Rudi Karpf

Emissions-related energy indicators

for flue gas treatment systems in waste incineration



TK

For Jana, Oxana and my parents

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Table of contents

1 Introduction and objectives 1

2 Contextual issues 3

2.1 Literature overview 3

2.2 Discrepancies in emission requirements across individual Acts and Ordinances 6

3 Characteristics of flue gas treatment 15

3.1 Flue gas treatment systems and components 15

3.2 System classification and description 17

3.2.1 Conditioned dry sorption with calcium hydroxide, SNCR system (V1) 18

3.2.2 Conditioned dry sorption with calcium hydroxide, SCR system (V2) 21

3.2.3 Conditioned dry sorption with calcium hydroxide, downstream scrubber, SNCR system (V3) 22

3.2.4 Two-stage dry sorption with calcium hydroxide and bicarbonate, SCR system (V4) 22

3.2.5 Two-stage scrubber with spray dryer, fabric filter, SNCR system (V5) 23

3.2.6 Two-stage scrubber with spray dryer, fabric filter, SCR system (V6) 24

3.2.7 Energy-optimized conditioned dry sorption with calcium hydroxide, SNCR system (V1‘) 24

3.2.8 Energy-optimized conditioned dry sorption with calcium hydroxide, downstream scrubber, SNCR system (V3‘) 25

4 Energy demand in flue gas treatment 27

4.1 Inventory analysis structure 27

4.2 Cumulative energy demand for the production of flue gas treatment systems 31

4.2.1 Methodology for ascertaining the CED_p 31

4.2.2 CED_p for different flue gas treatment systems 36

4.3 Cumulative energy demand for the production/use of flue gas treatment systems 38

4.3.1 Examination of energy demand dependencies 39

4.3.2 Methodology for ascertaining the CED_U 48
4.3.3 CED_U for different flue gas treatment systems 52
4.4 Cumulative energy demand for the disposal of flue gas treatment systems 56
4.4.1 Methodology for ascertaining the CED_D 56
4.4.2 CED_D for different flue gas treatment systems 57
4.5 Total cumulative energy demand for flue gas treatment systems 58

5 Ascertainment of emissions-related energy indicators 65

5.1 Emissions-related energy indicators 65
5.2 Energy equivalent emission factors 67

6 Discussion of results 73

6.1 Cumulative energy demand for production and disposal 73
6.2 Cumulative energy demand for use phase 73
6.3 Energy balance for different gaseous pollutant loads 74
6.4 Energy indicators 74
6.4.1 K-plant technology indicator 75
6.4.2 K-additive indicator 75
6.4.3 K-operation indicator 76
6.5 Energy-equivalent emission factors 76
6.6 Conclusion 77

7 Summary 79

8 References 83

9 List of symbols 87

10 Appendix 93

10.1 Mass and energy balance for ascertainment of CED_P 94
10.2 Process parameters for CED_U inventory analysis 106
10.3 Mass and energy balance for ascertainment of CED_U 110
10.4 Mass and energy balance for ascertainment of CED_D 118

Acknowledgements **133**

Advertiser index **137**

Key word index **141**



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Between 1988 and 2001, Rudi Karpf acquired extensive experience in the field of emissioncontrol technology for power plants, waste-to-energy plants and industrial processes (iron/steel, glass etc.) at the ABB/Alstrom plant manufacturing company. Due to his specialist knowledge, broad range of experience and exemplary personal dedication, he has made significant contributions to the development of emission control systems.

Since 2001, Rudi Karpf has held the post of Managing Director at the energy and environmental engineering consulting company ‚ete.a Ingenieurgesellschaft mbH für Energie- und Umweltengineering & Beratung', focusing on planning, consultation and implementation in the fields of energy and emission control technology.

Since 2006, Rudi Karpf has been a publicly sworn and certified expert on combustion engineering and emission control by the Gießen-Friedberg Chamber of Industry and Commerce (IHK).

Serving as references, Rudi Karpf has worked on numerous studies and reports, optimization processes and planning services encompassing waste-to-energy plants within the waste management sector and energy recovery of waste and biomass as well as thermal processes (e.g. the iron and NF industry and food industry) and studies and research projects in the field of power plants (e.g. the oxyfuel process).

1 Introduction and objectives

Securing future energy provision based on resource-efficient and environmentally-friendly methods of energy production and energy conversion is increasingly gaining in significance. This has led to a change in attitude towards waste treatment, whereby waste material is much more regarded as fuel for energy consumption rather than simply as refuse requiring disposal. Energy provision has therefore taken on equal, if not more importance than waste treatment, particularly at industrial sites employing waste material as fuel. As a result, the once more common primary fossil fuels such as natural gas, heating oil or coal have been increasingly substituted by waste material or waste fractions ('alternative fuels').

Since waste material is extremely inhomogeneous in composition and is subject to correspondingly high fluctuation margins, both temporally and in terms of single fractions, flue gas composition from waste incineration is equally subject to fluctuation.

Alongside other political concerns, this predicament was certainly a contributory factor in the legislature's decision to raise emission limit values from waste incineration plants as compared with conventional fossil fuel-fired combustion plants, at once both increasing the scope of substances subject to monitoring and placing more stringent limits on emission levels.

This has given rise to extensive developments in the regulation of emission limit values over the last 30 years, from the initial *TA-Luft 1974* (Technical Instructions on Air Quality Control) and subsequent *TA-Luft 1986*, to the adoption of a separate *Bundesimmissionsschutzverordnung (BImSchV* - German Federal Immission Control Ordinance) on waste incineration covered by the *17. BImSchV* (17th Federal Immission Control Ordinance) of 23 November 1990 (BGBl. [*Bundesgesetzblatt* - Federal Law Gazette] I p. 2545, p. 2832) [1]. With the adoption of articles 1 and 2 of the Ordinance of 27 January 2009 (BGBl. I p.129) [2] on the safeguarding of quality requirements set out in the 13th and 17th Federal Immission Control Ordinances, the standards applicable to large combustion plants and gas turbine plants set out in the *13. BImSchV* and to waste incineration and co-incineration facilities set out in the *17. BImSchV* were amended by means of long-term averages for the mass concentrations of nitrogen oxide emissions, thus establishing the current tightened limits.

These ongoing emission value reductions have led to the majority of existing waste incineration plants having to constantly adapt or extend their flue gas treatment plants. This has led to the many multi-stage and extremely complex plant facilities still in existence today. A further motive for multi-stage plants was the demand present during the 1990s for the extraction of recyclable materials from residue accrued via flue gas purification, such as the production of gypsum via the flue gas desulphurization process within the power plant sector.

Economic considerations have undoubtedly played a major role in improvements in simultaneous systems, such as dry and conditioned dry sorption methods, meaning that emission limit values fall well below those specified in the *17. BImSchV*, even where cost and energy savings are paramount.

Despite the current very low emission limit values, political acceptance of waste incineration is repeatedly called into question and it will ultimately only remain a tolerable option for the future if further reductions in emission limit values are attained.

Proponents and operators of waste incineration plants counter with the argument that the reduction of any one pollutant by even a few milligrams would incur a disproportionate level of additional expenditure on equipment and energy.

The aim of this study is to demonstrate such discrepancies or dependencies between attainable emission reductions and the emissions-generating energy input necessarily incurred by flue gas treatment technologies in attaining those reductions.

The study initially focuses on current investigations and assessments related to this issue, as well as on the legal emission requirements. Due to the wide range of components involved in flue gas treatment systems and their consequent numerous combination possibilities, six different system Variants are presented and compared. It is notable in the context of the present study that both single and two-stage or multi-stage systems are considered in the set of Variants, which differ not only in their structure and additive use but also in their separation capacity. These six basic Variants reflect the systems frequently employed in practice and represent non-congruent procedural steps with their respective target emission levels. Based on the fact that each of these Variants is already in operation in thermal waste incineration plants, the assessment draws on many years of existing operative experience. In order to allow a comparison of the systems and especially of the requisite energy demands for achieving different separation rates and emission levels, the relevant cumulative energy demand (CED) is ascertained. This means that the energy demand, which itself leads to the release of emissions, is ascertained for the entire life cycle of the plant, from construction, through operation and ultimate plant disposal after a certain period of operation (approx. 20-30 years). Thus, the production of semi-finished products such as steel, aluminium, plastics, etc. and the production of consumables such as lime, sodium hydroxide and ammonia, as well as the electrical energy used in operating the plant are taken into account. An energy demand credit due to high recycling rates and consequent return to the economic cycle is to be expected for the plant disposal process.

The individual energy demands for the Variants described are determined on the basis of mass, material and energy balances.

In line with experience, the operational phase represents the most energy-intensive phase when compared with those of production and disposal. Since the most significant dependencies between separation efficiency or emission level and the directly opposed energy demand are on the operational and process control levels, the calculation approaches employed draw on practical experience and form part of the inventory analysis.

Evaluation criteria for energy demand at the different emission reduction ratios are educed from the formulation of emissions-related energy indicators. This establishes a set of tools with which to assess emissions-generating energy demand in the context of emission reduction ratios.

2 Contextual issues

In order to comprehensively address the question of dependencies between the different emission reduction alternatives and associated energy demand, an overview is first presented on context-related literature as well as on previous assessments. This provides a clear delineation of the present study from existing evaluations and publications. A further aspect of emission reduction, especially that of emission levels from waste incineration plants, is considered and discussed in the context of other power generation plant types and their emission levels.

2.1 Literature overview

Energy-based life-cycle assessments of goods and services within the scope of process chain analyses are usually compiled by means of the ascertainment of the cumulative energy demand (CED), which in turn provides the basis for the present determination of emissions-related energy indicators. The scientific grounding for the definition and ascertainment of the CED was developed in Mauch's dissertation [3] and ultimately served as the basis for the VDI Guideline 4600 'Cumulative Energy Demand - Terms, Definitions, Methods of Calculation' [4]. By definition, the cumulative energy demand describes the total primary energy input which can be attributed and assigned to the production (CED_P), use (CED_U) and disposal (CED_D) of any goods or services. This includes a consideration of the process steps involved in the primary energy input.

$$CED = CED_P + CED_U + CED_D \quad (1)$$

The ascertainment of the CED is based on the clear definition of assessment boundaries, within which trans-boundary material and energy flows are accurately defined and quantified. The boundaries are determined according to temporal, regional, and technological criteria. Experience to date shows that considerable effort and extensive expertise is required in order to formulate the assessment scope in such a manner that minimizes errors due to negligence, omissions and estimations (cf. [4]).

Definition of the assessment scope and creation of the mass, material and energy balancesis discussed in detail in [5], [6] and [7] in the context of waste treatment in thermal processes, thus providing a basis for the ascertainment of the CED. A thorough discussion of other approaches and analyses of scientific and technical assessment methods for waste treatment processes relevant to determining the CED are presented in [8].

The Institute of Energy Economics and Power Plant Engineering at the Technical University of Munich and the *Forschungsstelle für Energiewirtschaft - FfE* (Research Center for Energy Economics) was among the first to develop energy-based life cycleengineering (LCE) for goods and services within the framework of process chain analyses. Thus in [3], the Geiselbullach waste incineration plant for example is attributed with a specific cumulative energy demand (CED) of 62 MJ/Mg_{waste}[1] for production (cf. Figure 1) and 73 MJ/Mg_{waste} for operation of the plant. The specific CED for the München-Nord waste incineration plant however, was given as 174 MJ/Mg_{waste}.

1 Mg_{waste} refers to incinerated waste at a total annual waste volume of 107,000 Mg and a plant life cycle (assessment period) of 20 years [3] of 107,000 Mg.

The quoted energy demand figures are broadly attributed to the waste treatment plants as a whole but no breakdown in the specifications is given for the flue gas treatment facilities themselves.

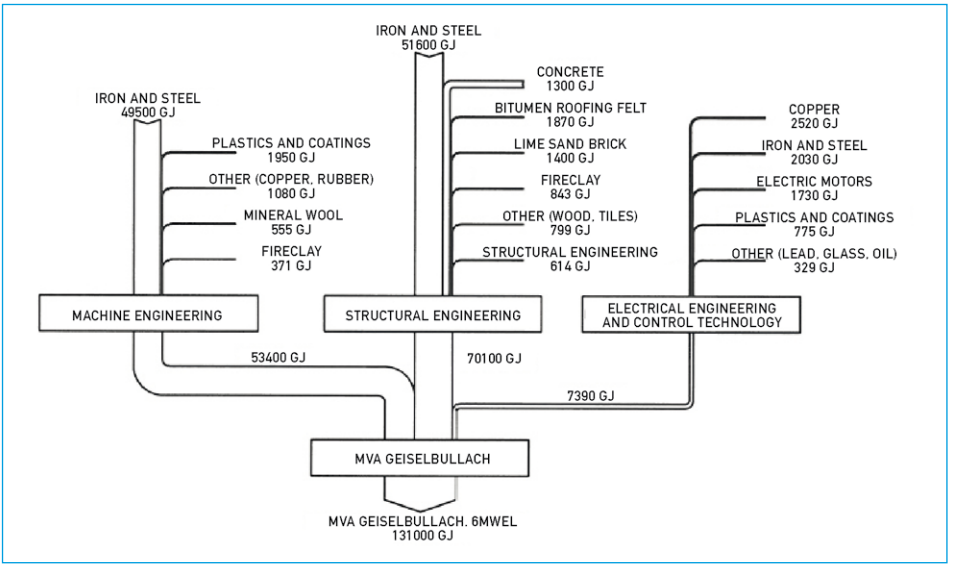


Figure 1: CED_P for the construction of the *MVA Geiselbullach* (Geiselbullach WtE) [3]

In 2001, *the Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen - LUA NRW* (North Rhine-Westphalia State Environment Agency) published a report [9] which considered the question of the effects on emissions of single-stage and simultaneous flue gas treatment systems, at that time employed almost exclusively for new projects. *'The specific objective of this evaluation was to present both a summary dealing with current and planned flue gas treatment systems for waste incineration plants,as well as a concise and defined ecological and economic comparison of the advantages and disadvantages of three selected exemplary systems. As a result, the impacts of the different systems on the emission levels were identified and presented by taking the different energy consumption values into consideration. The selected systems were divided into three categories, with the main distinguishing feature between category a and categories b and c being the use of a scrubber system. Categories b and c on the other hand differ in that they represent the highest possible recyclability of flue gas purification products which are reprocessed into marketable commercial products such as hydrochloric acid' [9].*

For specifically defined plant sizes and pollutant concentrations, the individual resource consumption values for lime, electrical power, LP steam and natural gas are ascertained. The externally released emissions are specified and compared by means of establishing energy equivalents and by taking the electricity mix for electricity generation into account. The aforementioned study on energy-related emissions focuses solely on the operation of the facilities. Neither production nor disposal are taken into account. Similarly, no calculations or assessments of energy demand at different pollutant concentrations and emission values are carried out.

The excess emissions from each flue gas treatment plant category for the basic design parameters of 100,000 m³/h flue gas volume flow are compared and the excess emissions from each plant are offset against external excess emissions (from resources and energy). '*The results clearly show, with the exception of the sulphur dioxide pollutant, a regular surplus load in emissions from the simplest plant designs (category a)*' *[9].*

Table 1: Excess emissions for each flue gas purification (FGP) system category and offsetting the external excess emissions[2] [9]

Pollutant	NO_x	HCl	SO	HF	Hg	TE
Excess emissions via simple FGP a onsite per hour as against b and c	7 kg	2 kg	100 g	10 g	0.8 g	1 µg
	10 kg	2.2 kg	150 g	10 g	0.9 g	1 µg
External excess emissions via 260 kWh 'energy equivalent' (category b) and 1285 kW (category c) (over 1 hour)	237 g	5 g	108 g	309 mg	2.4 mg	2.1 ng
	1.17 kg	24.5 g	533 g	1.53 g	12.1 mg	10.3 ng
Nett excess emissions via simple FGP a per hour as against b and c	6.763 kg	1.995 kg	***8 g****	9.69 g	0.798 g	0.998 µg
	8.83 kg	2.175 kg	***383 g****	8.5 g	0.888 g	0.99 µg

***** reduced emissions via category a

The ecological assessment carried out for the three different flue gas treatment systems resulted in a significant reduction in pollutants where more complex systems were employed. This ecological advantage was, however, offset in the study by the safety of the immissions which, in the case of the simple flue gas treatment systems, also clearly remained well below the emission limit values set out in the *17. BImSchV.*

A study [10] has been carried out by the *Institut für Energie- und Umweltforschung - ifeu* (Institute for Energy and Environmental Research) under the authority of the *Umweltbundesamt* (German Federal Environment Agency) entitled, '*Exemplary representation of high quality entire material recovery in an MSWI (Municipal Solid Waste Incineration) plant with special emphasis on climate impact*'. The aim of the investigation was to demonstrate the potential and prerequisite conditions for complete, high-quality recycling within the framework of the 2020 target and to assess this in the light of climate change as well as other environmental protection issues. For this purpose, the roughly 70 waste incineration plants existing in Germany were analysed, for example by way of screening. One of the first significant assertions resulting from this was that no relationship between purification techniques and emission values or between emission values and energy efficiency could be established. The correlations were considered too complex to be connected with simple categories such as wet/dry systems or moving bed filter/entrained flow adsorber performance features. Furthermore, the empirically determined values did not prove useful in establishing a systematic correlation between the level of energy demand and system type.

[2] 'TE' refers to toxicity equivalent of dioxin-/furan concentrations

The specific process management and system design as well as age and size of the facilities were noted as considerably more significant to environmental performance than typology of the installed technology. For this reason, a detailed analysis was carried out on the basis of a computational model for four exemplary MSWI plants with the aim of evaluating the material and energy recovery in the context of emissions from the plant itself. The key indicators selected were CO_2 (fossil), NO_X, mercury and cadmium. Resource and external energy consumption were also taken into account as were the emissions spared by the substitution of primary raw materials and energy sources [10].

Although the four plants were selected with regard to high-level compliance with material and energy use as well as emission minimization, one plant demonstrated only moderate compliance with these aspects in order to serve as a comparison. Consequently, the three modern plants revealed an overall positive environmental balance across the entire spectrum of indicators. The emissions prevented were consistently higher than those generated. As part of the material assessment, the generation of differentiated and specified material flows with high-value recycling potential (gypsum, hydrochloric acid etc.) was generally positively evaluated in terms of sustainable materials management. This means that primary resources are conserved and finite depositional environments are ceded more appropriate material flows. However, this point is considered of low priority in view of the rather limited mass flows and the scant reference to its environmental relevance [10].

A further attempt to determine the energy efficiency of flue gas purification in waste incineration plants has been made by [11]. Various energy indicators based on a sample plant were ascertained and compared. The analysis was based purely on energy flows. No primary energy input from other material flows, such as those from additives, were considered. In summary, it was asserted that alterations in flue gas purification mainly lead to alterations in electrical energy demand.

Energy demand has been ascertained for other power generation and energy conversion plants in the context of Life Cycle Assessments (LCA). For example, the structural complexity and ecological importance of amine scrubbing for CO_2 separation attributed to coal-fired power plants has been evaluated. The FfE Research Center for Energy Economics has applied energy-based Life Cycle Engineering (LCE) to energy provision. In this context, emissions from the electricity supply from thermal and nuclear power plants were analysed [12]. The scope of the investigated power plants ranges from nuclear power, through coal and lignite, gas and steam and combined heat and thermal power plants. Energy provision from waste incineration plants was not taken into account.

2.2 Discrepancies in emission requirements across individual Acts and Ordinances

With increasing industrialization and advancing economic growth in the second half of the twentieth century, air pollution continued to increase until its effects, such as forest decline or the visible corrosion of construction materials, could no longer be ignored.

The legislature responded with the creation and adoption of relevant guidelines and ordinances on compliance with emission limit values applicable to a wide range of emissions producers. These included, besides the main contributors from the power plant industry of the time, numerous resource-based industries such as the iron and steel industry as well as small-scale businesses such as printing companies. With the passage of the first *TA-Luft in 1974,* the emission limit values of various air pollutants were increasingly reduced along with the level of development in flue gas treatment technologies, or the number of emission-limiting pollutants was increased and updated, culminating in the current IPPC Directive.

The development of the statutory emission limit values for waste incineration was subject to the most significant amendments, compared to other emissions producers, in terms of both emission levels as well as in the scope of air pollutants subject to reduction. One reason for this undoubtedly lies in the lack of acceptance of waste incineration and consequent political pressure. Due to technological developments in individual flue gas treatment systems, the emission level attributed to waste incineration plants is significantly lower than that attributed to power plants, for instance. This has now led to significant discrepancies in the various guidelines and ordinances concerning the definition of emission limit values for individual pollutants, such as sulphur dioxide (SO_2).

Since the current guidelines and ordinances show such dissonance, a common basis must first be established which will allow a direct comparison of emission limit values. Thus, for example, the emission limit values for small and large-scale combustion plants contained in the *TA-Luft* and the *13. BImSchV* differ in terms of aggregate state (solid, liquid and gaseous) of the fuel, fuel type (coal, lignite, etc.) as well as rated thermal input classification (RTIC). Since waste, with the exception of hazardous waste, can be classified as a solid fuel, an immediate comparison with other solid fuels for each selected pollutant is perfectly acceptable. In order to provide comparability in relation to the rated thermal input, the data (cf. Figure 2) for waste incinerators in operation in Germany was taken as a basis. About two-thirds of all plants have a rated thermal input of between 50 MW and 250 MW, while all others lie below 50 MW.

It follows that a comparison is possible between the emission limit values set out in the *17. BImSchV* and those set out in the *13. BImSchV* for an RTIC 50 MW < RTI < 300 MW as well as for an RTI < 50 MW as set out in the *TA-Luft*. When comparing daily average values (DAV), Table 2 shows the existence of manifold discrepancies for the pollutants dust, sulphur dioxide (SO_2) and carbon monoxide (CO). The fact that the emission limit value for dust in the *17. BImSchV* is 50 % lower than that in the *13. BImSchV* and the *TA-Luft* is perfectly valid due to the particulate nature of many heavy metals and trace elements.

By contrast, the reasons for the discrepancy in the SO_2 emission limit value which is four times lower (sometimes even more) in the *17. BImSchV* than in the *13. BImSchV* and the *TA-Luft* are unclear. This discrepancy is also followed up in the new European Industrial Emissions Directive (IED), dated 24 November 2010 [14].

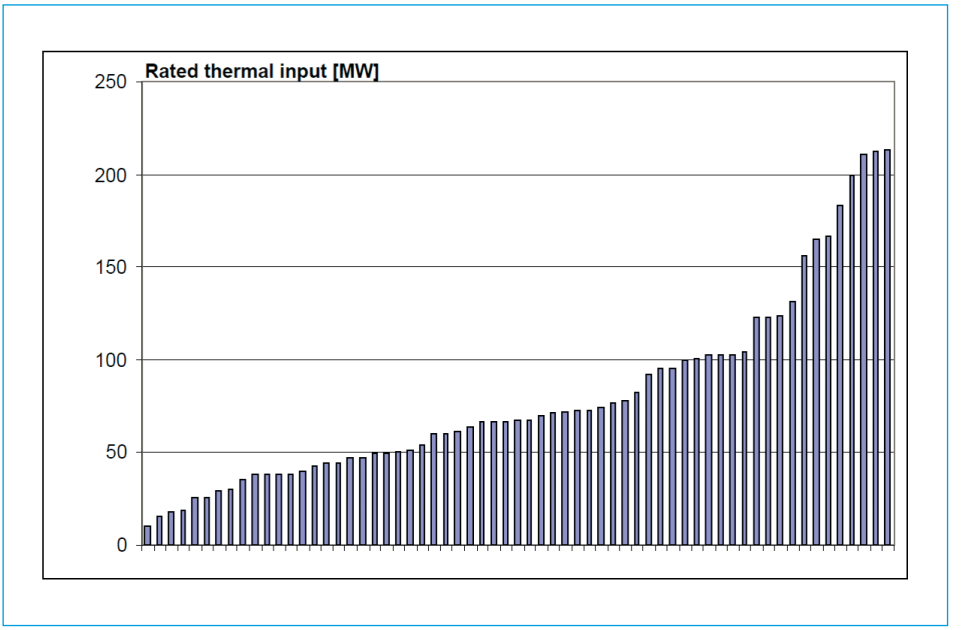


Figure 2: Rated thermal input in thermal treatment plants for municipal waste in Germany as of 2006 [13]

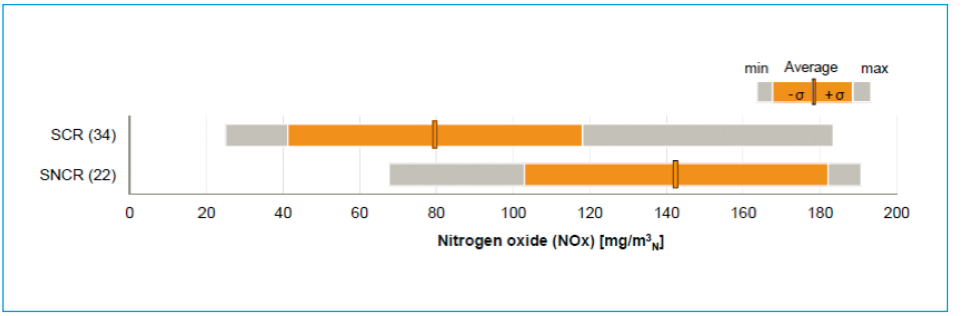


Figure 3: Comparison of selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) for flue gas denitrification (number of plants in brackets) [18]

A direct comparison between actual emissions generated and the limit values set out in the *17. BImSchV* reveals that the former again lie well below the latter (cf. also [17]). Figures 3 to 8 show the annual mean values along with the standard deviations for the emission limit values set out in the *17. BImSchV*, pertaining to plants currently in operation in Germany [18].

All plants comply with the limit values and consistently remain below them. The emission values attained differ depending on the plant and system technology installed (i.e. the use of a wet or dry, single stage or multi-stage system).

Table 2: Comparison of the emission limit values contained in different guidelines and ordinances for solid fuels and comparable rated thermal input [1, 14, 15, 16]

		17. BImSchV 2003 version		EG Guideline 2000/76		13. BImSchV 2004 version 50 MW < RTI < 300 MW	TA Luft 2002 version RTI < 50 MW
Pollutant	**Unit**	DAV	HHAV	DAV	HHAV	DAV	General requirements
O_2-reference percentage	[Vol.-% dry]	11		11		6	7 - 11
Dust	[mg/m³]	10	30	10	30	20	20
Total Organic Carbon (TOC)	[mg/m³]	10	20	10	20	-	50
Hydrogen chloride (HCl)	[mg/m³]	10	60	10	60	-	30
Hydrogen fluoride (HF)	[mg/m³]	1	4	1	4	-	3
Carbon monoxide (CO)	[mg/m³]	50	100	50	100	150	150
Sulphur dioxide (SO_2)	[mg/m³]	50	200	50	200	200 - 350	350 - 1300
Nitrogen oxide (NO_2)	[mg/m³]	200	400	200	400	200 - 400	150 - 500
Heavy metals							
Mercury (Hg)	[mg/m³]	0.03	0.05	0.05		0.03	0.05
		Single measurements		Single measurements		Single measurements	
Dioxins and furans	[ng/m³]	0.1		0.1		0.1	-
Class I	[mg/m³]	0.05	-	0.05		0.05*	0.05[2)]
Class II	[mg/m³]	0.5		0.5[1)]		0.5*	0.5[3)]
Class III	[mg/m³]	0.05		-	-	0.05*	1[4)]

The concentration data is based on standard temperature and pressure, dry state, for each oxygen reference value

DAV indicates daily average value; HHAV indicates half hourly average value

Heavy metals class I: Σ Cd/Tl

Heavy metals class II: Σ Sb, As, Pb, Cr, Co, Ni, Cu, Mn, V, Sn

Heavy metals class III: Σ As, benzopyrene, Cd, Co(aq), Cr(IV)

* not applicable to use of coal, untreated wood only

[1)] excluding Sn

[2)] applicable to Tl (single substance)

[3)] applicable to Pb, Co, Ni, Se, Te

[4)] applicable to Sb, Cr, CN, F, Cu, Mn, V, Sn

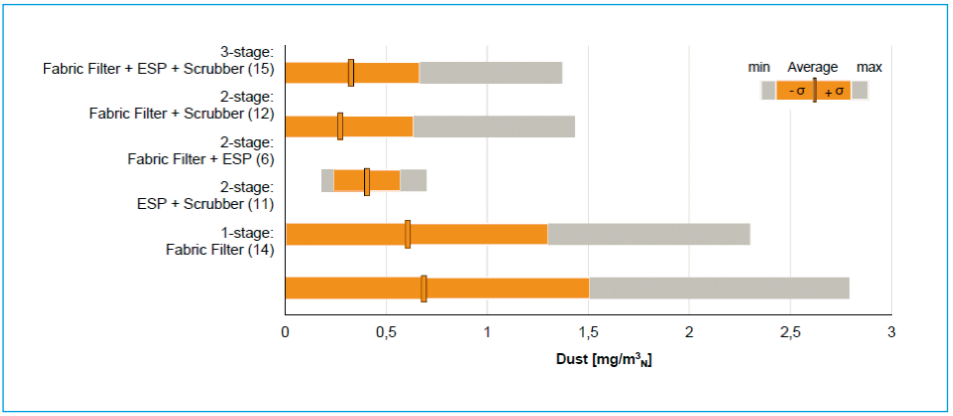


Figure 4: System comparison for the separation of dust (number of plants in brackets) [18]

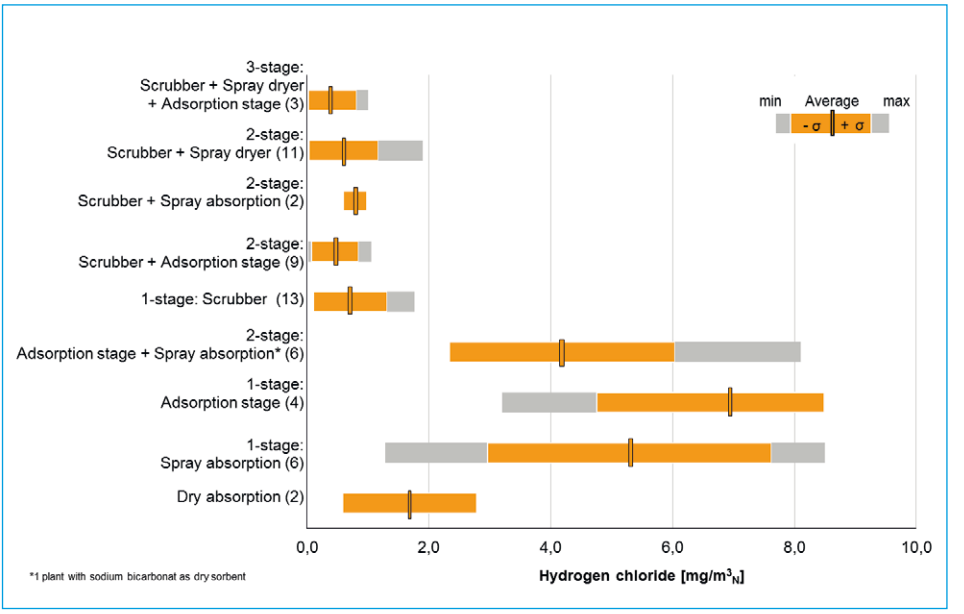


Figure 5: System comparison for the separation of hydrogen chloride (number of plants in brackets) [18]

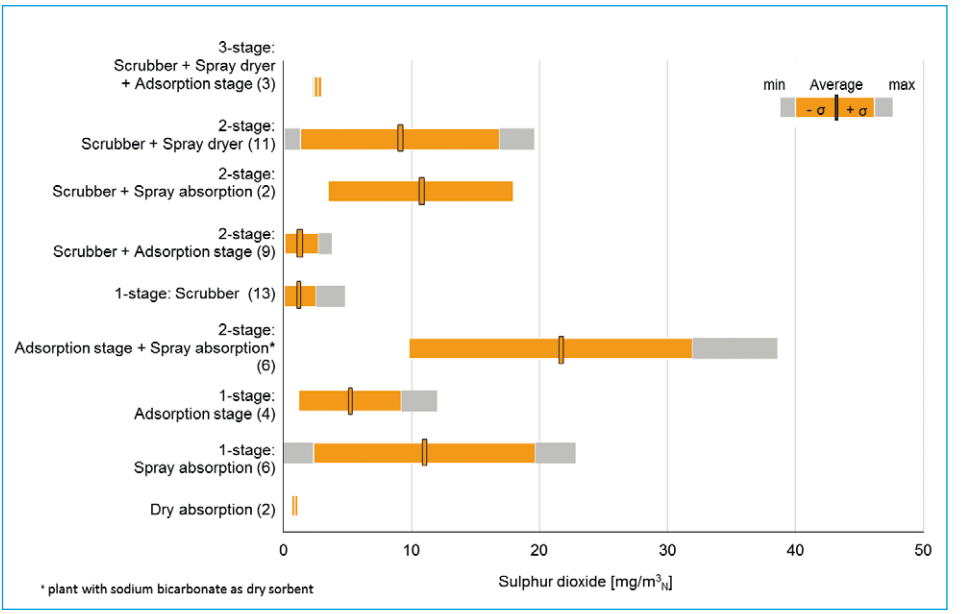


Figure 6: System comparison for the separation of sulphur dioxide (number of plants in brackets) [18]

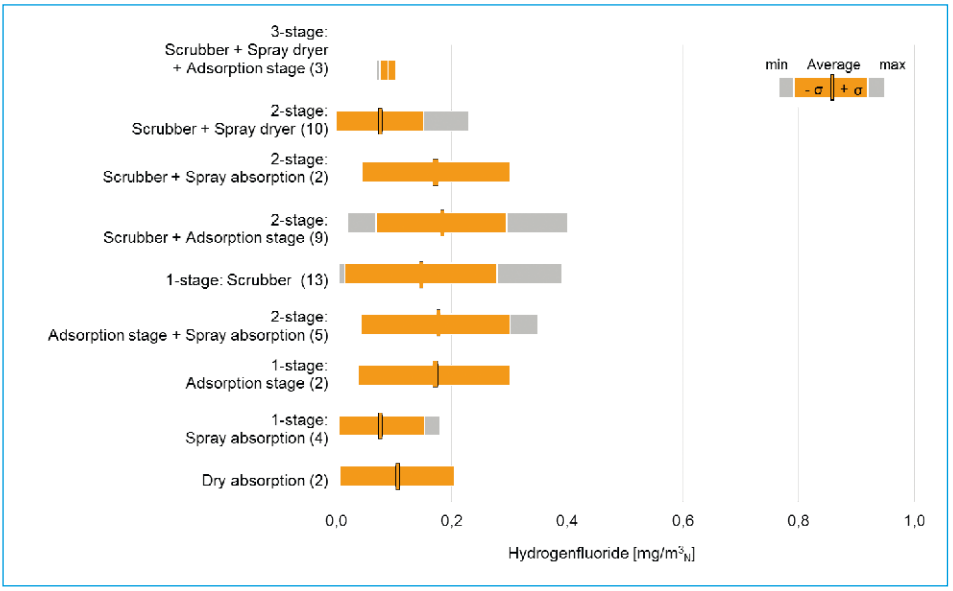


Figure 7: System comparison for the separation of sulphur dioxide (number of plants in brackets) [18]

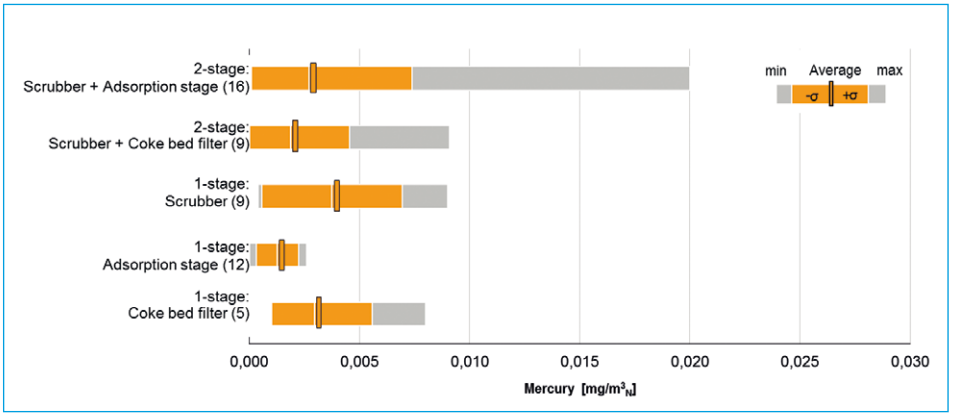


Figure 8: System comparison for the separation of sulphur dioxide (number of plants in brackets) [18]

Since the total energy demand required to ensure a certain pollutant separation or corresponding emission level using different flue gas treatment systems is not clear from previous assessments, the purpose of the present study on the ascertainment of emissions-related energy indicators is to establishan assessment criterion which will allow an ecological life-cycle assessment of future emission requirements in the context of the emissions-generating input necessarily incurred by emission reduction measures (flue gas treatment plants).

Another significant difference to the observations referred to in the literature is that the mass/material and energy analyses as well as the process conditions and dependencies considered here have been based on real plants, rather than on assumptions.

The results of this study thus represent not only a reliably sound technical but also political foundation for future discussion on the tightening of emission limit values.

Key word index

A

Absorption 15
Acid scrubber stage 24
Adsorption 15
Air pollutants 9
Air to cloth ratio 47
Ammonium hydroxide injection 22
Apparatus and steel construction 32
Assessment boundaries 3, 28
Assessment scope 28

B

Base plate 32
Bundesimmissionsschutzverordnung (BImSchV - German Federal Immission Control Ordinance) 1

C

Catalyst 24
Chemical influences 42
Cl/S ratio 42
Combined system 24
Component level 38
Compressed air demand 45
Construction 32
Credit 73
Cumulative energy demand (CED) 2, 3

D

Dedusting cycle 48
Dedusting frequency 45
Dedusting 47
Disposal phase 2
Disposal 73
Dry sorption methods 1
Dry sorption system 16
Dust conditioner 23
Dust layer 46
Dust resistance 47

E

Electrical installation 32
Electricity mix 4
Emission balance 82
Emission factors 81
Emission levels 1
Emission limit values 1
Emission minimization 6
Emission reduction ratios 2
Emission reduction 3
Emission requirements 6
Emissions 1
Emissions-related energy indicators 81
Energy and material flows 28
Energy demand 2, 4
Energy difference 70
Energy efficiency 6
Energy equivalent emission factors 81
Energy equivalents 4
Energy flows 58
Energy offtake 24, 57
Energy output 53
Energy-based life cycle engineering (LCE)..6
Enthalpy of vaporization 43
Equivalent energy demand 27
Evaporative cooling (EC) 26, 106
Excess emissions 5
Excess energy demand 90
External factors 38

F

Filter chamber 46
Filter cloth area 47
Filter elements 46
Filter hose dedusting 41
Filter medium 46
Filtration periods 46
Filtration rate 46
Flue gas composition 1
Flue gas conditioning 26
Flue gas cooling 26, 27
Flue gas enthalpy 43
Flue gas reheating 24
Flue gas scrubber 15
Flue gas treatment 1-5, 15
Flue gas treatment components 15
Flue gas treatment plants 1
Flue gas treatment system 2

G

Gaseous pollutant separation rate 22
Guidelines 9

H

HCl emission factor 81
Heating value 39, 73
Hybrid systems 22
Hygroscopic calcium chloride salts 45

I

Indicators 81
Individual consumption values 53
Influencing variables 38
Influential factors 40
Interval period 48
Inventory analysis 2
Inventory module 51
Isohumid changes in state 26

K

K-additive indicator 75
K-operation indicator 76
K-plant technology indicator 75

L

Life cycle assessments (LCA) 6

M

Mass, material and energy balances 2, 3
Material balances 35
Material tree graph 32
Mollier h-x-diagram 26

N

Network structure diagram 40
NH_3-slip 18
NH_3-stripping tower 22
Nitrogen oxide reduction 24
Nitrogen oxides 1

O

Operating energy demand 38
Ordinances 6

P

Packed scrubbers 15
Pollutant concentrations 4
Pressure loss 46
Primary energy input 30
Primary energy requirement 35
Procedural indicators 41
Process chain analysis 3
Process efficiency 43
Process parameters 30
Process stages 77
Production phase 2, 31

R

Rated thermal input classification (RTIC)..9
Ratio of chlorine to sulphur (Cl/S) 41
Recirculation of solids 42
Recuperative flue gas cooling 24, 80
Recycling 73
Reduced electricity generation 70
Reduced emissions 70
Relative humidity 24, 26
Residual material recirculation rates 47
Residual resistance 47
Residue 1
Resource consumption matrix 27
Resource consumption value 28
Re-use 56

S

Sankey Diagrams 59
SCR 10
Selective catalytic reduction (SCR) 10
Selective non-catalytic reduction (SNCR)..10
Selective separation efficiency 16
Separation efficiency 2
Separation potential 24
Separation rate 2
Simultaneous systems 16

Single inventory flow 49
SNCR 10
Sorbents 27
Sorption agent 15
Sorption filter 16
Specific cumulative energy demand 28
Specific diesel consumption 56
Specific energy consumption 30
Spray scrubbers 15
Stoichiometry 41, 45, 50
Surface masses 47
System boundaries 30
System matrix 16
System Variants 17

T

TA-Luft
(Technical Instructions on Air Quality Control) 1
Test results 44
Thermal recycling 56
Total efficiency 43
Total stoichiometry 51
Transportation distances 57
Transportation expenditure 30

U

Use phase 73

V

Variability analysis 39
Variants 2
Venturi scrubber 15

W

Wet and semi-dry/
dry air pollution control systems 15