128,05	-10,30%
6.C.1 Waste Incineration - Biogenic	33.104,88	40.095,24	21,10%
6.C.2 Waste Incineration - Other (non-biogenic)	28.847,64	39.327,12	36,30%
<b>Total</b>	<b>14.323.374,35</b>	<b>14.453.258,81</b>	

2006 an increase of 34 % was observed [OECD, 2008]. The total final energy consumption in 2005 amounted to 285 EJ. Between 1990 and 2005, this consumption increased by 23% [IEA, 2008].

In the IEA Report (2008) shares and trends in final energy consumption and related CO<sub>2</sub> emissions are given for various industrial activities as the following:<sup>6</sup>

**Cement industry:** Cement production represented about 70 – 80% of the energy use in the non-metallic minerals sub-sector, consuming 8.2 exajoules (EJ) of energy per year (7% of the total industrial fuel use). Global cement production grew from 594 million tonnes (Mt) in 1970 to 2 292 Mt in 2005, with the largest growth occurring in the developing countries, especially China. In 2005, China alone produced 46% of global cement output. India, Thailand, Brazil, Indonesia, Iran, Egypt, Vietnam, and Saudi Arabia together accounted for another 15%.

**Chemicals industry:** In 2004, the chemical and petrochemical industry consumed 34 EJ or 30% of the global industrial energy consumption. Production of chlorinated materials via oxychlorination, treatment of certain materials with elemental chlorine and production of chlorophenols and chloranil are relevant in the context of the Stockholm BAT/BEP guidelines and guidance and this study, but these processes comprise a small minority of the use of energy by the chemicals sector.

**Pulp and paper industry:** The pulp, paper and printing industry sector is the fourth largest industrial consumer of energy, consuming globally 5.7% of the total indus-

trial energy use or 6.45 EJ. The pulp and paper industry can produce energy as a by-product and currently satisfies 50% of its energy demand using biomass residues. Among the largest worlds producers of pulp and paper are China, Brazil, Indonesia, and Chile.

**Iron and Steel industry:** Total final energy use in iron and steel industries was 21.4 EJ in 2004, which accounts for the largest share of CO<sub>2</sub> emissions from the manufacturing sector (ca. 27%). This large figure is explained by the high energy intensity of steel production, its reliance on coal as the main energy source and relatively large volume of steel production globally. Major developing countries producing steel are China, Brazil, Turkey, Mexico, South Africa, and Iran as well as CEIT such as Russia, Ukraine and Poland. Non-ferrous metals industry: Half of the energy consumed in the non-ferrous metal production sector is for primary aluminum production. Aluminum production from ore used 5.3 EJ of primary energy in 2004, followed by primary production of copper (1.3 EJ). For some metals, e.g. lead, recycling (or secondary production) represents the largest share of global supply. Recycling is far less energy intensive than primary production. Metal production is operated in a large number of developing countries and CEITs. For instance, primary copper production is concentrated in Chile, China, Russia, Poland, Kazakhstan, Peru, Mexico, Zambia, Bulgaria, Philippines, Indonesia, and Brazil.

**Transportation:** Energy consumption in the transportation sector is the fastest growing end-use sector accounting for 75 EJ and 5.3 Gt CO<sub>2</sub> (in 2005). Road

5. Compiled using UNFCCC GHG Data Interface (<http://unfccc.int/di/DetailedByGas.do>)

6. The IEA uses a Tier 1 Sectoral Approach based on the 1996 IPCC Guidelines. Countries may be using a more detailed method that takes into account different technologies. Therefore, differences occur between IEA estimates and UNFCCC inventories [OECD, 2008].

transport is by far the largest energy user accounting for 89% of total energy consumption in the sector.

Residential Sector: Household energy consumption was 82 EJ in 2005 and associated with 4.5 Gt of CO<sub>2</sub> emissions. For a group of 19 IEA countries, a disaggregated end-user analysis showed that space heating was by far the most important energy user, accounting for 53% of the total household energy use in 2005, while water heating and cooking accounted for 16% and 5%, respectively.

**Electricity Sector:** Electricity production was responsible for 32% of the total global fossil fuel use in 2005 or 132 EJ. 66% of the global public electricity production was satisfied by the use of fossil fuels (coal, oil and natural gas). Among developing countries with significant contribution of fossil fuels in electricity production are China, India, Mexico, South Africa, and Turkey.

Across all fossil fuels, the technical fuel savings potential world-wide is between 21 EJ and 29 EJ per

year, with an associated CO<sub>2</sub> reduction potential of 1.8 Gt CO<sub>2</sub> to 2.5 Gt CO<sub>2</sub> per year. The largest savings are from improving the efficiency of coal-fired plants, which alone could provide savings of between 15 EJ and 21 EJ (1.4 Gt CO<sub>2</sub> to 2.0 Gt CO<sub>2</sub>). On a regional basis, just less than half the global savings would come from OECD countries, with the remainder from developing and transition countries [IEA, 2008].

There is no specific published energy consumption and GHG data on other sources of unintentionally produced POPs listed in Annex C.

This report is structured according to the twenty source categories listed in Annex C of the Stockholm Convention. Table 2 shows the linkage between Stockholm Convention Annex C source categories and chapters of this report. In the report, however, we have grouped the source categories by type, rather than following the order of Annex C. In addition, sources labeled "Not Applicable (N/A)" were deemed to be very small contributors to GHG and thus of low impact.

**Table 2. References to the Stockholm Convention Annex C source categories to chapters in the Report**

	Annex C source categories of the Stockholm Convention	Report chapters
<b>Part II</b>	(a) waste incinerators	II.1.1
	(b) cement kilns firing hazardous waste	II.3
	(c) production of pulp using elemental chlorine or chemicals generating elemental chlorine for bleaching	II.6
	(d) (i) secondary copper production	II.8.1
	(d) (ii) sinter plants in the iron and steel industry	II.8.2
	(d) (iii) secondary aluminum production	II.8.1
	(d) (iv) secondary zinc production	II.8.1
<b>Part III</b>	(a) open burning of waste	II.7.2
	(b) thermal processes in the metallurgical industry not mentioned in part II: -Secondary copper, aluminium, zinc and lead production -Sinter plants in the iron and steel industry primary aluminium production, magnesium production, primary base metals smelting -Secondary steel production	II.8.3   II.8.4
	(c) residential combustion sources	II.1.3
	(d) fossil fuel-fired utility and industrial boilers	II.4
	(e) firing installations for wood and other biomass fuels	II.1.2
	(f) specific chemical production processes releasing unintentionally produced POPs	II.6.2
	(g) crematoria	II.2
	(h) motor vehicles	II.5
	(i) destruction of animal carcasses	N/A
	(j) textile and leather dyeing and finishing	N/A
	(k) shredder plants for the treatment of end of life vehicles	N/A
	(l) smouldering of copper cables	N/A
	(m) waste oil refineries	II.7.1
<b>N/A</b>	<b>Not addressed in details in the Report</b>	



## II. Review of Part II and III in Annex C sources of unintentionally produced POPs of the Stockholm Convention

### II.1. Waste Incineration, firing installations for wood and other biomass fuels, residential combustion

#### II.1.1. Incineration of municipal solid waste, hazardous waste, sewage sludge and medical waste

Processes considered in this section are incineration of mixed Municipal Solid Waste (MSW), hazardous waste, sewage sludge and medical waste. Many of the conclusions, however, are applied to waste incineration in general. Waste incineration is the oxidation of the combustible material contained in the waste. Waste is highly heterogeneous material, consisting of organic substances (of fossil or biogenic origin), minerals, metals, and water. The organic substances in the waste burn once they reach the ignition temperature and come into contact with oxygen.

The waste incinerator process chain includes waste collection, delivery, storage, pretreatment, incineration/combustion/energy recovery, flue gas cleaning, solid residue management, and wastewater treatment. The main stages of the incineration process itself are (i) drying and degassing, (ii) pyrolysis and gasification, and (iii) full oxidation. These main stages generally overlap, meaning that spatial and temporal separation of these stages during incineration is only possible to a limited extent. The most commonly applied techniques for waste incineration are stoker or grate firing, rotary kilns and stationary or circulating fluidized bed combustion (FBC).

When waste is fully oxidized, combustion gases are formed that carry the majority of the waste energy as heat. This heat may be used for steam and / or electricity generation. Emitted flue gases usually contain as their major constituents water vapor, nitrogen, oxygen, carbon dioxide, and – among others – incomplete combustion products (CO, PCDD/F, PAH, PCB, etc.), acid gases (HCl, HF, SO<sub>2</sub>), nitrous oxides (NO, NO<sub>2</sub>), particulate matter (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, heavy metals) in the form of fly ash and volatile (heavy) metals (Cd, Hg). Chemical composition of flue gas varies and depends on the composition of input waste and operating conditions.

Depending on the combustion temperature, volatile (heavy) metals and inorganic salts contained in the waste evaporate to some extent and are transferred to the flue gas and the fly ash according to their temperature and their vapor pressures. The main solid residues of waste incineration are bottom ash (which usually is collected at the lower end of the grate or the kiln), fly ash (which is collected by particulate matter control devices), boiler ashes, ashes from FBC, other residues from flue gas cleaning (e.g., mixture of fly ash and calcium salts, gypsum, spent activated coke, etc.), and residues from waste water cleaning when a wet flue gas cleaning system is used.

### Sources of GHGs and POPs in the process

Relevant GHGs for the incineration process itself and energy source are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and to a lesser extent nitrous oxide (N<sub>2</sub>O). CO<sub>2</sub> emissions are caused by the incineration of waste. Fossil fuel use for the operation of start-up, shut-down and auxiliary burners increase the CO<sub>2</sub> emissions of a waste incineration plant. In some plants CO<sub>2</sub> is directly

emitted as a result of the operation of burners, which are required for the reheating of flue gas before treatment and release (e.g., for Selective Catalytic Conversion (SCR)) or by operation of afterburners. Offsite thermal treatment of bottom ash, slag and fly ash also leads to emissions of CO<sub>2</sub>. If fossil fuels are used for drying of sewage sludge (which is considered a “CO<sub>2</sub>-neutral” waste in many national GHG-inventories), fossil CO<sub>2</sub> emissions of the whole process can be substantial. Methane and carbon dioxide may be emitted by decomposition of waste during storage. However, if air from storage areas (bunkers) is used as a combustion air, GHG emissions during storage are negligible.

N<sub>2</sub>O is formed when combustion takes place in the fluidized bed reactors. The application of selective non-catalytic reduction (SNCR) usually leads to an increase of N<sub>2</sub>O emissions (the use of urea as a reagent promotes N<sub>2</sub>O formation) depending on the dose rate and the temperature. Emission values of N<sub>2</sub>O are higher when low NO<sub>x</sub> values are anticipated.

With respect to CO<sub>2</sub> one has to differentiate between CO<sub>2</sub> caused by the incineration of fossil (fuel/waste) carbon and CO<sub>2</sub> coming from biogenic sources (such as wood or sewage sludge). Analyses have shown that in the industrialized countries the share of fossil carbon contained in mixed MSW is in the range of 33 to 50% of the total carbon content [European Commission, 2006b]. As a rule, CO<sub>2</sub> coming from the incineration of sewage sludge is considered of biogenic origin (i.e., carbon-neutral) and as such not included in National GHG Inventories.

Typical fossil emission factors for GHGs are given in the Table 3 below.

**Table 3. Emission factors for different incineration processes (adapted from European Commission (2006b)) and S. Boehmer, unpublished data**

Process	GHG	Emission Factor (t/TJ)	Global Warming Potential (GWP)	Emission Factor (t CO <sub>2</sub> -eq./TJ)
MSW incineration	CO <sub>2</sub>	40 – 60	1	40 - 60
	CH <sub>4</sub>	0.012	21	0.25
	N <sub>2</sub> O	0.0005 - 0.001	310	0.155 - 0.31
MSW incineration in the fluidized-bed combustion system (FBC)	CO <sub>2</sub>	40 – 60	1	40 – 60
	CH <sub>4</sub>	n.a.	21	n.a.
	N <sub>2</sub> O	0.0025 – 0.005	310	0.775 - 1.55
MSW with SNCR	CO <sub>2</sub>	40 – 60	1	40 – 60
	CH <sub>4</sub>	n.a.	21	n.a.
	N <sub>2</sub> O	0.01-0.03	310	3.1 – 9.3
Hazardous waste incineration	CO <sub>2</sub>	50 - 105	1	50 - 105
	CH <sub>4</sub>	n.a.	21	n.a.
	N <sub>2</sub> O	0.014	310	4.3
Sewage sludge in FBC	CO <sub>2</sub>	0	1	0
	CH <sub>4</sub>	n.a.	21	n.a.
	N <sub>2</sub> O	0.006 – 0.3	310	2 - 97

n.a. – not available

Emissions caused by fossil fuel consumption of start-up/shut-down, auxiliary burners and burners used for re-heating of flue gases are in the range of 0.6 to 9% of the total fossil CO<sub>2</sub> emissions of the incineration plant for the MSW incineration. For hazardous waste and sewage sludge incineration, the contribution of fossil fuel consumption to total CO<sub>2</sub> emissions can be up to 30% of the total CO<sub>2</sub> emissions (calculated from the data given in Boehmer et al. (2006)).

Indirect emissions are caused by the energy consumption of the waste incineration plant, primarily by mechanical pre-treatment systems, by fans and pumps, pre-heating of combustion air, re-heating of flue gas and for flue gas treatment and waste water treatment systems.

If an incinerator has energy recovery and use, the exported energy (e.g. electric power, heat, steam) from the plant can lead to substitution of fossil fuels. Compared to the reduction of methane emissions from landfills, waste incineration – especially when operated as a Combined Heat and Power (CHP) plant – significantly reduces GHG emissions (see also Chapter III).

POPs generated in incineration process are formed by thermal processes only. Unintentionally produced POPs listed in Annex C of the Stockholm Convention are released into the air, water (when wet flue gas cleaning systems are installed or when residues are washed by liquids to remove some toxic substances) and from solid residues, e.g. as a result of leaching. The latter depends on the firing system, the type of waste and the flue gas cleaning system.

Mass balances of PCDD/PCDF releases for mixed MSW incinerators designed and operated in line with BAT and BEP, have identified fly ash as being the major release pathway (80% – 87%), followed by bottom ash (10% - 14%) and filter cake from waste water treatment (5%). Releases via flue gas are of minor importance (0% - 3%) [European Commission, 2006b; UNEP, 2006].

### Impact of BAT/BEP on GHG emissions

The Stockholm Convention stresses the importance of considering alternative waste disposal and treatment options that may avoid the formation and release of chemicals listed in Annex C of the Convention. For MSW these options include zero waste management strategies, waste minimization, composting, mechanical biological treatment, and an engineered contained landfill concept. Alternatives to hazardous waste incineration are waste minimization

and source separation, whereas for sewage sludge alternatives include land spreading for non-contaminated sludge and disposal to engineered landfills. The Basel Convention Guidelines [UNEP, 2005a] list some alternative techniques for the disposal of POPs-containing waste. Important alternatives for medical waste incineration include sterilization techniques, microwave treatment, alkaline hydrolysis and biological treatment. Each of these techniques requires final disposal of the treated waste in sanitary landfills.

Waste incineration is not a stand-alone technique, but should be embedded in an environmentally sound integrated waste management system (see Chapter III). The implementation of the waste hierarchy and of other relevant principles aims at a general reduction of the waste volume which otherwise should be incinerated. As a basic rule, only waste, which can not be reused, recovered or recycled, should be incinerated and only waste that cannot be incinerated should be landfilled.

For example, effective health-care waste management includes source reduction, segregation, resource recovery and recycling, training of personnel, collection at the site of generation and transport provisions.

BAT/BEP for waste incineration (MSW, hazardous waste, sewage sludge, and medical waste) includes the implementation of operational measures and effective end-of-pipe techniques for the removal of air pollutants such as PM, NO<sub>x</sub>, SO<sub>2</sub>, HCl, (heavy) metals and POPs. Waste water treatment as well as treatment and/or sound disposal of residues are also parts of BAT and BEP for waste incineration. BAT/BEP applied to the design and operation of waste incineration plants provide for continuous and stable operating conditions of the waste incineration plant, which will reduce requirements for maintenance and repair. Furthermore, the application of BEP increases the lifetime of a waste incineration plant and the operating hours between scheduled outages needed for maintenance and repair. BEP or good operating practices for the process specifically include the establishment of quality requirements, regular waste inspection and characterization, removal of non-combustibles prior to incineration at the incineration plant, proper handling, storage and pre-treatment, minimizing storage times, and proper waste loading. Ensuring continuous operation of a plant by avoiding frequent start-ups, upset conditions and shut-downs, optimizing combustion conditions, regular facility inspection and maintenance and monitoring of relevant process and emission parameters and proper

handling of residues are also BEP. Operator training and maintaining public awareness and communication are considered BEP.

BAT/BEP for waste incineration include appropriate selection of site, waste input and control techniques, techniques for operation and combustion, for flue gas treatment, solid residue and effluent treatment. To achieve best results for environmental protection as a whole it is essential to coordinate the waste incineration process with upstream activities (e.g. waste management techniques) and downstream activities (e.g. disposal of solid residues from waste incineration).

Concerning medical waste incineration it is preferable to use large, centralized units rather than small, decentralized units in order to avoid batch-type operation and recover energy more effectively.

With a suitable combination of primary and secondary measures, PCDD/PCDF emission levels in the air do not reach levels higher than 0.01–0.1 ng I-TEQ/Nm<sub>3</sub> (at 11% O<sub>2</sub>) [UNEP, 2006]. Even lower emission levels can be achieved under normal operating conditions in the appropriately designed waste incineration plant. BAT for discharge of waste water from the effluent treatment plants receiving wet flue gas treatment scrubber effluent are associated with PCDD/PCDF concentration levels of well below 0.1 ng I-TEQ/l [UNEP, 2006]. BAT for the treatment of solid residues includes separate collection and storage of residues with different levels of contamination. Some residues require pre-treatment before reuse (e.g. bottom ash) or other - pre-treatment before final disposal in dedicated landfills (e.g. fly ash, sludge from waste water treatment). The European Commission's BAT Reference (BREF) Document on waste incineration fully describes BAT for waste incineration [European Commission, 2006b].

The application of BAT and BEP to the incineration process has both, positive and negative impacts on GHG emissions:

In addition to the prevention and reduction of POPs emissions, BAT and BEP provide the basis for high energy efficiency and reduced process demand of energy, which means more energy output with the same waste throughput. Stable operating conditions and continuous operation reduce the need to repeatedly shut-down and start-up the plant or to operate auxiliary burners – processes consuming fossil fuels, such as heating (light) fuel oil or natural gas. In addition, the application of BAT and BEP helps to optimize the process by increasing the efficiency

of end-of-pipe techniques over the life-time of the plant and as such leads to the reduction of GHGs and POPs emissions.

However, minimization of POPs emissions is only one part of BAT and BEP and has to be seen in the context of the overall goal of environmental protection. Reducing emissions such as PM, NO<sub>x</sub>, HCl, SO<sub>2</sub>, heavy metals and POPs by end-of-pipe techniques leads to an increase in the energy consumption of every combustion installation. Energy is used in the form of power, heat or steam. In some plants CO<sub>2</sub> is directly emitted as a result of the operation of burners, which are required for the reheating of flue gas before treatment and release (e.g., in SCR) or by operation of afterburners. (Offsite) thermal treatment of bottom ash, slag and fly ash will also result in additional emissions of CO<sub>2</sub>. Treatment of waste water from incineration adds to the total energy consumption of the incineration plant by increasing its cumulative direct or indirect GHG emissions.

Most process integrated and end-of-pipe techniques are for the co-removal of many pollutants including heavy metals and particle bound POPs by using electrostatic precipitators (ESP), bagfilters (BF) or other highly effective particulate removal control devices. For these techniques it is hardly possible to allocate costs, energy demand or GHG emission factors for every single pollutant. Normally, the most relevant pollutant is taken as a reference for such calculations, e.g. PM for ESP or BF, NO<sub>x</sub> for SCR systems or SO<sub>2</sub> for Flue Gas Desulphurization (FGD) (spray dryers or wet scrubbers.)

The most important techniques used as stand alone techniques for POPs reduction are absorption techniques (e.g. by using activated coke) and catalytic techniques (using SCR or catalytic BFs). Afterburners and quenching of flue gases are not commonly applied at large waste incineration plants, but may be applied at medical waste incinerators.

The Table 4 describes some relevant factors for analyzing impact of BAT for various end-of-pipe techniques on GHG emissions.

Table 5 provides data on energy production and consumption of a typical incineration plant for MSW, designed and operated according to BAT [European Commission, 2006b; Stubenvoll et al., 2002].

Typical values for energy recovery are 400 – 600 kWh per tonne of the incinerated MSW for pure power generation and 300 – 400 kWh/t for electrical power plus 1,200 – 1,500 kWh/t for heat in the CHP mode. Energy

Table 4. Impact of different end-of-pipe techniques commonly used in incineration plants on energy consumption

End-of-pipe technique	Energy needed as		Stand alone technique for POPs	Remark	Switch between energy source
	Power	Heat			
Afterburner	x		yes	For organic substances only (not for heavy metals)	Limited
Quenching	x	x (waste heat from flue gas only)	yes	Higher energy demand for downstream waste water treatment plant; reduced energy recovery temperatures < 200°C required to prevent de-novo synthesis	Not possible
Electrostatic precipitator (ESP)	x		no	In some countries ESP have been replaced by BFs; co-benefit: removal of particle-bound POPs and (heavy) metals.	Not possible
Bagfilter (BF)	x		no	High energy consumption compared to ESP; co-benefit: removal of particle-bound POPs and (heavy) metals	Not possible
Spray dry scrubber	x	x (waste heat from flue gas only)	no	In combination with ESP or BF, reduction of acid gases, particles, volatile metals; co-benefit of POPs removal (not a stand alone technique for POPs removal)	Not possible
Wet scrubber	x	x (waste heat from flue gas only)	no	In combination with ESP or BF, reduction of acid gases, particulates, soluble metals; co-benefit of POPs removal (not a stand alone technique for POPs removal).	Not possible
Selective catalytic reduction (SCR)	x	x (in some cases but not always)	yes (gas phase POPs only; simultaneous reduction of NO <sub>x</sub> )	Pre-heating of flue gas necessary in the clean gas mode; NO <sub>x</sub> reduction and POPs oxidation; raw gas mode: Hg oxidation (Oxidized Hg can be removed in downstream wet scrubbers)	Switch to gas/gas heat exchangers possible
Catalytic BFs	x		yes	removal of particulate matter, (heavy) metals and POPs	Not possible
Dry absorption using resins	x		yes		Not possible
Activated carbon; activated coke (fixed bed, flow injection, entrained flow reactor)	x		yes	CO <sub>2</sub> emissions caused by incineration of spent reagents	Not possible

Table 5. Energy production/consumption of a typical MSW incineration plant operated according to BAT [European Commission, 2006; Stubenvoll et al., 2002].

Plant type	Electricity produced (kWh/t waste*)	Heat produced (kWh/t waste*)	Self demand: electricity – whole plant (kWh/t waste*)	Self demand: heat – whole plant (kWh/t waste*)	Self demand: electricity – FGCwh** (kWh/t waste*)	Self demand: heat – FGCwh** (kWh/t waste*)
Power generation only	400 - 600	None	60 - 150	21 – 470	40 – 60	0 – 120
Combined heat and power (CHP)	300 - 400	1,200 – 1,500	60 - 150	21 – 470	40 – 60	0 – 120

\* Calculations are based on a calorific value of waste of 10 GJ/t (equivalent to 2,778 kWh/t) which is considered a typical value for industrialized countries;

\*\* FGCwh - Whole Flue Gas Cleaning systems for removal of all air pollutants

demand of techniques applied mainly for the removal of POPs from flue gas (e.g. catalytic BFs, SCR – for NO<sub>x</sub> reduction and POPs oxidation, and activated carbon) is in the range of 8 – 15 kWh electrical power per tonne of incinerated waste and is about 60 kWh heat per tonne of incinerated waste for SCR [Stubenvoll et al., 2002]. Compared to the energy produced by incineration of waste, application of such flue gas cleaning systems consumes only 1.3 to 3.8% of the total electricity production and 4 to 5% the total heat production. The most crucial parameter for high energy recovery is the location of the site, so that the heat generated can be used (e.g. for district heating purposes or to drive chillers). Given the other positive effects of BAT and BEP (stable and continuous operation, long operating hours, reduced efforts for maintenance and repair), it can be assumed that the benefits in terms of energy efficiency and GHG emissions achieved by BAT and BEP far outweigh the drawbacks of energy consumption by flue gas cleaning systems used for POPs removal (see also Chapter III).

Recommended BAT includes avoiding mixing of low-contaminated bottom ash with highly contaminated (in terms of POPs and heavy metals) fly ash, thus enabling their separate treatment and/or disposal. Usually bottom ash and fly ash are thermally treated when use for construction or road-building material is anticipated. Thermal treatment removes both POPs and (heavy) metals making it difficult to allocate CO<sub>2</sub> emissions from thermal treatment solely to POPs. Energy demand of thermal treatment is in the range of 150 – 440 kWh/t of waste [European Commission, 2006b]. However, due to high costs market penetration of this technique is low (with the exception of Japan).

The contribution of POPs removal from waste water to the total energy demand of a waste incineration

plant is low [European Commission, 2006b; Stubenvoll et al., 2002].

It is highly recommended that the integrated approach of environmental protection is applied. More specifically high energy recovery should be one goal of waste incineration but not the only one – other is safe disposal of waste and that includes (in the context of the precautionary principle) a certain oversizing of flue gas cleaning systems. Waste incineration plants should be designed and operated that even under the worst conditions with respect to waste input – e.g., highly contaminated waste with high pollutant concentration and with low calorific value – and operating conditions (e.g., partial load), emissions are below BAT associated emission levels.

However, prior to waste incineration more emphasis should be given to other principles which are effective before articles become waste and in general to the principles of the waste hierarchy. These principles should be valid and considered important even in countries where waste incineration is favored by law.

## II.1.2. Firing installations for wood and other biomass fuels

The main purpose of plants for the combustion of wood and other biomass fuels is energy generation. Large-scale installations combusting wood and other biomass fuels usually use fluidized bed combustors and stoker or grate furnaces. Technologies for small-scale plants include underfeed furnaces and cyclone suspension furnaces. Energy recovery boilers in the pulp and paper industry apply specific combustion conditions. Technology selection is related to fuel properties and required thermal capacity [UNEP, 2006].

## Sources of GHGs and POPs in the process

Globally, biomass provides around 46 EJ of bioenergy in the form of combustible biomass and wastes, liquid biofuels, renewable municipal solid waste (MSW), solid biomass/charcoal, and gaseous fuels. Around 8.6 EJ/yr of biomass is used for heat and power generation. Industrial use of biomass in OECD countries was 5.6 EJ in 2002, mainly in the form of black liquor in pulp mills, biogas in food processing plants, and bark, sawdust, rice husks and etc. in process heat boilers [Sims et al., 2007].

CO<sub>2</sub> emissions result from complete combustion of biomass. Combustion of virgin biomass is considered CO<sub>2</sub>-neutral in many government policies. However, combustion of non-virgin biomass or chemically treated woods (and other potentially co-fired waste) may contain significant quantities of non-biomass combustible material that may result in emissions of additional GHGs, mostly in form of CO<sub>2</sub>. Other GHGs may be formed through incomplete combustion (e.g., nitrous oxide and methane). The IPCC emission inventory guidelines indicate emissions in a range of 10-100 kg/TJ for CH<sub>4</sub> and 1.5-15 kg/TJ for N<sub>2</sub>O [IPCC, 2006].

Indirect GHG emissions occur upstream and downstream the process chain including energy consumption for mechanical fuel preparation. When thermal processes such as e.g., drying are used, such emissions can become significant.

Chemicals listed in Annex C of the Stockholm Convention can be unintentionally generated during the combustion of wood and other biomass fuels or co-incineration of a mixed fossil-biogenic waste as practiced in some industrial activities such as furniture industry, production of card-boards, and, pulp and paper industry. Fuel quality and/or use of treated wood or non-virgin biomass play a major role in PCDD/PCDF formation during biomass combustion at biomass firing installations and during co-combustion of biomass and fossil fuels. Combustion of contaminated wood leads to significantly higher PCDD/PCDF emissions than combustion of uncontaminated wood. Nevertheless, reported values vary in a wide range. The respective emission factor table of the Toolkit is given in the Annex 1 of this report. The Toolkit estimates a default emission factor for emission into the air from biomass power plants in a range of 50 - 500 µg TEQ/TJ for clean or mixed biomass [UNEP, 2005b].

PCDD/PCDFs may be formed during wood combustion via precursors such as phenols and lignin, or via de-novo reactions in the presence of particulate car-

bon and elemental chlorine. High emission levels of POPs can be expected from burning treated wood (wood waste). Wood residues (waste and industrial) often contain various types of contaminants (chromated copper arsenate, pentachlorophenol, creosote, preservatives, adhesives, resins, paint and other surface coatings). Another major source of PCDD/PCDF can be salt-laden wood waste burnt in power generating boilers at pulp and paper mills [UNEP, 2006]. PCDD/PCDF can also be released through combustion residues. In ashes from wood combustion, their concentrations tend to increase with a decreasing particle size.

## Impact of BAT/BEP on GHG emissions

For biomass-fired plants, particularly wood-fired installations, emission levels associated with BAT are generally well below 0.1 ng I-TEQ/Nm<sub>3</sub>. BAT to reduce PCDD/PCDF emissions include the control of fuel quality (including exclusion of treated woods and non-virgin biomass and other waste), optimized combustion technology, optimized air supply, mixing and residence time as well as optimized plant operation. Secondary measures for flue gas cleaning include rapid quenching, fly ash separators, catalytic oxidation (e.g. in combination with catalytic reduction of NO<sub>x</sub>) [UNEP, 2006].

For the large scale combustion of woody biomass pulverized combustion, stationary Bubbling Fluidized Bed Combustion (BFBC) and Circulating Fluidized Bed Combustion (CFBC) as well as the spreader stoker and reciprocating grate firing techniques are considered to be BAT. The use of advanced computerized control systems to achieve high boiler performance with improved combustion conditions that support the reduction of air pollutant emissions are part of BAT [European Commission, 2006a].

In general, CO<sub>2</sub> emissions can be reduced through improved combustion efficiency. CHP is the most important technical and economical measure to increase fuel efficiency. Compared to fossil fuels the electric efficiency of biomass fired power plants is generally low due to fuel induced technical limitations in achievable steam temperature and pressure. Co-generation is, therefore, the most important BAT measure whenever economically feasible (defined by the level of local heat demand) [European Commission, 2006a].

Combustion for heat and steam generation remains state-of-the-art, but advancing technologies include second-generation biofuels, biomass integrated-gasification combined-cycle (BIGCC). These emerging technologies are not yet considered as BAT.

Low fuel quality (e.g. varying calorific value, inhomogeneous particle size, and contaminants) decreases stability of operations and requires more comprehensive flue gas cleaning in order to avoid increasing emissions of POPs and other air pollutants. Appropriate fuel quality control and plant design is necessary to avoid adverse effects of the use of biomass as a renewable energy carrier.

As far as biomass is considered CO<sub>2</sub>-neutral efficient use of biomass can reduce CO<sub>2</sub> emissions by substitution of fossil fuels, which otherwise would have to be used for energy generation. But the use of biomass should be sustainable without depletion of carbon stocks, e.g., through deforestation, limitation of food supplies, loss of biodiversity, impact on water resources and other ecosystem services [Sims et al., 2007].

### II.1.3. Residential Combustion Sources

This section considers the combustion of wood, biomass pellets, coal, gas, as well as other organic matter mainly for residential heating and cooking. Combustion takes place in hand-fired stoves or fireplaces or, in the case of wood pellet combustion and larger central heating systems, in automatically fired installations [UNEP, 2006].

#### Sources of GHGs and POPs in the process

Combustion of fossil fuels in households is one of the largest sources of CO<sub>2</sub> in the world. Energy consumption in households was 82 EJ in 2005. The associated CO<sub>2</sub> emissions (including indirect emissions from electricity use) were 4.5 Gt CO<sub>2</sub>. Households are the only major end-use sector where the increase in energy consumption since 1990 has been greater in OECD countries (+22%) than in non-OECD countries (+18%) [IEA, 2008].

Electricity, district heating steam, light fuel oil and natural gas are the main energy commodities used in OECD countries, providing 72% of total household energy requirements in 2005. In non-OECD countries, renewable energy (mostly traditional biomass) remains the dominant energy commodity accounting for 59% of final energy use, but its share is decreasing.

Studies have shown that significant levels of chemicals listed in Annex C of the Stockholm Convention are released from residential combustion sources. The amount of chemicals released depends primarily on the quality of the fuel used (coal, household waste, sea-salt laden driftwood and treated wood are significant sources of PCDD/PCDF) as well as combustion efficiency and loading conditions. The

efficiency of combustion depends upon the combustion temperature, how well the gases are mixed, residence time, sufficient oxygen and the fuel properties. Higher emissions occur during non-stationary conditions such as start up and shut down periods. Given their large numbers, residential combustion appliances contribute significantly to overall releases of chemicals listed in Annex C [UNEP, 2006].

#### Impact of BAT/BEP on GHG emissions

The use of efficient combustion of clean, untreated fuels for cooking and heating is of primary importance for reducing the formation and release of chemicals listed in Annex C. BAT consider enclosed low emission burners with ducted flues and the use of dry, well-seasoned, untreated wood. For countries or regions where these fuels and appliances are not available, BAT/BEP for residential combustion include ensuring separation of household waste from fuel to avoid burning of such waste in cooking and heating appliances. In all countries the use of chemically treated wood or sea-salt laden driftwood and the use of plastics as a firelighter or fuel should be avoided. The abatement technologies commonly used in industrial settings are not generally available for smaller residential heating and cooking appliances. However, the use of well-designed stoves with good operation can be effective in reducing chemicals listed in Annex C with the important added benefit of improving indoor air quality [UNEP, 2006].

In developed countries GHG emission reduction measures in the residential sector are focusing on an increase of energy efficiency for heating, cooling, ventilation and air conditioning, hot water supply, lighting systems and the electricity consumption of household appliances. The various measures in this sector fall into three categories: reducing energy consumption and embodied energy in buildings, switching to low-carbon fuels including a higher share of renewable energy use, or controlling the emissions of non-CO<sub>2</sub> GHG gases.

There is a risk of increasing POPs releases in case of a switch from liquid or gaseous fossil fuels to solid biomass as a renewable energy carrier. In particular, small stoves offer fewer opportunities for the control of combustion conditions and for flue gas cleaning. In the industrialized nations and in urban areas in developing countries (in cold winter climates), heating is generally provided by a district heating system or by an onsite furnace or boiler. Due to increasing prices of fossil fuels and the promotion of renewable energy sources, a switch from fuel oil or natural gas to solid biomass can be observed. The use of small

stoves may have particularly negative impact with the increased air pollution by fine particles and releases of unintentionally produced POPs. In these cases, preference should be given to units with automatically controlled fuel supply and use of standardized, or at least dry and homogenized fuels.

In both developed and developing countries the combustion of solid fuels shows the highest potential of unintentional POPs releases in the residential sector. In developing countries coal and biomass burning stoves are dominating the energy supply of households in rural areas. Worldwide, about three billion people use solid fuels – biomass and, mainly in China, coal – in household stoves to meet their cooking, water heating and space heating needs. Most of these people live in rural areas with little or no access to commercial sources of fuel or electricity. Most household stoves use simple designs and local materials that are inefficient, highly polluting and contribute to the overuse of local resources. The comparison of GHG emissions from biomass-fired stoves vs. coal-fired stoves highly depends on the choice of the fuel. Options available to reduce domestic cooking energy needs include: 1) improved efficiency of biomass stoves; 2) improved access to clean cooking fuels, both liquid and gaseous; 3) access to electricity and low-wattage and low-cost appliances for low income households; 4) non-electric options such as solar cookers; 5) efficient gas stoves; and 6) small electric cooking equipment such as microwaves, electric kettles or electric frying pans.

Improved biomass stoves with ducted flue gases and a stack can save from 10 to 50% of biomass consumption for the same cooking service at the same time reducing indoor air pollution by up to one-half [Levine et al., 2007]. In developing countries the use of improved stoves does not only reduce POPs emissions, but also has a positive impact on human health through reduced indoor and local air pollution. Measures on competence building and training in this field are part of the BAT/BEP and should be introduced as components of the Party's national implementation plan [UNEP, 2006].

Energy efficiency measures potentially reduce both, GHG emissions and releases of unintentionally produced POPs. The actual benefits need to be evaluated taking into account the LCA. In case of the direct use of fossil fuels, the switch from coal to fuel oil or to natural gas leads to decreasing CO<sub>2</sub> emissions due to the decreasing C to H ratio of the fuels. In case of an optimized control of combustion conditions, potential releases of POPs will be significantly reduced. The optimized combustion of natural gas reduces unintentionally produced POPs emissions to

almost zero. Operation conditions can be improved by buffer systems (hot water storage) and through regular maintenance and repair. The CO<sub>2</sub> and POPs emissions from electricity consumption depend on the energy mix used for electricity generation and will not be discussed further.

The IPCC Working Group III concluded in the 4th Assessment Report [Levine et al., 2007] that substantial reductions in CO<sub>2</sub> emissions from energy use in buildings can be achieved over the coming years using existing mature technologies for energy efficiency. These measures include structural insulation panels, multiple glazing layers, passive solar heating, heat pumps; biomass derived liquid fuel stoves, high-reflectivity building materials, thermal mass to minimize daytime interior temperature peaks, direct evaporative, cooler, solar thermal water heaters, cogeneration, district heating and cooling systems, etc. AR4 suggests that, globally, approximately 29% of the projected baseline emissions by 2020 can be avoided cost-effectively through mitigation measures in the residential and commercial sectors. This estimate represents a reduction of approximately 3.2 billion tonnes of CO<sub>2</sub>eq in 2020 at zero net cost.

## II.2. Crematoria

Cremation is the disposal of a cadaver by the process of burning. This can be undertaken in either an uncontrolled, open burning fashion on funeral pyres, or in a controlled fashion within a cremator, installed within a crematorium or crematory. Only the latter is discussed in this document.

Cremators typically consist of two main combustion chambers. In the first (or primary) combustion chamber, the coffin containing the cadaver is placed and the necessary heat for burning is provided by one or two main support burners (typically in the order of 200–300 kW). These are usually natural gas fired, although in some locations they are light fuel oil fired. Within the secondary chamber, further combustion air may be added, and an afterburner system supports completion of combustion. The secondary chamber is sometimes used to pre-heat combustion air for the primary chamber.

Cremation is a religiously and culturally important accepted practice for many cultures and countries as a way of dealing with the death of human beings. It is essential that any discussion regarding the design and operation of crematoria must be duly dignified, with consideration of the sometimes conflicting relationship between social and cultural requirements and environmental concerns [UNEP, 2006].

### Sources of GHGs and POPs in the process

The relevant source of GHG in the cremation process is the use of supplementary fossil fuels to support burning of the coffin and the cadaver. However, on a national or global scale these emissions are within the statistical uncertainties of inventories and in most cases not even reported.

The formation and emission of POPs from cremators is possible due to the presence of these substances, precursors and chlorine in the cadavers and in some co-combusted plastics (e.g. coffin furnishings, which have been phased out in some countries). De-novo synthesis may be the major formation pathway, when the residence time of flue gases in the reformation window (200-400°C) is long.

Although measurements of PCDD/PCDF releases have been made in crematoria, there are few or no consistent data for PCB and HCB emissions. Due to the nature of the process, ashes are an ethical product and are often not subject to any control; spreading of ashes on water, for example, is a potential release source for unintentionally produced POPs. A study done in the United Kingdom showed that levels of unintentionally produced POPs in ashes were low enough to be considered insignificant in terms of potential exposure risks [Edwards, 2001]. In many countries depositions left within the cremator chambers and ducts are removed during routine maintenance and buried at depth within the crematorium grounds (the same way as metals recovered from the hearth and recovered ashes).

### Impact of BAT/BEP on GHG emissions

BAT include primary measures to ensure good combustion behavior (minimum temperature, residence time and oxygen requirements), monitoring of relevant parameters (e.g. temperature, oxygen and CO content) and the implementation of secondary measures, such as flue gas cleaning and monitoring of emissions. Suitable flue gas cleaning systems use (combinations of) particulate matter abatement and activated carbon treatment. In addition, coffin and coffin fittings should be made of combustible material. The use of articles and personal items containing PVC, metals and other chlorinated compounds should be avoided. For BEP, countries should aim to develop facilities that are capable of meeting the minimum furnace temperature, residence time and oxygen content criteria.

Proper design and operation of crematoria are part of BAT and BEP as well as the use of clean fuels to support burning. Whereas primary measures have the co-benefit of optimizing combustion behavior and reducing fuel demand, secondary measures increase the energy consumption of a plant (see Chapter III). Overall, both effects can be neglected due to very low contribution to national or global GHG emissions.

## II.3. Cement kilns firing hazardous waste

The cement manufacturing process includes the decomposition of calcium carbonate ( $\text{CaCO}_3$ ) at about 900 °C to calcium oxide ( $\text{CaO}$ , lime) (calcination) and  $\text{CO}_2$ , followed by the clinkering process at about 1,450 °C in a rotary kiln. The clinker is then ground together with gypsum and other additives to produce cement. The main cement-making processes are known as dry, wet, semi-dry and semi-wet processes.

Various fuels (conventional and waste) are used to provide the necessary energy required for the process. The conventional fuels include solid fuels (e.g. coal, petroleum coke), fuel oil and natural gas [European Commission 2009]. Coal is dominating the fuel mix in many countries and regions, such as China (94%); India (96%), Southeast Asia (82%) and the United States (66%). Natural gas is the dominating fuel in states of the former Soviet Union (68%) [IEA, 2007]. When defining a fuel mix, the local availability of the fuels (e.g. availability of domestic coal or gas), the technical possibilities and the long-term guarantee of supply are the main parameters that are taken into consideration [European Commission, 2009].

### Sources of GHGs and POPs in the process

The  $\text{CO}_2$  emissions per kilogram of cement produced depend on the energy and electricity intensity of clinker and cement production, the clinker ratio, the fuel types used at the cement kiln and the  $\text{CO}_2$  emissions profile of the electricity consumed. Additional emissions arise from calcination in the clinker production process [IEA, 2007] (Fig. 3). Most electricity is used for grinding with the increasing energy demand coming from the use of clinker substitutes.

The combustion process in the kiln may potentially result in the formation and subsequent emissions of chemicals listed in Annex C of the Stockholm Convention mainly into the air. The Toolkit [UNEP, 2005b] suggests default emission factors for PCDD/PCDF emissions as given in Table 6.

Figure 3. Mass balance for the production of 1 kg cement using the dry process (adopted from [European Commission, 2009]).

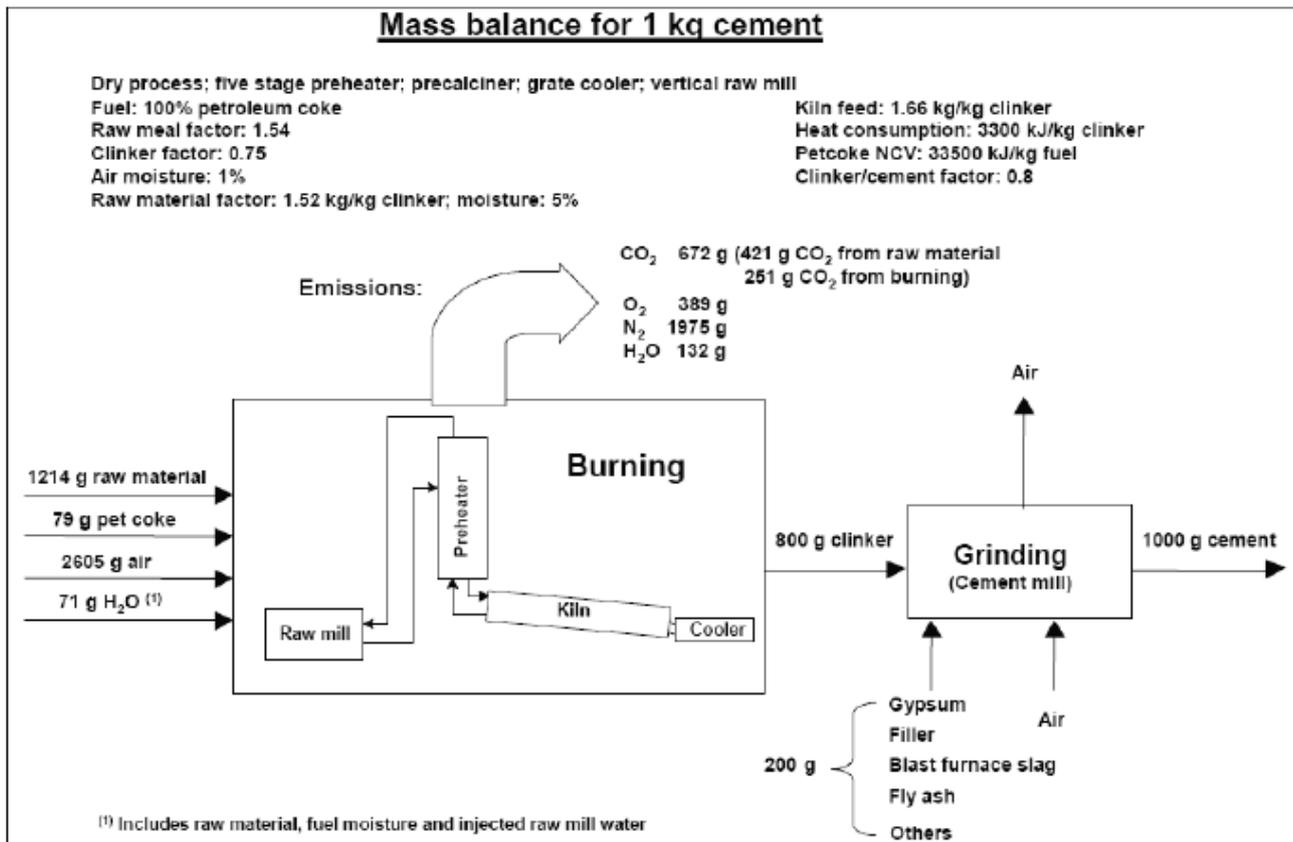


Table 6. Emission factors for cement production [UNEP, 2005b].

Classification	Emission factors – µg TEQ/t of cement				
	Air	Water	Land	Product	Residue
Shaft kilns	5.0	ND	ND	ND	ND
Old wet kilns, ESP temperature >300°C	5.0	ND	ND	ND	ND
Rotary kilns, ESP/FF temperature 200-300°C	0.6	ND	ND	ND	ND
Wet kilns, ESP/FF temperature <200°C	0.05	ND	ND	ND	ND
Dry kilns preheater/precalciner, temperature <200°C					

ND - Not Determined/No data, NA - Not Applicable

### Impact of BAT/BEP on GHG emissions

For new plants and major upgrades, BAT for the production of cement clinker are considered to be a dry process kiln with a multi-stage preheating and pre-calcination. For existing installations, varying degrees of re-construction may be needed. Among BAT/BEP measures include rapid cooling of exhaust gases to a temperature lower than 200 °C, optimized process monitoring and control, optimized heat recovery from the exhaust gas, good maintenance, housekeeping and procedures appropriate to the safe acceptance, handling and storage

of wastes, selection and control of substances entering the kiln, continuous supply of waste as a fuel with specifications for heavy metals, chlorine, sulfur, no use of the waste-derived chlorine containing fuel during start-up and shutdown. In general, waste should be fed through the main burner or the secondary burner for preheater/precalciner kilns. The combustion zone temperature has to be maintained above 850 °C for a sufficient residence time (2 s) for the secondary burner. Furthermore, waste feed containing organic compounds that could act as precursors for unintentionally produced POPs should not be used in the raw material mix.

Rotary kilns are generally equipped with electrostatic precipitators; on account of the relatively high exhaust gas temperatures. Fabric filters are also used, particularly on preheater kilns, where exhaust gas temperatures are lower. Additional end-of-pipe techniques installed at cement kilns include absorbent addition, activated carbon injection, activated carbon filter, SCR and SNCR. These measures are usually installed for the purpose of controlling pollutants other than unintentionally produced POPs (such as PM, NO<sub>x</sub>, SO<sub>2</sub>, metals), but they may also lead to a simultaneous reduction in emissions of chemicals listed in Annex C. This is particularly the case for SCR and activated carbon techniques. Performance requirements based on BAT for the control of PCDD/PCDF in flue gases should be < 0.1 ng I-TEQ/Nm<sub>3</sub> with reference conditions of 273 K, 101.3 kPa, 11% O<sub>2</sub> and a dry gas basis [UNEP, 2006]. Information on additional energy consumption from end-of-pipe techniques in the case of cement plants is scarce but it should be comparable to the consumption of similar flue gas cleaning devices in other sectors (see Chapter III).

There are basically three approaches for reducing GHG emissions in cement production: technology improvements in clinker making for less energy use, the use of clinker substitutes, and the use of low-carbon fuels. These fuels include substitutes for coal or petroleum coke by lower carbon waste derived fuels, cleaner oil or natural gas. The use of wastes as a fuel should be carefully evaluated and appropriate BAT/BEP measures taken on a site specific basis.

### Technology improvements in clinker making.

Efficient dry kilns equipped with preheaters use approximately 3.3 GJ/t clinker, a wet kiln uses 5.9 – 6.7 GJ/t clinker, while a dry kiln with pre-heaters and pre-calciners consumes under optimized conditions around 2.9 GJ/t clinker. Thermal energy optimization techniques can be implemented at different units of the plant including cooler, kiln, preheater, calciner, material preparation and mills. The appropriate number of cyclone stages for preheating is determined by the throughput and the moisture content of the raw materials. Depending on the local raw material situation regarding moisture content and burnability fuels have to be dried by the remaining exhaust gas heat. For raw material input which contains less than 8.5% moisture, on a modern cement plant the drying can be completed using the exhaust gas from a multi-stage four to six) preheater. Three cyclone stages are only used in special cases with very wet material [European Commission, 2009].

Most countries have experienced a downward trend in the thermal energy intensity required to produce a tonne of clinker between 1990 and 2004. Generally, this has been due to the increasing share of dry process cement kilns. However, many countries that already had high shares of dry process kilns have improved their thermal energy intensity per tonne of clinker as even more efficient dry process kilns have been introduced.

Rapid economic development and demand growth for cement has provided an opportunity for some developing countries to achieve relatively high levels of energy efficiency by building efficient dry process plants. Until recently, this was not the case in China, where small-scale kilns and inefficient shaft kilns dominated production. The situation is changing rapidly and by 2004 large and medium-scale plants accounted for 63% of production with 45% of the total output coming from dry kilns. The energy intensity per tonne of clinker has declined from about 5.4 GJ/t clinker in 1990 to 4.5 GJ/t clinker in 2004 [IEA, 2007].

Grinding is the largest electricity demand in the cement industry. Currently about 100 kWh/t of cement is consumed in rotary kilns for grinding raw materials, at the kiln and for grinding cement. The current state-of-the-art technologies, using roller presses and high-efficiency classifiers, are much more efficient than previously used technologies consuming 80 – 90 kWh/t of clinker [IEA, 2007].

Waste heat recovery can be used for electricity generation in CHP plants to cover the electricity needs. For instance, cement plants in Japan generate around 10% of their electricity needs from CHP and China estimates a potential of 35 – 40 kWh/t clinker. It appears that Japan has so far taken up a significant part of this CHP potential [IEA, 2007]. Furthermore, excess heat is recovered from clinker coolers or kiln off-gases for district heating. The Organic Rankine Cycle (ORC) and the conventional steam cycle are in operation in CHP plants. With more effective preheater towers and clinker coolers the amount of unutilized heat will be reduced and the scale of economics may be unfavorable for cogeneration especially in cases where the majority of heat is needed for drying processes [European Commission, 2009].

**The use of clinker substitutes.** The most widely used cement type is Portland cement, which contains 95% of cement clinker. The most common clinker substitutes are waste products such as fly ash (mostly from coal-fired power plants) or granulated blast furnace slag or natural pozzolana (volcanic ash).

The direct use of steel slag in the kiln as a substitute for limestone involves adding steel slag into the back or “feed-end” of the kiln through a relatively uncomplicated and inexpensive delivery and metering system, which can be used at virtually all kiln types. Producing alternative cement types including these products is far less energy intensive leading to lower CO<sub>2</sub> emissions in the clinker production [IEA, 2007].

**The use of waste as a fuel.** Used tires, wood, plastics, chemicals and other types of waste are co-combusted in cement kilns in large quantities. This use of waste as a fuel in cement kilns can contribute to lower CO<sub>2</sub> emissions, if fossil fuels are replaced with waste that would otherwise have been disposed of, without any or with less energy recovery.

When changing the fuel mix the specific energy consumption per tonne of clinker can vary due to various reasons (calorific value, moisture content, and burnability). With waste derived fuels of a lower calorific value, the amount of required fuel is higher compared to conventional (fossil) fuels [European Commission, 2009].

Pollutant emissions of a cement plant may increase by the use of waste and waste derived fuels. Special attention has to be given to heavy metals in the input materials. In most cases flue gas cleaning devices of cement kilns are designed for the control of particles, SO<sub>2</sub> and NO<sub>x</sub> and the abatement efficiency of gaseous heavy metals such as mercury is low.

European cement manufacturers derived 3% of their energy needs from waste as fuels in 1990 and 17% in 2005. For example, cement producers in Belgium, France, Germany, the Netherlands, and Switzerland have increased average fuel substitution rates from 35% to more than 70% of the total energy used. However, such high substitution rates can only be accomplished if a tailored pre-treatment and surveillance system is in place.

The total global consumption of waste derived fuels in the cement industry is highly uncertain. Worldwide, the industry consumed a reported 112 PJ of biomass and 34 PJ of waste, but this is likely to be a substantial underestimate. There is apparently little use of waste derived fuels outside the OECD countries, although the comparison of country data from various sources with the IEA statistics implies that the use of waste and waste derived fuels is systematically under-reported. From a technical perspective, the use of waste materials could be increased to 1 – 2 EJ per year, although there would be differences among

regions due to varying availability of the source material [IEA, 2007].

**GHG emission reduction potentials.** The combined technical potential of GHG reduction measures is estimated at 30% globally, varying between 20 and 50% for different regions. Energy efficiency improvement has historically been the main contributor to emission reduction and show the highest reduction potential today. Benchmarking and other studies have demonstrated a technical potential for up to 40% improvement in energy efficiency. Countries with a high potential still use outdated technologies, like the wet process clinker kiln. [Bernstein et al., 2007].

Reduced fuel consumption will reduce the flue gas volumes and, therefore, the overall emission load. Modern cement kilns operating in accordance with BAT/BEP can comply with the threshold values for PCDD/PCDF emissions, when they use hazardous waste as a fuel. Reported PCDD/PCDF emission concentrations of modern cement kilns are generally low independent of the type of fuel used. Therefore, the replacement of old kilns with modern multi-stage preheater / precalciner kilns will have a positive impact on both, CO<sub>2</sub> and unintentionally produced POPs emissions.

Waste can substitute fossil fuels in the operation of a cement kiln but this does not necessarily reduce CO<sub>2</sub> emissions depending on the waste properties and the alternative disposal option. Only OECD countries currently use high shares of waste as a fuel for cement kilns. This requires tailored pre-treatment of waste and sophisticated monitoring and quality control. Increasing fuel prices or waste disposal problems may induce an inappropriate use of waste in kiln operations. There is a risk of increasing unintentionally produced POPs emissions, when BAT/BEP guidelines and guidance are not followed. Higher inputs of heavy metals (particularly mercury) with input materials will entail increased emissions of the respective substances as well. Therefore, the promotion of waste as a fuel should be linked to the introduction of BAT/BEP kiln technologies and operation practices.

## II.4. Fossil fuel-fired utility and industrial boilers

The generation of power (steam and/or electricity) from fossil fuels generally involves the combustion of natural gas, crude oil or petroleum derivatives of various types, or coals. Natural gas consists mostly of methane (CH<sub>4</sub> - > 80%vol.) and ethane (C<sub>2</sub>H<sub>6</sub> - < 20%vol.),

while crude oil contains a wide variety of gaseous, liquid and solid hydrocarbons starting with propane (C<sub>3</sub>H<sub>8</sub>) and continuing with an increasing carbon (C) to hydrogen (H) ratio (C/H-ratio). Coals are commonly classified according to their age of geological formation and include anthracites, bituminous, sub-bituminous, lignite and brown coals. The fixed carbon content of the oldest coals called anthracites is typically well above 80% and the volatile matter less than 10%. Lignite or brown coals are the youngest and lowest rank coals with a fixed carbon content of less than 20% and a content of volatile matter as high as 50%. The amount of GHG emitted from fossil fuels increases as the C/H-ratio increases. All combustion processes used for power generation from fossil fuels are generally designed to maximize combustion efficiency, while minimizing fuel consumption. Combustion processes of fossil fuels vary greatly depending on the type of fossil fuel burned.

Rotating internal combustion engines directly coupled to an electric generator or steam boilers generating high pressure steam that drives a steam turbine coupled to an electric generator are usually used for the combustion of fossil fuels. Rotating internal combustion engines using gaseous or liquid fossil fuels include gas turbines and diesel engines. Generally, rotating internal combustion engines are the most energy efficient, but also bear high costs for converting fossil fuel to energy as they can only use very high grade fossil fuels such as natural gas and light fuel oil. Their high fuel costs limit their application to small stationary (households, small industry, small peak load power generators) and mobile (automobiles and machinery, ships, aircrafts, and etc.) installations. The overall efficiency of large rotary internal combustion engines can be greatly enhanced by combining them with a heat recovery steam generator, which utilizes the waste heat contained in the flue gas to generate high pressure steam used to drive a steam turbine/electric generator set. In such a combined cycle mode, net efficiencies may exceed 60%.

Fossil fuel fired steam boilers include the vast majority of power generating facilities using different types of fossil fuels. The average efficiency of coal-fired steam boilers for electricity generation currently in use is about 35%, with the most modern coal-fired power plants achieving net efficiencies in excess of 45%. Fuel efficiency can be greatly improved above 60%, if electricity generation is combined with the use of low pressure steam and/or hot water for industrial process applications or heating purposes, e.g. in district heating.

## Sources of GHGs and POPs in the process

Common GHG generated is CO<sub>2</sub>. Converting quantitatively all carbon contained in the fossil fuel to CO<sub>2</sub> and thus liberating the contained energy is the sole purpose of power generation using fossil fuels. Power generation by combusting fossil fuels is by far the main source of carbon dioxide. Electricity production was responsible for 32% of total global fossil fuel use in 2005, accounting for 132 EJ. It was also the source of 41%, or 10.9 Gt, of energy-related CO<sub>2</sub> emissions.

Due to its lower combustion temperature, FBC of coal is a source of nitrous oxide emissions (N<sub>2</sub>O), particularly when combined with urea based SNCR systems, which is often the case in OECD countries. This, however, is not a concern with anhydrous ammonia, aqueous ammonia or urea based SCR systems, regardless of the type of combustor.

Unintentionally produced POPs can be generated when very small quantities of chlorine are present in the fossil fuel or in fuel additives. However, typically high combustion temperatures designed to ensure complete combustion minimize the formation of unintentionally produced POPs. Some chlorine must be present in the fuel, fuel additives or combustion air in order to form thermally stable chlorinated hydrocarbons. Under normal circumstances, only small quantities of unintentionally produced POPs result from combustion of natural gas due to the very low quantities of chlorine in the fuel. Similarly, only very small quantities of POPs are formed during the combustion of fuel oil; however, this can change with the presence of chlorine-containing fuel additives (e.g., waste oils and lubricants). Coals, however, typically contain sufficient chlorine concentrations to induce formation of unintentionally produced POPs. Combination of coal with wastes, biomass, sewage sludge, meat and bone meal, and other biological material may increase formation of unintentionally produced POPs further. However, the excess of SO<sub>2</sub> relative to HCl of several orders of magnitude in different coal types effectively limits the formation of chlorinated POPs to negligible amounts as SO<sub>2</sub> effectively inhibits the formation of elemental chlorine, the availability of which is necessary for the formation of unintentionally produced POPs.

Air emissions of PCDD/PCDF from coal-fired power plants usually do not exceed 0.05 pg I-TEQ/Nm<sub>3</sub> equivalent to less than 0.02 g I-TEQ per coal-fired power plant per year. Emission factors for PCDD/PCDF from fossil fuel fired power generation facili-

ties vary in the range of 0.5 µg I-TEQ/TJ for natural gas and light fuel oil fired facilities to 2.5 µg I-TEQ/TJ for heavy fuel oil fired facilities to 10 µg I-TEQ/TJ for coal fired facilities and up to 35 µg I-TEQ/TJ for co-firing waste [UNEP, 2005b]. Solid residues (fly ash) from coal-fired facilities may also contain some quantities of POPs in the concentration range close to those found in the air emissions.

### Impact of BAT/BEP on GHG emissions

The primary focus for installing BAT/BEP flue gas cleaning systems in fossil-fired utility and industrial boilers is to reduce SO<sub>2</sub>, NO<sub>x</sub>, particulates and heavy metals. Even though not the primary objective, the effective reduction of unintentionally produced POPs is also achieved additionally.

Primary measures BAT/BEP for fossil-fuel fired utilities and industrial boilers include monitoring of chlorine content in the fuel, control of key combustion process parameters (e.g., furnace temperature ≥ 1,000 °C, proper mixing and sufficient residence time in the furnace of ≥ 1 sec, sufficient O<sub>2</sub> content of more than 2%vol.wet, continuously low CO levels of less than 30 ppm), proper equipment design, and maintenance.

Secondary measures consist of the installation of suitable air pollution control equipment including SCR systems for the control of nitrogen oxides (NO<sub>x</sub>). SCR systems operated at temperatures between 300 °C and 400 °C are also known for their effectiveness in controlling gaseous POPs emissions and are used for PCDD/PCDF control on a large scale. Other end-of-pipe recommended techniques for controlling release of particle-bound POPs include ESPs and baghouse filters for the collection of fly ash. Also wet and dry FGD systems will remove gaseous and particle bound POPs.

Formation of unintentionally produced POPs during the combustion of fossil fuels can be significantly reduced by optimizing combustion conditions with co-benefits for energy recovery and reduced GHG emissions. Higher steam parameters (temperature and pressure) in fossil fuel fired steam boilers, better mixing for more efficient combustion, and closer process control and optimized heat recovery equipment design are essential for achieving higher energy generation output and reduction in unintentionally produced POPs releases.

Maximized energy recovery significantly reduces the amount of fossil fuels needed to generate a given

quantity of usable power and as such formation of unintentionally produced POPs. Power generation units featuring ultra supercritical steam boilers and/or integrated (coal) gasification combined cycle (IGCC) plants offer net energy efficiencies of more than 45%. Compared to the conventional subcritical steam boilers with a net efficiency of around 30% - 35% these high efficiency power generation units burn 25% - 35% less fossil fuels resulting in a comparable reduction in GHG and associated POPs emissions. Studies showed that the United States could easily reduce GHG emission by approximately 30% by replacing old, low efficiency subcritical fossil fuel fired utility steam boilers with ultra supercritical fossil fuel fired utility steam boilers and/or IGCC plants [McIlvaine Company, 2008].

As fuel is by far the largest portion of the overall operating costs for power generation facilities, both in terms of operating costs and GHG emissions, reduction of fuel consumption through efficiency improvements for lower fuel consumption per unit of power generated is the most promising approach to reduce simultaneously GHG and unintentionally produced POPs emissions. One way to achieve this is by replacing existing low efficiency fossil fuel fired power generating units with new highly efficient ultra supercritical fossil fuel fired utility steam boilers and/or IGCC plants. Furthermore, improvements in energy efficiency resulting in lower fuel consumption will produce the same double effect for GHGs and unintentionally produced POPs as well as heavy metals and mercury. Combined with necessary secondary state-of-the-art flue gas cleaning systems (ESP or baghouses for particulate control, SCR for NO<sub>x</sub> control and FGD for SO<sub>2</sub> control) further reductions of unintentionally produced POPs emissions in fossil fuel fired utility and industrial boilers are possible. The application of these end-of-pipe techniques is associated with the insignificant energy consumption trade-offs in the range of 1 to 5% of the total energy output of a plant (See Chapter II.1.1 on incinerators).

## II.5. Motor vehicles, particularly those burning leaded gasoline

Gasoline and Diesel fuels derived from crude oil are most commonly used as motor fuel for internal combustion engines in motor vehicles. Natural gas, biomass derived ethanol or biodiesel and other fossil fuels have currently only a very small share in the use as fuel for motor vehicles except in few selected countries (e.g. natural gas in the Netherlands or biomass derived ethanol in Brazil).

## Sources of GHGs and unintentionally produced POPs in the process

Combustion of gasoline and diesel fuel in motor vehicles is one of the largest sources of CO<sub>2</sub> emissions in the world [Sims et al., 2007]. In 2006, the transport sector accounted for about 23% of the world's energy-related CO<sub>2</sub> emissions with the highest growth rate over the last decade among energy-using sectors.

During most of the twentieth century, gasoline technology included the use of tetraalkyllead (TAL) as an anti-knock compound. TAL was used to prevent pre-ignition of fuel in hot cylinders in high-compression engines. In addition to TAL, ethylene dichloride or dibromide were added to scavenge the lead to lead halides, thus preventing buildup of lead oxide in the engine. In the presence of chloride, formation of unintentionally produced POPs during the combustion process is facilitated. Unleaded gasoline does not contain chlorinated metal scavengers, but some small amount of chloride is usually present in motor fuels as well as lubricants. Diesel fuel, combusted in vehicle engines, also gives rise to PCDD/PCDF formation for the same reason. Combustion of gasoline and diesel in motor vehicles can also be associated with emissions of particulates and heavy metals.

## Impact of BAT/BEP on GHG emissions

BAT/BEP include prohibition of leaded gasoline with halogenated metal scavengers. Additional measures include installation of diesel oxidation catalysts, particulate filters and catalytic converters. Reduction in fuel consumption by vehicles and conversion of motor fleet to electric, solar, fuel cell or other alternative means of vehicle power is recommended by the Stockholm Convention BAT/BEP guidelines and guidance.

There is no direct correlation between the use of leaded gasoline and fuel consumption; other variables predominate. As a result, there is no direct impact on GHG emissions by eliminating leaded gasoline and scavengers. Since BAT for diesel engines include additional air pollution control devices for minimization of particulates and CO emissions and more complete combustion of fuel to CO<sub>2</sub>, there is little direct impact of BAT on the GHG emission reduction with the exception of hydrocarbon reduction.

A full life-cycle assessment on energy demand for vehicle travel is beyond the scope of this study. However, any conversion of the gasoline or diesel fleet to, for example, electricity will require an analysis of emissions of unintentionally produced POPs and GHG

from the facilities used to provide the incremental power that will replace gasoline. For the purposes of this study, however, the direct fuel substitution or use of pollution control devices reducing release of unintentionally produced POPs and other contaminants (particulates, heavy metals) do not have significant impact on GHG emissions.

## II.6. Production of pulp using elemental chlorine or chemicals generating elemental chlorine, specific chemical production processes releasing Annex C chemicals, textile and leather dyeing and finishing

### II.6.1. Production of pulp using elemental chlorine

The process for making paper generally involves pulping wood fiber, which consists of cellulose, hemicellulose, lignin and extractives. The process is varied and produces a diverse set of products. To make white paper, chemicals are used to dissolve most of the lignin. Bleaching under oxidative conditions using chlorine, chlorine dioxide, ozone and peroxides is used to remove residual lignin and improve paper brightness. Chlorine is manufactured by electrolysis of NaCl in water with the concomitant production of NaOH. Large scale production of ClO<sub>2</sub> is accomplished by acidic reduction of sodium chlorate, NaClO<sub>3</sub>, which is produced in a similar NaCl electrolytic process [Kirk-Othmer Encyclopedia of Chemical Technology, 2003]. Ozone is made by separation of diatomic oxygen into oxygen atoms in an electric field.

## Sources of GHGs and unintentionally produced POPs in the process

The primary common GHG generated in the pulp industry is CO<sub>2</sub>, mainly due to energy use. As the Stockholm Convention BAT/BEP guidelines and guidance calls for "elemental chlorine free" bleaching process without the use of elemental chlorine, energy impacts of BAT/BEP represent only a minor part of the overall energy use in the pulping industry.

For years, elemental chlorine and hypochlorite were used in the bleaching process. In the 1980s, it was discovered that the reaction between chlorine and

the aromatics in lignin resulted in the production of 2,3,7,8-tetrachlorodibenzo-p-dioxin and 2,3,7,8-tetrachlorodibenzofuran.

### Impact of BAT/BEP on GHG emissions

Chemically, the presence of elemental chlorine is the trigger for unintentionally produced POPs production. A process called ECF or TCF — elemental chlorine-free or totally chlorine-free — eliminates the presence of elemental chlorine and thus, generation of PCDD/PCDF. ECF bleaching uses chlorine dioxide as one of the bleaching agents, while use of TCF process consumes oxygen, ozone and peroxides. In practice, a large majority of the conversion of pulp bleaching away from elemental chlorine has resulted in ECF mills.

Primary BAT measures for the pulp industry include reduction of use or elimination of elemental chlorine, use of other additives that do not contain the dibenzodioxin or furan structure, use of wood that does not contain chlorinated phenols and reduction in the amount of bleaching agent needed by judicious wood management.

According to Natural Resources Canada [Francis et al., 2002], bleaching operations account for approximately 19% of steam and 16% of electricity use per ton of the product produced. A study by the National Council for Air and Stream Improvement found that, on base year 1995, changing bleach plants from the nominal 15% use of  $\text{ClO}_2$  to 100%  $\text{ClO}_2$  would cause a net increase of  $2.7 \times 10^5$  tC per year [NCASI, 1998]. The authors estimated the total  $\text{CO}_2$  emissions of the forest and paper industry to be  $3.0 \times 10^7$  tC/yr, about 2/3 of which emits from manufacturing facilities.

Based on these 1995 estimates, completion of substitution of chlorine by chlorine dioxide (from 15% to 100%) - known as compliance with the “cluster rule” in the US—would increase industry carbon emissions by about 1%. Much of the difference stems from the manufacturing energy intensity of the alternative chemical bleaching agents: elemental chlorine vs. sodium chlorate which is converted to chlorine dioxide or, oxygen which has been isolated from air, stored and shipped as a liquid and electrochemically converted to ozone.

Energy use represents significant costs for the pulp and paper industry in terms of  $\text{CO}_2$  emissions and actual costs. Therefore, a reduction in energy use per unit of product is the first mitigation approach used. The aforementioned Canadian study addressed opportunities for energy reduction in the pulp and pa-

per process. Utilizing these energy reduction strategies could greatly offset the approximately 1% added carbon emissions from the use of chlorine dioxide instead of chlorine as a bleaching agent.

### II.6.2. Specific chemical processes releasing unintentionally produced POPs, especially production of chlorophenols and chloranil

Various chlorinated pesticides are listed on Annex A as materials to be eliminated. This chapter deals with processes that may generate Annex C chemicals, especially PCDD, PCDF, PCB and HCB. Chemical processes discussed in this chapter utilize heat, light and various raw materials in order to synthesize chemical products. A large number of those products, and as result a large number of those processes, are derived from chlorine.

#### Sources of GHGs and unintentionally produced POPs in the process

Most energy usage in the overall chemical industry is for synthesis of large volume, building block chemicals; that is, chemicals used as raw materials for most other commercial chemicals. The most energy-consuming processes include electrolysis of brine to generate chlorine and sodium hydroxide and combustion of coal or gas to make steam for cracking naphtha or natural gas liquids into hydrocarbon building blocks. Energy use for the chemicals sector in the USA, not including raw materials, was approximately  $3.2 \times 10^{12}$  MJ in 1998 or about 3% of the total national energy consumption ( $100 \times 10^{12}$  MJ) [EIA, 1998].

**Oxychlorination.** In this process, chloride as HCl is oxidized to chlorine by oxygen over a copper catalyst in the presence of an organic substrate such as ethylene. The organic substrate reacts with the chlorine in situ, and the process entails relatively milder conditions than those required to accomplish the oxidation without the organic substrate. Use of oxychlorination allows conversion of elemental chlorine to salable products at a yield of about 98-99 percent on chlorine, rather than having to isolate or neutralize large volumes of byproduct HCl.

Because of the presence of the copper catalyst, carbon, hydrogen, oxygen and chlorine, generation of side product unintentionally produced POPs, along with high molecular weight materials, is common in oxychlorination. This stream of side product materials comprises a small minority of the chlorine used in the process, but it should be isolated and destroyed before sale of the product.

**Chlorination of aromatics.** Some processes can give rise to dibenzodioxin or dibenzofuran structures. This can occur in the chlorination of aromatic hydrocarbons of phenols, as in the treatment of 1,2,4-trichlorophenol with base, or chlorination of phenol or aniline in the process of making chloranil dye.

**Other chemical reactions.** Some processes contain preformed dibenzodioxin and dibenzofuran structures which can then be chlorinated (for example as derived from lignin in paper bleaching).

### Impact of BAT/BEP on GHG emissions

Virtually all chemical processes end with a purification step. The aim of purification is to isolate a commercially valuable material from by-products or other potentially commercially valuable materials independently from unintentionally produced POPs content in the stream. For chemical processes involving by-product unintentionally produced POPs, the purification step—generally distillation—is used to isolate usable product by segregating unintentionally produced POPs into a relatively non-volatile, high-boiling-point stream known as “heavy ends” or “still bottoms.” Thus, BAT for these chemical processes include a well-run and adequate separation/distillation step.

Unintentionally produced POPs in the isolated high-boiling-point stream can then be destroyed in an appropriate hazardous waste incinerator that often includes a heat-recovery boiler. Products of this combustion process are CO<sub>2</sub> and some amount of HCl. That HCl can be neutralized with base and discarded as salt (sodium chloride) water or, under certain circumstances, isolated, purified and either sold as an aqueous muriatic acid solution or returned to a chemical process.

Other primary BAT measures include elimination of carbon electrodes for chloralkali production with a substitution for more energy efficient titanium electrodes; elimination of alkali treatment of 1,2,4,5-tetrachlorobenzene and 2,4,5-trichlorophenol; elimination of phenol route to chloranil; controlled production of pentachlorophenol with insignificant heat or energy loss/production; and, use of hydrogen in oxychlorination/reduction in aromatics in oxychlorination feeds. Also, oxychlorination catalyst maintenance and temperature uniformity control, mitigate the tendency of fixed bed catalysts to become fouled and coked over time, and concomitantly reduce generation of unintentionally produced POPs.

Distillation is used for unintentionally produced POPs isolation because of large differences in boiling points between unintentionally produced POPs and products. Distillation in these processes is a relatively minor part of the total energy use. In fact, energy for distillation can be harvested as waste heat from exothermic reactions responsible for making the desired product or heat recovery from other processes resulting in low or zero net energy use in the distillation process.

Overall, the use of energy for isolation and destruction of unintentionally produced POPs represents only a minor part of the overall industry energy usage. This is mainly because the processes regulated by Stockholm comprise a minority of the energy-consuming chemical processes, and wastes which must be destroyed constitute a small percentage of the product. The largest source for generation of by-product unintentionally produced POPs in the chemical industry results from the oxychlorination process used to manufacture ethylene dichloride and various chlorinated solvents. In the USA, there were approximately 7 mln metric tons of oxychlorination capacity in 2000. A conservative estimate of heavy ends production contaminated at ppm or ppb levels of unintentionally produced POPs is approximately 2% of that production or about 140,000 metric tons. Heavy ends have a thermal value of about 10 MJ/kg. Thus, the energy value of that material is approximately  $0.014 \times 10^{12}$  MJ. Natural gas is used to bring the incinerator to stable operating conditions and during introduction of liquid waste, but this energy source and associated CO<sub>2</sub> emissions are much smaller than CO<sub>2</sub> production from waste incineration. And waste incineration represents a very minor part of the total chemical industry sources of GHGs (see also Chapter II.1.1).

Oxychlorination catalyst is usually not regenerated due to a relatively low value of copper. Otherwise, regeneration would require heat and energy with the relative increase in GHG emissions. Fluidized bed catalysts experience decreased particle size by attrition in the bed, and in modern plants particles carried through the process are accumulated in waste water solids. These solids can be landfilled in a hazardous waste landfill, dried at cost of some energy or burned later with some energy recovery. The overall impact on GHG emissions seems to be insignificant compared to the whole process.

Overall, energy or GHG costs for the aforementioned other primary BAT measures appear to have a very small energy or GHG penalty, if any at all.

## II.7. Smoldering of copper cables and opening burning of waste

### II.7.1. Smoldering of copper cables

In this process, intended to recover copper wire, jacketing is burned and the brittle char is cracked away. It should be noted that this is an unacceptable practice. While this was a commercial process up to about twenty years ago, nowadays it is only found as an informal recycling business. Combustion in this sort of operation is poor to smoldering, and highly polluting for a number of reasons, including unintentionally produced POPs generation.

#### Sources of GHGs and unintentionally produced POPs in the process

Carbon dioxide and small amounts of various hydrocarbons are emitted from the burned jacketing as well as from any fuel used to sustain combustion. Poor combustion of carbon- and chlorine-containing material in the presence of copper is a recreation of the known chemistry of unintentionally produced POPs formation in incinerator flue gases.

#### Impact of BAT/BEP on GHG emissions

The BAT/BET guidelines and guidance stipulate process elimination. Among suggested alternatives are stripping jacketing from wire manually, chopping wire and separating jacket from metal and in some specialized cases, well-controlled combustion of fine-gauge or grease-contaminated wire. All these processes are well-known.

Emissions of CO<sub>2</sub> from the use of fuel to support jacket combustion and from the burning jacket itself are non-zero, but have insignificant impact on the global environment, and elimination of the process eliminates not just unintentionally produced POPs but also those emissions. Only a small amount of fuel energy is expended in wire stripping, wire chopping, and in recycling polymer jacketing. Elimination of unintentionally produced POPs is significant in the copper cable smoldering, while the magnitude of GHG emissions is insignificant.

### II.7.2. Open burning of waste

Open burning of waste is a process wherein refuse from individual homes or refuse collected from a number of homes, is combusted without benefit of

emission control technology. It can take the form of individual action, so-called "backyard burning" or concerted action by authorities wherein material at a common drop-off or dumpsite is burned for volume reduction. It has the advantage of being accessible, low-tech and easy to initiate. In some cases, waste can burn spontaneously, especially if aided by combustion of methane derived from anaerobic decomposition (landfill gas). When used for destruction of electronic waste, open burning becomes a large source of unintentionally produced POPs as well as PAHs, particulates, CO, heavy metals and other toxic substances.

#### Sources of GHGs and unintentionally produced POPs in the process

Carbonaceous material is burned, with CO<sub>2</sub> as the major, ultimate product of combustion, accompanied by other GHG including, methane and other hydrocarbons, nitrous oxide and various minor products formed depending upon materials used for combustion. Poor, low-temperature and incomplete combustion have been known as relatively large sources of PCDD/PCDF, PCB and HCB. When electronics are burned, large sources of copper, particulates and halogens can be present at low temperatures facilitating formation of unintentionally produced POPs.

#### Impact of BAT/BEP on GHG emissions

The only reasonable guidance is for elimination of the process, since by its definition, it is uncontrolled or at best poorly controlled. It is possible that the process is improved by burning only dry, highly combustible material at high temperature, but there is little scientific evidence that these conditions improve the process sufficiently to make it acceptable.

By eliminating open burning, large amounts of CO<sub>2</sub> and other GHG derived from uncontrolled combustion are eliminated. On the other hand, waste exists and must be avoided, recycled or discarded (*Chapter III*). To the extent that waste avoidance truly eliminates a material that reaches its end of life, and the avoidance is not offset by energy or material expenditure at another point in the product chain, less GHG is generated. There may be a net energy benefit if engineered materials can be reused or recycled rather than discarded and replaced.

Vegetable waste, which comprises a large part of open burned material, can be composted. In principle, aerobic composting leading to CO<sub>2</sub> production could be considered superior to anaerobic process producing methane. However, composting is neces-

sarily an active process. If the process is aided mechanically, emissions of CO<sub>2</sub> from fuel use should be considered. If composting is facilitated manually, care must be taken to avoid parts of the compost going anaerobic.

For waste that will be discarded but not recycled, composted or burned under uncontrolled circumstances, the two remaining alternatives are incineration, possibly with energy recovery, and landfilling. Incineration processes are considered elsewhere in the report (Chapter II.1.1). Landfilling should be subdivided into engineered landfills and ad hoc landfills, e.g., dumps. Fires are rare at engineered landfills. Since landfills are known to emit some CO<sub>2</sub> and methane, they are potential sources of GHG. But archaeological studies have shown that the majority of material does not degrade in a landfill, and thus, for the period of time waste resides there, less CO<sub>2</sub> is emitted than from the open burning. Harvesting methane for destruction or fuel use reduces its GHG impact. This is especially the case if harvested landfill gases are combusted to generate useful heat and electric power. Total generic evaluation of GHG equivalent from landfills versus alternatives is difficult (For additional references see Chapter III).

Since dumps are not protected by daily cover, water imbibition can induce the anaerobic degradation process. Without methane recovery for subsequent generation of heat, the impact on GHG of such methane emissions is significant. Cases where dumps are burned inadvertently or intentionally for volume reduction devolve to the base open burning case.

Elimination of open burning leads to significant reduction in unintentionally produced POPs emissions. Quantification of the GHG impact of alternatives to open waste burning is complex and depends on destruction methods, energy recovery and types of processes. Life cycle approaches should provide guidance for development of improved waste handling priorities and hierarchies. (Further details are provided in Chapter III).

## II.8. Thermal processes in the metallurgical industry in Parts II and III of Annex C

### II.8.1. Secondary copper, aluminum, zinc and lead production

Copper, aluminum, zinc, and lead are recovered in facilities specifically designed for recovered metal

and to the feed material properties such as metal content, size distribution, oxide content, degree of contamination, etc. Secondary production usually consists of the following steps: pre-treatment of the secondary raw materials, melting, holding and casting. A whole range of processes has been developed for the variety of secondary raw materials. These processes include rotary furnace, reverberatory furnace, bath furnace such as the Isa-smelt furnace or the QSL furnace (only for Pb), shaft furnace (only for Al), Kayser Recycling System (KRS) furnace (only for Cu), and Waelz kilns (only for Zn). [European Commission, 2001a].

#### Sources of GHGs and POPs in the process

Secondary copper, aluminum, zinc and lead production are important recycling activities globally as high recovery rate from scraps can be achieved using modern technologies. For example, in the EU, recycling rates for these four metals are typically between 70 and 100%, depending on the type of scrap. Secondary production of metals consumes less energy than primary production from ores. The highest energy savings are reached in the case of aluminum, where its production from recycled metal uses down to 5% of energy used for primary production. Lead production from recycled metal can use down to 50% of the energy of primary production [European Commission, 2001a].

In most processes, gaseous, liquid or solid fossil fuels are used as a heat source and/or as a reducing agent. Fuel mixes will depend on the furnace type. For secondary copper, aluminum, zinc, and lead production, major CO<sub>2</sub> emissions are from the use of fossil fuels. Since pyrometallurgical processes are highly heat intensive and the process gases contain a lot of heat energy, energy and heat recovery are practiced extensively in these sectors. Possible techniques include:- the use of technologies that recover heat (recuperative burners, regenerative burners, and heat exchangers), the use of hot gases to raise steam or produce heat for other process stages, the use of oxygen enriched air or pure oxygen in the burners, the use of low mass refractories, the use of hot gases from melting stages to preheat the furnace charge. Many of these measures and techniques generate energy savings not associated with the impact on unintentionally produced POPs releases.

Secondary raw material often consists of scrap contaminated with carbon and chlorine containing products. The presence of organic contaminants on the scrap which is fed into the furnace or other sources of carbon (e.g., partially burnt fuels or reducing agents)

can generate fine carbon particles which react with chlorine to produce PCDD/PCDF. The de novo synthesis temperature window can be present in some part of the furnaces and in some air pollution control devices.

In the specific case of secondary aluminum production, the magnesium removal involves the use of chlorinated compounds which can lead to HCB and PCDD/PCDF emissions.

### Impact of BAT/BEP on GHG emissions

Process design and configuration are influenced by the expected variation in feed materials. A large variety of processes are recommended, in conjunction with raw materials properties and with suitable gas collection and abatement systems.

Primary BAT/BEP are regarded as pollution prevention techniques to reduce or eliminate the generation and release of unintentionally produced POPs and include the following processes:

- Pre-sorting of feed material using thermal, mechanical (stripping, milling/grinding) or chemical techniques (solvent, caustic scrubbing);
- Effective process control aiming at maintaining operational stability at parameter levels that contribute to the minimization of PCDD/PCDF releases (e.g., keeping temperature above 850°C);
- For secondary aluminum production the choice of demagging materials and the associated control process should be carefully considered. The use of hexachloroethane has been shown to give rise to high emissions of PCDD/PCDFs and HCB [UNEP, 2006].

Secondary BAT/BEP include a number of pollution control techniques. These techniques do not eliminate the generation of unintentionally produced POPs, but serve as means to contain, prevent or reduce emissions. Among them are fume and gas collection including furnace-sealing and use of hooding; high efficiency dust removal in conjunction with the recycling of collected particulate matter; afterburners followed by rapid quenching of hot gases to temperature below 250°C, and adsorption on activated carbon, followed by the removal using high efficiency dust removal systems.

The pre-sorting measure can have a neutral to low impact on the GHG emissions. The optimal operating temperature for secondary production is metal-specific (copper, aluminum, zinc or lead). For Zn, operating temperatures are probably lower than 850°C.

It also depends on the type of furnace used, and on the type of raw materials fed into the furnace. As a consequence, the impact of the primary measure proposing a minimal temperature of 850°C should be assessed on a site-by-site basis. Impacts on GHG emissions in the process can be medium to high and positive or negative.

Concerning secondary measures, data are scarce, but it is assumed that their impact can be neutral to very low (additional energy consumption probably far lower than 1% of the overall energy consumption).

Secondary production of copper, aluminum, zinc, and lead are important unintentionally produced POP sources, but consumes significantly less energy than primary production from ores. Application of BAT/BEP measures can generate low GHG negative impacts largely outweighed by highly positive impact on unintentionally produced POPs minimization and small compared to the total energy consumption of a plant.

### II.8.2. Sinter plants in the iron and steel industry

The blast furnace route (integrated steelworks) is currently the major route to produce steel and is expected to remain as such in the next decade. Nevertheless, the share of the secondary steel route (using electric arc furnaces (EAF) – see II.8.4) is gradually increasing worldwide.

Integrated iron and steel processes consist of the following main production steps: sinter plants, pelletization plants, coke oven plants, blast furnaces, basic oxygen steelmaking, and casting. Blast furnaces achieve improved performance by prior physical and metallurgical preparation of the burden which improves permeability and reducibility. This pre-treatment step may be carried out through a sintering plant, where fine particles of iron ores and, in some plants, secondary iron oxides wastes are agglomerated by combustion. Sintering involves the heating of this iron-containing feed with flux and solid fossil-fuel (coke breeze or coal) to produce a semi-molten mass, which solidifies into porous pieces of sinter which is then fed into the blast furnace.

#### Sources of GHGs and POPs in the process

Blast furnaces consume about 60% of the overall energy demand of integrated steelworks, whereas the sinter plant consumption accounts for 9% only. On an integrated steelwork, approximately 90% of

the imported energy is ultimately derived from coal. Figures are similar for the sintering process step as 85% of the energy consumption is derived from solid fossil-fuel (coke). Therefore, in sintering plants, CO<sub>2</sub> derives from the use of solid fossil-fuel.

Two potentially reusable waste energy options are available: the sensible heat from the main exhaust gas and the sensible heat of the cooling air from the sinter cooler located downstream of the sinter strand. In the first case, waste gas recirculation is used to save energy. In the second case, there are at least five different ways to recover waste heat. For the latter case, energy savings up to 30% have been reported [European Commission, 2001b].

Two alternatives to the traditional blast furnace route are known. They include direct reduction using natural gas. The use of natural gas instead of coke results in reduced CO<sub>2</sub> emissions compared to the traditional blast furnace route. The second alternative, smelting reduction uses coal as a fuel. Only two sites are currently in operation and energy requirements are difficult to assess.

The iron sintering process is a major source of PCDD/PCDF. The overall mechanism of PCDD/PCDF formation in the sinter process is complex. Several processes occurring at different positions within the bed owing to the vertical and longitudinal temperature distributions within the sinter bed are responsible. Formation of PCDD/PCDF is likely to occur within the sinter bed itself rather than downstream in the waste gas system. Dioxins are generated due to the presence of carbon from coke, oxygen from air, chlorine from ore and organic chlorides in secondary raw materials, metallic catalysts from minerals and coke, precursors such as PCBs and chlorophenols in raw materials [European Commission, 2001b].

### Impact of BAT/BEP on GHG emissions

It is recommended that primary BAT/BEP are implemented together with the appropriate secondary measures to ensure the greatest minimization and reduction of POPs emissions. Primary BAT/BEP include stable and consistent operation of the sinter strand. To minimize the formation and release of PCDD/PCDF, operating parameters requiring stable and consistent management include: strand speed, bed composition, and bed height, use of additives, and minimization of oil content in mill scale, minimization of air in-leakage through the strand, ductworks and off-gas conditioning systems, and minimization of strand stoppages. Furthermore, the continuous

parameter monitoring to ensure optimum operation of the sinter strand and off-gas conditioning systems, recirculation of off-gases; feed material selection to minimize unwanted substances in the feed of the sinter strand, feed material preparation, and urea injection are proposed BAT/BEP. However, urea used to decrease formation of PCDD/PCDF by a maximum of 50% can also promote increased emissions of NH<sub>3</sub>. Recommended secondary measures are adsorption / absorption and high-efficiency dedusting, fine wet scrubbing, removal of particulate matter from sinter off-gases, and hooding of the sinter strand.

Primary measures such as stable and consistent operation of the sinter strand and recirculation of off-gases can be beneficial in terms of energy savings and thus CO<sub>2</sub> emission reduction from sinter plants. Some secondary measures can lead to an increase in energy consumption, from 2-15 MJ/t sinter for fabric filters to 100 MJ/t sinter for a fine wet scrubbing system. This represents a maximum increase of 10% in the total energy consumption of a sinter plant [European Commission, 2001b].

As BAT/BEP guidelines and guidance strongly encourage the implementation of both, primary and secondary measures, the overall impact of BAT/BEP on CO<sub>2</sub> emissions can be viewed as neutral or slightly positive. If the whole integrated steelwork is taken into account, the impact of BAT/BEP on energy use concentrated on the sintering process step only is very low, with a maximum of 1% rise in the total energy consumption [European Commission, 2001b].

The use of alternatives can enable a low-to-medium positive impact in terms of CO<sub>2</sub> emission reduction. Based on currently available data, the direct reduction route offers a better CO<sub>2</sub> reduction potential than the smelting reduction route [European Commission, 2001b]. However, it should be emphasized that this assessment is dependent on the availability of appropriate fuels and metallic raw materials. There are some restrictions as to the raw materials used for both alternatives and if raw material physical specifications are not met, CO<sub>2</sub> impacts can be very low to neutral.

Overall, the impact of primary and secondary BAT/BEP on energy consumption and CO<sub>2</sub> emissions in sinter plants is neutral or slightly positive. Alternatives to the sintering process are likely to generate low-to-medium positive impacts in terms of CO<sub>2</sub> emissions. However, impacts of alternative processes should be assessed on a plant-by-plant basis as they are dependant on the availability of appropriate fuels and metallic raw materials.

### II.8.3. Thermal processes in the metallurgical industry not mentioned in Annex C Part III: Primary aluminum production, magnesium production, primary base metals smelting

Primary aluminum is produced from bauxite ore that is converted into alumina using the Bayer process. Alumina undergoes an electrolytic reduction in a molten bath of cryolite to produce aluminum. There are two ways to produce magnesium: the thermal reduction process, where calcined dolomite reacts with FeSi to produce Mg vapor, and the electrolytic production, where Mg is produced by electrolysis of magnesium chloride which is obtained by chlorination of MgO.

Primary base metals production involves the extraction and refining of nickel, lead, copper, zinc and cobalt. A large variety of pyrometallurgical processes are in operation worldwide. The applicability of a particular process is governed by the type and variability of the raw material (metal ore) available.

#### Sources of GHGs and POPs in the process

Primary metal production consumes far more energy than secondary metal production. This is particularly true for the electrolysis-based processes consuming very high amount of energy. For example, typical specific electricity consumption for primary aluminum or magnesium production is 15,000 kWh/t [European Commission, 2001a]. Pyrometallurgical processes use fossil fuels as a heat source and as reducing agents. These processes may also use the sulphur in the ores as a heat source and reducing agent and consequently emit less carbon gases. Electrolysis-based processes use carbonaceous materials as well. For primary metal production, GHG emissions will mainly consist of CO<sub>2</sub> emissions from carbon-based materials.

Energy and heat recovery is practiced extensively in these sectors, especially in the case of pyrometallurgical processes. Among techniques used for energy and heat recovery recuperative burners, regenerative burners, heat exchangers, the use of hot gases to raise steam or produce heat for other process stages, the use of oxygen enriched air or pure oxygen in the burners, the use of low mass refractories, the use of hot gases from melting stages to preheat the furnace charge. Many of these measures and techniques generate energy savings that are not associated with uPOP emissions.

In addition, primary production of aluminum and magnesium results in perfluorocarbons (PFCs) and SF<sub>6</sub> emissions, respectively. Once they are formed, PFCs cannot be removed from the gas stream with existing technologies. Hence, the only strategy implemented to minimize PFC emissions consists in limiting the anode effect in the electrolysis cells. This approach is unlikely to impact unintentionally produced POPs emissions. In the 2000s, research studies have been assessing various SF<sub>6</sub> substitutes in the magnesium industry. Substitutes such as HFC-134a (which still has a significant Global Warming Potential GWP) and SO<sub>2</sub> have recently been reported to be tested at an industrial scale. No information is available on the impact of SF<sub>6</sub> substitutes on unintentionally produced POPs. This impact is likely to be neutral.

Primary aluminum and primary base metal smelting are not thought to be significant sources of releases of PCDD/PCDFs compared to secondary metal production. If chlorinated compounds or additives are used, PCDD/PCDFs may be emitted given the presence of carbonaceous material (from fuels or from carbon-based anodes). However, magnesium production can lead to significant PCDD/PCDF emissions originated in the chlorination furnace, where magnesium oxide is converted into magnesium chloride.

#### Impact of BAT/BEP on GHG emissions

Primary BAT/BEP are focused on quality control of the feed material and effective process control. For primary aluminum production different processes emit different GHGs. For example, older self baking anode using the Soderberg process emits more PFCs than processes using prebaked anodes. Other alternatives have been proposed (e.g., inert anode), but are at the research or development stage [UNEP, 2006]. Alternative processes for primary base metals smelting include hydrometallurgical processes and flash smelting technology which emit less GHGs. Alternative processes in magnesium production are still at the assessment stage.

Secondary measures have not been developed specifically to control emissions of unintentionally produced POPs but control other pollutants. These measures include

- use of fabric filters, complete hood coverage of cells, fume collection and treatment, low-NO<sub>x</sub> burners, alumina scrubber, afterburner, wet or semi-dry scrubbing, and bagfilters in primary aluminum production; high efficiency gas cleaning and conversion of SO<sub>2</sub> to sulfuric acid, fume and

gas collection, and high-efficiency dust removal in primary base metals smelting;

- treatment of off gases (wet scrubbers, wet ESPs, followed by incineration or activated carbon adsorption) and treatment of effluent designed specifically for the control of PCDD/PCDF emissions in magnesium production.

Primary BAT/BEP measures dealing with feed quality and process control have positive impacts on energy savings and reduced GHG emissions. Choice of an alternative process is dictated, above all, by the raw material (metal ore) properties. For example, process switching from a pyrometallurgical route to a hydro-metallurgical route may not be feasible from a techno-economical point of view, and even from a technological point of view. The energy and GHG impact of alternative processes may be high (positive or negative) and should be assessed on a site-by-site basis.

Since primary metals production is very energy intensive, the energy use impact of BAT/BEP secondary measures is considered to be relatively low.

#### II.8.4. Other thermal processes in the metallurgical industry not mentioned in Annex C Part III: Secondary steel production

The direct smelting of iron-containing secondary raw materials is usually performed in Electric Arc Furnaces (EAF). The major feedstock is ferrous scrap, which may include scrap from inside steelworks, cut-offs from steel product manufacturers and post-consumer scrap (used vehicles etc.). A batch process consists of several basic steps to produce carbon steel and low alloyed steel: raw material handling and storage, furnace charging with/without scrap preheating, melting, steel and slag tapping, ladle furnace treatments for quality adjustment, slag handling, and continuous casting. To produce high alloyed steel, some additional treatments are needed.

##### Sources of GHGs and POPs in the process

EAF steel production from scrap is an important recycling activity that contributes to the recovery of steel resources and waste minimization. Production of steel from scrap is considerably less energy-consuming than production from iron ore (traditional blast furnace route – see Chapter II.8.2 on sinter plants). The energy consumption savings can reach about 75% [European Commission, 2001b].

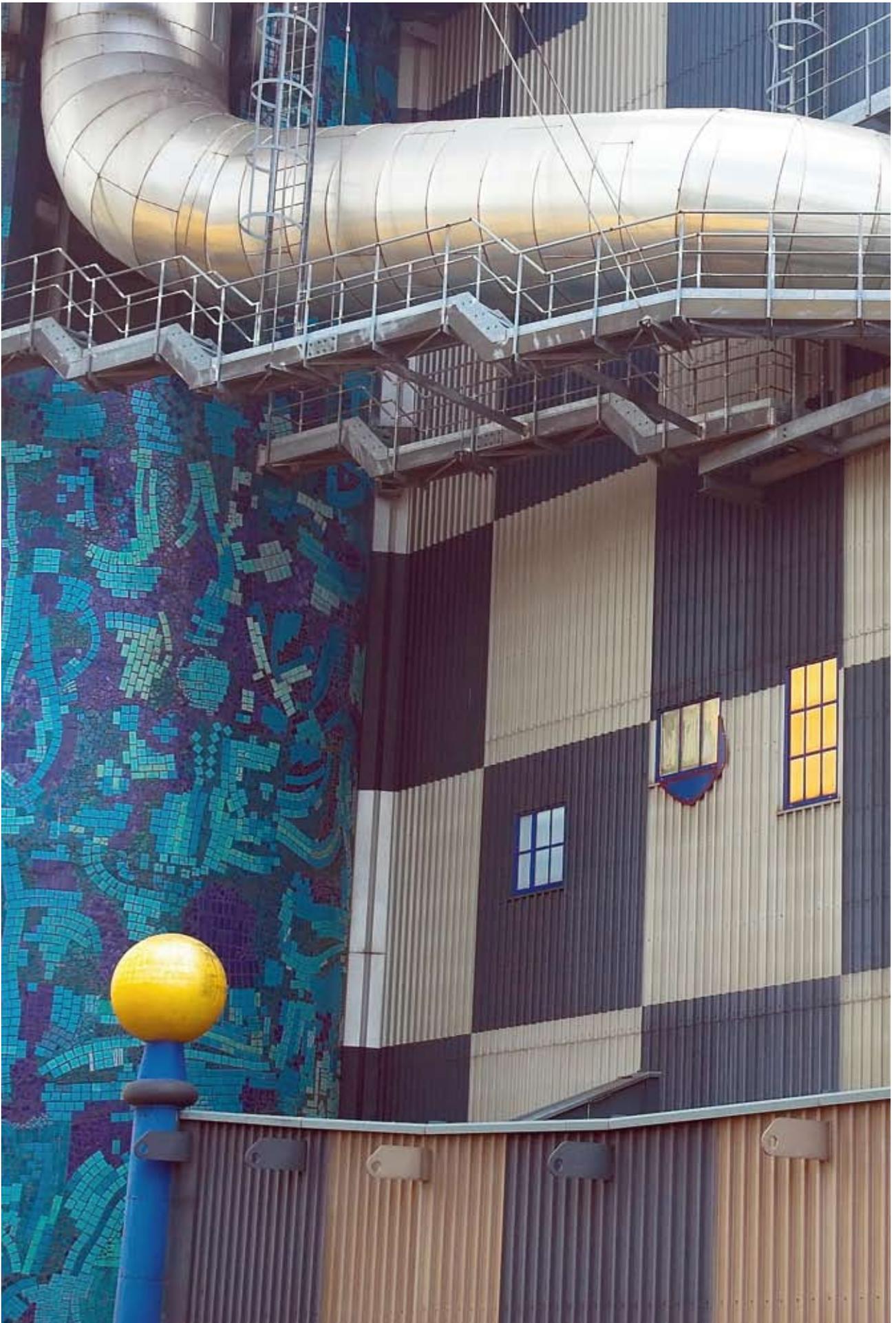
The energy input is mainly derived from electricity. GHG emissions are thus strongly linked to the way electricity is produced within a country or region. However, additional CO<sub>2</sub> emissions can happen in some of the following circumstances:

- the process is increasingly using oxygen enrichment to enhance productivity,
- oxy-fuel burners may be used to assist in early stages of the melting,
- some carbon-based raw materials are used as reducing agents.

Numerous measures and techniques have been implemented to optimize the process in order to increase productivity including high power operation, water cooled side walls and roofs, oxy-fuel burners, automation, efficient power electronics to enhance power supply, etc.. Many of these measures and techniques generate energy savings, which are not associated with unintentionally produced POP releases.

Only one technique is likely to lead to a significant increase in the release of organic micro-pollutants including unintentionally produced POPs: scrap preheating where scrap is contaminated with organic compounds such as paints, plastics or lubricants. The recovery of heat from waste gases to pre-heat the raw material may allow energy savings up to 25% of the overall electricity input. To avoid additional unintentionally produced POPs emissions, while using this technique, additional off-gas treatments may be necessary and offset the overall energy savings [European Commission, 2001b].

EAFs are known to be major emission sources of unintentionally produced POPs, since high temperatures are observed in the arc furnace and scraps in the feed usually contain organic materials and chlorine (in plastics, paintings, oils, and other materials). Therefore, from the furnace charging step to the slag handling step and, in the case of high alloyed steel, to the additional metallurgical treatments, unintentionally produced POPs are very likely to be emitted into the atmosphere. Primary off-gases (from the furnace itself) accounts for approximately 95% of the total emissions of an EAF [European Commission, 2001b]. Solid residues in the form of dust collected by the air pollution control devices for EAF have been found to contain significant levels of PCDD/PCDFs. Therefore it is important that these wastes are contained and managed appropriately.



### Impact of BAT/BEP on GHG emissions

BAT/BEP are concentrated on productivity improvement and product quality enhancement. No alternative to the graphite electrode is operating at the present time. Among primary BAT/BEP measures, though not applicable to all process designs or plants, are raw material quality, conditions of furnace operation, off-gas conditioning system designs, and a continuous parameter monitoring system.

Secondary measures include off-gas dust collection, fabric filter dust collectors (or baghouses), external post-combustion system coupled with rapid water quench, and adsorbent injection.

Primary and secondary measures for solid waste are recycling, treatment to recover valuable metals, minimizing dust generation from hauling and handling, disposal in an environmentally sound manner. Measures for wastewater are closed-loop water systems, recycling, and treatment of residual wastewater.

### Impact of BAT/BEP on GHG emissions

Most of the primary BAT/BEP measures should lead to low positive impacts in terms of energy saving. Raw material switching may have (negative or positive) low impacts. This option should be assessed on a site-by-site basis as its feasibility is strongly governed by the local availability of alternative raw materials.

Three of the secondary BAT/BEP measures in secondary steel production have low negative impact on energy use and CO<sub>2</sub> emissions. Each step such as post-combustion, solid waste minimization (through recycling of precipitated EAF dust by returning them to the EAF) and off-gas collection in conjunction with fabric filters accounts for a maximum of 5% increase in the overall electricity consumption [European Commission, 2001b].



### III. Cross-cutting considerations (waste management, training and awareness raising, testing, monitoring and reporting)

#### Waste Management

In the industrialized countries and rapidly urbanizing countries, the amount of waste, which requires treatment and disposal, is growing. Waste collection and treatment systems are very complex serving many goals and requiring the intervention and coordination of many stakeholders and the application of different techniques. To ensure a coherent waste management system, all the actions at different levels should follow a commonly agreed strategy.

The overarching principle of waste management is the effective implementation of the waste hierarchy - which means in this order:- prevention, reduction, reuse, recycling, recovery, incineration including reuse, recycling and/ or recovery of incineration byproducts (heat, metals, ash, gypsum, etc.) and final disposal in engineered landfills. The introduction of principles such as product warranties and producer responsibilities may be effective even before articles become waste.

Whereas in the past, important goals of waste management were the reduction of the mass of waste and its hazardous potential, now in addition to BAT and BEP, the reduction of GHG emissions also becomes more important.

To achieve this, every waste management activity should be optimized concerning energy consumption and emissions of CO<sub>2</sub> and CH<sub>4</sub>. In addition, interrelations between different waste treatment and disposal options should be investigated on a regional, national or international level.

Treatment and disposal of waste result in emissions of GHGs. Direct CO<sub>2</sub> emissions are caused either by (co-)incineration, gasification or pyrolysis of (parts of) the waste. Other incineration-related GHGs are methane and N<sub>2</sub>O. Methane and CO<sub>2</sub> may be emitted by decomposition of waste during storage of waste. Disposal in landfills leads to emissions of CO<sub>2</sub> and methane. Indirect emissions may be caused by the energy consumption of the individual treatment and disposal activities. For wastes, the relevant POPs formation mechanism is by thermal processes only. Other treatment and disposal operations may lead to the release of POPs which are introduced into the system by chemicals or as impurities.

Other applied non-thermal waste treatment techniques include composting, application to soils and anaerobic or alcoholic fermentation with subsequent use of the formed biogas as fuels or chemicals. Since these techniques are applied to certain types of biogenic waste, CO<sub>2</sub> emissions are politically defined as GHG-neutral in many countries (e.g. in member states of the European Union). Furthermore they have no potential for POPs formation, since they are non-thermal and involve no chemical formation mechanisms of unintentionally produced POPs. For these reasons these techniques are considered outside the scope of this section.

With respect to GHG emissions there is a difference between disposal of waste in landfills and waste incineration. In landfills, CH<sub>4</sub> and CO<sub>2</sub> are formed uncontrolled by aerobic and anaerobic degradation of the putrescible fraction as the main constituents. Non-biodegradable fractions (such as plastic, tires) remain more or less unchanged. If waste is incinerated, both the biodegradable and the non-biodegradable carbon are converted to CO<sub>2</sub> rather than CH<sub>4</sub> irrespective of the techniques used. Open burning, burning of landfill sites or incineration of waste in badly designed and operated plants, is characterized by incomplete combustion resulting in high emissions of CO as well as PCDD/PCDF and other organic substances. However, due to the wide difference in the order of magnitude (in general CO<sub>2</sub> concentrations are 10–100 times higher than CO<sub>2</sub> emissions even in case of open burning) and due to the lack of recognized emission factors, national GHG inventories do not differentiate between incineration techniques.

GHG emissions resulting from disposal of waste with a mixed biogenic-fossil composition in landfills are higher compared with incineration due to higher GWP of methane. One option to reduce GHG emissions of landfills is to capture the landfill gas (mostly CH<sub>4</sub> and CO) with subsequent incineration. Methane and CO

are oxidized this way to CO<sub>2</sub>, which is regarded as biogenic CO<sub>2</sub>. The possibility of energy recovery is an additional benefit of this technique.

From a perspective of GHG emissions savings, one may come to the erroneous conclusion that the optimal solution is final disposal of waste in landfills with capture and incineration of landfill gas with or without energy recovery. Unfortunately complete capture of landfill gas is technically not possible – capture rates are in the range of 15% – and with progressing degradation methane content of the landfill gas decreases, requiring the use of fossil fuels to enable incineration.

Modern waste incineration plants offer the benefit to use both the biodegradable as well as the non biodegradable carbon, as energy source. In addition, waste incineration reduces the volume of waste, destroys or at least minimizes formation of potentially harmful substances, disinfects waste and enables the recovery of some residues. On the contrary to landfills, pollutants are concentrated in a controlled fashion, which makes their environmental sound treatment technically and economically more feasible. Thus, many countries have introduced a legal ban of landfilling biodegradable waste. However, it should be noticed that waste incineration is only one technique for the disposal of waste. Other applied techniques, such as mechanical-biological treatment or mechanical treatment have no potential for on-site unintentionally produced POP formation (GHG are emitted in the form of CO<sub>2</sub>, N<sub>2</sub>O or methane), but still require an incineration step for a certain high-calorific waste fraction.

Waste incineration and introduction of a specially engineered landfill concept are not stand-alone techniques, but have to be embedded in an environmentally sound fully integrated waste management system. The Stockholm Convention BAT/BEP guidelines and guidance [UNEP, 2006] give reference to the Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal and especially outlines some important principles to be considered in the development of waste and hazardous waste strategies, such as the reduction principle and the integrated LCA principle. Implementation of the waste hierarchy and application of the above mentioned principles will, in general, reduce emissions of all polluting substances (including GHG and POPs) simply by providing the basis of longer life time of goods, increased reuse of products, higher recovery and recycling rates. Furthermore, the application of recommended BAT/BEP for

waste incineration includes the implementation of operational and effective end-of-pipe techniques for the removal of pollutants such as PM, NO<sub>x</sub>, SO<sub>2</sub>, HCl, HF, CO, heavy metals and POPs. Waste water treatment as well as treatment and/or sound disposal of residues are also parts of BAT/BEP (more detailed provided in Section II.1.1).

Waste disposal techniques other than BAT and BEP include open burning of waste and dumping of

waste on sites or landfills, which are not suitable for this process or which lack the simplest engineering provisions (such as control of waste input, good lining, coverage of surface or capture and incineration of landfill gas). Burning of landfill sites causes additional adverse impacts on the environment. These processes are not in line with the provisions of BAT and BEP and thus cause high emissions of GHG (CO<sub>2</sub>, methane), POPs and (heavy) metals into the air and water.

**Table 7. Energy production/consumption of a typical MSW incineration plant operated according to BAT [European Commission, 2006; Stubenvoll et al., 2002].**

Treatment or disposal technique	GHG emissions	GHG reduction techniques	POPs formation potential	POPs reduction technique
Incineration (BAT/BEP)	CO <sub>2</sub> from carbon in waste; CH <sub>4</sub> from storage; N <sub>2</sub> O from incineration or from application of SNCR; fossil fuel use for start-up/shut down, auxiliary burners and for re-heating of flue gas	Reduction of fossil fuel use and increased energy recovery; for the reduction of N <sub>2</sub> O: use of ammonia as reagent for SNCR, optimization of SNCR process, high combustion temperature	High	Process-integrated and end-of-pipe (BAT/BEP)
Open burning, accidental burning	CO <sub>2</sub> , CO, CH <sub>4</sub> from carbon in waste, potentially other chemicals		Very high, one of the largest global sources	Prohibition
Disposal on landfills (engineered and waste dump)	CO <sub>2</sub> , CH <sub>4</sub> from biodegradable carbon in waste; higher GHG emissions and potential for burning in waste dumps	Capture and incineration of landfill gas (oxidation of CH <sub>4</sub> ); "biogenic" oxidation of methane	Little or no formation	No, since no formation
Land treatment (e.g. spreading of sewage sludge)	CO <sub>2</sub> , CH <sub>4</sub> from biodegradable carbon in waste		No formation	No, since no formation
Recycling, reclamation, regeneration, recovery operation	By use of fossil fuels to cover energy demand	Fuel switch to low carbon fuels, increase of energy efficiency	Very low formation (see Section II.4)	(See Section II.4)

## Management of flue gas and other residues

While GHG emissions are generally an intended by-product resulting from energy generation and thermal treatment of waste, POPs emissions are always an unwanted incomplete combustion byproduct. Since the intended generation of GHGs is often also inevitably accompanied by the unintended generation of a variety of harmful air pollutants (e.g. particulate matter,  $\text{NO}_x$ , heavy metals, acid gases, etc.) the various end-of-pipe techniques described in different sections of the report are widely applied to control these other air pollutants thus protecting human health and the environment.

As they would be applied in any event (as part of BAT) the associated energy cost should be allocated to the smooth and legal operation of the air pollution control device itself. Thus, application of GHG cost versus pollution reduction benefit should be applied outside consideration of the Stockholm Convention. POPs reduction should be seen as an additional benefit.

In addition it should be noted that BAT are by definition those techniques, which are developed on a scale that allows economically and technically viable implementation in the sector in question. Implementation of BAT aims at the minimization of impacts on the environment as a whole, which means that a shift of pollution between the various environmental media – air, water, soil, including waste management considerations – should be prevented and cross-media aspects (e.g. energy consumption, residue generation, POPs formation) considered on a general level.

Reducing emissions such as dust,  $\text{NO}_x$ ,  $\text{SO}_2$ , HCl, HF, heavy metals and POPs by end-of-pipe techniques leads to an increase of the energy consumption of every combustion installation. Energy is in general used in the form of electrical power, heat or steam. In some plants  $\text{CO}_2$  is directly emitted as a result of the operation of burners, which may be required for the reheating of flue gas before treatment and release (e.g. SCR), or by operation of afterburners. (Offsite) thermal treatment of bottom ash, slag and fly ash will also result in additional emissions of  $\text{CO}_2$ . Treatment of waste water from incineration adds to the energy consumption of an incineration plant thus increasing its (direct or indirect) GHG emissions.

Most process integrated and end-of-pipe techniques offer the possibility for the co-removal of many pollutants, e.g. by separation of particles using ESPs or BFs, heavy metals and particle bound POPs are removed, too. For these techniques it is hardly possible to allocate costs, energy demand or GHG emissions to one single pollutant. Normally, the most relevant pollutant is taken as reference for such calculations, e.g. PM for ESPs or BFs,  $\text{NO}_x$  for SCR or  $\text{SO}_2$  for FGD (spray dry or wet scrubbers).

The most important end-of-pipe techniques used as stand-alone techniques for POPs reduction are adsorption techniques (using resins or activated coke), catalytic BFs, afterburner and quenching of flue gases. Particle bound heavy metals are removed by BFs, ESPs and fine wet scrubbers. Pre-cleaning of flue gases can be done with cyclones that are efficient for separation of larger particles. However, heavy metals preferably condense into or adsorb onto particles of much smaller sizes than effectively collectable by cyclones.

Volatile metals (e.g., Hg) are removed by adsorption on activated coke (often together with POPs) and by absorption in wet scrubbers. Oxidation of elemental Hg by catalysts (SCR) or by the addition of bromine species ( $\text{CaBr}_2$ , HBr, etc.) with subsequent reaction to ionic  $\text{Hg}_2^+$  in wet scrubbers is also discussed in the literature.

Operating these other environmentally beneficial air pollution control techniques typically requires some energy, which has to be produced elsewhere or by the plant itself thus reducing the energy exported from the plant in question. Both may result in some increased emission of GHGs unless energy is produced from renewable sources.

As a rule, the energy demand of flue gas cleaning systems is in the range of 1 – 5% of the energy output of a combustion plant (this number can be higher in the case of waste incineration plants and some specific industrial production plants – see specific sections), the most energy-intensive techniques are wet systems for acid gas removal. The electricity demand of stand-alone techniques for POPs removal is in the range of an ESP or a BF. Thus, it can be concluded that the environmental benefit of these end-of-pipe techniques is in general unquestionable high. However, detailed analyses with respect to GHG emissions have to be done on a case by case basis considering various options for flue gas cleaning. This may include LCA.



## Training of decision makers and technical personnel

There is a need to raise awareness, build capacity, transfer technology, and provide technical assistance, particularly to developing countries and countries with economies in transition.

As indicated in this report, there are opportunities for synergies and avoidance of trade-offs for energy conservation and releases of unintentionally produced POPs and other pollutants. Significant polluting sectors include:- combustion sources for electric power generation, industrial boilers, waste incinerators and residential burning, and, industrial processes such as cement production, chemicals production, metallurgical processes (primary and secondary base metals, iron and steel, aluminium and magnesium) and pulp and paper production.

Experience gained in prevention and control of pollution by developed countries should be utilized. This expertise is reflected in the Stockholm Convention BAT/BEP guidelines and guidance [UNEP, 2006]. Environmental performance guidance and standards for many industrial and other sectors are reflected in the World Bank Group (WBG) International Finance Corporation (IFC) Environmental, Health and Safety Guidelines (EHS). These comprehensive WBG IFC Guidelines take a multi-pollutant, multi-media approach to sources and include energy efficiency considerations.

Training in available environmental methodologies, practices and tools, should be provided at both managerial and technical or operating levels in public and private sector organizations involved in the implementation of the BAT/BEP guidelines and guidance.

The Stockholm Convention BAT/BEP guidelines and guidance and the WBG/IFC EHS Guidelines could be the basis for user friendly training tools.

The GEF has provided technical and financial support for the developments of National Implementation Plans for POPs and National Action Plans for unintentionally produced POPs. This has been very effective in raising awareness and helping some Parties comply with their Stockholm Convention requirements. Now these Plans need to be modified since new chemicals have been added to the Convention, and more experience has been gained in the application of BAT/BEP. Support for continuing capacity building and the updating of unintentionally produced POPs National Action Plans specified by the Convention should be provided. With regard to benefits and trade-offs in the management of GHG and POP emissions the complexity of many BAT and the required holistic and preventive approach for introducing BEP should be taken into consideration.

Life cycle management, in addition to relevant health and safety issues, should be given priority consideration in capacity-building, with a risk prevention and reduction approach.

## Testing, monitoring and reporting

For monitoring and reporting of POPs see the BAT/BEP guidelines and guidance and the Toolkit [UNEP, 2005b; 2006]. Monitoring and reporting of GHG is done on a national basis based on a commonly agreed methodology, international reporting of GHG emissions is required by the UNFCCC in its Guidelines [UNFCCC, 1999].



## IV. Discussion on capturing benefits and avoiding trade-offs in the promotion of energy conservation and unintentionally produced POPs reduction

The goal of this section is to identify opportunities and trade-offs in the management of two environmental problems: GHGs and POPs. For POPs management in this section, we have assumed application of state-of-the-art technology as described in the Stockholm Convention BAT/BEP guidelines and guidance.

This section offers some considerations concerning benefits and trade-offs in applying BAT/BEP on GHG emissions. The discussion for each individual category focuses on the primary objective of what each specific category seeks to accomplish, namely:

The following qualitative cost-benefit discussion is structured according to these six types of primary objectives. In each case "cost" relates to the additional GHG emissions resulting from additional energy consumption by various techniques. "benefit" means reduction of POPs emissions by applying these various techniques.

Some techniques are end-of-pipe, most commonly used in combustion, incineration and metal production:

- Particulate matter removal by means of filtering (e.g. ESPs, baghouses, etc.)
- NO<sub>x</sub> removal by means of catalytic reduction (e.g. SCR, etc.)

Category	Primary Objective
Waste incineration	Disposal of waste
Open waste burning	Disposal of waste
Fossil fuel combustion	Energy generation (for heating and/or electric power)
Biomass combustion	Energy generation (for heating and/or electric power)
Motor vehicles	Energy generation (for transportation)
Residential combustion	Energy generation (for heating, cooking, lighting)
Crematoria	Culturally/spiritually/religiously motivated funeral practice
Cement kilns firing waste	Fuel cost reduction
Pulp production using Cl <sub>2</sub>	Optimizing production cost and product quality
Chemical production processes	Optimizing production cost and product quality
Iron/steel sintering	Metal production (primary, from natural resources)
Secondary steel production	Metal production (secondary, recycling)
Primary Al and Mg production	Metal production (primary, from natural resources))
Secondary Al, Cu, Zn, Pb production	Metal production (secondary, recycling)
Smoldering of copper cables	Metal production (secondary, recycling)

- Acid gas removal by means of dry, semi-dry or wet alkali scrubbing (e.g. FGD)
- High vapor pressure heavy metal removal by means of adsorption (e.g. activated carbon reduction, baghouses).

These end-of-pipe techniques – which have different selectivities – are often installed in series in order to ensure the effective removal of a variety of pollutants. All are effective to some extent in removing particle bound and/or gas-phase POPs providing so-called “co-benefits” for the environmental quality (more details on end-of-pipe techniques and their impact on GHG emissions are given in Chapter III).

## 1. Disposal of Waste

Waste disposal is the primary objective of open waste burning and controlled waste incineration. In both cases, the quantity of GHG emissions is largely determined by the (fossil) carbon content of the waste and the efficiency of burning.

Open waste burning results in POPs and GHG costs and provides no benefit other than a certain volume reduction of waste. Controlled waste incineration is typically combined with complete waste destruction or inertization, effective flue gas cleaning and some form of energy recovery. By the latter, overall GHG emissions are reduced by offsetting intentional combustion of some other fuel to obtain energy.

There is simply no reliable way to separate POPs and GHG in open burning; thus, the only way to provide benefit is to reduce both simultaneously by reduc-

ing and eliminating the practice. In case of waste incineration, in addition to primary measures highly effective end-of-pipe POPs removal techniques can be used, which, however, require some additional energy consumption and thus cause in most cases some additional GHG emissions. Even in the absence of energy recovery, the benefit of POPs removal greatly outweighs the cost of the additional GHG emissions (see also Chapter II.1.1 and III). Co-benefits of POPs removal by end-of-pipe techniques primarily intended to remove other air pollutants (e.g. PM, NO<sub>x</sub>, heavy metals) can also be realized at essentially no additional cost in GHG.

## 2. Energy Generation

In case of energy generation from fossil fuel or biomass the reduction of GHG emissions and POPs emissions are usually directly proportional for any given installation; however, they often vary greatly among various given installations. Expressed another way, absent a change in technology or in some cases fuels, POPs and GHG reduction from a given facility is accomplished simultaneously and by lower activity. This is despite the fact that the relative quantity of POPs emitted from the various types of fossil fuels or biomass combustion (utility and industrial boilers, biomass boilers, residential combustion, motor vehicles, etc.) vary greatly depending on the type of fuel, type of combustion technology used and efficiency of energy generation achieved. The amounts of POPs as well as the amounts of GHGs emitted are usually a direct function of the amount of fuel consumed (with the exception of residential combustion sources). Co-benefits of POPs removal

by end-of-pipe techniques (e.g. SCR, ESP, bagfilter) primarily intended to remove other air pollutants (e.g. PM, NO<sub>x</sub>, heavy metals) can also be realized in technologies where they are appropriate.

### 3. Cremation

Cremation is a funeral practice which may be deeply rooted in a society's culture, religion and/or spiritual practices. Therefore ethical considerations typically prevail even though cremation is technically a combustion process and as such should be subjected to technical considerations with respect to POPs and GHG emissions. The benefit of reducing comparatively large quantities POPs emissions by management of decorative materials burned as part of ritual, as well as the application of end-of-pipe techniques greatly outweighs the small cost of negligible amounts of additional GHG emissions resulting from efficient, intensive combustion. Co-benefits of POPs removal by end-of-pipe techniques primarily intended to remove other air pollutants (e.g. particulate matter and heavy metals, NO<sub>x</sub>) can also be realized.

### 4. Fuel Cost Reduction

The use of certain types of waste as supplementary fuels, e.g. in cement kilns, is motivated by the reduction in fossil fuel costs. Typically, high calorific, low ash waste is used in high temperature thermal processes such as cement kilns to partially substitute fossil fuels. Overall, the GHG emissions caused by the high calorific waste quantitatively offsets GHG emissions from fossil fuel to some extent. If material recovery or reuse is not possible the high calorific waste would otherwise have to be disposed of (preferably by means of waste incineration), its use in a manufacturing process offsets fossil fuel combustion and can result in a net decrease in GHGs emitted. Since POPs can be generated by waste- or fuel-fired cement kilns, adequate control techniques are required in any event. Co-benefits of POPs removal by end-of-pipe techniques primarily intended to remove other air pollutants (e.g. PM) can also be realized.

### 5. Production Cost and Product Quality

As noted in the text, there are two main POPs drivers in the chemical categories: chemistry in a particular process and POPs generation as a result of combustion for energy generation. For elemental chlorine bleached pulp, the particular chemistry generates POPs, and the solution is alternative technology. There is a slight energy penalty for the alternative reagents, and thus a slightly higher cost for the benefit

of virtually complete POPs elimination from what was once a major source.

In oxychlorination, chemical side reactions generate POPs that should be separated and destroyed. Usually this separation is accomplished by distillation. While in principle there could be a cost associated with distilling product to purify it and isolate POPs in the high boiling material (sometimes called "still bottoms" or "heavy ends"), in practice process heat can be used and there is effectively no cost penalty beyond initial capital investment for isolation of by-product POPs.

These separated POPs are usually destroyed by means of hazardous waste incineration. As described elsewhere, the thermal value of the material being destroyed may be sufficient to propagate that thermal destruction. There may, on some occasions, be a requirement for natural gas combustion as a primer for the hazardous waste incinerator, but the cost penalty and GHG generated from this use of natural gas is very small by comparison with the benefit of POPs destruction. There is capital cost associated with building the incineration equipment.

### 6. Metal Production / Recycling

In this sector, the primary objective is to produce a product of a sought quality. Technical options are chosen according to this wanted quality and to raw materials that are available. From an energy saving point of view, secondary metal production/recycling of metals is preferred over primary metals production as it generally is accomplished with less energy consumption than primary metals production. Thus, tonne-for-tonne the GHG emissions from secondary metals production are generally far less than from primary metals production. Unfortunately the opposite is true for the POPs emissions in many cases. Correct application of BAT/BEP primary measures can minimize the unwanted formation of POPs in the first place, and should be considered the first mitigation step as it generally results in no additional GHG emissions. As in other cases, more energy efficient processes are generally advantageous for reducing GHG as well as POPs emissions.

Furthermore, adequate end-of-pipe techniques allow for effective POPs control. The benefit of POPs removal greatly outweighs the cost of a comparatively small amount of additional GHG emissions caused by these end-of-pipe techniques. Co-benefits of POPs removal by end-of-pipe techniques primarily intended to remove other air pollutants (e.g. PM, NO<sub>x</sub>, and heavy metals) can also be realized.

For the processes mentioned in Annex C, there are four general cases describing the relationship between POPs and GHG (however, overlaps may occur):

### Efficiency improvements where POPs and GHG generation are closely correlated

More efficient production processes entail a reduction in the activity, and reduces both POPs and GHG emissions.

An example related to cross-sectoral aspects is reduction in combustion for energy generation triggered by reduced demand or more efficient technology. It has been said, "Conservation is the first fuel". From the perspective of pollution generation, conservation is the first mitigation strategy. As there is less demand for fossil energy there is less combustion needed to generate it and less POPs and GHG generation.

In the case of fossil fuel combustion a fuel switch from coal to fuel oil or natural gas simultaneously mitigates GHG and POPs emissions. Fuel switching is usually accompanied by increased efficiency (electricity efficiency of a modern coal fired plant is in the range of 40-44%, whereas electricity efficiency of a modern combined cycle gas turbine can reach levels between 50 - 58%). However, even though environmentally desirable, such a fuel switch significantly increases cost and puts additional strain on already very limited natural gas and crude oil resources.

Additionally, effective implementation of a waste hierarchy and introduction of appropriate policy or technology will increase the useful life of goods and decrease mass of waste which needs treatment or disposal (e.g. by incineration or disposal on landfills). This is also equivalent to a reduction of activity.

### Alternative waste disposal pathways where ultimate impacts are uncertain without further analysis.

It is generally agreed that open burning should be minimized to reduce production of POPs; reducing the practice will result in a direct reduction of GHG as well. However, the need for environmental sound waste management does not disappear if open burning is curtailed; there may be emissions that arise due to the use of alternate technology for waste treatment and disposal.

In both the Stockholm and Basel Conventions, parties recognize that an overarching waste hierarchy and philosophy is important to reduction of emissions from waste processes. In many cases, however, clear choices are not obvious without rigorous study of

specific emissions. For example, landfilling eliminates much of the CO<sub>2</sub> associated with burning waste, but due to anaerobic decomposition of materials, may be associated with generation of methane. GHG impact of methane can be reduced to some extent by capture and combustion, especially if used to offset other fossil fuels. Open burning results in significant CO<sub>2</sub> and POPs emissions; BAT/BEP waste incineration results in significant CO<sub>2</sub> emissions, but those emissions may be mitigated if energy recovery is part of the process.

The point simply is: the priority of steps in a waste hierarchy is not always intuitive. We have provided qualitative to semi-quantitative evaluations of trade-offs among a number of, for example, waste processes. More exact answers will require more precise study.

### Specific measures for GHG emission reduction, where POPs and GHG generation are closely correlated under one technology but to less extent under the new technology for GHG reduction.

The new technology shows lower direct and/or indirect GHG emissions but direct and/or indirect POPs emissions may occur (e.g. energy supply by renewable energies). Biomass combustion as an alternate technology to mitigate GHG emissions increases the risk of POPs emissions. In this case GHG emission reduction should not deteriorate the efforts on air pollution control.

Other examples can be found in metal industries. For iron sintering plants, stable and consistent operation of the sinter strand and recirculation of off-gases can be beneficial in terms of energy savings and thus CO<sub>2</sub> and POPs emission reduction.

Specific measures for unintentionally produced POPs reduction, where POPs and GHG are correlated only to a minor extent or not at all; POPs reduction technology results in little GHG impact.

Adequate end-of-pipe techniques allow for effective POPs control. The benefit of POPs removal greatly outweighs the cost of a comparatively small amount of additional GHG emissions caused by these end-of-pipe techniques. Co-benefits of POPs removal by end-of-pipe techniques primarily intended to remove other air pollutants (e.g. NO<sub>x</sub>, particulate matter and heavy metals) can also be realized.

As noted in Section III of the Report, BAT applied for reduction of other pollutants from incineration can have the additional benefit of reducing POPs at a low or negligible cost in GHG. In any case it should be more closely examined how application of BAT



and BEP (both as primary measure as well as end-of-pipe) affects the overall GHG emissions of a source category. This could be done by alternative LCAs.

In the case of the use of elemental chlorine for pulp bleaching or oxychlorination for production of organics, specific chemical reactions give rise to POPs, unmodulated by the need for energy. Simply changing the amount of energy used in the process might reduce POPs indirectly via reduced energy production, but will have no effect on the specific chemistry of those processes.

On the other hand, application of BAT and BEP—bleaching with  $\text{ClO}_2$  and isolation and destruction of by-product POPs respectively—has the effect of minimizing production and emission of POPs. Use of these two processes carries little if any energy penalty in the context of the overall process, and thus little if any GHG penalty.

In addition, there is another issue with respect to choices of alternative technologies for any given process. In some cases, mitigation of POPs emissions in one source category involves the potential to switch POPs and GHG generation to another source category. As examples:

- Waste incineration vs. open burning vs. land-filling vs. composting;
- Combustion of gasoline for transportation vs. use of electricity generated from combustion

of fossil fuels. Direct fuel switching in combustion devices between coal, oil, natural gas and biofuels/biomass, especially for production of electricity;

- Centralized district heating plants using biomass vs. residential combustion sources based (at least to some extent) on fossil fuels.

In both the Stockholm and Basel Conventions, parties recognize that an overarching waste hierarchy and philosophy is important to reduction of emissions from waste processes. In many cases, however, clear choices are not obvious without a rigorous study of specific emissions.

For example, landfilling eliminates much of the  $\text{CO}_2$  associated with burning waste, but due to anaerobic decomposition of materials, may be associated with generation of methane. GHG impact of methane can be reduced to some extent by capture and combustion, especially if used to offset other fossil fuels. Open burning results in significant  $\text{CO}_2$  and POPs emissions; BAT/BEP waste incineration results in significant  $\text{CO}_2$  emissions, but those emissions may be mitigated if energy recovery is part of the process.

The point simply is: the priority of steps in a waste hierarchy is not always intuitive. We have provided qualitative to semi-quantitative evaluations of trade-offs among a number of, for example, waste processes. More exact answers will require a more precise study.



## V. Conclusions

While potential global sources of unintentionally produced POPs, some of the Stockholm Convention Annex C processes are relatively minor global sources of GHGs. These include crematoria, destruction of animal carcasses, textile and leather dyeing with chloranil, shredder plants for end-of-life vehicles, smoldering of copper cables and waste oil refineries. Adherence to BAT/BEP guidelines and guidance will lead to reduction of unintentionally produced POPs releases with no, or insignificant penalty for GHG emissions.

For other significant GHGs and unintentionally produced POPs global sources, there are three ways to classify unintentionally produced POPs and GHG reduction strategies: 1) approaches to unintentionally produced POPs reduction which also reduce GHGs and vice versa (synergy); 2) unintentionally produced POPs reduction methods which increase GHGs (trade-off), or, 3) situations where the two emissions are not closely related.

Many of the unintentionally produced POPs reduction technologies corresponding to Stockholm BAT and BEP aim at improving the combustion conditions, increasing the energy efficiency, raising energy recovery rates (e.g. by use of combined heat and power systems) and improving the quality of solid residues from emission reduction systems (waste incineration, firing installations for wood and other biomass fuels, residential combustion, cement kilns, fossil fuel fired utilities and industrial boilers). For certain categories, a simple change in type of fuel - for example, from coal to natural gas - can make a positive difference in GHG and potentially unintentionally produced POPs emissions with little impact on the underlying process. However, the analysis is not so clear in other cases of fuel or technology switch - for example, changing motor transportation from gasoline, or diesel fuel, to electricity from the grid. Similar situations are observed in primary and secondary metal production. This is especially true when differences in efficiencies, types of combustion (as well as necessary changes in

engines), fuel delivery systems, and emissions (from all sources in the process chain) are taken into account. For these situations, more comprehensive life cycle considerations are appropriate.

In some cases, elimination of a process such as open burning of waste or smoldering of copper cables can, on face value, eliminate generation of GHG – e.g. CO<sub>2</sub> as well as unintentionally produced POPs. However the need to deal with the waste remains. Every waste management activity should be optimized concerning energy consumption and emissions of CO<sub>2</sub> and methane (CH<sub>4</sub>) according to waste hierarchy principles (i.e., prevention, reduction, reuse, recycling, recovery, incineration including reuse, recycling and/or recovery of incineration by-products and final disposal in the landfill). Interrelations between different waste treatment and disposal options should be considered on a national, regional, and international level. Landfilling generates methane, a more potent GHG than carbon dioxide. If this methane is fully captured and combusted, there is less emitted CO<sub>2</sub> than if all the waste were incinerated, but there is some potential for creating unintentionally produced POPs in the process (Unfortunately, complete capture of landfill methane is technically impossible with capture rates below 15%). Alternatively, a modern BAT/BEP incinerator could be constructed and unintentionally produced POPs emissions would be curtailed; however, this expensive solution must be operated carefully and will still result in GHG emissions. Overall, the implementation of the waste hierarchy and integrated life cycle principles will, in general, reduce emissions of all polluting substances (including GHGs and unintentionally produced POPs) by providing the basis for a longer life time of goods, with increased reuse of products, higher recovery and recycling rates.

The substitution of non-elemental-chlorine bleaching techniques for chlorine bleaching of pulp or segregation and destruction of unintentionally produced POPs from chemical production, while possessing major potential for reduction of unintentionally produced POPs, will engender little differential impact on global GHG when those specific operations alone are considered - not the larger energy consumption of the total pulp and paper, or the total chemical sector. These Annex C source categories basically represent the third category of GHG and unintentionally produced POPs relationships, where the two emissions are not closely related.

This study suggests three guiding principles as a preliminary analysis for Annex C source categories of the Stockholm Convention that involve significant combustion for heat, energy generation, and destruction of waste (Part II a), d); Part III b)-e),h))<sup>7</sup> which represent globally significant GHGs and unintentionally produced POPs sources:

**Good combustion practices** will tend to reduce generation of unintentionally produced POPs, even if they are not eliminated.

**Maximizing thermal efficiency** will reduce GHG emissions as well as, potentially, unintentionally produced POPs by reducing the overall activity leading to both. This includes improved fuel efficiency through combined heat and power strategies or higher temperature/efficiency processes e.g., in the electrical energy generating sector. Maximizing carbon efficiency such as a simple substitution of coal for natural gas will reduce GHGs. Efficiency improvements on the demand side also tend to be beneficial as they reduce the emission generating activity (e.g., insulation of buildings).

**Utilization of specific BAT and BEP** for combustion or thermal processing will reduce both generation and emission of unintentionally produced POPs across a wide range of combustion sources from biomass to iron sintering to cement manufacture. In some cases, there will also be synergistic benefits with respect to reduction in other pollutants or increased thermal efficiency. The utilization of specific BAT/BEP end-of-pipe technology appropriate for mitigating other air pollutants, (such as particulates, heavy metals including mercury, SO<sub>2</sub> and NO<sub>x</sub>) will generally be beneficial for reducing unintentionally produced POPs emissions, even though the power requirements of these end-of-pipe-techniques inevitably cause some small amounts of additional GHG emissions.

However, there are probably no simplifying assumptions beyond these that will help the analysis of complex fuel switching proposals or complex waste hierarchy and treatment alternatives. These problems could benefit from further work that takes into account life cycle considerations. Such analysis may add further clarity for specific and possibly generic situations.

7. Annex C source categories are listed according to the Stockholm Convention text.

## List of References

- Bernstein, L., J. Roy, K. C. Delhotal, J. Harnisch, R. Matsuhashi, L. Price, K. Tanaka, E. Worrell, F. Yamba, Z. Fengqi, 2007: Industry. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Boehmer S., Kuegler I., Stoiber H., and B. Walter (2006). Abfallverbrennung in Österreich. Report-0113. Federal Environment Agency Austria, Vienna (in German).
- Edwards P. (2001). Review of emissions from crematoria in the UK. AEA Technology Report. Resurgam 44:81–128 and Pharos International 67:3.
- Energy Information Administration (1998). Manufacturing Energy Consumption Survey, 2001. Available at: <http://www.eia.doe.gov/emeu/mecs/contents.html>
- European Commission (2001a). Integrated Pollution Prevention and Control, Best Available Techniques Reference Document on the non-ferrous metals industries. Available at: <http://eippcb.jrc.es/reference/>
- European Commission (2001b). Integrated Pollution Prevention and Control, Best Available Techniques Reference Document on the production of iron and steel. Available at: <http://eippcb.jrc.es/reference/>
- European Commission (2006a). Integrated Pollution Prevention and Control, Reference Document on best available techniques for large combustion plants. Available at: <http://eippcb.jrc.es/reference/>
- European Commission (2006b). Integrated Pollution Prevention and Control, Reference Document on the best available techniques for waste incineration. Available at: <http://eippcb.jrc.es/reference/>
- European Commission (2009). Integrated Pollution Prevention and Control, Draft Reference Document on the Best Available Techniques on Cement, Lime and Magnesium Oxide Manufacturing Industries. Available at: <http://eippcb.jrc.es/reference/>
- Fiedler H. (2007). National PCDD/PCDF release inventories under the Stockholm Convention on Persistent Organic Pollutants, *Chemosphere* 67(9): S96-S108.
- Francis D. W., Towers, M. T. and T. C. Browne (2002). Energy cost reduction in the pulp and paper industry - An energy benchmarking study. Canadian Industry Program for Energy Conservation. Available at: <http://oee.nrcan.gc.ca/publications/infosource/pub/cipec/pulp-paper-industry/pdf/pulp-paper-industry.pdf>
- IEA (2006). Proceedings of the IEA/WBCSD Workshop on energy efficiency and CO<sub>2</sub> emission reduction potentials and policies in the cement industry; 4-5 September 2006, IEA, Paris, France.
- IEA (2007). Tracking industrial energy efficiency and CO<sub>2</sub> emissions. IEA, Head of Communication and Information Office, Paris, France.
- IEA (2008). Worldwide trends in energy use and efficiency - Key insights from IEA indicator analysis. IEA, Head of Communication and Information Office, Paris, France.
- IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.
- Kirk-Othmer Encyclopedia of Chemical Technology (2003). Fourth Edition. John Wiley & Sons, Hoboken, NJ, USA.
- Levine M., Üрге-Vorsatz D., Blok K., Geng L., Harvey D., Lang S., Levermore G., Mongameli Mehlwana A., Mirasgedis S., Novikova A., Rilling J., and H. Yoshino (2007). Residential and commercial buildings. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- McIlvaine Company (2008). Utility E-Alert #903, December 19, 2008.
- National Council for Air and Stream Improvement (1998). Estimated CO<sub>2</sub> emissions resulting from compliance with U.S. Federal environmental regulations in the forest products industry. Special Report No. 98-02, Available at: <http://www.ncasi.org/publications/Detail.aspx?id=1098>
- OECD (2008). CO<sub>2</sub> emissions from fuel combustion. IEA, OECD Publishing, Paris, France.
- Sims R.E.H., Schock R.N., Adegbululge A., Fenhann J., Konstantinaviciute I., Moomaw W., Nimir H.B., Schlamadinger B., Torres-Martinez J., Turner C., Uchiyama Y., Vuori S.J.V., Wamukonya N., and X. Zhang (2007). Energy supply. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Stockholm Convention on persistent organic pollutants (POPs) (2001). Text of the Convention is available at: <http://chm.pops.int/Convention/tabid/54/language/en-US/Default.aspx#convtext>
- Stubenvoll J., Boehmer S., and I. Szednyi (2002). State of the art for waste incineration plants. Federal Austrian Ministry of Agriculture and Forestry, Environment and Water Management, Vol. 24/2002, Vienna, Austria.
- UNEP (2005a). General technical guidelines for the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants (POPs). Basel Convention Series. SBC Nr. 2005/1.
- UNEP (2005b). Standardized Toolkit for identification and quantification of dioxin and furan releases. 2nd Edition. IOMC, Geneva, Switzerland. Available at: [http://www.pops.int/documents/guidance/toolkit/ver2\\_1/Toolkit-2005\\_2-1\\_en.pdf](http://www.pops.int/documents/guidance/toolkit/ver2_1/Toolkit-2005_2-1_en.pdf)
- UNEP (2006). Guidelines on Best Available Techniques and Provisional Guidance on Best Environmental Practices relevant to Article 5 and Annex C of the Stockholm Convention on persistent organic pollutants. Geneva, Switzerland. Available at: <http://chm.pops.int/Programmes/BATBEP/ProcessesProcedures/tabid/187/language/en-US/Default.aspx>
- UNFCCC (1999). Guidelines for the preparation of National Communications by Parties included in Annex I to the Convention, COP-5, FCCC/CP/1999/7. Available at: <http://unfccc.int/resource/docs/cop5/07.pdf>
- UNFCCC (2008). Report on national greenhouse gas inventory data from Parties included in Annex I to the Convention for the period 1990–2006. XXIXth Session of SBI, FCCC/SBI/2008/12. Available at: <http://unfccc.int/resource/docs/2008/sbi/eng/12.pdf>
- WBG IFC (2007) Environmental, Health, and Safety Guidelines Available at: <http://www.ifc.org/ifcext/sustainability.nsf/Content/EnvironmentalGuidelines>

Annex 1. Emission factors for emissions into air and releases into residues of the Toolkit Category 3 (Heat and Power Generation) [UNEP, 2005b].

Sub-categories	Facilities	Fuels	Emission into air µg TEQ/TJ	Release in residue
Fossil fuel power plants	Power boilers (well operated and maintained power steam generators)	Fossil fuel/waste co-firing	35	ND
		Coal	10	14 µg TEQ/TJ
		Heavy fuel	2.5	ND
		Shale oil	1.5	1.2 µg TEQ/t ash
		Light fuel oil/natural gas	0.5	ND
Biomass power plants	Power boilers (well operated and maintained power steam generators)	Mixed biomass	500	ND
		Clean wood	50	15 µg TEQ/TJ
Landfill/Biogas Combustion	Boilers, motors/ turbines and flaring	Biogas-/landfill gas	8	8 µg TEQ/TJ
Household heating and cooking with biomass	Stoves	Contaminated biomass	1,500	1,000 µg TEQ/tash
		Virgin biomass	100	10 µg TEQ/tash
Domestic heating and cooking with fossil fuels	Stoves	High-chlorine coal	15,000	30,000 µg TEQ/tash
		Coal	100	tash
		Oil	10	5,000 µg TEQ/tash
		Natural gas	1.5	tash NA NA

<http://stapgef.unep.org>